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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 376

EFFECT OF HIGH AIR VELOCITIES ON THE DISTRIBUTION AND PENETRATION OF A FUEL SPRAY

By A. M. Rothrock
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Summary

By means of the N.A.C.A. Spray Photography Equipment high-speed moving pictures were taken of the formation and development of fuel sprays from an automatic injection valve. The sprays were injected normal to and counter to air at velocities from 0 to 800 feet per second. The air was at atmospheric temperature and pressure. The results show that high air velocities are an effective means of mixing the fuel spray with the air during injection.

Introduction

A year ago, Beardsley and the author (Reference 1) published information on the effect of low air velocities (60 feet per second) on the penetration and dispersion of fuel sprays for compression-ignition engines. The results showed that although during injection the moving air had little effect on the main body of the spray, the fuel on the edge of the spray was blown away from the main body when the air was directed counter to the spray. It was shown, in addition, that the air distributed the fuel throughout the spray chamber at the end of injection. The air velocity used in these experiments was much lower than that in engines employing a small orifice through which the piston forces the air. In combustion chambers of the shape employed by the National Advisory Committee for Aeronautics in its research on precombustion chambers (Reference 2) and in chambers of the type employed with the Acro-Bosch system (Reference 3), air velocities of several hundred feet per second may be obtained. Under these conditions the velocities are equal to or greater than the velocity of the fuel spray after it has traversed an inch or so of the combustion chamber. Consequently, we may expect that these air velocities will have a marked effect on the fuel spray.

To determine the effect of air velocities of several hundred feet per second on fuel-spray formation, a series of tests has been conducted at the Langley Memorial Aeronautical Laboratory, Langley Field, Va., in which air velocities were calculated to be as high as 800 feet per second. All tests were made with the fuel injected into air at atmospheric pressure and temperature. From the results showing the effect of air density on spray formation obtained by Joachim and Beardsley (Reference 4) and from the results showing some effects of air temperatures on spray formation obtained by Gelalles (Reference 5), it can be concluded that any effects observed in the present tests will be magnified under engine-operating conditions.

Apparatus and Methods

The apparatus consisted of the photographic apparatus of the N.A.C.A. Spray Photography Equipment (Reference 6), an injection system of the same design as that employed with the N.A.C.A. Spray Photography Equipment (Reference 7), and a single-cylinder test engine with a special cylinder head, The cylinder head (Figure 1) was of the vertical disk form similar to that employed by Spanogle and Foster (Reference 8). For the present tests, a small rectangular orifice connected the head or spray chamber with the cylinder. There were no valves in the head. Instead, both faces were opened to the atmosphere. Consequently, the air displaced by the piston of the engine was forced through the narrow opening into the surrounding air, which was at atmospheric pressure. The fuel-injection system was operated through a clutch so that a single injection was obtained when the clutch was engaged. By means of a gearing unit the injection could be timed to start at any crank angle. The start of injection with relation to the crank angle was determined by mounting the injection valve directly over the flywheel of the engine and spraying onto a piece of heavy paper attached to the flywheel. The start of injection for successive tests with the same timing did not vary by more than 0.5 crank degree. The period of injection as measured from the spray photographs was approximately 0.003 second. The engine speed was maintained constant at 800 r.p.m.

The air velocity for an engine speed of 800 r.p.m. was computed by assuming that the rate of air displacement by the piston was equal to the rate of compression in the cylinder plus the rate of discharge through the orifice:

$$6Anv_\theta = c\,\frac{p_o}{p_\theta}\,a\sqrt{\frac{(p_\theta - p_o)\,2g}{\rho_o}} + \frac{6nV_\theta}{p_\theta}\,\frac{dp_\theta}{d\theta} \qquad (1)$$

in which

θ - crank angle in degrees.
n - engine r.p.m. = 800.
A - area of the engine piston = 19.65 square inches.
v_θ - velocity of the piston at any crank angle θ = inches per degree.
p_o - atmospheric pressure = 14.7 pounds per square inch.
p_θ - pressure in the cylinder at the angle θ.
a - area of the discharge orifice = 0.695 square inch.
g - gravitational acceleration = 386 inches per second per second.
V_θ - volume in the cylinder at the angle θ.
ρ_o - density of the air at atmospheric pressure and temperature = 4.43×10^{-5} pounds per cubic inch.
c - coefficient of discharge of orifice, assumed to be 1.00.

As both v_θ and V_θ are functions of θ, instead of integrating equation (1), $\frac{p_{\theta_2} - p_{\theta_1}}{\theta_2 - \theta_1}$ was substituted for $\frac{dp_\theta}{d\theta}$. In the solution of the equation, $\theta_2 - \theta_1$ was taken as 10 degrees. Each successive value of p_{θ_2} was obtained by using the preceding value of p_{θ_2} for p_{θ_1}. The velocity S through the orifice was then computed from the conventional flow equation:

$$s_\theta = c\sqrt{\frac{p_\theta - p_o \; 2g}{\rho_o}} \qquad (2)$$

The results of these computations are shown in Figure 2. The maximum velocity, 813 feet per second, occurred 45 degrees before the piston reached top center. The pressure in the engine cylinder at this position was shown by equation (1) to be 20.1 pounds per square inch, resulting in a differential pressure of 5.4 pounds per square inch. In the test results the start of injection is given in crank degrees. The corresponding velocity is obtained from Figure 2.

The injection valve (Figure 3) was the same that Beardsley and Joachim used (Reference 9) in their comparison of sprays from centrifugal and noncentrifugal sprays. In the present investigation a 0.020-inch diameter orifice was used with a noncentrifugal stem in the injection valve. An injection pressure of 3,500 pounds per square inch was used in all the tests.

Analysis

When a jet of air is directed against a fuel spray, the moving air will tend to carry the drops of fuel in the direction of motion of the air. If the drops be dispersed to such a distance as to have no mutual influence on each other, the effect of the moving air on the motion of the drops can be determined by equating the force exerted by the air on the fuel drop to the product of the mass of the drop multiplied by its acceleration in the direction of air flow. Considering only the motion imparted to the fuel drop by the moving air:

$$m\,\alpha = \psi\,\rho_a\,v_a^2\,\pi\,r^2 \qquad (3)$$

in which

m - mass of the fuel drop.
α - acceleration of fuel drop caused by moving air.
ψ - coefficient of friction of drop.
ρ_a - density of air.
r - radius of drop.
v_a - velocity of the air with respect to the fuel drop.

But

$$m = \frac{4}{3}\,\pi\,r^3\,\rho_f \qquad (4)$$

in which ρ_f is the density of the fuel drop. Substituting the value of m from equation (4) in equation (3) and solving for α,

$$\alpha = \frac{3}{4}\,\psi\,\frac{\rho_a}{\rho_f}\,\frac{1}{r}\,v_a^2 \qquad (5).$$

The velocity v_a is, at all times, equal to the difference between the velocity of the fuel drop v_f and the velocity of the air v_1. Moreover the acceleration of the drop is equal to dv_f/dt. Substituting these values in equation (5),

$$\frac{dv_f}{dt} = K\,(v_1 - v_f)^2 \qquad (6)$$

in which

$$K = \frac{3}{4}\,\psi\,\frac{\rho_a}{\rho_f}\,\frac{1}{r}\,.$$

Integrating equation (6), considering v_1 as constant and that $v_f = 0$ when $t = 0$, the velocity of the fuel drop is given by

$$v_f = \frac{v_1^2 \, Kt}{1 + v_1 \, Kt} \qquad (7).$$

However, v_f is equal to ds/dt in which s is the distance traveled by the drop because of the force of the moving air. Integrating again, the value of s is expressed by

$$s = v_1 \, t - \frac{1}{K} \log_e (1 + v_1 \, Kt) \qquad (8).$$

Since $s = 0$ when $t = 0$, all the values in equation (8) are known with the exception of ψ which appears in the constant K. The value of ψ depends on the Reynolds Number of the flow conditions. Reynolds Number is expressed as $\frac{2 v_a r \, \rho_a}{\mu}$, in which μ is the coefficient of viscosity of the air. According to the work of Lunnon (Reference 10), the value of ψ for the conditions met with in this work varies between 0.16 and 0.24. For the present analysis the value of 0.24 will be used to show the maximum effect of the air flow.

The curves in Figure 4, computed from equation (8), show the distance traversed by individual drops of various diameters in an air flow of 600 feet per second at a density corresponding to atmospheric temperature and pressure. Figure 5 shows the effect of various air velocities on the distance traversed by a drop 0.002 inch in diameter in air at the same density. The drop diameter of 0.002 inch corresponds to the mean diameter obtained by Kuehn for an injection pressure of 3,500 pounds per square inch (Reference 11). The figure shows that, for air at low densities, velocities of 300 feet per second or more are required to deflect a single drop a distance of 1 inch in 0.001 second - approximately 10 crank degrees at 1,500 engine r.p.m.

Figure 6 shows the effect of various air velocities on the distance traversed by a single drop 0.002 inch in diameter in an air density corresponding to a compression ratio of 14:1. This density represents that obtained in the combustion chamber of a compression-ignition engine close to top center. It is seen that velocities as low as 200 feet per second cause appreciable deviation in the path of individual spray drops.

Experimental Results

Air directed normal to the fuel spray.- Figure 7 shows the effects of low air velocities directed normal to the fuel spray. In the test from which the upper record was taken the calculated air velocity was 130 to 0 feet per second during the injection, and in the test from which the lower record was obtained the calculated air velocity was 350 to 60 feet per second. It must be remembered that a certain time interval, approximately 0.00025 second or 1.2 crank degrees, elapsed after the start of injection before the spray encountered the moving air. The upper photograph is similar to those obtained in previous tests in which the spray was injected into air at atmospheric pressure. The lower photograph shows that the air carried away a small amount of the fuel from the edge of the spray. There is also shown a slight bending of the main body of the fuel spray.

Figure 8 shows the effect of an air velocity of 600 to 250 feet per second at the start of injection. In this case the air jet tore the fuel away from the edge of the spray. Also an appreciable amount of the fuel was carried away with the air to the part of the chamber not reached by the spray. A comparison of Figure 8 with the computed data shown in Figure 4 leads to the conclusion that the main body of the spray was probably too dense to permit the air to have as much effect upon it as the computations show. That is, because of the closeness of the fuel drops they did not act individually, but more as a single body. However, the main body was deflected to a greater extent than was recorded in the previous figure.

Figure 9 shows the effects of air velocities of approximately 800 feet per second on the fuel spray. In this case when the spray reached the air jet, the air deflected the spray from its original path and tended to disperse the main body of the spray throughout the chamber. The air broke up the main body of the spray so that it destroyed the central core. The figure shows that with air velocities of about 800 feet per second good mixing of the fuel and air can be obtained even though the air is at a low (atmospheric) density. As the general effects shown in the photographic records agree with those shown in the computed curves, it can be concluded that, neglecting the possible effects of temperature, air velocities of approximately 400 feet per second will effectively disperse the fuel from a single round-hole orifice throughout the combustion chamber of a high-speed compression-ignition engine in the time available for efficient combustion.

Air directed counter to the fuel spray.- Figure 10 shows that, with an air velocity between 100 and 350 feet per second, the main body of the fuel penetrated into the orifice from which the air issued. However, the fuel at the edge of the spray was torn away and blown upward toward the top of the chamber. The mixing of the fuel with the air was better in this case than with the air directed normal to the fuel spray for the same velocities. It is seen that, as was reported in Reference 1, the spray after cut-off was quickly diffused throughout the spray chamber.

With an air velocity of approximately 600 feet per second (Figure 11), the penetration of the spray decreased and the main body of the spray became broader than with the lower velocities. Partial dispersion of the spray, throughout the chamber was completed before cut-off, although the center of the spray still penetrated into the orifice connecting the cylinder with the spray chamber.

With an air velocity of approximately 800 feet per second (Figure 12), the dispersion was still further improved and the air tore considerable spray away from the main body carrying it to the top of the spray chamber. Although the main spray still reached the orifice connecting the cylinder and the spray chamber, the spray intensity was materially decreased.

The air directed counter to the fuel spray is, as is shown by the photographs, an effective means of dispersing the fuel throughout the spray chamber. However, this dispersion is obtained at a considerable sacrifice. As was mentioned in the second section of the report, the pressure required to give the velocity of 800 feet per second was 5.4 pounds per square inch which must be attributed to the pumping losses of the engine. To obtain velocities of even half this much in the engine would require an even higher pressure difference between the cylinder and the combustion chamber. Consequently, it can be concluded that, although air flow in the combustion chamber should materially increase the combustion efficiency of the engine because of the better mixing of the fuel with the air, this increase may be more than balanced by the additional pumping losses of the engine. Previous mention has been made of successful examples of engines in which the air flow is produced by forcing the air through a small passage. In these cases where the overall efficiency of the engine is improved by the use of air flow it can be concluded that the increased pumping losses are less than the gain due to the increased combustion efficiency. Consequently, it is well to point out that in designing an engine in which high air velocities are employed within the combustion chamber care must be taken to keep the pumping losses as low as possible by means of smooth air passages.

It was shown in Reference 1 that when air flow is produced by means of a restriction between the cylinder volume and the combustion space, the maximum air velocity occurs at approximately 25 degrees before top center. Furthermore, the air velocity then rapidly drops to zero except for such residual air movement as may persist because of the momentum of the air. Consequently, if air flow produced in this manner is to be used effectively the injection of the fuel must start about 25 degrees before top center on the compression stroke. This early start of injection increases the possibility of early ignition and a rapid rise in pressure. In cylinder heads such as used on the Tartrais Peugeot engine (Reference 1), the piston is made with a displacer. As top center is approached, the displacer closes the passage between the displacement volume and the combustion chamber and the remaining air is forced through small holes in the displacer. By this method extremely high air velocities of a small cross section can be obtained when the piston is close to the top center position. The objections to such a system are the losses caused by the energy required to force the air through the small passages.

Another method of employing air flow consists of constructing vanes in the intake system of the engine so that the air is given a definite directional motion as it enters the engine. Tests made by Hesselman, Ricardo, and Kemper with systems of this type have definitely proved that the air flow persists during the compression stroke and decreases the fuel consumption of the engine (Reference 1). Air flow produced in this manner need not be accompanied by as large a pumping loss as is experienced when the air flow is produced by the motion of the piston, since it is not a question of producing air flow but of directing the flow of air as it comes into the cylinder. Of course, if higher velocities be created by restricting the intake passage additional pumping losses will result.

Conclusions

The following conclusions are drawn from the tests presented:

1. High air velocities of approximately 400 feet per second are necessary to break up the central core of a fuel spray from a single round-hole orifice during the injection period in a high-speed compression-ignition engine,

2. Lower velocities have little effect on the main body of the spray during injection, but break up the spray at the end of injection.

3. Air velocities directed counter to the spray have more effect on the spray dispersion than velocities directed normal to it.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 10, 1931.

References

1. Rothrock, A. M. and Beardsley, E. G. : Some Effects of Air Flow on the Penetration and Distribution of Oil Sprays. N.A.C.A. Technical Note No. 329, Dec., 1929.

2. Joachim, W. F. and Kemper, Carlton : The Performance of Several Combustion Chambers Designed for Aircraft Oil Engines. N.A.C.A. Technical Report No. 282, 1928.

3. Wild, J. E. : Combustion Chambers, Injection Pumps, and Spray Valves for Solid-Injection Oil-Engines. S.A.E. Journal, May, 1930.

4. Joachim, W. F. and Beardsley, E. G. : The Effects of Fuel and Cylinder Gas Densities on the Characteristics of Fuel Sprays for Oil Engines. N.A.C.A. Technical Report No. 281, 1927.

5. Gelalles, A. G. : Some Effects of Air and Fuel Oil Temperatures on Spray Penetration and Dispersion. N.A.C.A. Technical Note No. 338, May, 1930.

6. Beardsley, E. G. : The N.A.C.A. Photographic Apparatus for Studying Fuel Sprays from Oil Engine Injection Valves and Test Results from Several Researches. N.A.C.A. Technical Report No. 274, 1927.

7. Rothrock, A. M. : Pressure Fluctuations in a Common-Rail Fuel Injection System. N.A.C.A. Technical Report No. 363, 1930.

8. Spanogle, J. A. and Foster, H. H. : Performance of a High-Speed Compression-Ignition Engine Using Multiple Orifice Fuel Injection Nozzles. N.A.C.A. Technical Note No. 344, June, 1930.

9. Joachim, W. F. and Beardsley, E. G. : Factors in the Design of Centrifugal Type Injection Valves for Oil Engines. N.A.C.A. Technical Report No. 268, 1927.

10. Lunnon, R. G. : Fluid Resistance to Moving Spheres. Proceedings, Royal Society of London, April, 1928.

11. Kuehn, Dr. R. : Atomization of Liquid Fuels. Part III: Critical Discussion of Experimental Results. Mixing the Atomized Fuel with Air. N.A.C.A. Technical Memorandum No. 331, Sept., 1925.

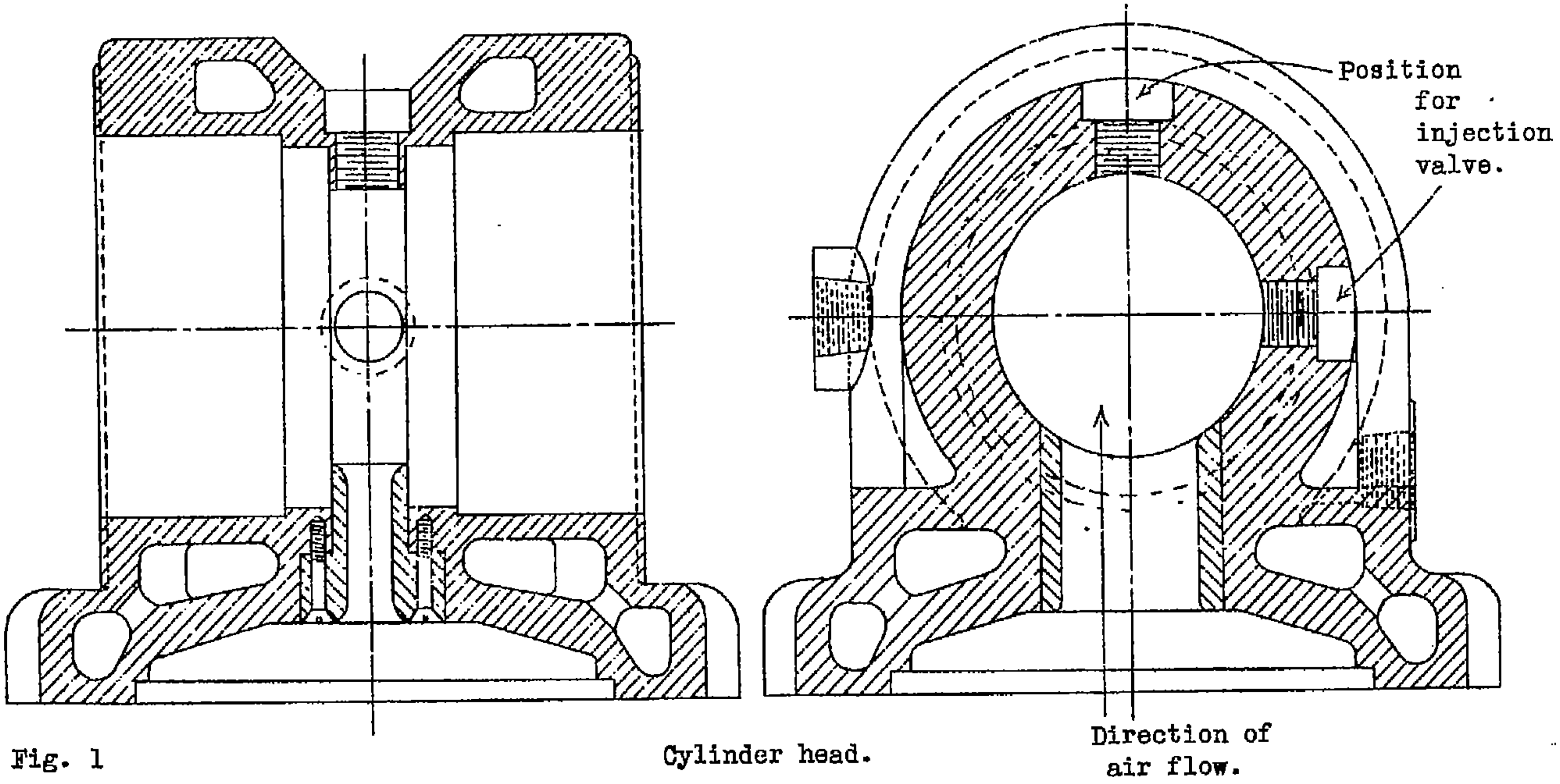


Fig. 1 Cylinder head.

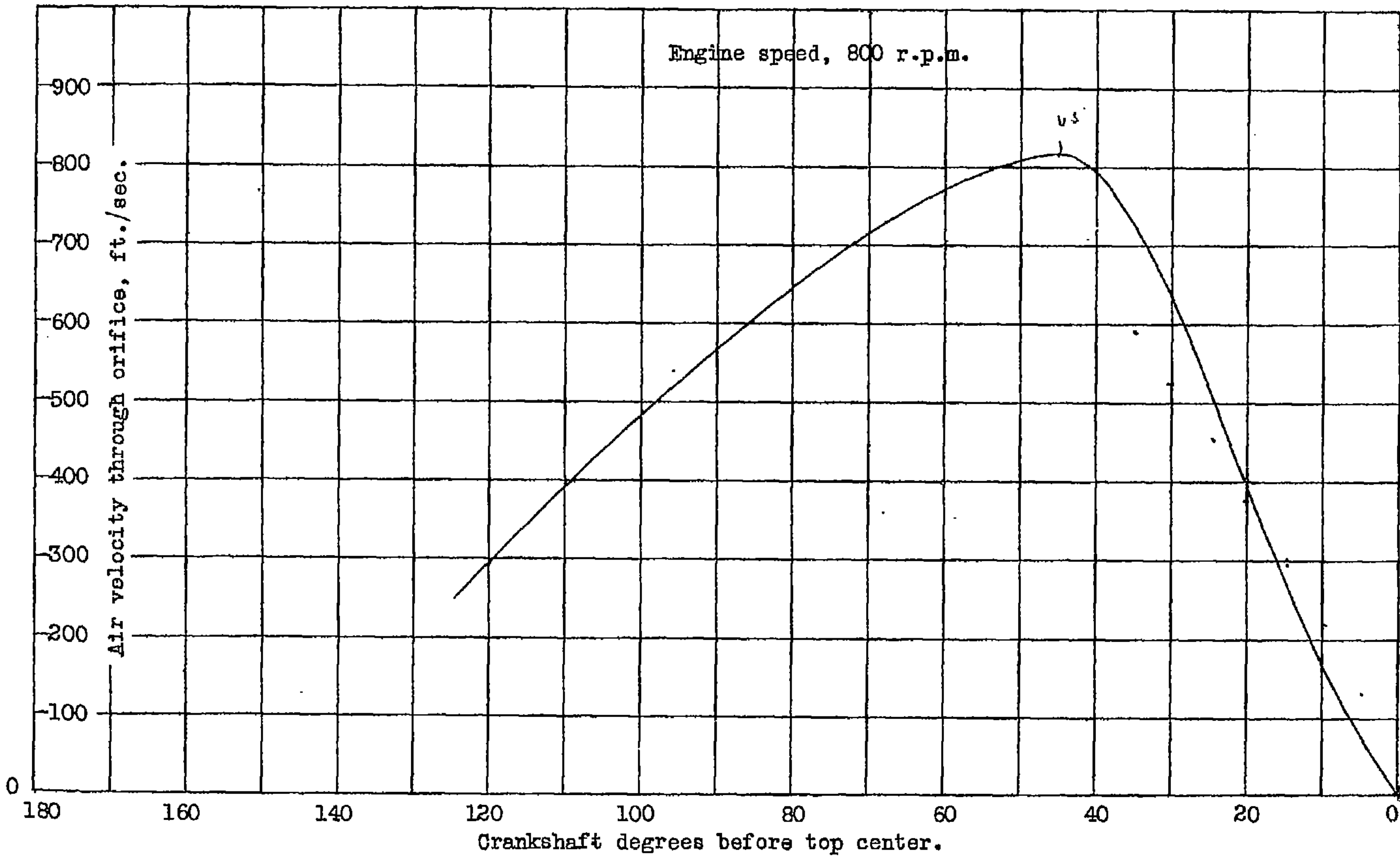


Fig. 2 Computed air velocities.

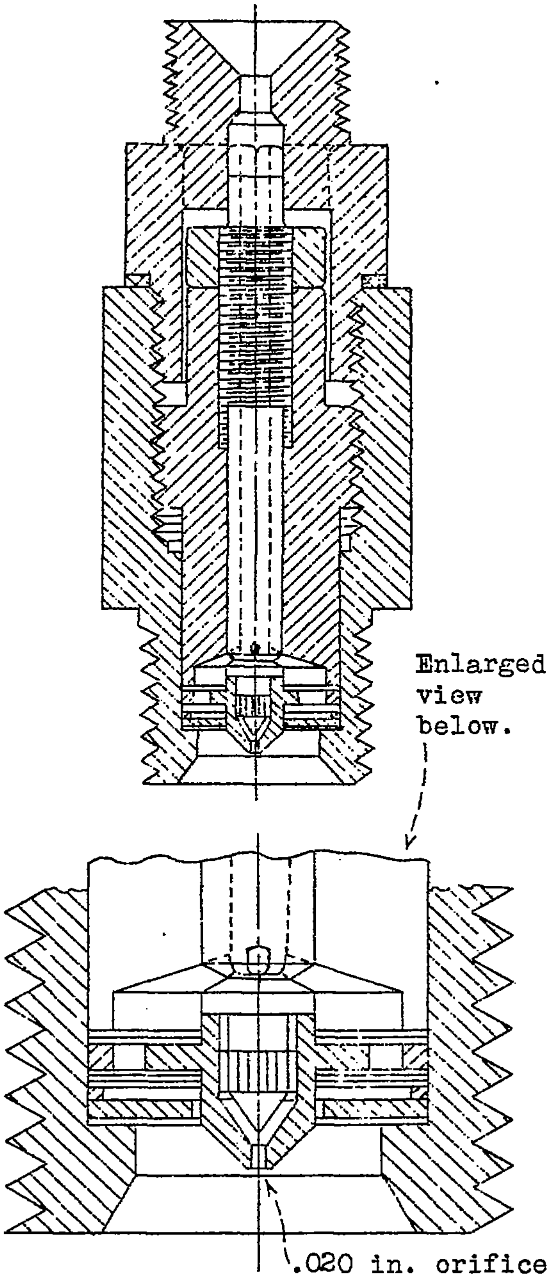


Fig. 3 Injection valve used in tests.

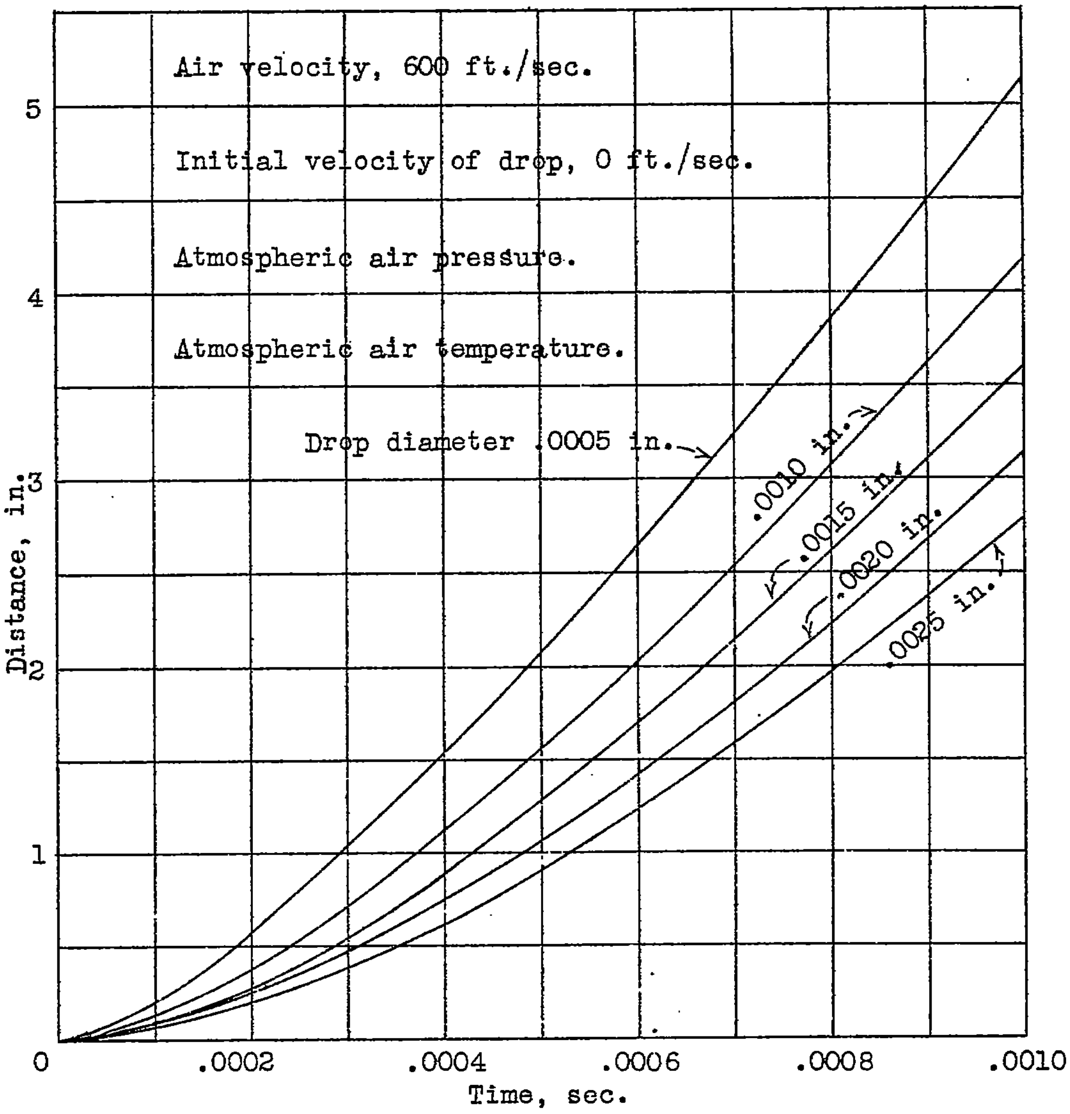


Fig. 4 Effect of drop diameter on distance traversed by a single fuel drop in moving air.

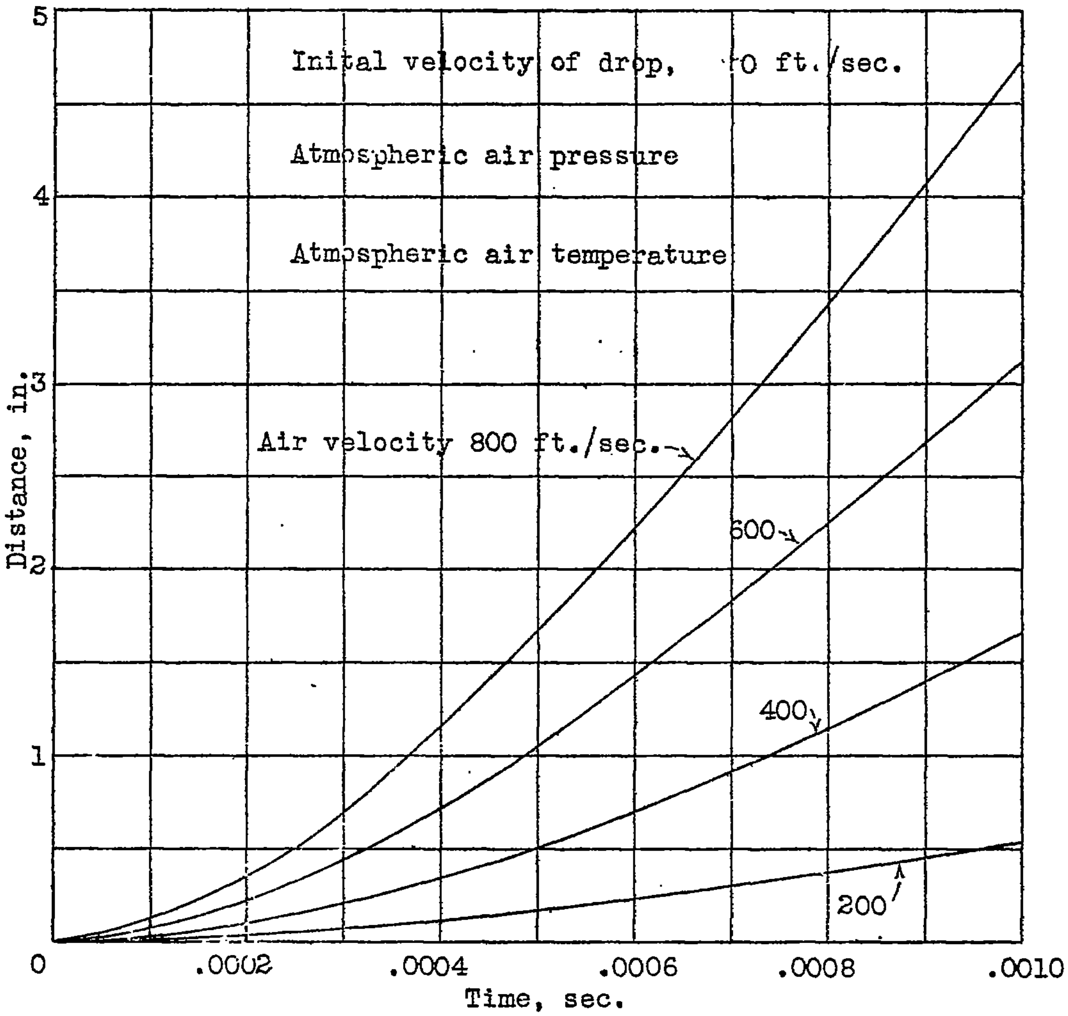


Fig. 5 Effect of air velocity on distance tranversed by a single drop .002 in. in diameter.

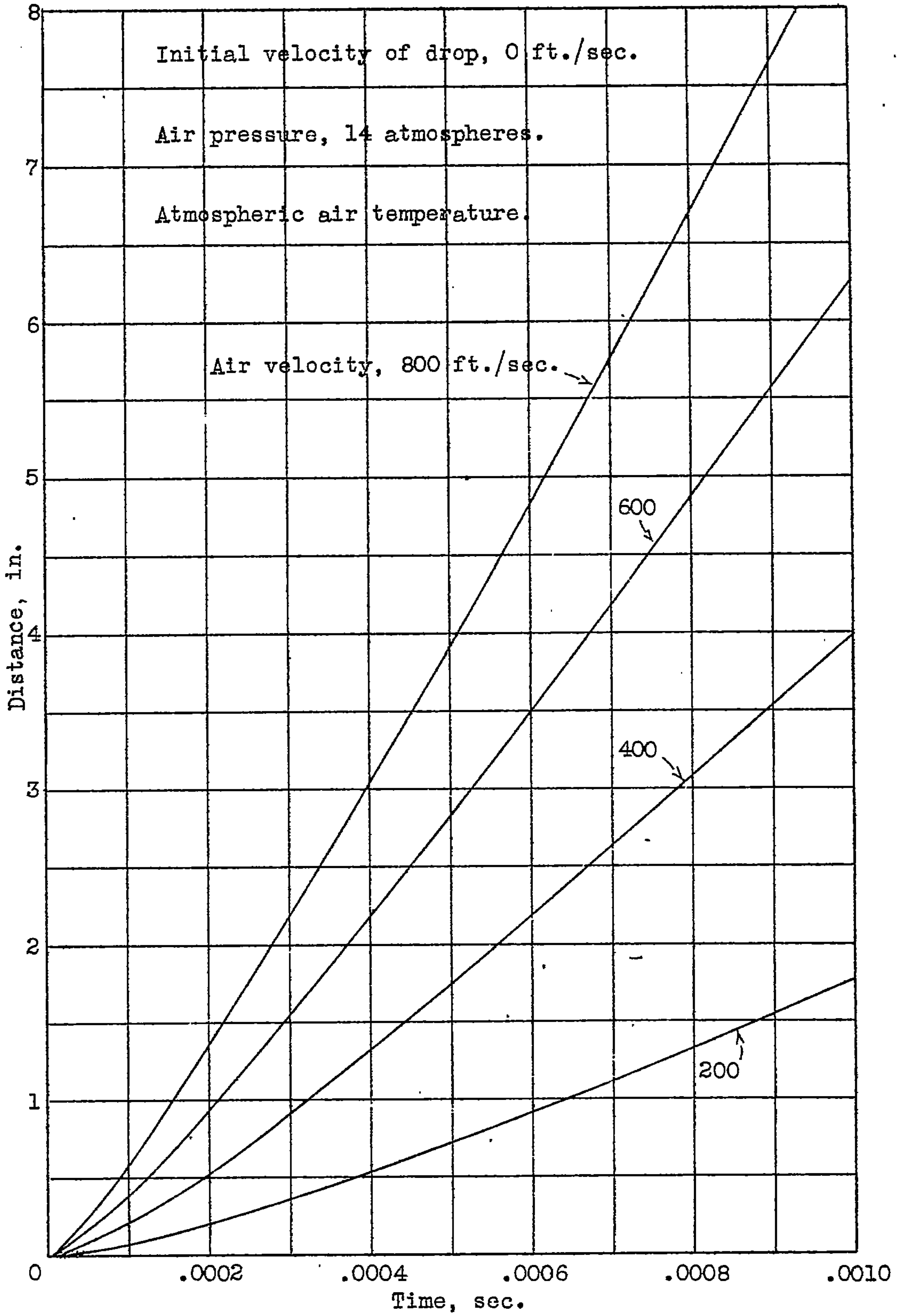
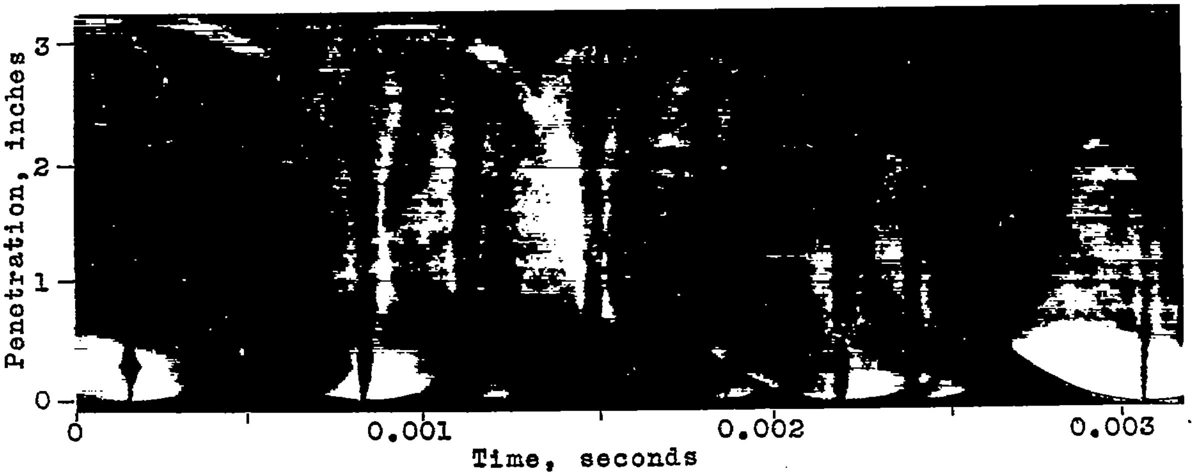
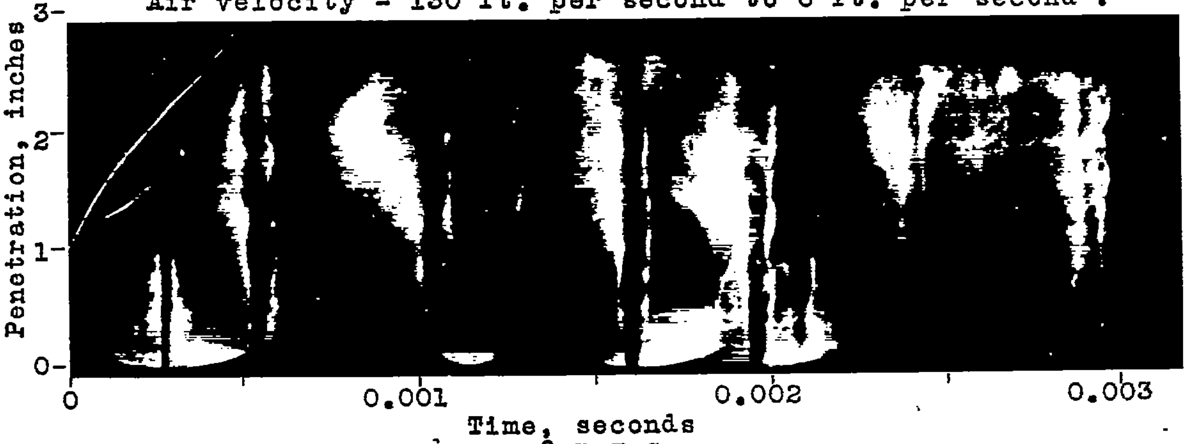


Fig. 6 Effect of air velocity on distance traversed by a single fuel drop .002 in. in diameter.

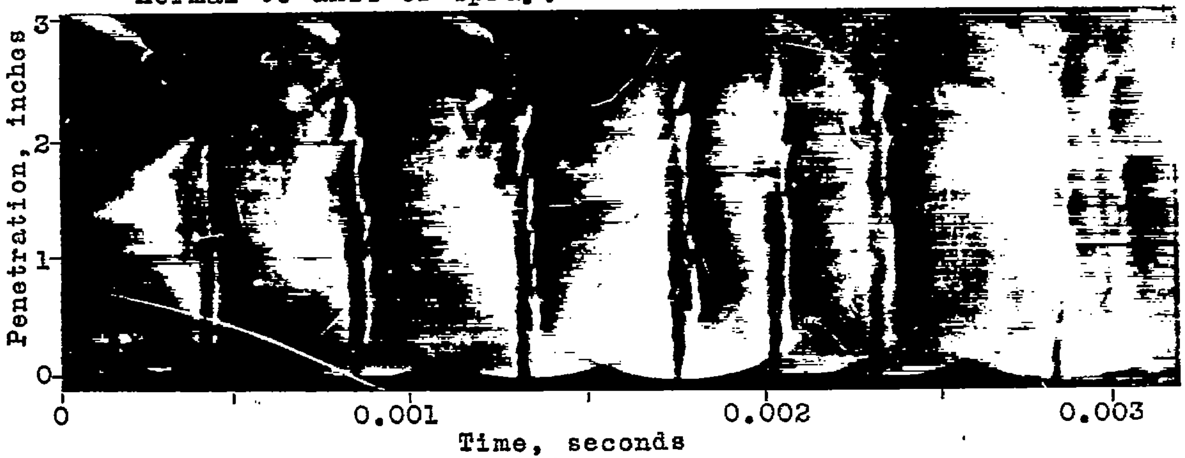


Start of injection - 8° B.T.C.
Air velocity - 130 ft. per second to 0 ft. per second .



Start of injection -18° B.T.C.
Air velocity - 350 ft. per second to 60 ft. per second.

Fig.7 Effect of low air velocity on fuel spray with air directed normal to axis of spray.



Start of injection - 28° B.T.C.
Air velocity - 600 ft. per second to 250 ft. per second.

Fig.8 Effect of medium air velocity on fuel sprays with air directed normal to axis of spray.

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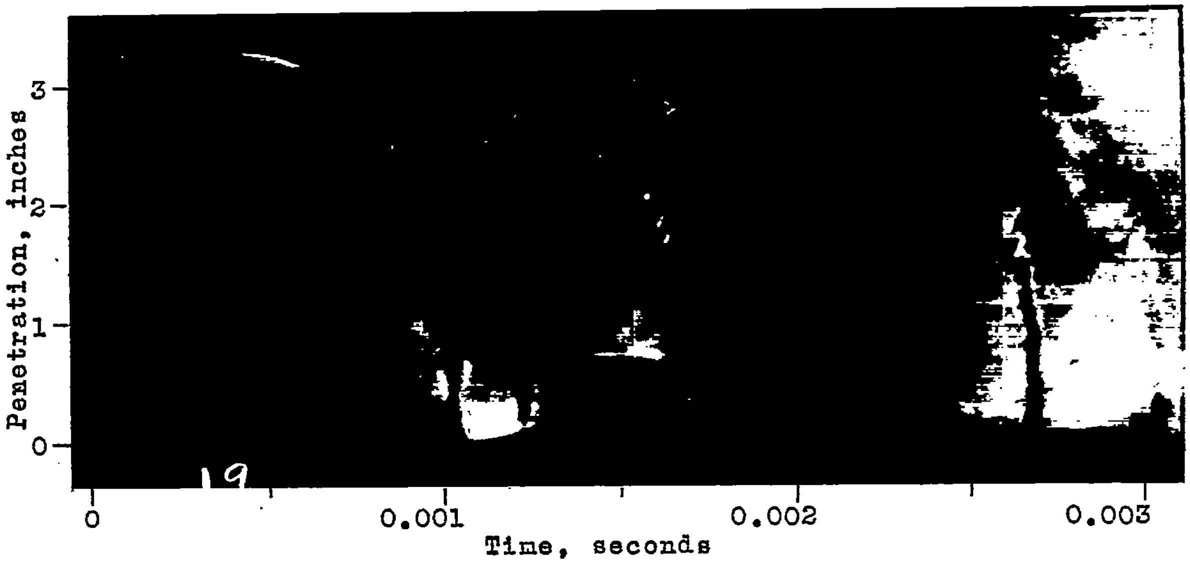
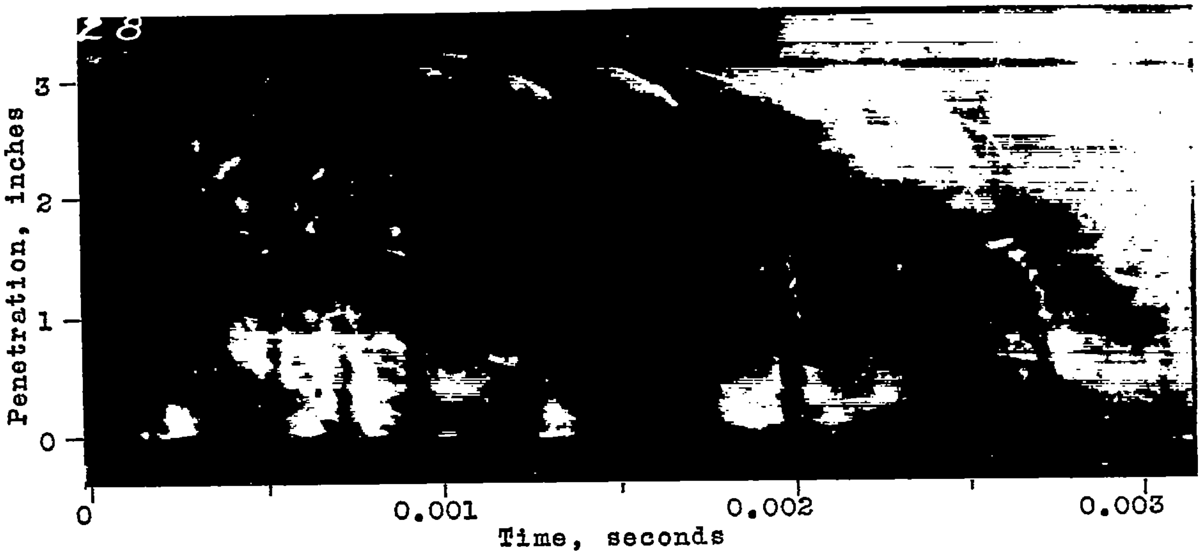


Start of injection - 38° B.T.C.
Air velocity - 790 ft. per second to 500 ft. per second.



Start of injection - 48° B.T.C.
Air velocity - 800 ft. per second to 710 ft. per second.

Fig.9 Effect of high air velocity on fuel sprays with air directed normal to axis of spray.

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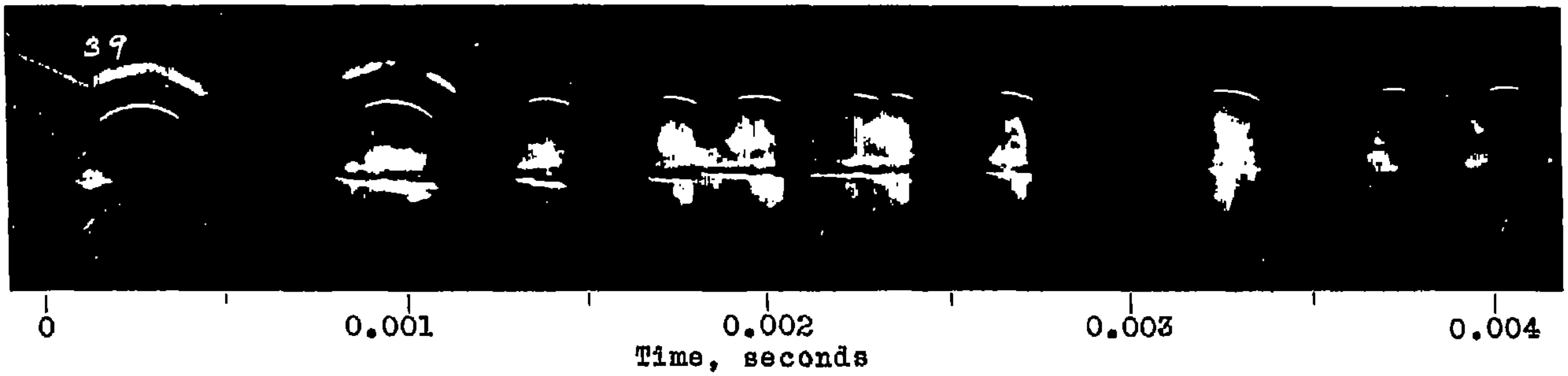
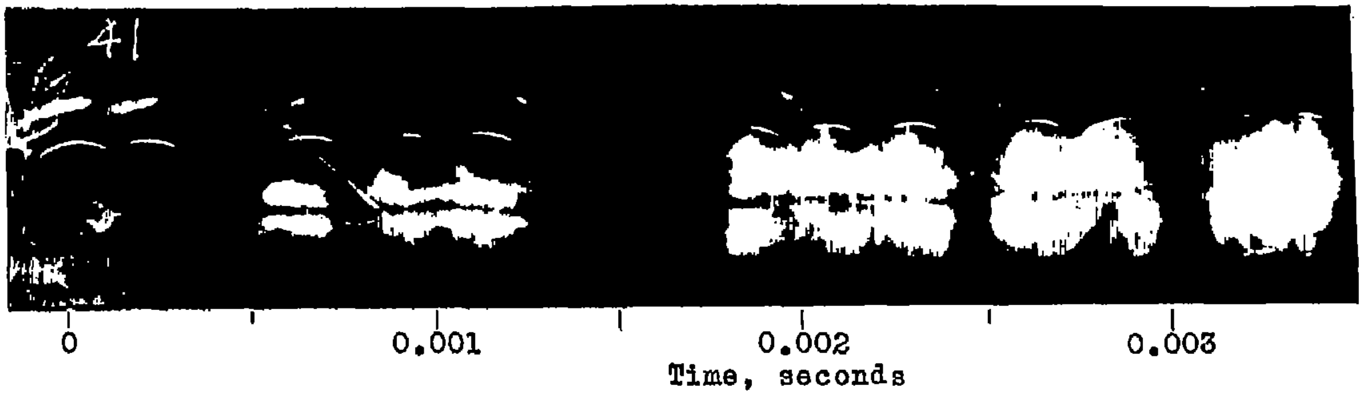


Start of injection - 8° B.T.C.
Air velocity - 130 ft. per second to 0 ft. per second.
Scale: ⊢⊣ = 1 in.



Start of injection - 18° B.T.C.
Air velocity - 350 ft. per second to 60 ft. per second
Scale: ⊢⊣ = 1 in.

Fig.10 Effect of low air velocities on fuel spray with air directed counter to spray.

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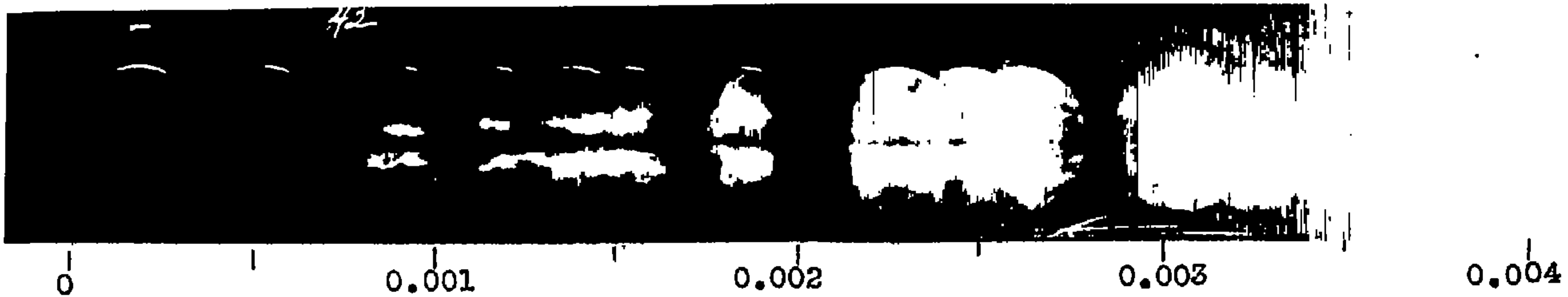
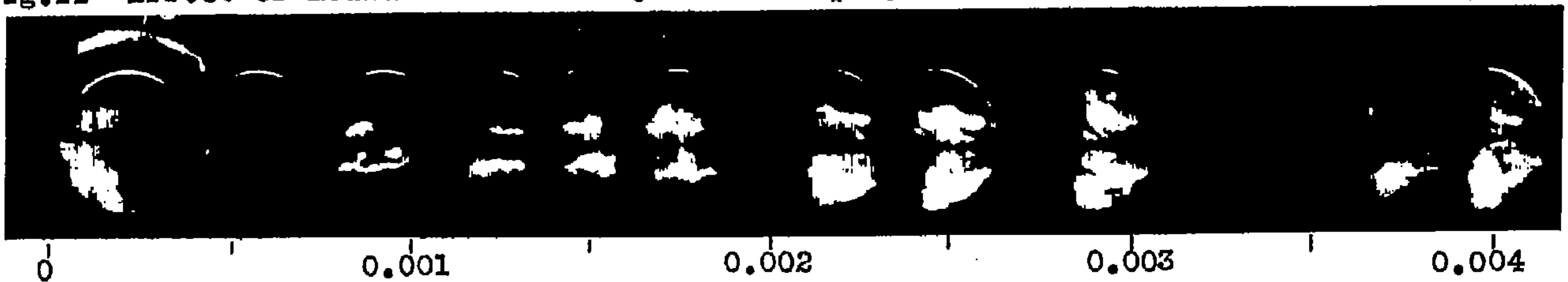


Time, seconds

Start of injection - 28° B.T.C.

Scale: ⊢⊣ = 1 in. Air velocity - 600 ft. per second to 250 ft. per second.

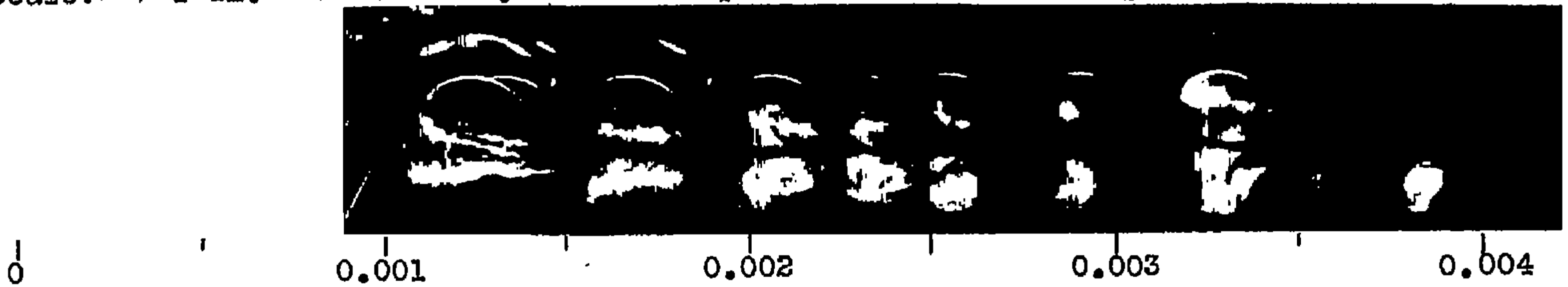
Fig.11 Effect of medium air velocity on fuel spray with air directed counter to spray.



Time, seconds

Start of injection - 38° B.T.C.

Scale: ⊢⊣ =1 in. Air velocity - 790 ft. per second to 500 ft. per second.



Time, seconds

Start of injection - 48° B.T.C.

Scale: ⊢⊣ =1 in. Air velocity - 800 ft. per second to 710 ft. per second.

Fig.12 Effect of high air velocities on fuel spray with air directed counter to spray.

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