NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 520

A COMPARISON OF FUEL SPRAYS FROM SEVERAL TYPES OF INJECTION NOZZLES

By DANA W. LEE

1935

AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight $=mg$

g, Standard acceleration of gravity $=9.80665$ m/s^2 or 32.1740 ft./sec.^{2}

m, Mass $=\frac{W}{g}$

I, Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu.ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure $=\frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o}=\frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s. the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of *c.p.* from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_o, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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By DANA W. LEE
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REPORT No. 520

A COMPARISON OF FUEL SPRAYS FROM SEVERAL TYPES OF INJECTION NOZZLES

By Dana W. Lee

SUMMARY

A series of tests was made of the sprays from 14 fuel-injection nozzles of 9 different types, the sprays being injected into air at atmospheric density and at 6 and 14 times atmospheric density. High-speed spark photographs of the sprays from each nozzle at each air density were taken at the rate of 2,000 per second, and from them were obtained the dimensions of the sprays and the rates of spray-tip penetration. The sprays were also injected against Plasticine targets placed at different distances from the nozzles, and the impressions made in the Plasticine were used as an indication of the distribution of the fuel within the spray. Cross-sectional sketches of the different types of sprays are given showing the relative sizes of the spray cores and envelops. The characteristics of the sprays are compared and discussed with respect to their application to various types of engines.

INTRODUCTION

Since the development of the N. A. C. A. spray-photographic apparatus, a large number of spray photographs have been reproduced in various technical publications of the Committee. Some of these publications being concerned chiefly with engine performance, the spray photographs were used in connection with the description of the fuel-injection system of the engine. Other publications have dealt entirely with certain characteristics of fuel sprays, such as the rate of spray-tip penetration, spray cone angle, atomization and distribution of the fuel; and with the effects on the spray characteristics of such factors as nozzle design, injection pressure, physical properties of the fuel, density and velocity of the air into which the injections took place. The purpose of the present report is to summarize many of these previously reported tests and to present and discuss the results of some recent tests made with nine different types of nozzles. These recent tests were made under the same conditions for each nozzle so that the results might be directly compared.

The list of references given at the end of this report includes most of the N. A. C. A. technical papers in which spray photographs appear; with each reference is combined a short summary of the portion concerned with fuel-spray characteristics. The first Committee publications containing fuel-spray photographs appeared in 1926; the present report was prepared in 1934. All the photographs and data presented were obtained at the N. A. C. A. engine-research laboratories at Langley Field, Va.

APPARATUS AND TEST PROCEDURE

Sketches of the various types of nozzles used to produce the sprays discussed in this report are shown in figure 1. The plain nozzles having cylindrical orifices are similar to those used in previous investigations at this laboratory. The seat angle is 150° and the angle of the conical approach to the orifice is 60°. Three nozzles of this type were tested, two having orifice diameters of 0.020 inch and orifice lengths of 0.010 and 0.100 inch, and one having an orifice diameter of 0.060 inch and a length of 0.180 inch.

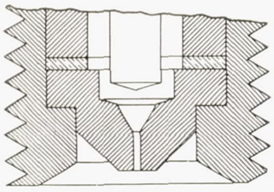
The lip nozzle has an orifice diameter of 0.014 inch and an orifice length-diameter ratio of 2. The angle between the axis of the fuel jet and the surface of the lip on which it impinges is 45°.

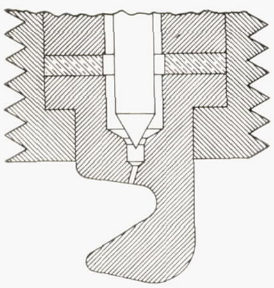
Two impinging-jets nozzles were used, one having 2 orifices each 0.020 inch in diameter, and the other having 4 orifices each 0.030 inch in diameter. In the 4-orifice nozzle (not shown in fig. 1) the plane through 2 of the orifices is at right angles to that through the other 2, all 4 jets meeting at a common point. The angle between opposite jets is 74° in each case.

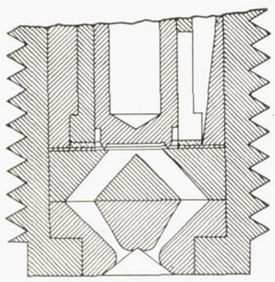
The annular-orifice nozzles differ from the others in that the seating surfaces also form the discharge orifices, which therefore vary in area with the injection pressure. Two nozzles of this type were tested; they had spray cone angles of about 45° and 125°.

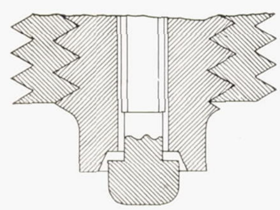
The pintle nozzle combines some of the characteristics of the plain and the annular-orifice nozzles. The enlarged views of the orifice show the valve stem lifted 0.015 inch and 0.038 inch, these values having been found to be of particular interest.

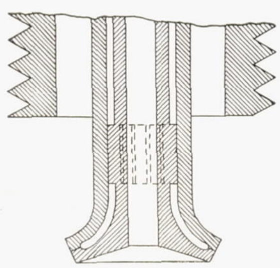
The multiple-orifice nozzle has six orifices in one plane. The two center orifices have diameters of 0.019

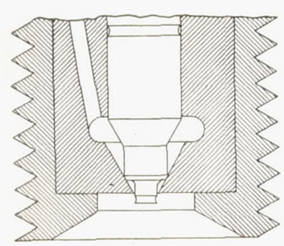

(a) Plain nozzle.

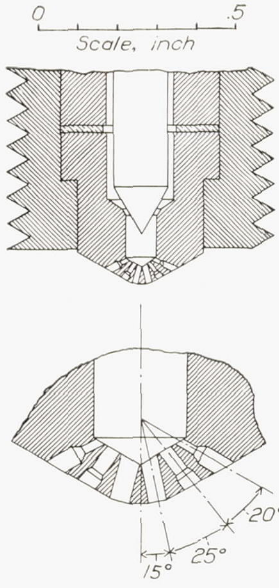

(b) Lip nozzle.


(c) Nozzle with two impinging jets.

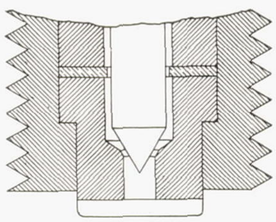

(d) Nozzle with an annular orifice of varying area. Spray cone angle, 45°.

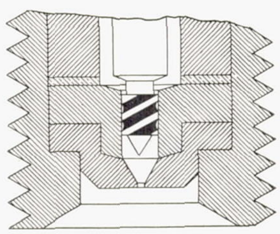

(e) Nozzle with an annular orifice of varying area. Spray-cone angle, 125°.

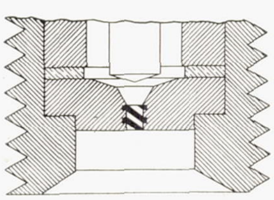

(f) Pintle nozzle, showing valve stem seated.



(g) Multiple-orifice nozzle with enlarged view of orifices


(h) Slit nozzle. Slit, 0.008-inch wide.


(i) Centrifugal nozzle.


(j) Nozzle with helical grooves in the orifice walls.

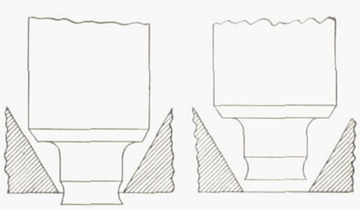

Enlarged views of pintle-nozzle orifice, showing valve stem lifted 0.015 inch (left) and 0.038 inch (right).

FIGURE 1.—Sketches of the nine types of nozzles.

inch, the next two 0.014 inch, and the outer two 0.008 inch. The length of each orifice is twice its diameter.

The orifice of the slit nozzle is 0.008 inch wide and 0.085 inch long. It was formed by making a saw cut across the end of the nozzle, just deep enough to cut into the bottom of the cylindrical well below the stem seat.

A combination nozzle (not shown in fig. 1) was constructed by cutting a 0.005-inch slit across the end and through the center of each orifice of a multiple-orifice nozzle like the one shown in the figure.

The centrifugal nozzle is the same as the plain nozzle except that the fuel passes through helical grooves on the valve stem, thus acquiring a whirling motion before it goes through the cylindrical orifice. There are four grooves on the valve stem, the helix angle is 30°, and the total area of the grooves and clearance space is 0.00052 square inch. The diameter of the orifice is 0.020 inch and its length is 0.010 inch.

The ninth type of nozzle has a large cylindrical orifice on the walls of which are cut two helical grooves. The diameter of the orifice is 0.040 inch; its length is 0.060 inch. The grooves have a square cross section, are 0.010 inch on a side, and each makes one complete revolution.

All the nozzles except the two having annular orifices were used in automatic differential-area injection valves similar in principle to that shown in figure 2 (a). The stems of these valves slide in the valve bodies with lap fits; fuel under pressure enters the valves below the lap and lifts the stems against the force of helical springs bearing on them above the lap. As soon as the stem is lifted from the nozzle seat, fuel begins to flow through the nozzle and an additional stem area is exposed to the fuel pressure so that the stem lifts rapidly. When the fuel pressure drops at the end of the injection period, the spring quickly returns the stem to its original position; but there frequently follows a series of bounces of the stem caused either by the elasticity of the parts or by pressure waves set up in the fuel in the injection tube by the sudden stoppage of the flow. (See references 1 and 2.) These bounces result in secondary fuel discharges that follow the main disharge.

The annular-orifice nozzles are built integrally with their injection valves. A sketch of the valve that produced the sprays with cone angles of 45° is shown in figure 2 (b). The seat on the valve stem is held against that on the valve body by a helical spring around the upper end of the stem. Fuel enters the spring chamber and passes down along the valve stem to the nozzle. When the force exerted by the fuel on the enlarged end of the stem exceeds that of the spring, the valve opens. No additional area being uncovered by the opening of the valve, the stem motion is not accelerated as is the case with the differential-area valves, and the opening and closing are relatively slow. A sketch of the injection valve with an annular orifice that produced the sprays with cone angles of 125° is shown in figure 2 (c). The elastic deflection of the valve parts is sufficient to open the orifice.

All of the injection valves except the two with annular orifices were equipped with screw stops to limit the lifts of the valve stems, but it was only for the tests with the pintle nozzle that such a stop was used. In all other tests the stop was removed so that the stem was lifted by the fuel pressure until the force due to that pressure was balanced by the opposing spring force.

As the injection system of the N. A. C. A. spray-photographic apparatus as behen described in reference 2, only a brief mention of its characteristics will be necessary here. Fuel under pressure in a large reservoir is released to the injection tube by a mechanically operated needle valve. Another valve terminates the injection period by opening the injection tube to the atmosphere. Only one injection can be made without resetting the apparatus. With certain exceptions detailed later, the following settings of the injection system were observed for all tests: reservoir pressure, 4,000 pounds per square inch; valve-opening pressure, 3,500 pounds per square inch; initial pressure in the injection tube, 1,500 pounds per square inch. The setting of the cams controlling the time during which the fuel under pressure in the reservoir was released to the injection valve remained the same for all tests, but the injection period varied somewhat with the different types of valves and nozzles, an average value being about 0.004 second. Although this injection period is longer than would be used in modern high-speed engines, it was adopted for these tests because it allowed the sprays to become fully developed before cut-off. The viscosity of the Auto-Diesel fuel used for the tests described in this report was 0.055 poise at 20° C. and atmospheric pressure.

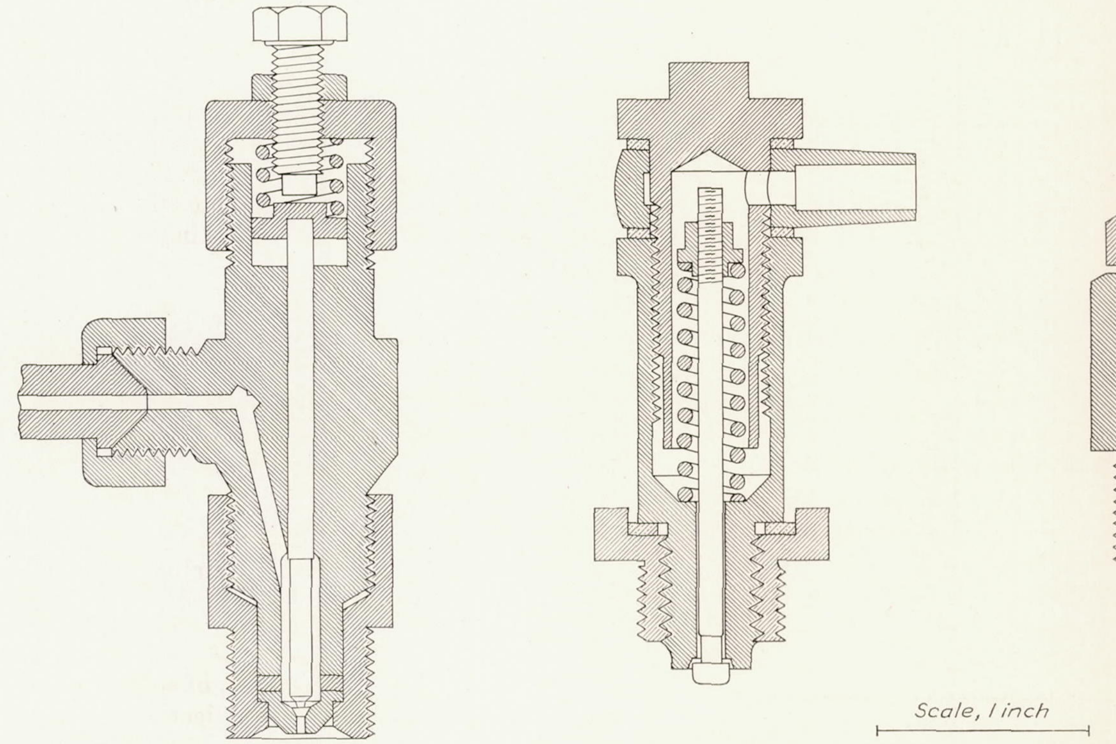
The test procedure followed for each of the 14 nozzles was as follows:

1. Spark photographs were taken with the N. A. C. A. spray-photographic apparatus (reference 3) showing the development of the sprays in air at room temperature and at densities [1] of 1, 6, and 14 atmospheres. When the spray was nonsymmetrical about the axis, two sets of photographs were taken, the nozzle being rotated 90° between sets.

2. The rate of spray-tip penetration and the width of the spray at different distances from the nozzle were measured from the photographs.

3. Individual discharges from each of the nozzles were caught and weighed on an analytical balance.

4. The sprays were injected against smoothly surfaced pieces of Plasticine placed at various distances



(a) Valve with a differential-area spring-loaded lapped stem. Constant orifice area.

(b) Annular-orifice valve with spring-loaded stem. Variable orifice area.

(c) Springless annular-orifice valve. Variable orifice area.

FIGURE 2.—Sketches of the three types of injection valves.

[1] Values of air density are given in this report as atmospheres, that is, as so many times the density of "standard" air (0.0765 pound per cubic foot). Although not conventional, this term is convenient, inasmuch as the values are the same as those of the engine compression ratios giving equal air densities at top center. Air densities equal to those in engines are used rather than the corresponding air pressures, for it has been shown in reference 4 that changing the air density has a much greater effect on the spray characteristics than changing the air pressure.

from the nozzles, in air at the three previously mentioned densities. The impressions made by the sprays in the Plasticine served as an indication of the distribution of the fuel within the sprays.

5. Cross-sectional sketches of the sprays were made showing the relative sizes of the spray cores and envelops. The dimensions for the cores were obtained from the impressions in the Plasticine and those for the envelops from the spray photographs. In the preparation of these sketches the sprays were arbitrarily divided into three regions: (1) the inner region, where the velocity and concentration of the fuel is sufficient to cause it to penetrate the Plasticine to a depth of one-eighth inch or more (represented by solid black); (2) the intermediate region, where the fuel penetrates the Plasticine less than one-eighth inch (represented by lines); and (3) the outer region, where the fuel makes no impression in the Plasticine (represented by dots). Actually the two inner regions are not distinct but blend into one another and constitute what is referred to as the "spray core." The division between the core and the outer region, which is referred to as the "spray envelop," is distinct in most cases although it is not so sharp as represented in the sketches. The directions of the lines in the middle regions are not intended to indicate the directions of the motion of the fuel drops, and the spacing of the lines only approximately represents the depths of the impressions in the Plasticine at the corresponding points. No attempt was made to represent the distribution of the fuel in the envelops.

A close examination of the photographs made with the high-speed photographic apparatus will show that there is some blurring of the image caused by the motion of the fuel during the time of the spark discharge. The spark circuit described in reference 5 produces single sparks of such a short duration that spray photographs taken with its light are not blurred. This circuit was used to photograph the early stages of sprays from the 14 nozzles tested, injected into air at atmospheric density and room temperature. Many details of spray structure are shown that are not discernible on the other photographs.

DISCUSSION

CHARACTERISTICS OF SPRAYS FROM THE NINE TYPES OF NOZZLES

Plain nozzles (figs. 3 to 11).—The simplest example of a plain nozzle is a hole drilled in a flat plate. Although such a nozzle is easily made and will usually perform satisfactorily, its coefficient of discharge is sometimes as low as 0.65. The coefficient may be raised to values as great as 0.95 by providing a conical approach to the nozzle bore and relieving all sharp edges. (See reference 6.)

Sprays from this type of nozzle are conical in form. (See figs. 3 to 6.) Data presented in reference 7 show that the apex angle varies from 10° to 25°, depending on the orifice diameter, the orifice length-diameter ratio, and the density of the air into which the sprays are injected. Reference 7 also shows how the rate of spray-tip penetration varies with the injection pressure, orifice diameter, length-diameter ratio, and air density. Increasing the orifice diameter, provided that the injection pressure remains constant, tends to increase the rate of spray-tip penetration; it also tends to lower the average injection pressure (reference 8) and, therefore, the rate of spray-tip penetration. The net result will depend on the pressure at the nozzle and on the tube diameters for the injection system under consideration. With the system used for the present tests, spray-tip penetration increased with increase in orifice diameter up to 0.030 inch and then decreased. As the orifice length-diameter ratio is increased from 0.5 to 10, the spray-tip penetration first decreases, then increases, and finally decreases again. The values of the length-diameter ratio for the maximum and minimum penetration points have been determined for orifice diameters from 0.008 to 0.040 inch. They vary from about 7 and 3 for the 0.008-inch orifice to about 4 and 1 for the 0.040-inch orifice. Figures 7 (a), (b), and (c) show the effect of air density on the rate of spray-tip penetration for sprays from the three plain nozzles used in the present tests. Additional data on spray-tip penetration and spray-cone angle may be found in reference 9.

The distribution of the fuel within sprays from plain nozzles is very uneven. For several inches after leaving the nozzle, most of the fuel is concentrated in a narrow central core and is moving forward very rapidly. Surrounding the core is an envelop composed of the slowly moving fuel drops that have been torn away from the core. After the first few inches, the distinction between core and envelop becomes less marked as more and more of the fuel loses most of its velocity relative to the air. The diameter and length of the core varies with the density of the chamber air; the core becomes much shorter and slightly thicker with increasing air density. (See figs. 8 and 9 and references 5 and 10.)

The fineness of the atomization of sprays from plain nozzles increases with the fuel-injection velocity and with a decrease in the orifice diameter. Tests made at this laboratory (reference 11) indicate that neither the orifice length-diameter ratio nor the air density has any decided effect on fuel atomization, but tests made at other laboratories (references 10 and 12) indicate that the atomization becomes finer as the air density is increased.

The two 0.020-inch orifice plain nozzles included in the test program represent the type used in high-speed engines in which the fuel is injected directly in the main combustion chamber and typify the usual limits of orifice length-diameter ratio. The nozzle with the 0.060-inch orifice represents either the case of a large engine with direct injection or that of a small precombustion-chamber engine.

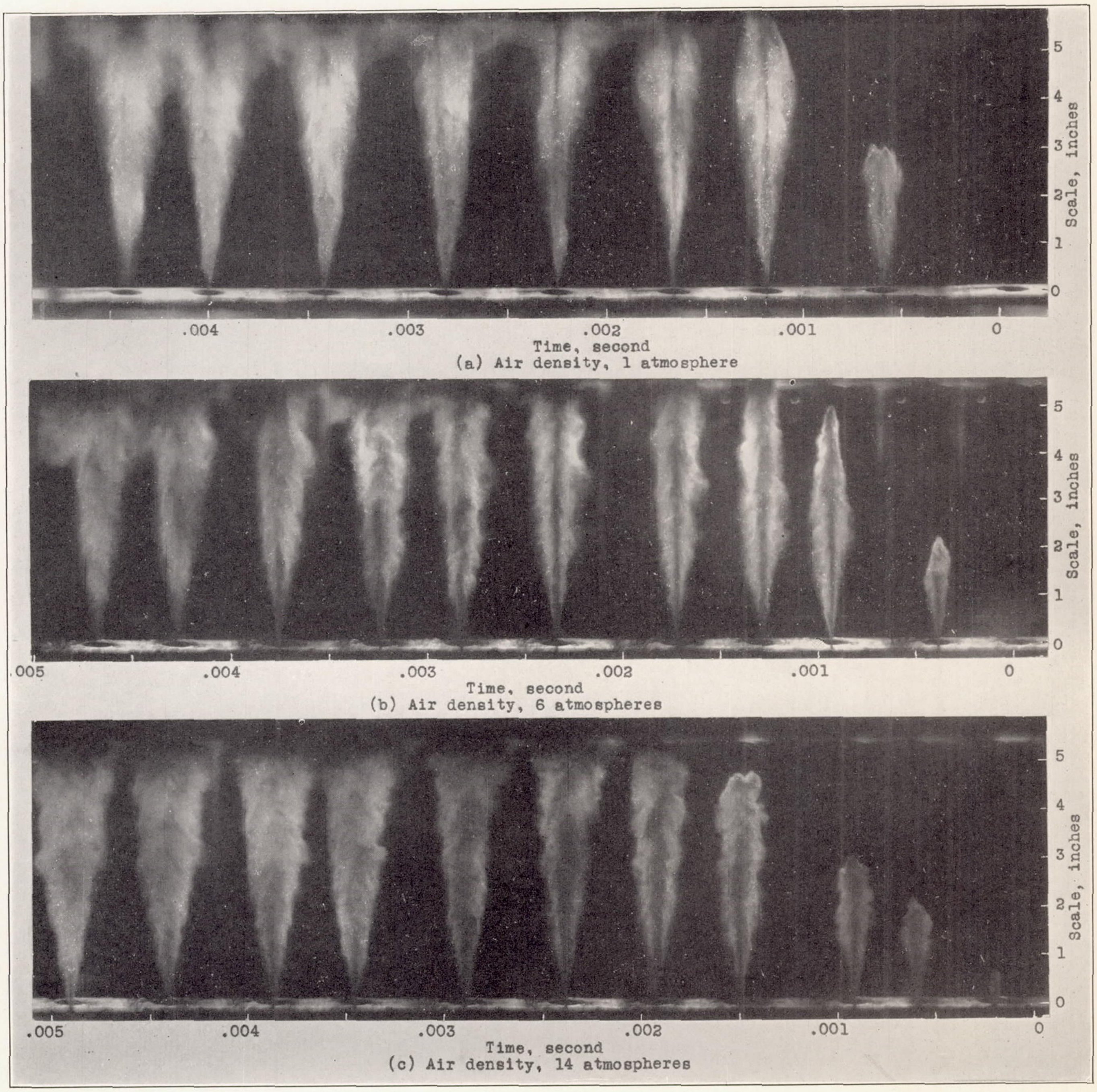


FIGURE 3.—Fuel sprays from a plain nozzle injected into air having different densities. Orifice diameter, 0.020 inch; orifice length, 0.010 inch.

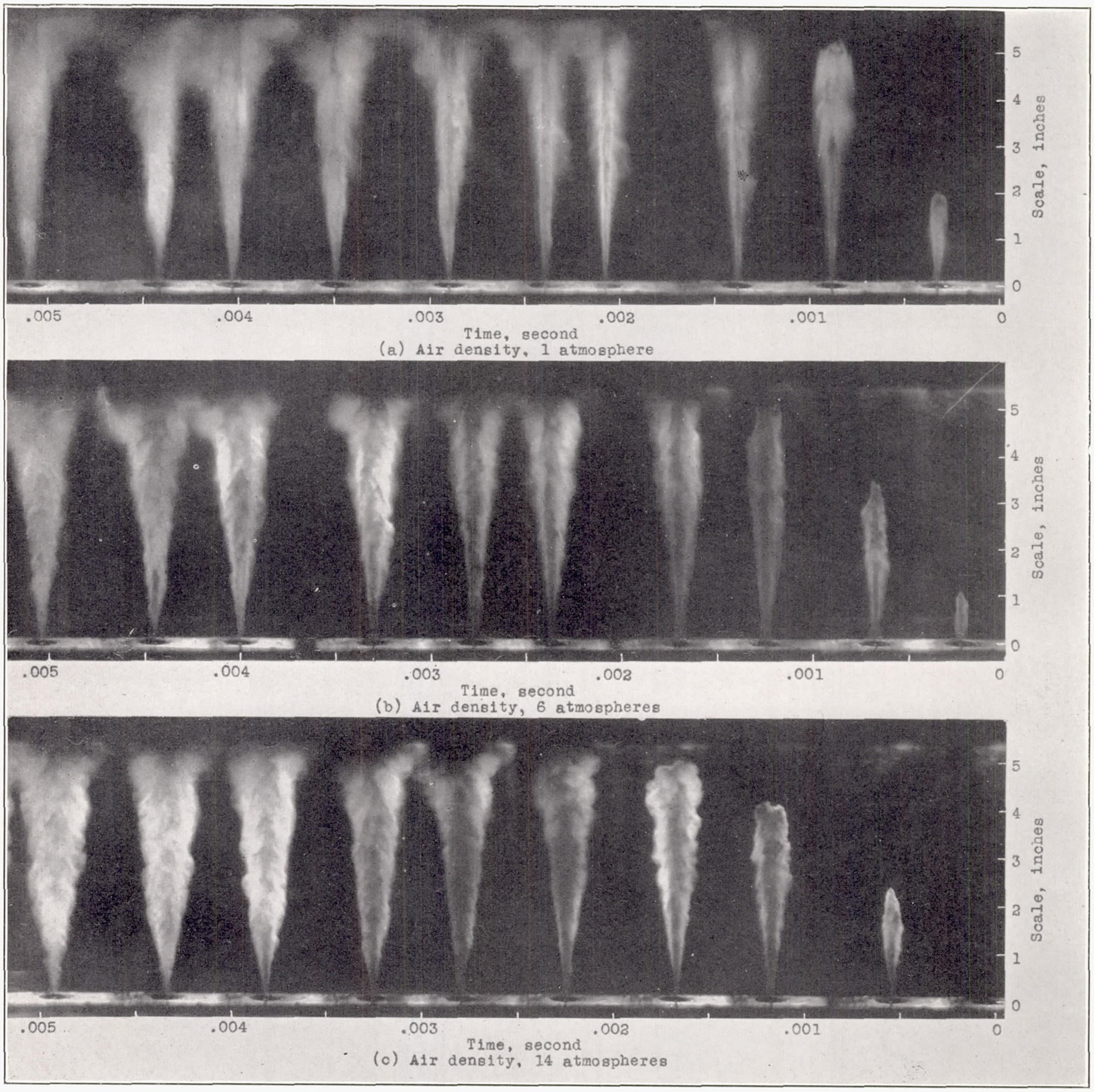


FIGURE 4.—Fuel sprays from a plain nozzle injected into air having different densities. Orifice diameter, 0.020 inch; orifice length, 0.100 inch.

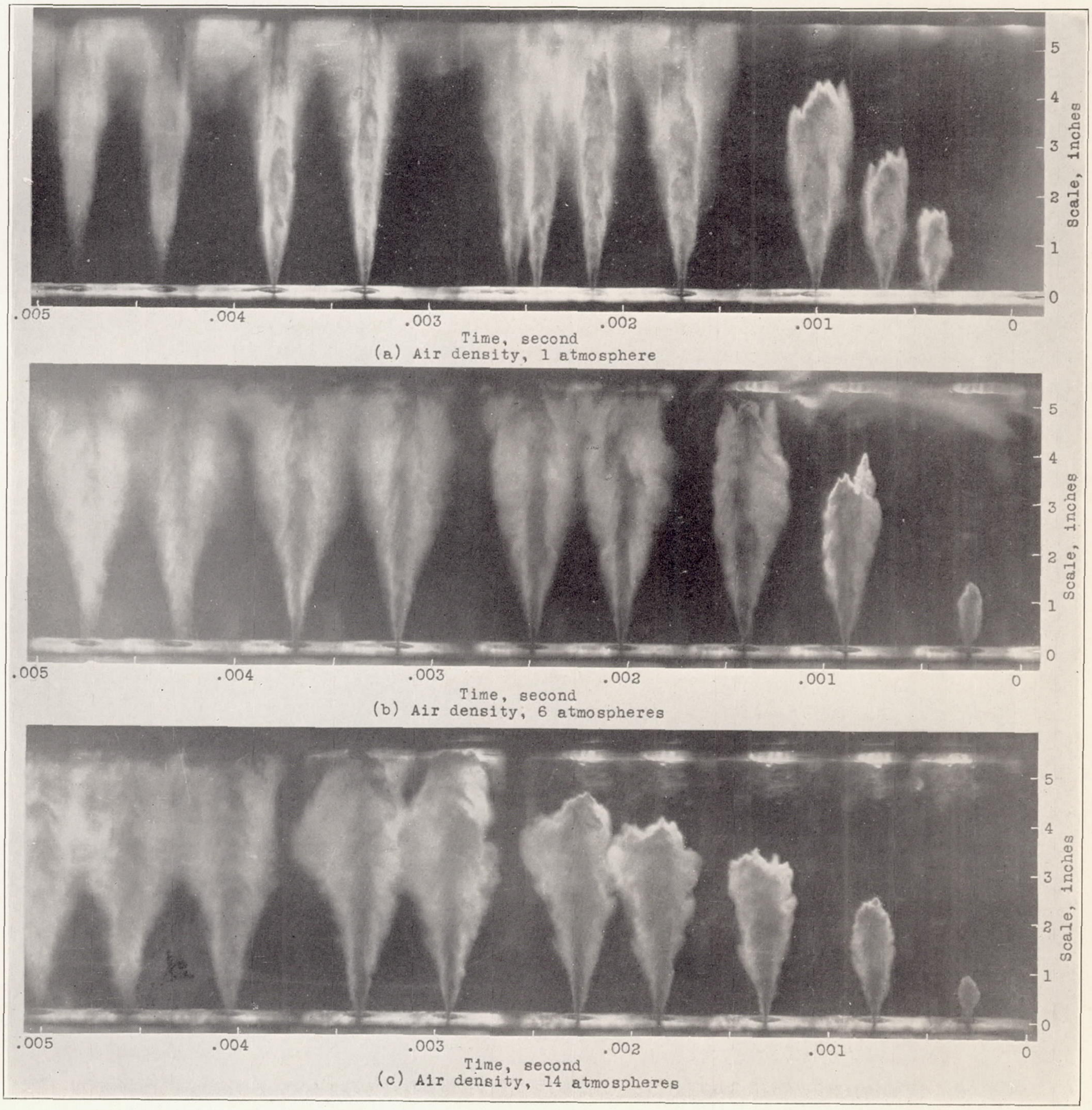


FIGURE 5.—Fuel sprays from a plain nozzle injected into air having different densities. Orifice diameter, 0.060 inch; orifice length, 0.180 inch.

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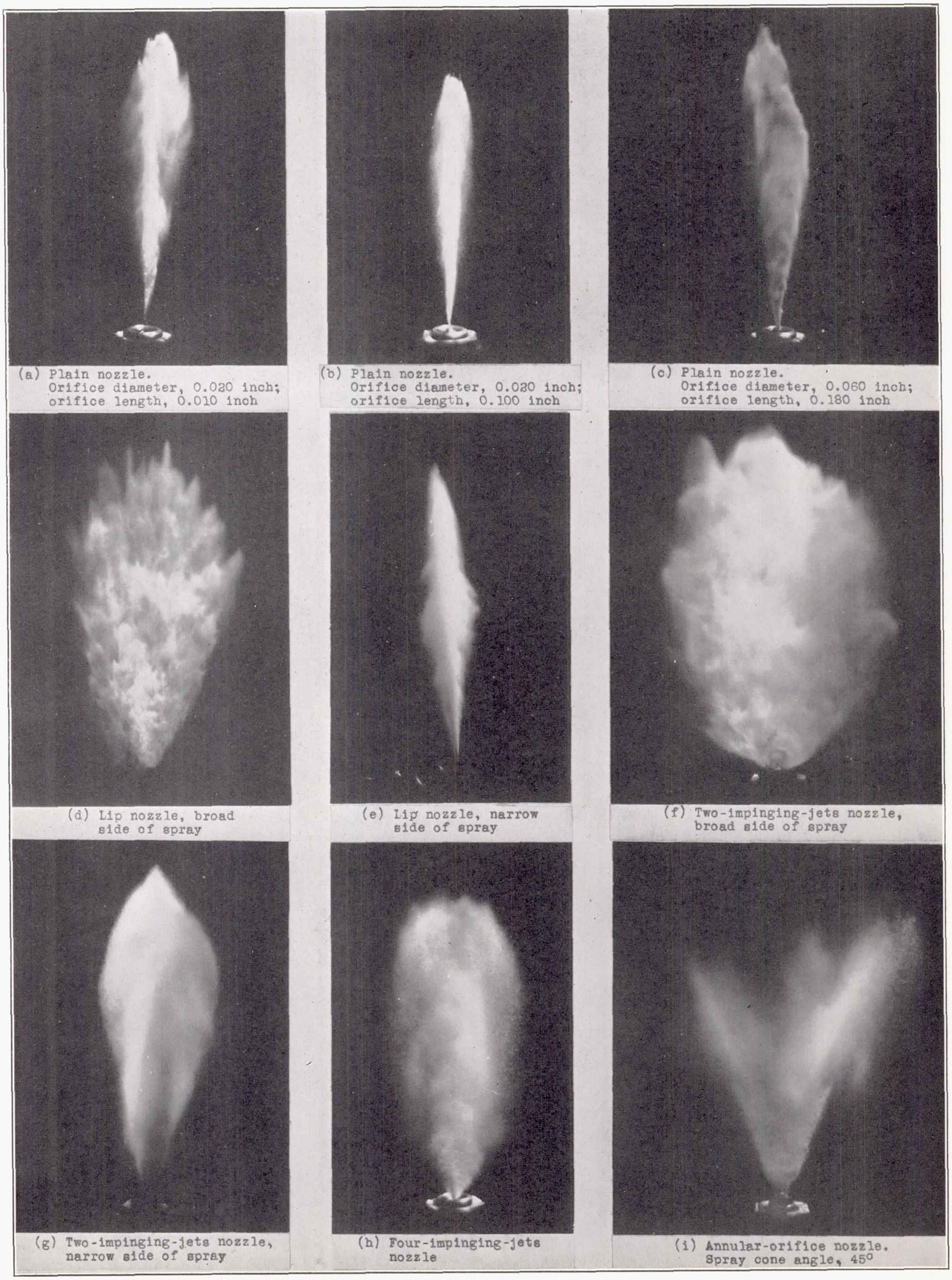
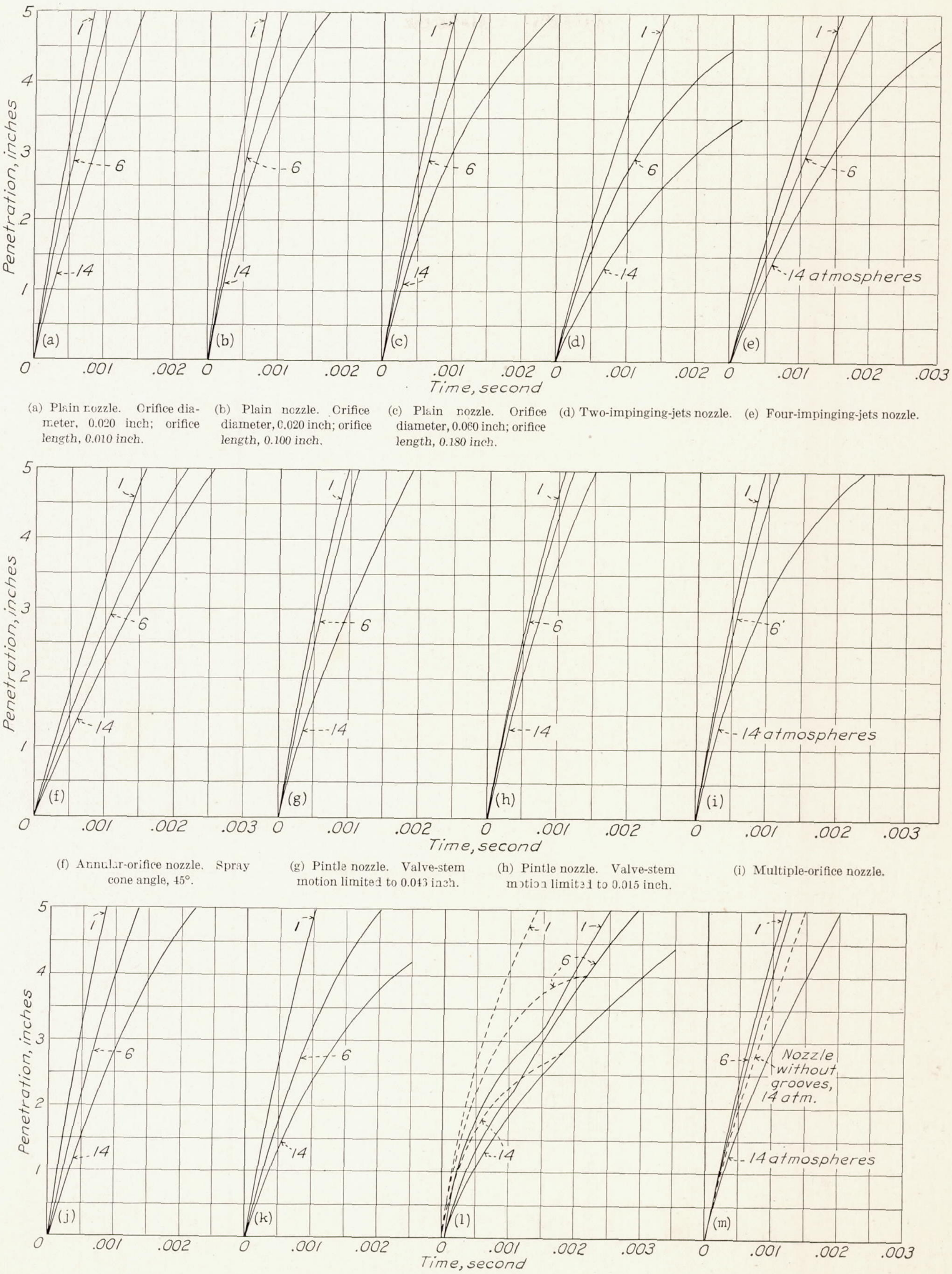


FIGURE 6.—Photographs of the early stages of sprays from the nozzles tested. Injection pressure, 4,000 pounds per square inch; air density, 1 atmosphere.



(a) Plain nozzle. Orifice diameter, 0.020 inch; orifice length, 0.010 inch.

(b) Plain nozzle. Orifice diameter, 0.020 inch; orifice length, 0.100 inch.

(c) Plain nozzle. Orifice diameter, 0.060 inch; orifice length, 0.180 inch.

(d) Two-impinging-jets nozzle.

(e) Four-impinging-jets nozzle.

(f) Annular-orifice nozzle. Spray cone angle, 45°.

(g) Pintle nozzle. Valve-stem motion limited to 0.043 inch.

(h) Pintle nozzle. Valve-stem motion limited to 0.015 inch.

(i) Multiple-orifice nozzle.

(j) Slit nozzle.

(k) Combination multiple-orifice and slit nozzle.

(l) Centrifugal nozzle. Dashed lines represent initial portion of spray, noncentrifugal. Solid lines represent main portion of spray, centrifugal.

(m) Nozzle with helical grooves in the orifice walls.

FIGURE 7.—Effect of air density on the tip penetration of sprays from the nozzles tested.

The total discharge-orifice areas of the different nozzles tested and the weights of fuel discharged per injection are listed in table I. Notice that although the area of the 0.060-inch orifice is 9 times that of the 0.020 by 0.010 inch orifice, its discharge weight is only 2.6 times as great. Computations based on these discharge weights show that the effective injection pressure for the 0.020-inch nozzle was 12 times that for the 0.060-inch nozzle. This extreme difference in effective injection pressure is due to the fact that when nozzles with large orifices are installed in the injection valves used for the present tests, the flow area past the valve seat is much less than that through the nozzle, so that most of the pressure drop takes place before the nozzle is reached. (See reference 2.)

TABLE I.—ORIFICE AREAS AND DISCHARGE WEIGHTS OF 14 TESTED NOZZLES

Nozzle	Specifications	Total orifice area	Discharge weight
		Square inch	*Pound*
Plain	Orifice diameter, 0.020 inch; length, 0.010 inch.	0.00031	0.00032
	Orifice diameter, 0.020 inch; length, 0.100 inch.	.00031	.00036
	Orifice diameter, 0.060 inch; length, 0.180 inch.	.00283	.00084
Lip	Orifice diameter, 0.014 inch	.00015	.00017
2-impinging-jets	Diameter of each orifice, 0.020 inch	.00063	.00058
4-impinging-jets	Diameter of each orifice, 0.030 inch	.00283	.00075
Annular orifice	Spray cone angle, 45°	Variable	.00264
	Spray cone angle, 125°	Variable	.00035
Pintle	Valve-stem motion limited to 0.046 inch.	Variable	.00064
	Valve-stem motion limited to 0.015 inch.	Variable	.00053
Multiple orifice	Two 0.019 inch, two 0.014 inch, and two 0.008 inch diameter orifices.	.00100	.00074
Slit	Slit length, 0.085 inch; width, 0.008 inch.	.00068	.00049
Combination multiple orifice and slit.	Cylindrical orifices as in multiple-orifice slit width, 0.005 inch.	.00122	.00087
Centrifugal	Orifice diameter, 0.020 inch; length, 0.010 inch.	.00031	.00015
Cylindrical orifice with grooves.	Orifice diameter, 0.040 inch; grooves, 0.010 inch square.	.00146	.00081

Photographs were also taken of sprays from the 0.020 by 0.100 inch orifice impinging on a glass plate placed 3 inches away from the nozzle, and set at 90° and at 45° to the spray axis. As figures 10 and 11 show, there was little reflection of the spray from the plate, most of it spreading out along the surface of the glass. In figures 10 (b) and 10 (c) the spray may be seen turned a second time by the chamber walls so that it moves backward toward the nozzle.

Because of the poor distribution of the fuel in sprays from nozzles having single cylindrical orifices, they are generally used only in engines of the precombustion-chamber type or in direct-injection engines having a rapid air movement past the nozzle, which distribute the fuel throughout the combustion chamber.

Lip nozzles (figs. 6, 8, and 12).—The photographs of figure 12 show that the fuel does not rebound from the lip to any great extent but is spread out into a wedge-shaped sheet of spray extending in the same direction as the lip surface. When figure 12 (a) was taken, the injection valve was set at such an angle that the plane of the spray was at right angles to the camera axis. The construction of the glass-sided pressure chamber used when the sprays were photographed in air at densities above atmospheric prevented the photography of the sprays at this angle when they were injected into the chamber. Figures 12 (b), (c), and (d) show the narrow sides of the sprays. Notice how closely they follow first the lip surface and then the chamber wall. The cores of the sprays have the form of a narrow sheet and break up close to the lip. The fuel is fairly well distributed across the sprays, as is shown by the impressions in the Plasticine. (See fig. 8 (b).) The different angles at which the impressions appear in the photographs do not signify any twisting of the sprays but are merely a result of the manner in which the Plasticine targets were assembled for photographing. Distances to the targets were measured from the end of the lip. Spray-atomization tests made with the nozzle shown in figure 1 (b) and described in reference 11 showed that impingement had no effect on the size of the fuel drops. Although lip nozzles produce sprays similar to those from slit nozzles, the round orifice of the former is less likely to become clogged than a narrow slit and erosion of the orifice will have less effect on the shape of the spray. Lip nozzles have not been used to any great extent. In most applications where a spray of such a form is desired, multiple-orifice nozzles having two or more round orifices are used. Three cases in which lip nozzles were used are described in references 13, 14, and 15.

Impinging-jets nozzles (figs. 6 to 9 and 13 to 15).—Nozzles of the impinging-jets type have plain round orifices whose axes intersect at a point close to the nozzle. Two such impinging jets form a flat spray at right angles to the plane through the orifices and four impinging jets form a thick conical spray. Preliminary experiments on impinging-jets nozzles conducted at this laboratory (reference 16) showed that the jets should be smooth and uniform in size, that they should impinge close to the orifice, and that an angle of 74° between the jets resulted in a well-dispersed spray. Tests reported in reference 11 showed that sprays from the same impinging-jets nozzle used in the present tests have very good fuel distribution but poor atomization and penetrating power. Poor atomization is probably not a characteristic of impinging jets, however, but in this particular case may have been due to the large volume of the passages in the nozzle between the stem seat and the orifices and to the severe bouncing of the valve stem after cut-off.

Figures 13 and 14 show the wide and the narrow sides of sprays from the nozzle having two 0.020-inch impinging jets. The cores of these sprays are approximately elliptical in section and disintegrate very close to the nozzle, as shown by the impressions in the Plasticine targets (fig. 8 (c)). Notice that a large

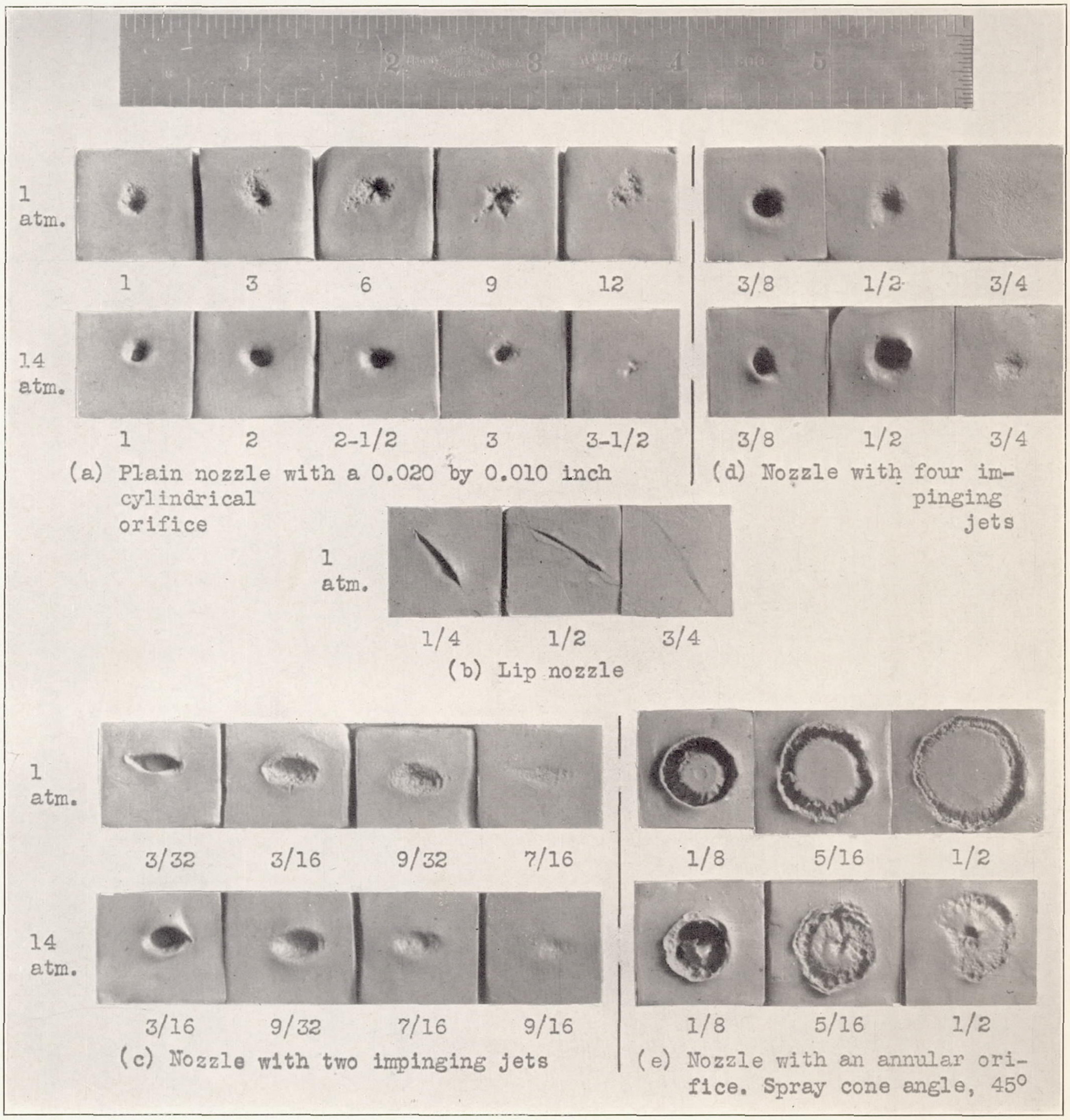


FIGURE 8.—Impressions made in Plasticine targets by fuel sprays from different nozzles. Distance from nozzle to target, in inches, is shown below each target; the air density is shown at the end of each row.

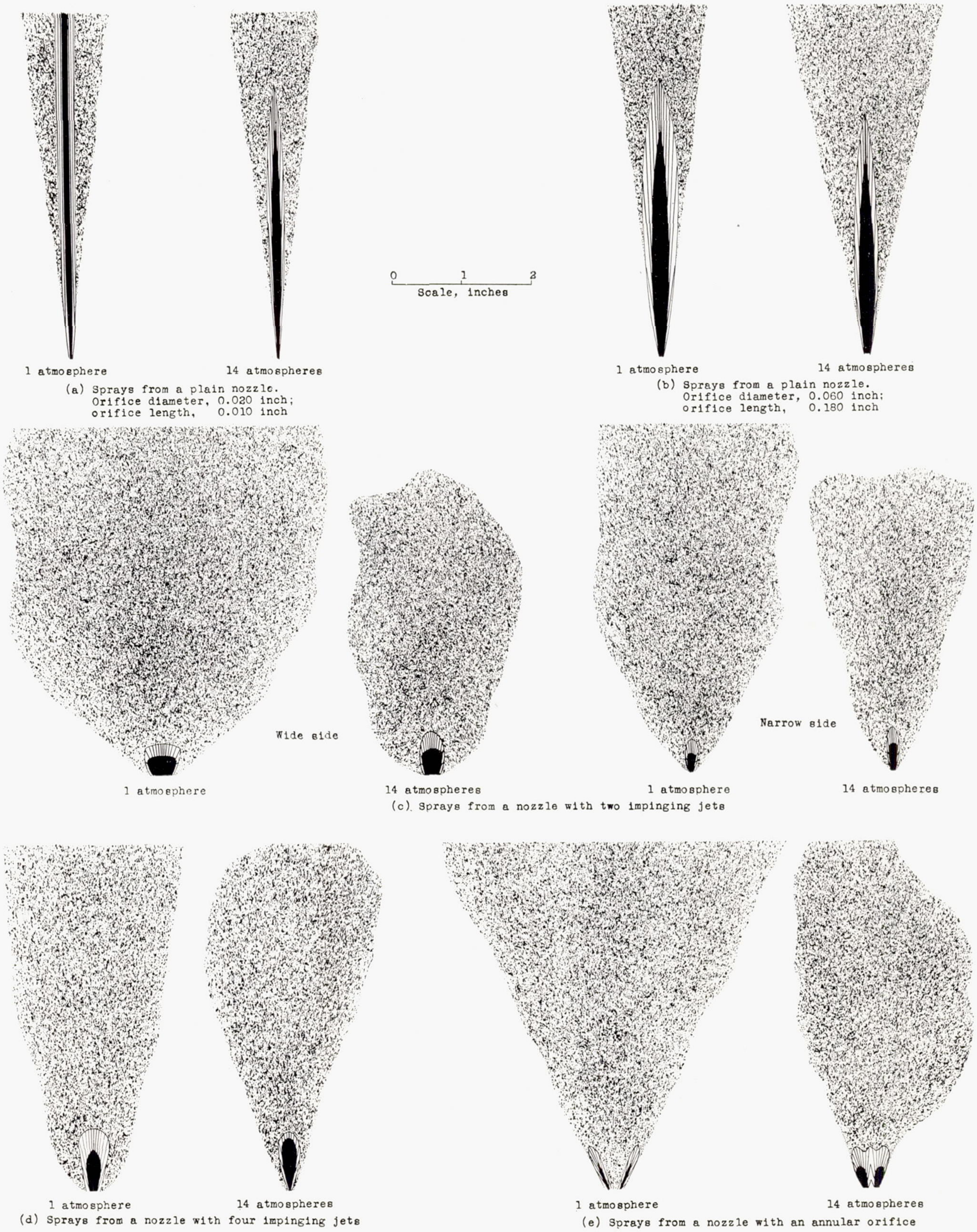


FIGURE 9.—Cross-sectional sketches of fuel sprays from different nozzles, showing relative sizes of the spray cores and envelops.

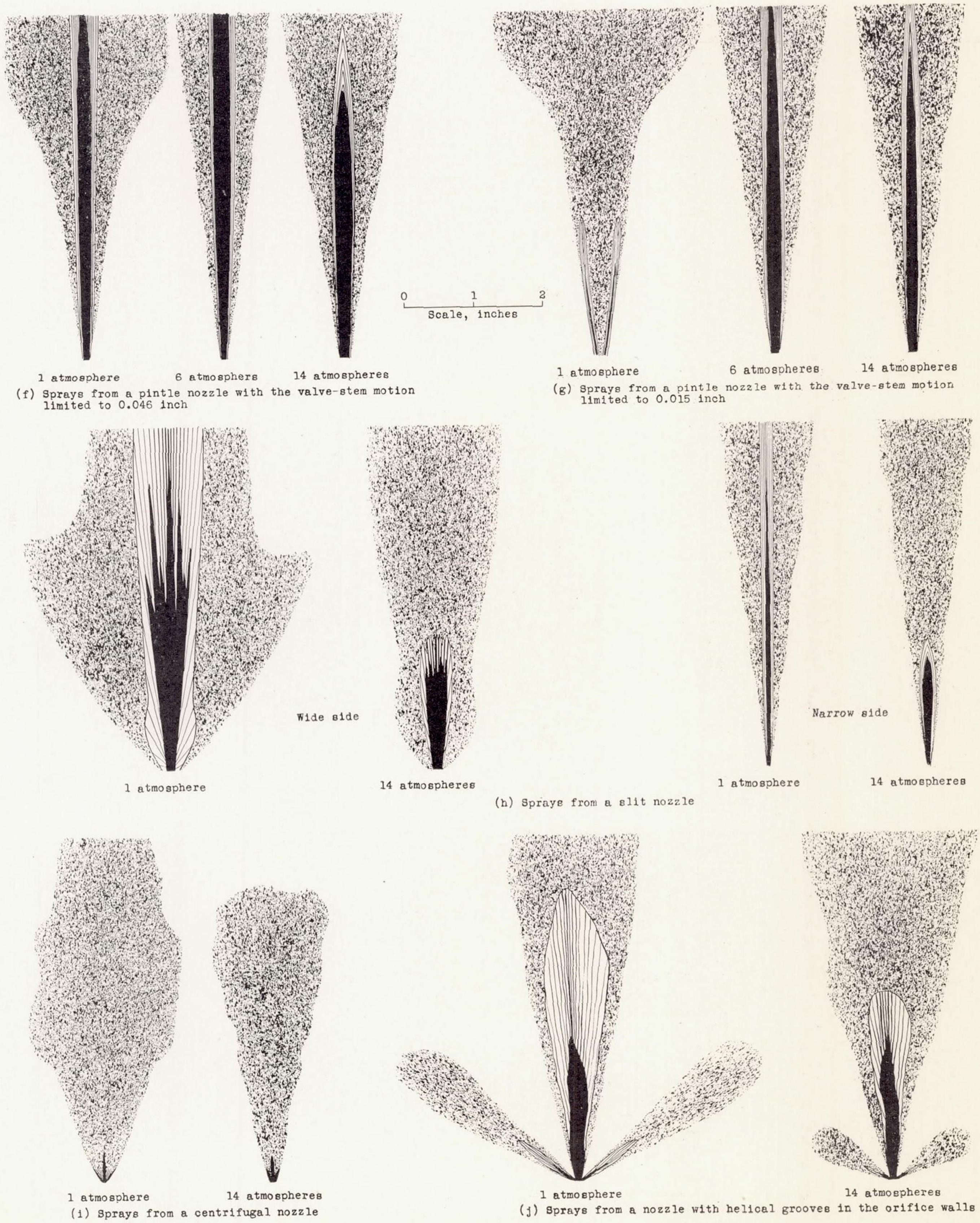


FIGURE 9.—Continued.

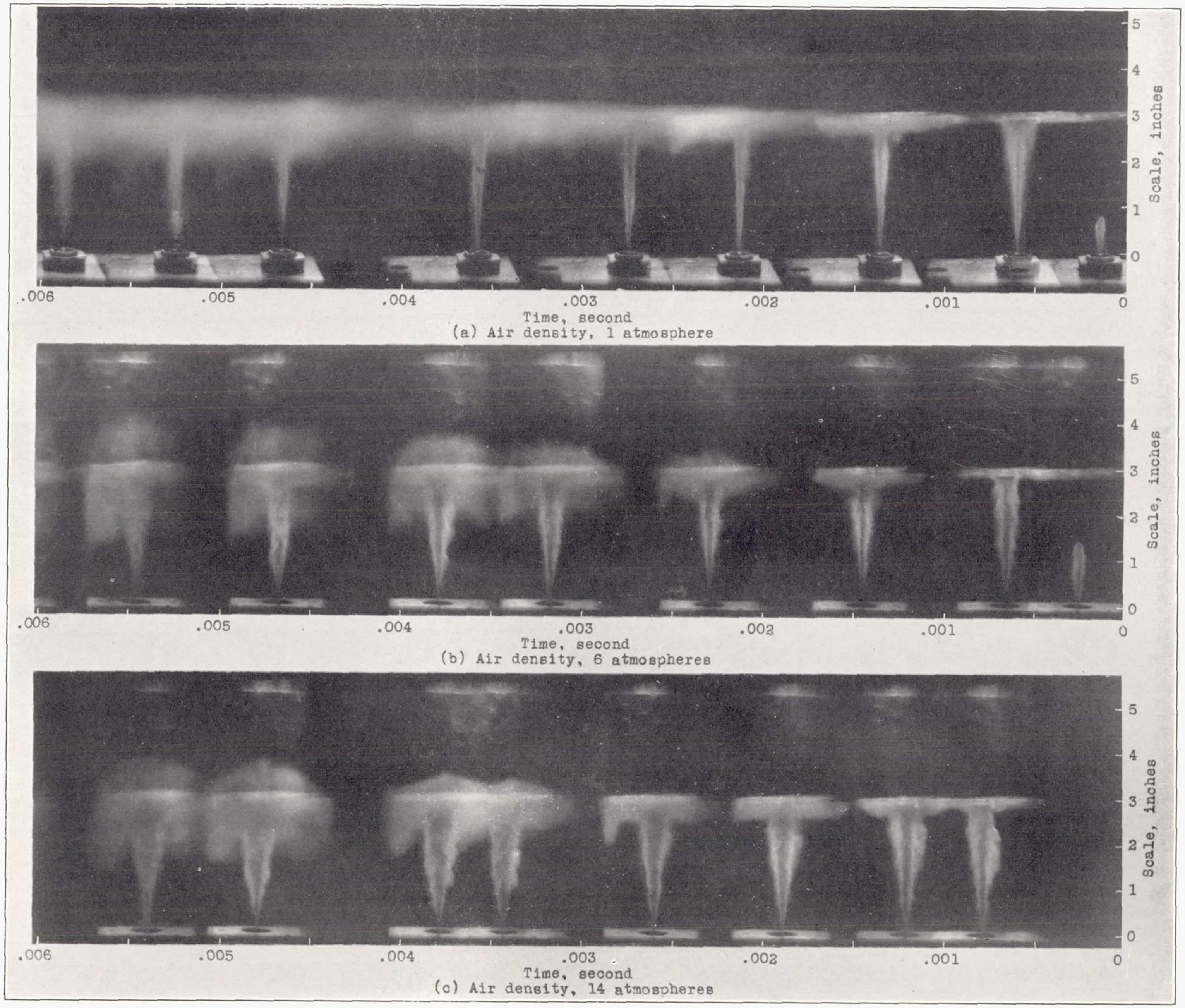


FIGURE 10.—Fuel sprays from a plain nozzle striking a plate set at 90° to the spray axis, in air having different densities. Orifice diameter, 0.020 inch; orifice length, 0.100 inch.

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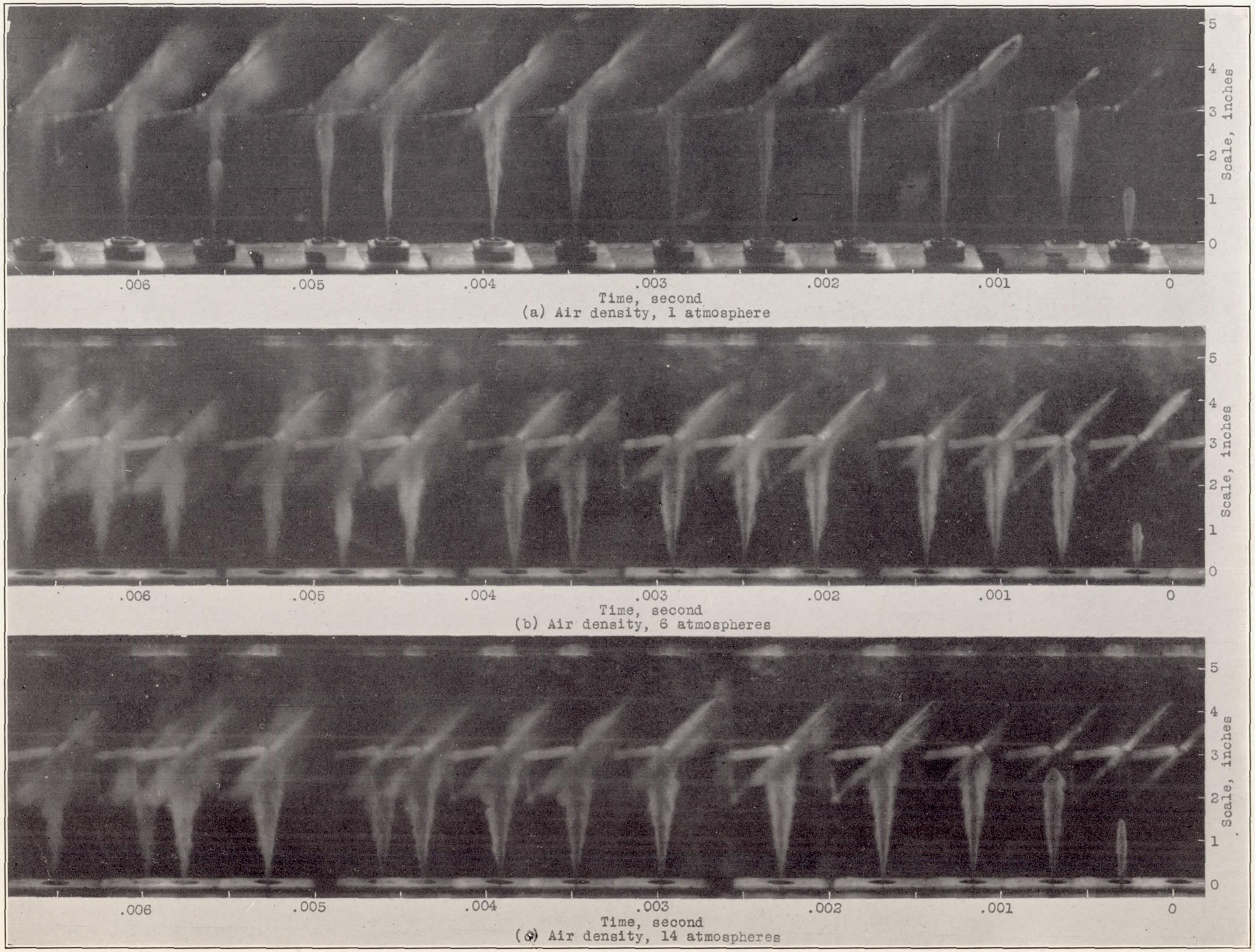


FIGURE 11.—Fuel sprays from a plain nozzle striking a plate set at 45° to the spray axis, in air having different densities. Orifice diameter, 0.020 inch; orifice length, 0.100 inch.

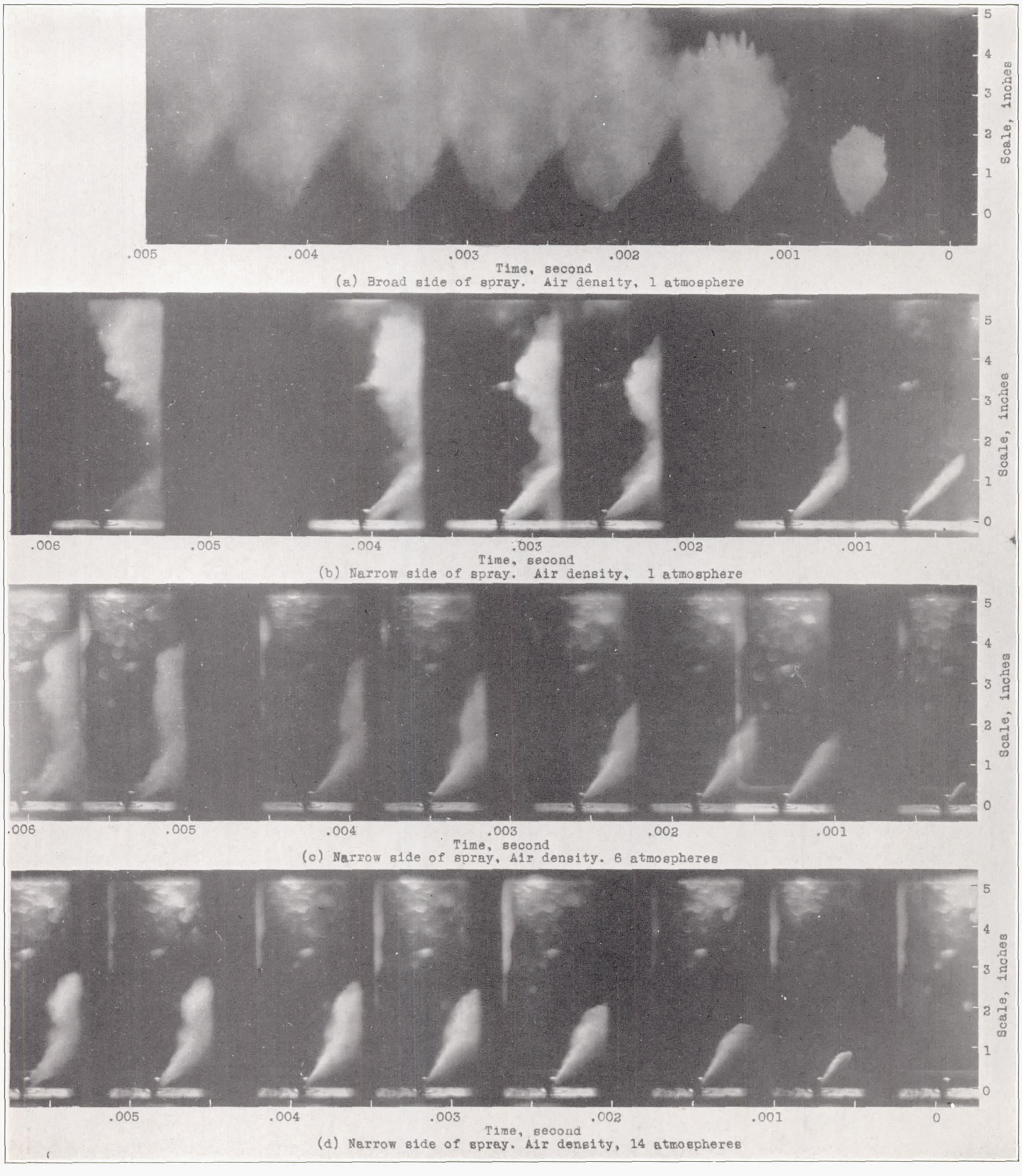


FIGURE 12.—Fuel sprays from a lip nozzle injected into air having different densities.

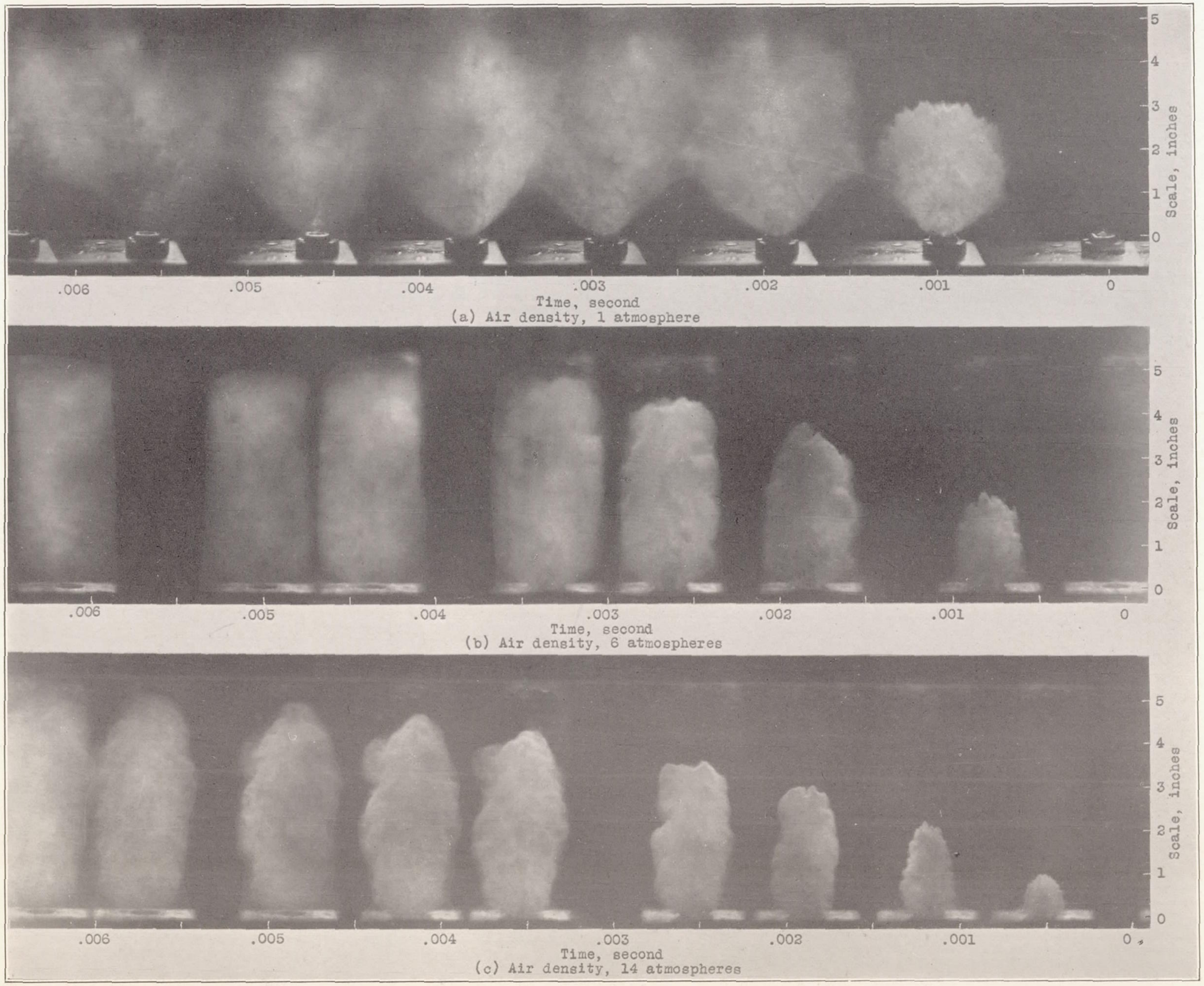


FIGURE 13.—Fuel sprays from a nozzle with two impinging jets injected into air having different densities. Wide side of spray shown.

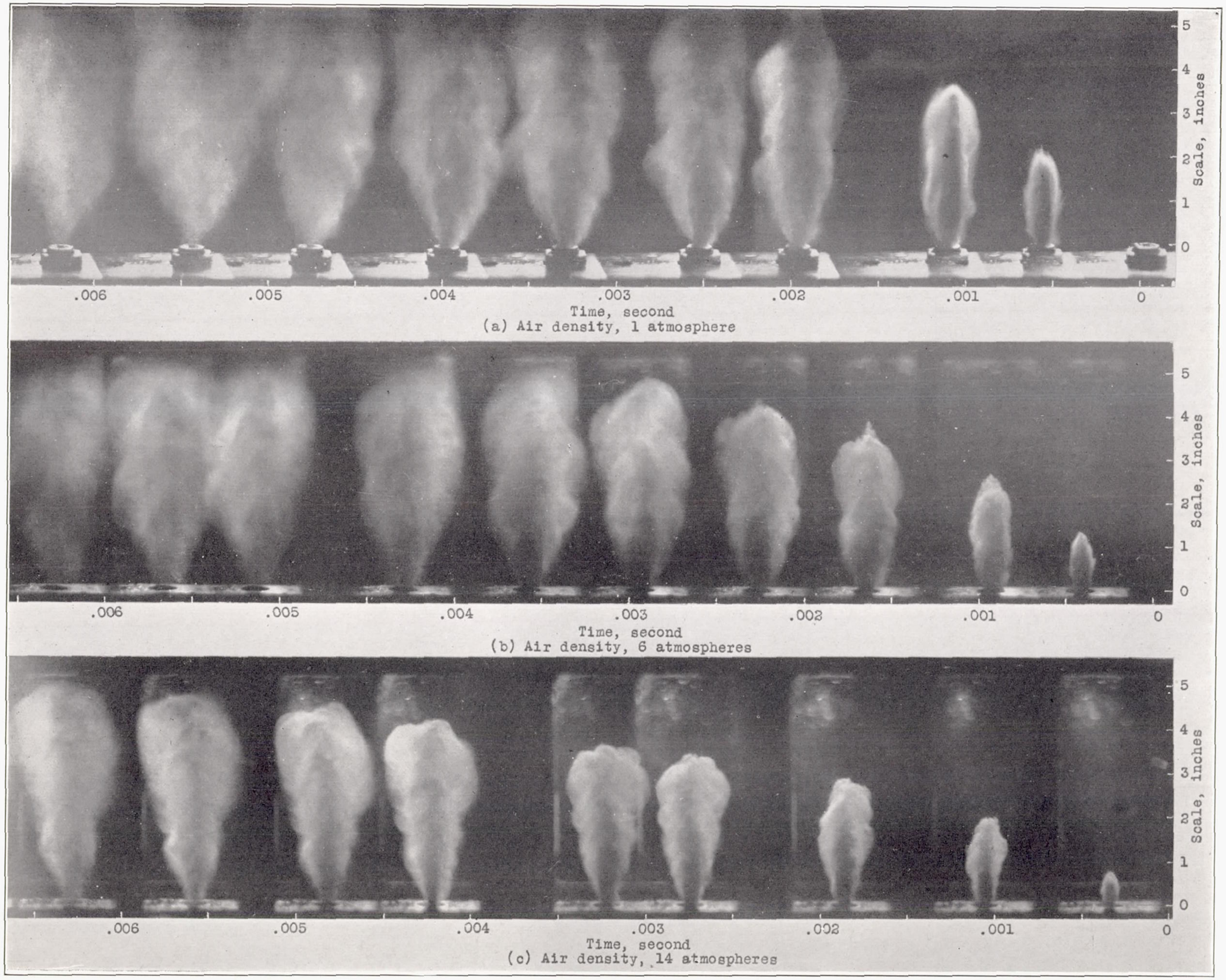


FIGURE 14.—Fuel sprays from a nozzle with two impinging jets injected into air having different densities. Narrow side of spray shown.

increase in the air density has little effect on the spray core. Notice also that an increase in the air density results in a small increase in the size of the spray core in contrast to the effect on the cores of sprays from plain nozzles.

Photographs of sprays from a nozzle having four 0.030-inch impinging jets are shown in figure 15. Figure 8 (d) shows that the spray cores are circular in section, persist a little longer than those in sprays from nozzles with two impinging jets, and increase somewhat in size and length with increasing air density. The large total-orifice area of the four-jets nozzle caused the effective injection pressure to be low. The valve stem was not held away from its seat during the entire injection period, resulting in an intermittent fuel discharge. No measurements of the coefficient of discharge of impinging-jets nozzles have been made at this laboratory but the data in table I indicate that they are somewhat less than for plain nozzles of the same total-orifice area. No engine tests have been made with the four-jets nozzle but the two-jets type has been used with good results in a 2-stroke-cycle spark-ignition engine in which fuel injection took place before the start of the compression stroke (reference 17). The use of impinging-jets nozzles will probably be limited to cases where the air density at the time of injection is quite low or where directed air movement is employed.

Annular-orifice nozzles (figs. 6 to 9 and 16 to 18).—Most annular-orifice nozzles are built integrally with their injection valves, the valve stems having enlarged ends on which the seating surfaces are located. The spray may be in the form of a hollow cylinder or a hollow cone of any angle desired. The width of the nozzle orifice, and therefore that of the spray core, varies with the injection pressure; but the cone angle of the spray as it leaves the nozzle is unchanged. The distribution of the fuel in such sprays is good, provided that the valves and nozzles are in excellent mechanical condition. Erosion of the orifice walls by grit in the fuel is particularly serious for the opening is so narrow that even slight scoring upsets the fuel distribution. The orifice walls are usually also the valve-seating surfaces and scoring of them prevents tight seating. Another common cause of poor fuel distribution is eccentricity of the valve stem. Both of these faults are illustrated by the photograph in figure 18 (a), which is a view taken along the axis of the nozzle shown in figure 1 (e). This nozzle had been used for about 100 hours before the photograph was taken. When it was new, the sprays from it were much more uniform and concentric. (See reference 18.)

The two valves having annular orifices were operated at the same injection pressure as all the other valves (4,000 pounds per square inch), but the valve-opening pressure for these valves was about 1,000 pounds per square inch and the initial pressure used was about 500 pounds per square inch. The conical cores of the sprays disintegrated close to the nozzles. Increasing the air density from 1 to 14 atmospheres reduced the cone angle of the spray cores from the 45° nozzle to about 35° and reduced the cone angle of the envelop to a lesser extent. Another effect of increasing the air density was to cause more of the fuel to be deflected into the space inside the hollow conical core. The sprays were unsymmetrical, probably owing to eccentricity of the valve stems.

The use of sprays from annular orifices in compression-ignition engines seems to be decreasing. One favorite arrangement is to place a wide-angle nozzle directly over the center of the piston, thus reducing to a minimum the distance the spray must travel. Annular-orifice nozzles have been used in spark-ignition engines for the injection of both gasoline and fuel oil (reference 19). In these engines the injection takes place during the intake stroke or during the early part of the compression stroke. As there is more time for the mixing of the fuel and the air, good distribution of the fuel in the sprays is not so important as with compression-ignition engines.

Pintle nozzles (figs. 7, 9, 18, 19, 20, and 21).—Pintle nozzles are also known as "pin" nozzles. Although many of them have annular orifices, they are discussed as a separate type because the sprays they produce are not like those from large-diameter annular orifices. Pintle nozzles are modifications of the plain type, a projection on the valve stem extending through the orifice so that an annular space is formed. The projecting part may be cylindrical, conical, or it may be smallest at the orifice exit, expanding beyond this point. The pintle in the nozzle tested is of this last mentioned style, with an expansion angle of 20°.

When the stem is barely lifted from its seat, the fuel is directed against the pintle by the conical approach to the orifice and is then deflected by the surface on the end of the pintle so that it leaves in the form of a hollow cone having an angle determined by that of the pintle surface. As soon as the stem lifts a little more, however, the cone angle of the spray decreases and the major part of the fuel charge leaves the nozzle at an angle only slightly greater than would be the case were the pintle not present. A study of figure 1 (f), including the enlarged views with the stem lifted 0.015 and 0.038 inch, will help to clarify this point. As the stem returns to its seated position at the end of the injection period, the spray angle increases. These changes in spray angle are clearly shown in figure 19 (a), the spray angle being greatest at the beginning and end of the injection period. This difference is much reduced when the air density is increased. The changing spray angle is strikingly illustrated in figure 19 (d). In this case the valve-opening pressure was reduced to 3,000 pounds per square inch with the result that the valve opened sooner and closed after about 0.0038 second, reopened quickly and closed again at about 0.005 second, opened for the third time

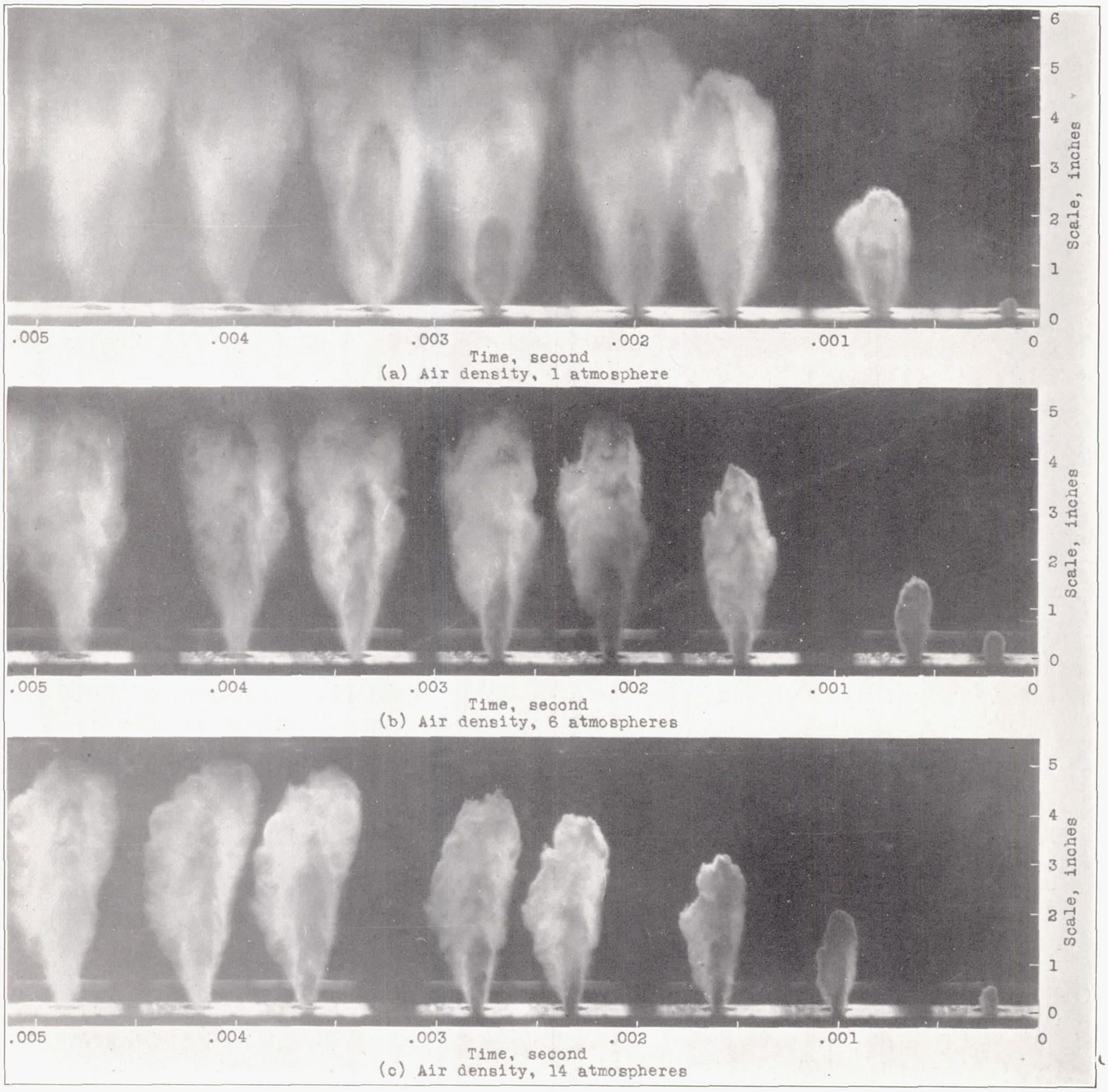


FIGURE 15.—Fuel sprays from a nozzle with four impinging jets injected into air having different densities.

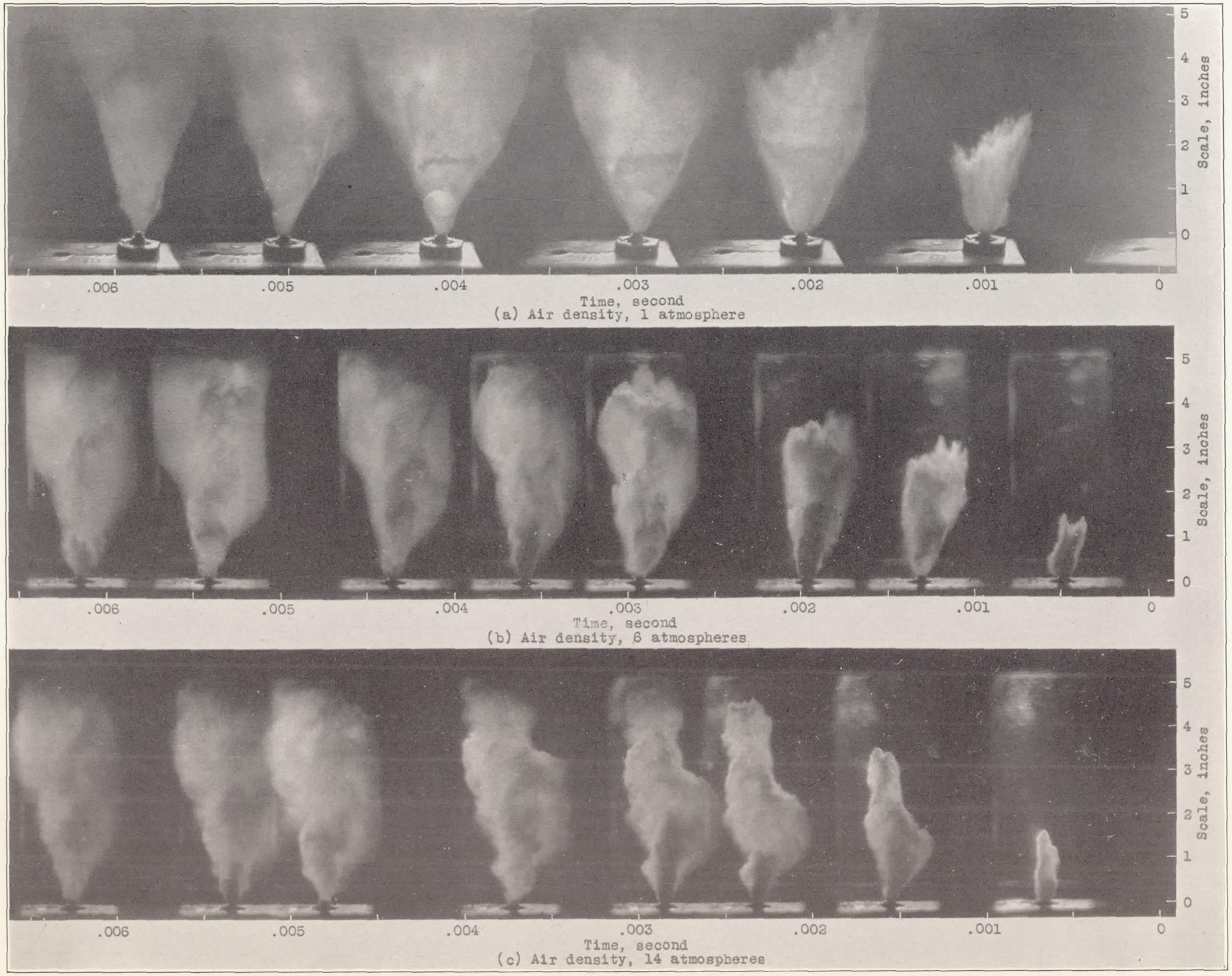


FIGURE 16.—Fuel sprays from a nozzle with an annular orifice of varying area injected into air having different densities. Spray cone angle, 45°.

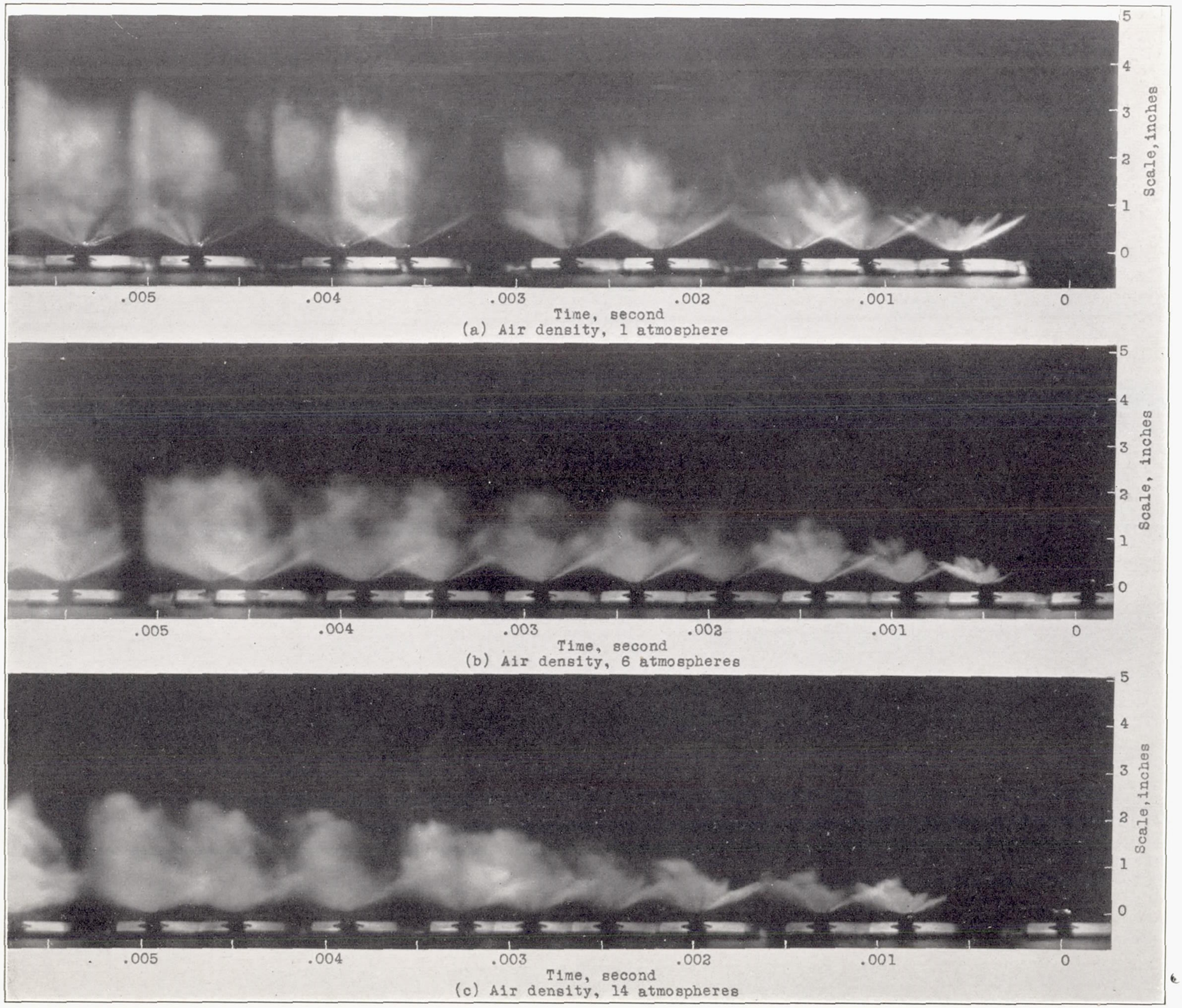
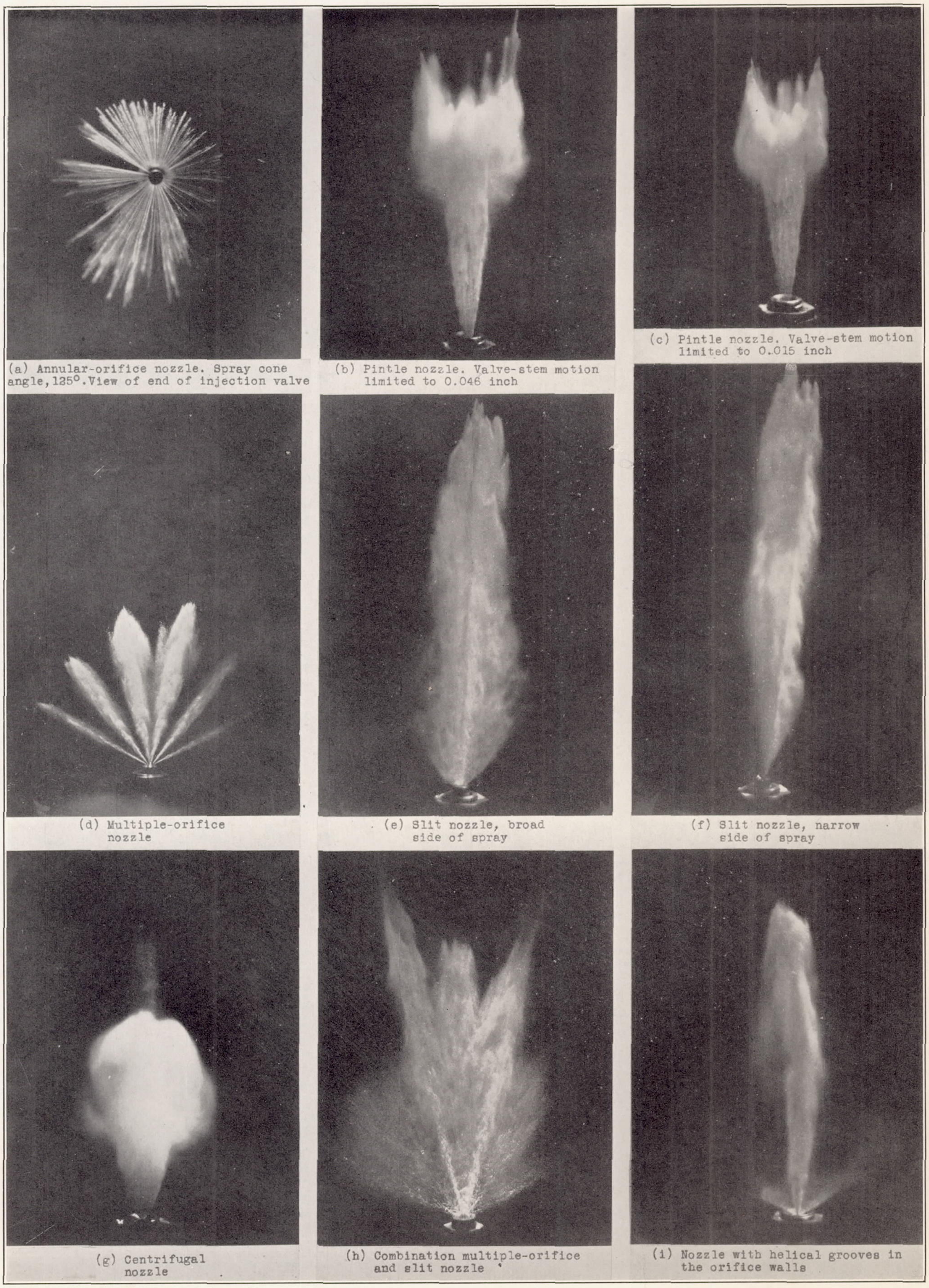


FIGURE 17.—Fuel sprays from a nozzle with an annular orifice of varying area injected into air having different densities. Spray cone angle, 125°.



(a) Annular-orifice nozzle. Spray cone angle, 125°. View of end of injection valve

(b) Pintle nozzle. Valve-stem motion limited to 0.046 inch

(c) Pintle nozzle. Valve-stem motion limited to 0.015 inch

(d) Multiple-orifice nozzle

(e) Slit nozzle, broad side of spray

(f) Slit nozzle, narrow side of spray

(g) Centrifugal nozzle

(h) Combination multiple-orifice and slit nozzle

(i) Nozzle with helical grooves in the orifice walls

FIGURE 18.—Photographs of the early stages of sprays from the nozzles tested. Injection pressure, 4,000 pounds per square inch; air density, 1 atmosphere.

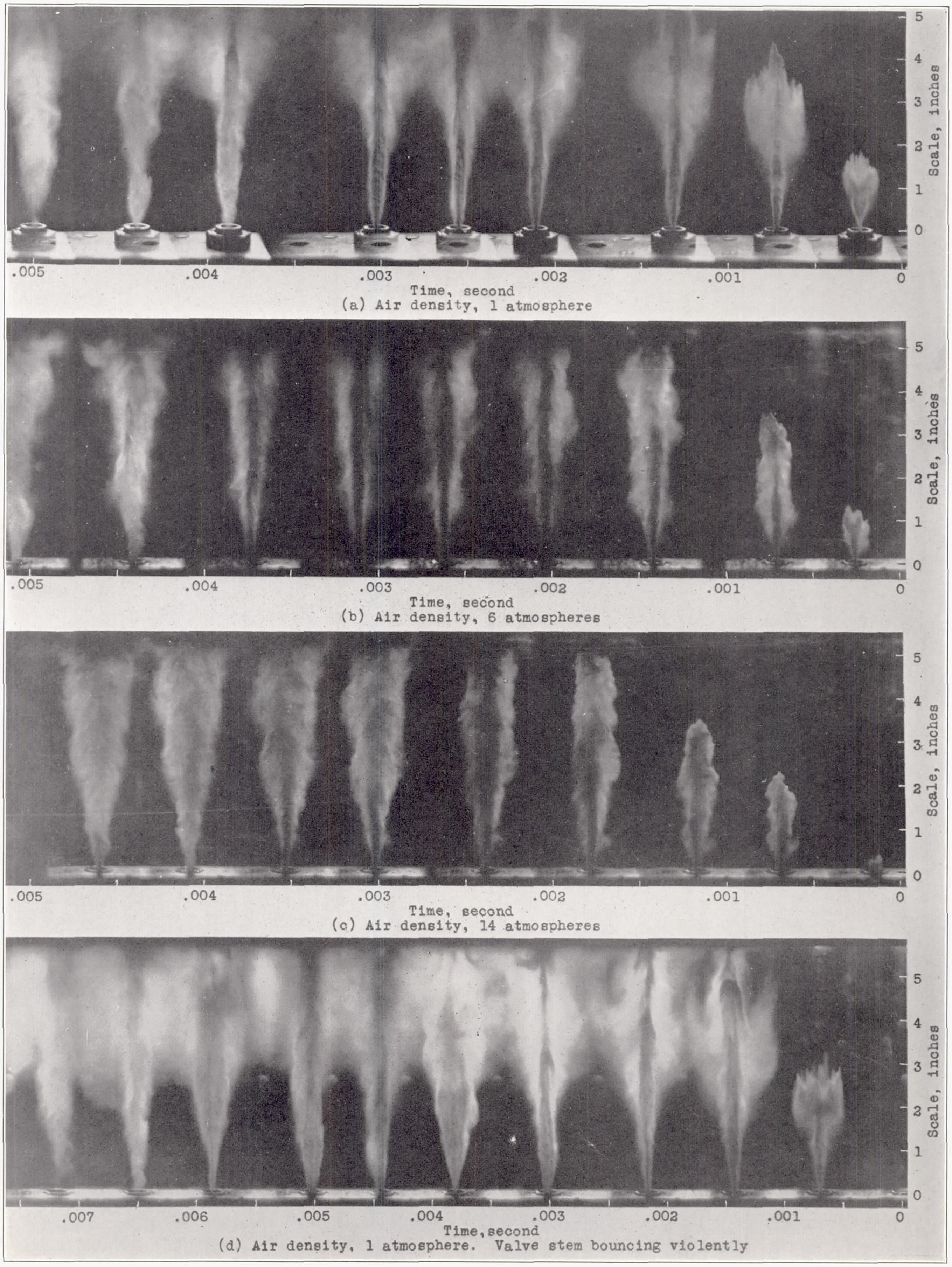


FIGURE 19.—Fuel sprays from a pintle nozzle injected into air having different densities. Valve-stem motion limited to 0.046 inch.

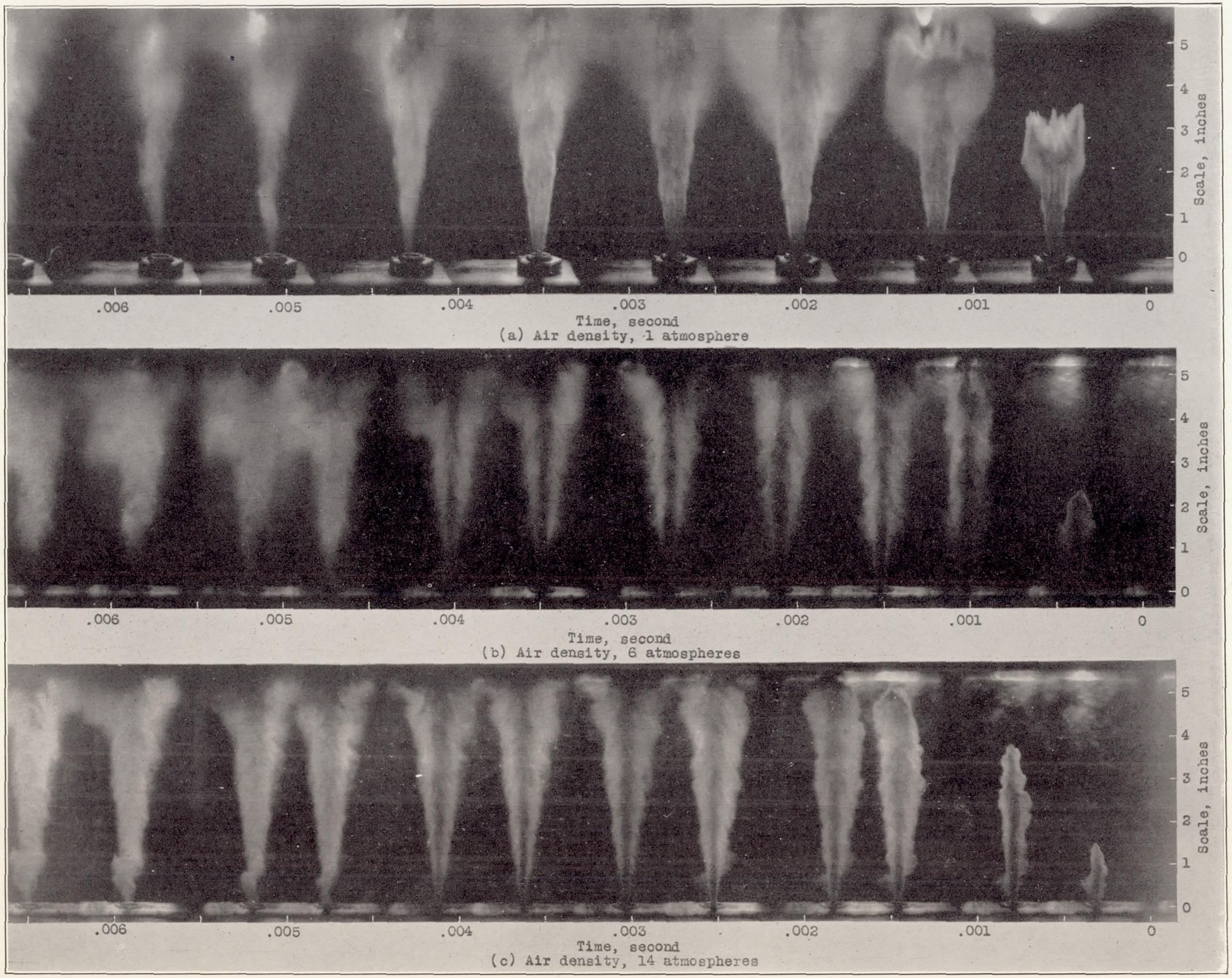


FIGURE 20.—Fuel sprays from a pintle nozzle injected into air having different densities. Valve-stem motion limited to 0.015 inch.

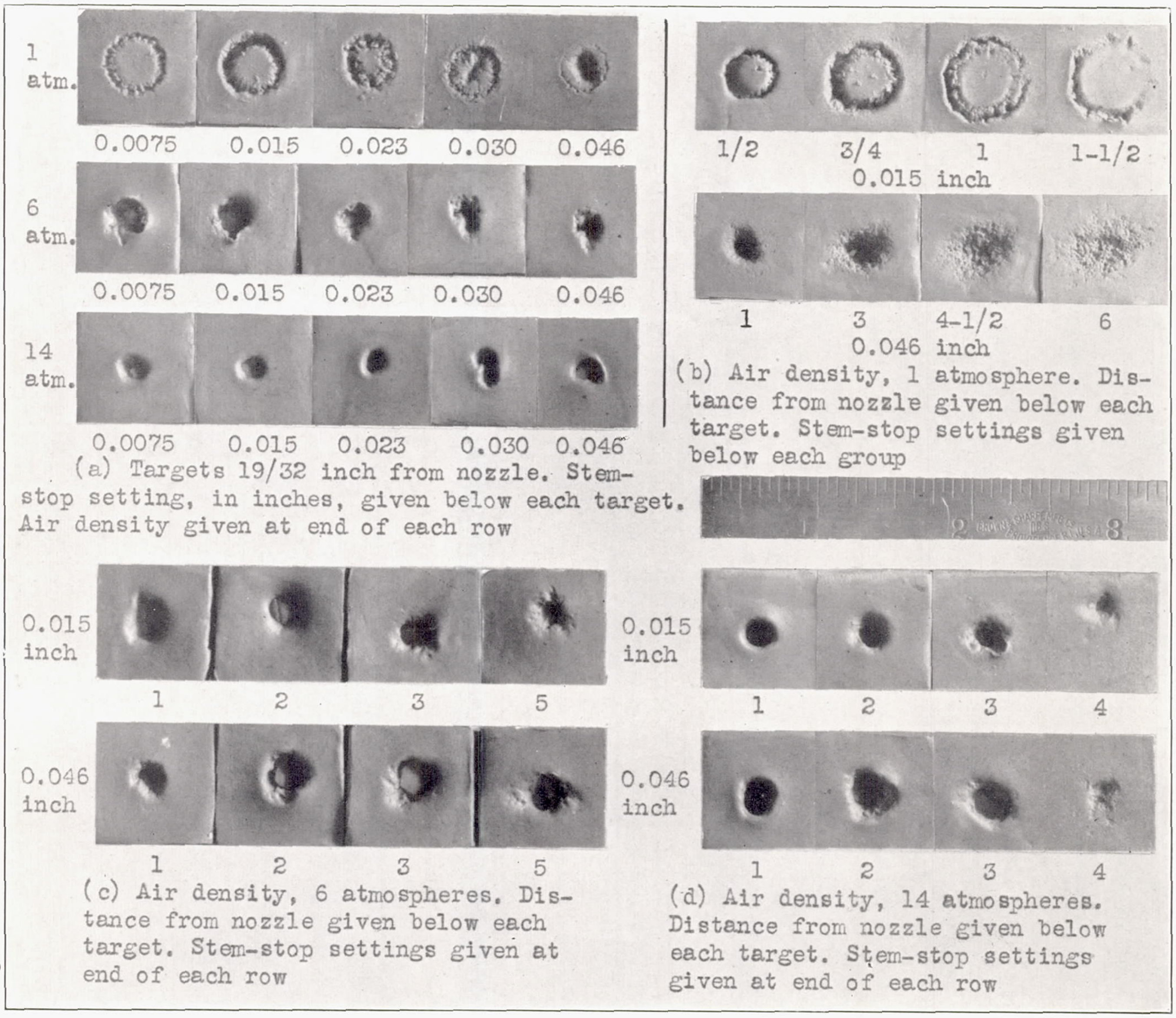


FIGURE 21.—Impressions made in Plasticine targets by fuel sprays from a pintle nozzle. Variables are air density, distance from nozzle to target, and stem-stop setting.

and finally closed shortly after 0.006 second. (See reference 2.)

A comparison of the photographs in figure 19 with those of sprays from two other nozzles of the same style but with pintle angles of 8° and 30° (reference 20) showed that, although in air at atmospheric density the spray angle increased with increasing pintle angle, the difference decreased as the air density was increased until at 18 atmospheres the sprays were nearly alike. The rate of spray-tip penetration for sprays from pintle nozzles of the style tested at this laboratory increases slightly with decreasing pintle angle and is about the same as that for sprays from corresponding plain nozzles.

All the previously mentioned tests with the pintle nozzle were made with the movement of the valve stem limited to 0.046 inch, the condition under which this valve is ordinarily used. The interesting variation in spray angle with stem lift led to the installation of a screw stop to limit the lift to values less than 0.046 inch. Figure 20 shows the appearance of sprays from the pintle nozzle with the stem lift limited to 0.015 inch. The spray in air at atmospheric density remained at an angle of about 20° throughout the injection period, but in air at densities of 6 and 14 atmospheres the spray appeared to be very much like those made with the stem motion limited to 0.046 inch.

The results of the Plasticine target tests made with pintle-nozzle sprays are particularly interesting and help to explain their unusual behavior. Figure 21 (a) shows how the distribution of the fuel in the spray close to the nozzle changes with air density and with different limitations of the stem motion. Notice that in air at atmospheric density, as the limit of the stem motion is increased, the fuel distribution shifts from one extreme to the other; in air at a density of 6 atmospheres the change is much less; at 14 atmospheres there is almost no change. Impressions were also obtained with the stem lift limited to 0.038 inch; but they were the same as those made with a stem lift of 0.046 inch, indicating either that the stem does not lift higher than 0.038 inch under these injection conditions or, if it does, that further lift has no effect on the spray. The other groups of targets (figs. 21 (b), (c), and (d)) show the distribution of the fuel at different distances from the nozzle, with the stem motion limited to 0.015 inch and 0.046 inch, in air at densities of 1, 6, and 14 atmospheres.

Pintle nozzles have attained widespread use in light, high-speed, compression-ignition engines, especially those with divided combustion chambers and those having high-velocity air flow.

Multiple-orifice nozzles (figs. 7, 18, 22, and 23).—In a quiescent combustion chamber, the fuel sprays must be distributed to all parts of the chamber. The most satisfactory type of nozzle thus far developed for this purpose is one containing a number of small cylindrical orifices. The large amount of data available on the characteristics of sprays from such orifices makes it possible to design multiple-orifice nozzles that will perform satisfactorily in combustion chambers of many different forms. In the multiple-orifice nozzles used at this laboratory, angles of 20° to 30° between the axes of the separate jets have been found to give good results (reference 21). Very small orifices have been added between the larger ones for the purpose of supplying fuel to the air close to the nozzle and their use has resulted in a slight gain in engine performance but the gain is not considered sufficient to justify the added complication of the nozzle (reference 22). Reducing the angle between the individual sprays, thus eliminating the blank spaces between them, has not resulted in any improvement in engine performance. The use of a nozzle having 16 orifices in 3 planes, and a fuel pump having a very high rate of discharge, resulted in poor engine performance. Such results as these show that multiple-orifice nozzles that appear from spray photographs to give good fuel distribution do not always give good engine performance. Experiments have shown that in nozzles of the type shown in figure 1 (g) the small side orifices must be made larger than would be indicated by the amount of air they are to serve, probably because the pressure of the fuel at these orifices is reduced after injection begins by the flow of fuel past them toward the larger orifices (reference 23).

Slit nozzles (figs. 7, 9, 18, 22, 24, and 25).—Slit nozzles are similar in construction to plain nozzles, a narrow slit taking the place of the cylindrical orifice. The characteristics of the spray are quite different, however, resembling in many respects those of sprays from lip and annular-orifice nozzles. The shape of the sprays depends on the dimensions of the slit and on the form of the passage between the stem seat and the slit. Tests made at this laboratory have shown that, if the bottom of the cylindrical passage between the valve seat and the orifice is made conical instead of flat, the spray core tends to separate into two widely divergent jets. The width of the spray may be increased without this separation by making the bottom of the passage spherical with its radius about twice that of the cylindrical passage. The photographs of figures 24 and 25 show that the sprays from the slit nozzle tested were not symmetrical in either plane, probably owing to the fact that the plane of the slit was not quite parallel to the axis of the nozzle. The nozzle was rotated 180° between the time of taking figures 25 (b) and 25 (c). The shapes of the cores of the sprays from the slit nozzle tested are indicated by the Plasticine target tests (fig. 22 (b)). The impressions are very ragged and show that the plane of the core twisted through an angle of about 50° after leaving the nozzle. In the photograph the targets are arranged to show this twisting, the plane through the slit being parallel to the row of targets in each case. When making the cross-sectional sketches of the sprays from the slit nozzle (fig. 9 (h)), the cores were assumed

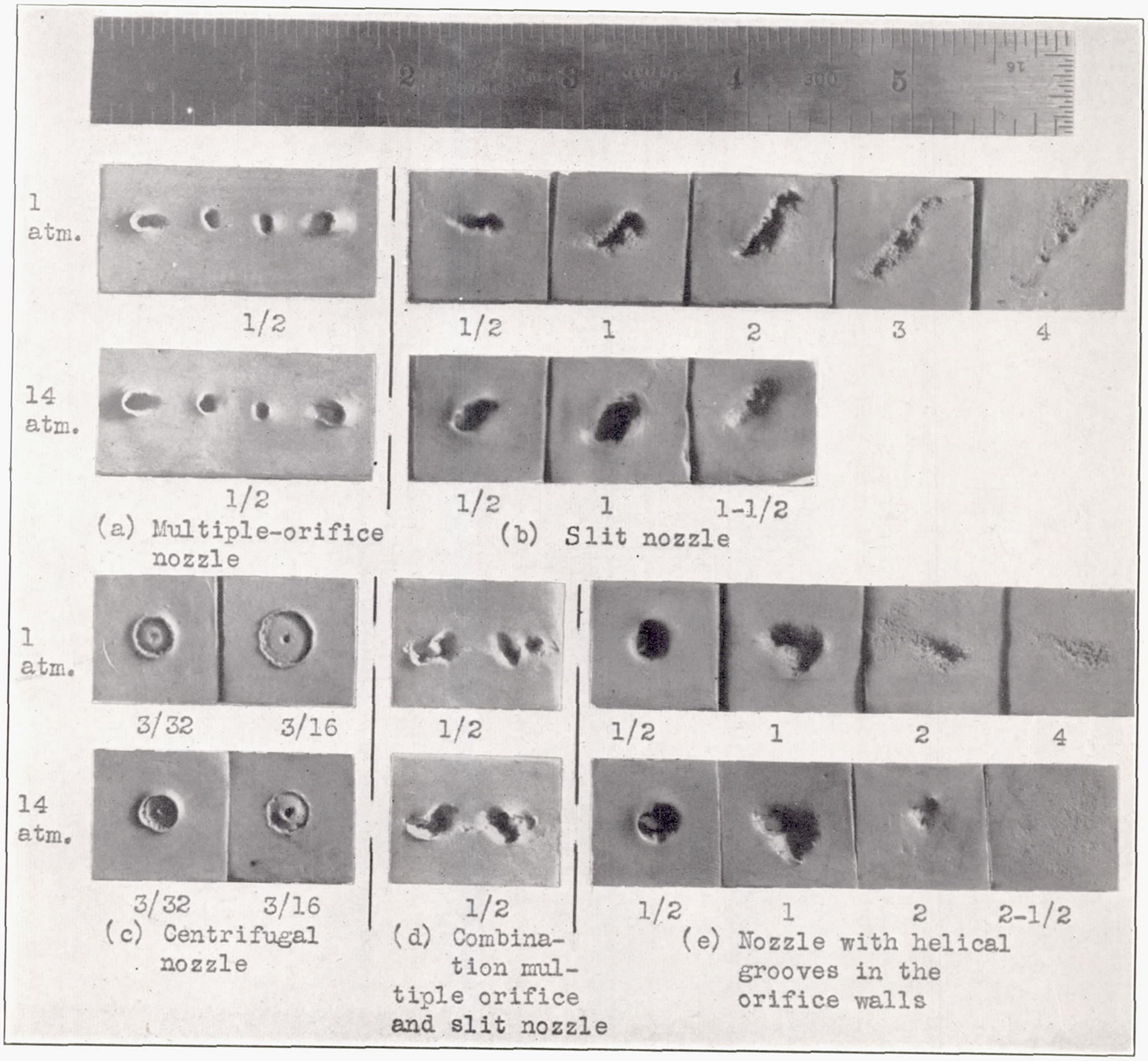


FIGURE 22.—Impressions made in Plasticine targets by fuel sprays from different nozzles. Distance from nozzle to target, in inches, is shown below each target, the air density is shown at the end of each row.

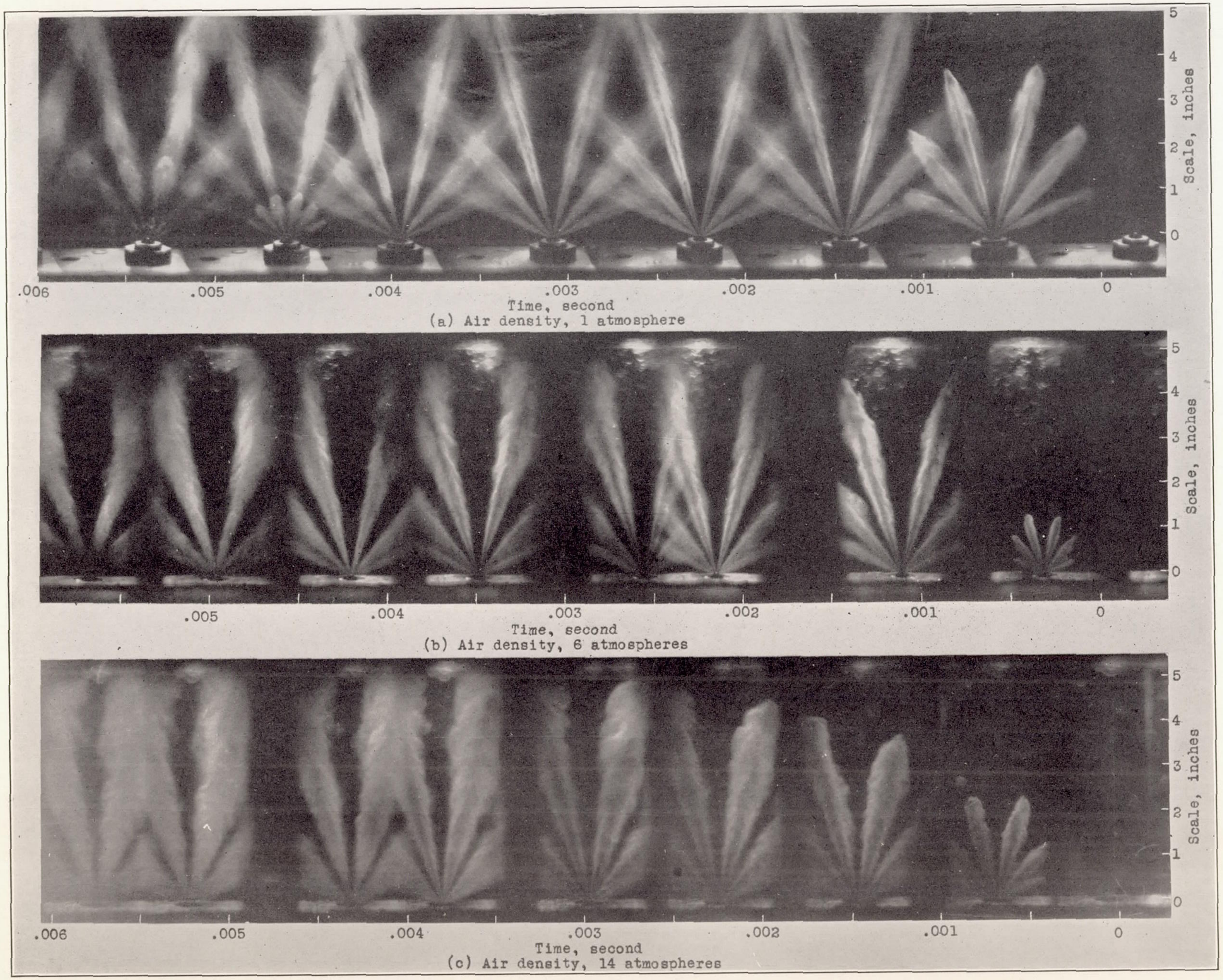


FIGURE 23.—Fuel sprays from a multiple-orifice nozzle injected into air having different densities.

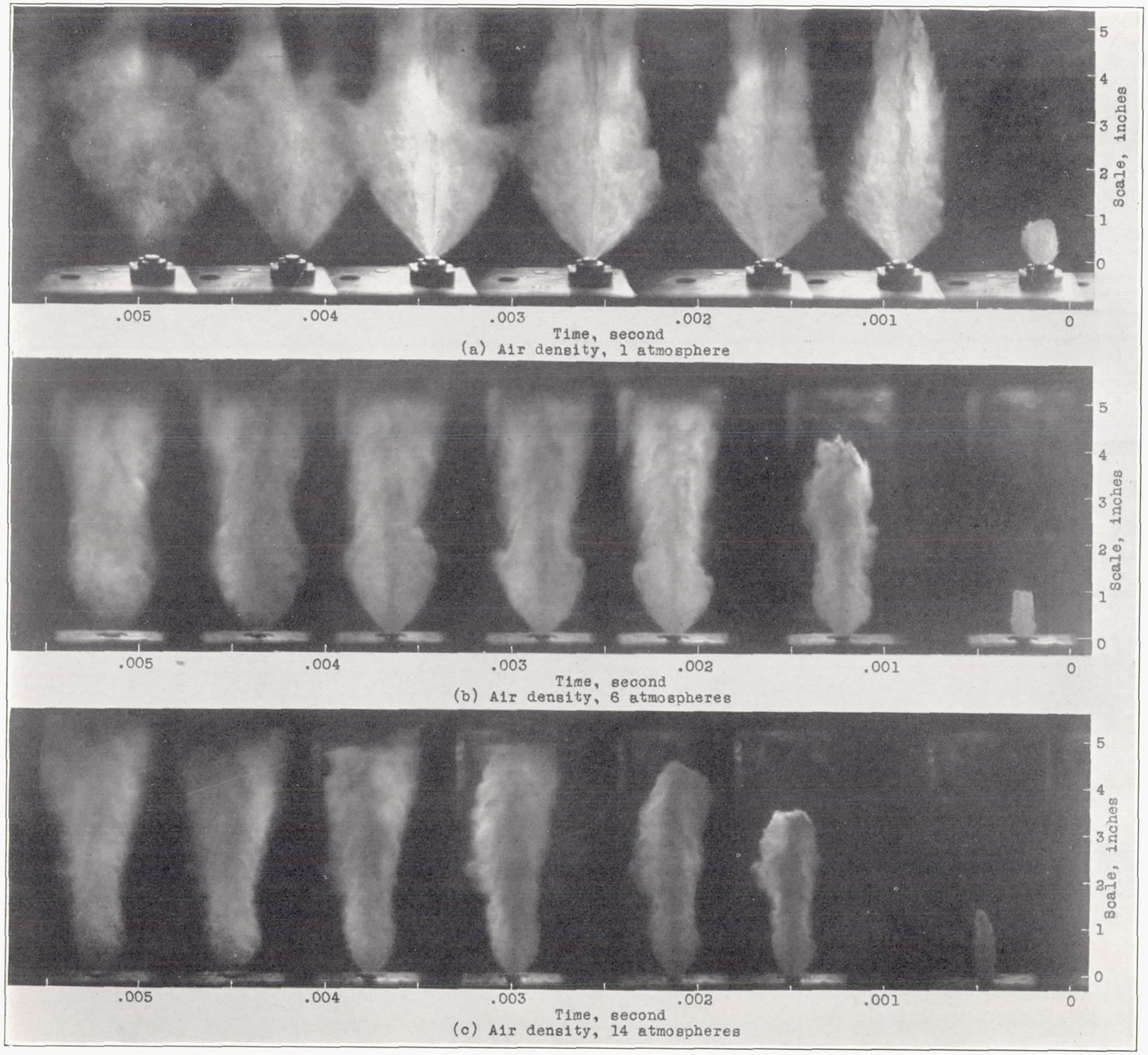


FIGURE 24.—Fuel sprays from a slit nozzle injected into air having different densities. Wide side of spray shown.

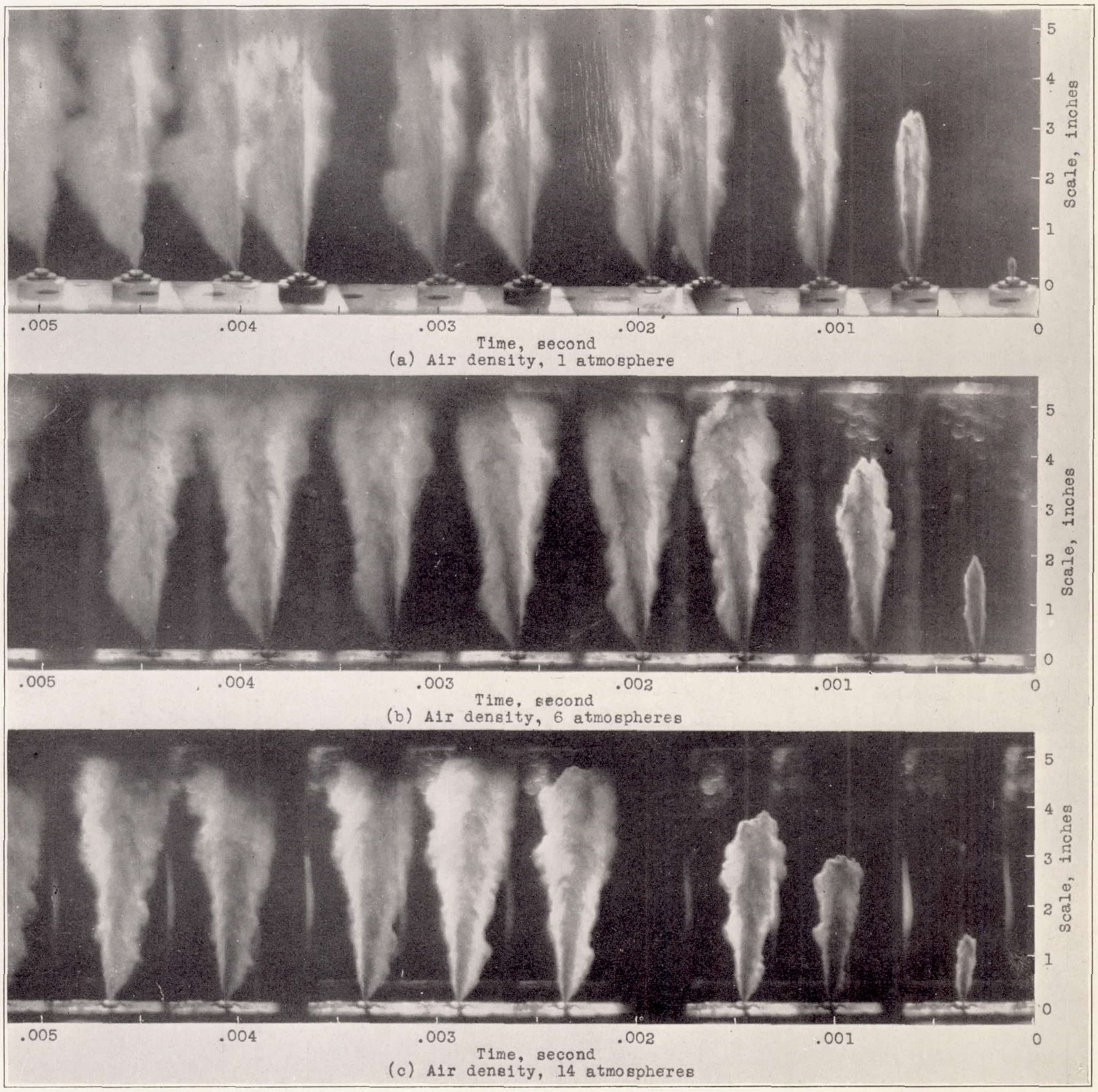


FIGURE 25.—Fuel sprays from a slit nozzle injected into air having different densities. Narrow side of spray shown.

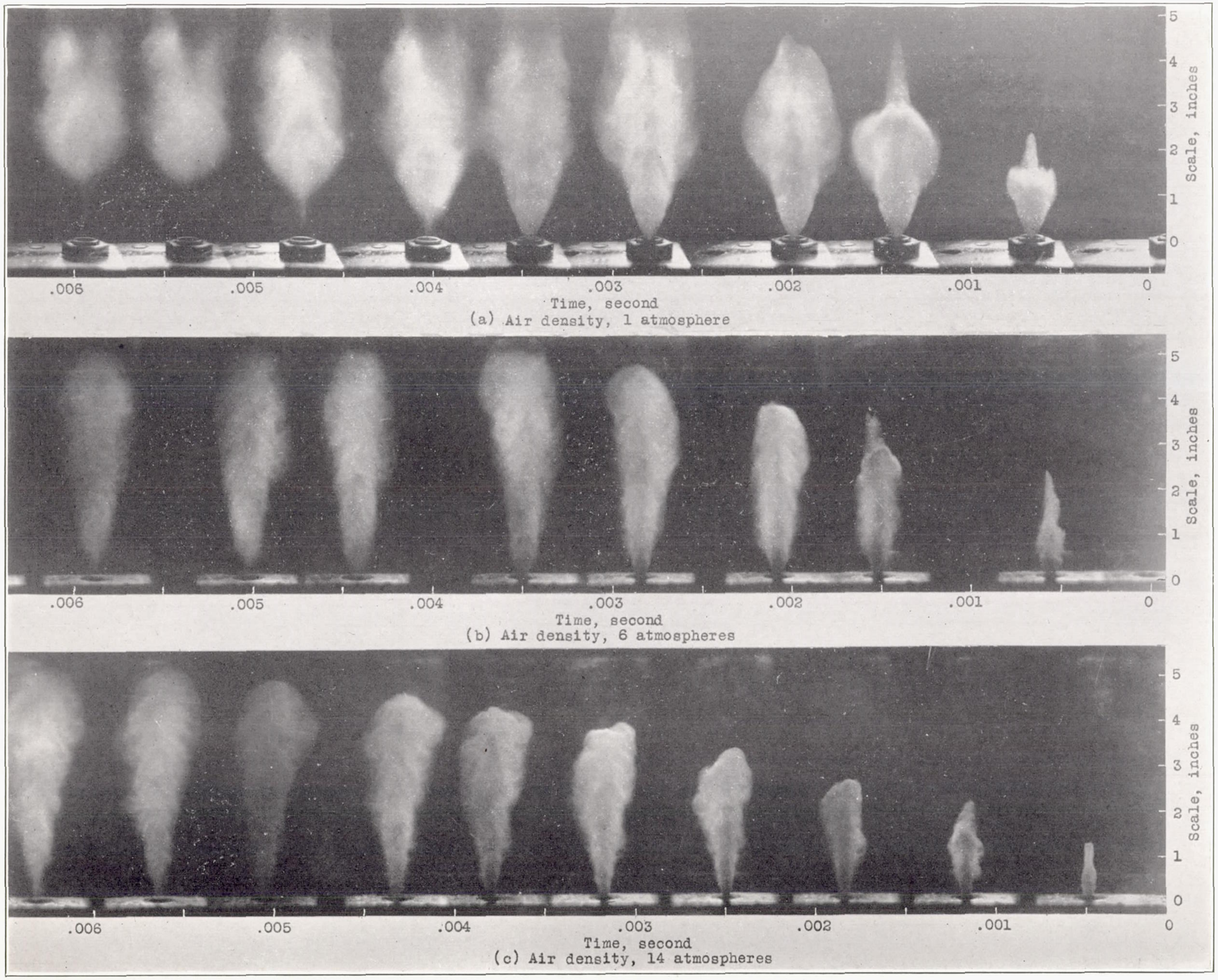


FIGURE 26.—Fuel sprays from a centrifugal nozzle injected into air having different densities.

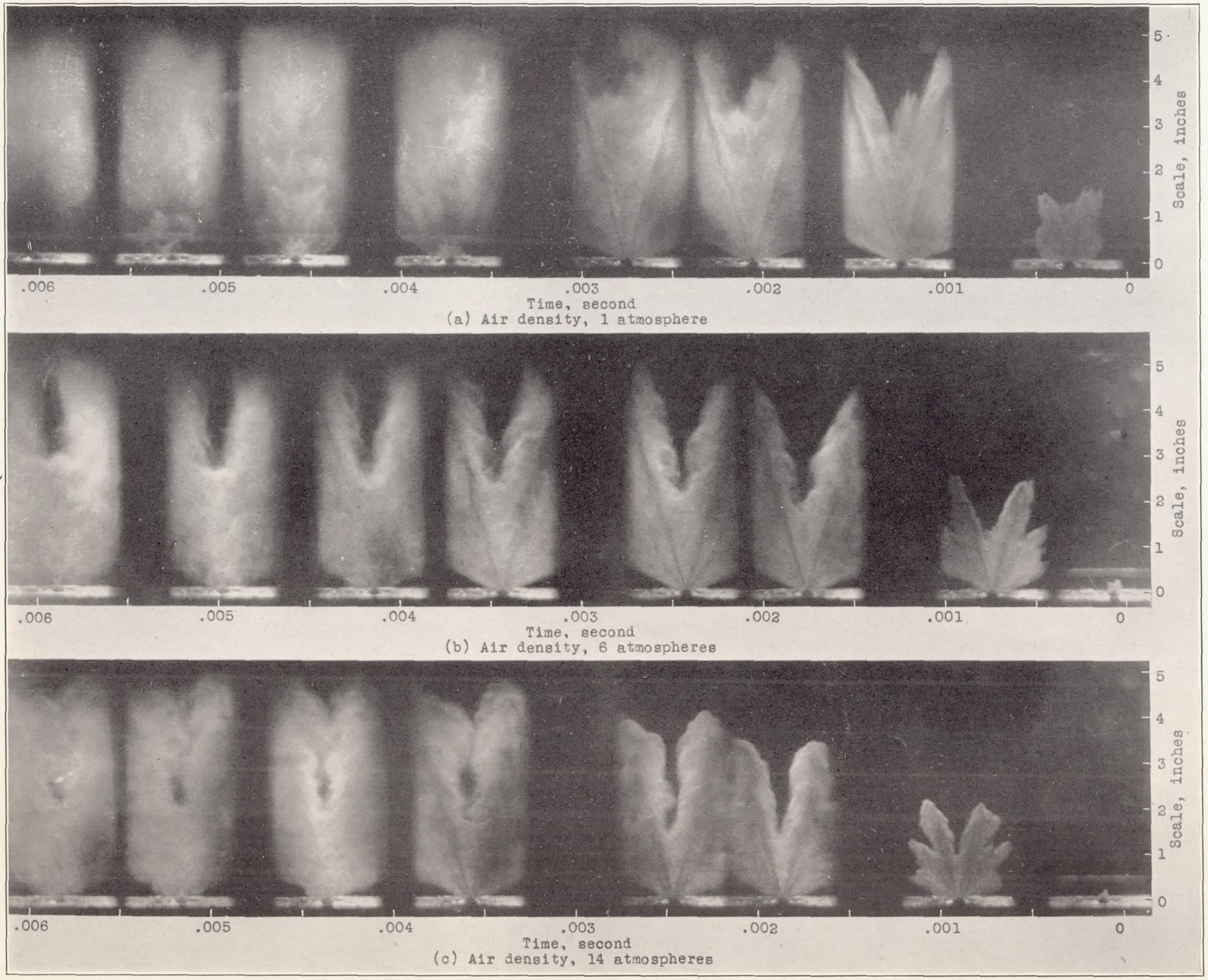


FIGURE 27.—Fuel sprays from a combination multiple-orifice and slit nozzle injected into air having different densities.

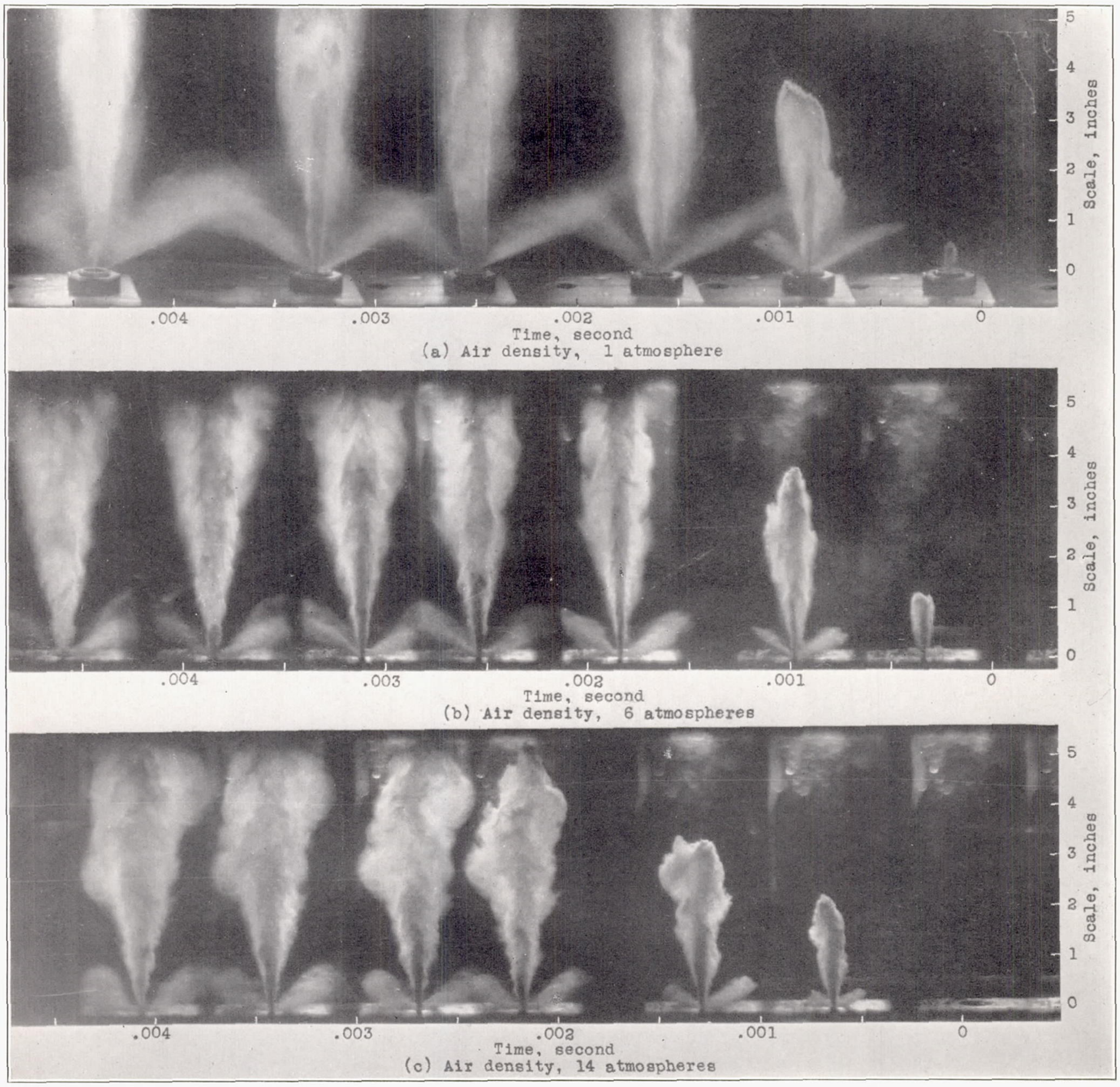


FIGURE 28.—Fuel sprays from a nozzle with helical grooves in the orifice walls injected into air having different densities.

to have remained parallel to the slit. The dimensions of the spray cores were obtained from the Plasticine targets but the corresponding true dimensions of the envelops could not be obtained from the spray photographs. For the wide views the envelops were drawn as they appeared in the photographs but for the narrow views they were assumed to have the same appearance as sprays from the 0.020-inch orifice plain nozzle.

Slit nozzles are used where a simple design is desired but where the sprays from a plain nozzle would penetrate too far. The fuel distribution in sprays from slit nozzles being easily changed by scoring of the orifice walls or by clogging of parts of the narrow slit, particular care should be taken to keep the fuel clean.

Centrifugal nozzles (figs. 7, 9, 18, 22, and 26).—With centrifugal nozzles, a rotary motion is imparted to the fuel by helical grooves on the valve stem causing the spray to expand immediately on leaving the orifice. The spray angle increases as the pitch of the grooves is decreased, as the ratio of the orifice area to groove area is increased, as the orifice length-diameter ratio is decreased, and as the air density is decreased. Some centrifugal nozzles are so constructed that the amount of whirling of the fuel may be increased as the engine load is increased. The rate of spray-tip penetration is considerably less than with plain nozzles, decreasing in general as the spray angle increases. Both spray angle and spray-tip penetration increase as the areas of both the orifice and grooves are increased proportionately, and a slightly higher rate of penetration is obtained when the valve seat is located between the grooves and the orifice, rather than above the grooves. (See references 4, 7, 24, and 25.)

Sprays from the centrifugal nozzles used at this laboratory are composed of two parts. At the beginning of each injection period, a small portion of the fuel charge is injected without any rotary motion. This fuel was probably left in the nozzle between the grooves and the orifice at the end of the preceding injection and it forms a spray similar to those from plain nozzles. The rest of the fuel charge is injected with rotary motion and spreads out into a hollow cone surrounding the earlier nonrotating spray. The two parts may be seen distinctly in the photographs of figure 26. Apparently very little fuel is contained in the nonrotating spray for, although its initial velocity is high, its penetrating power is low, and it is soon overtaken by the main discharge. In figure 7 (l) two sets of curves are given for the penetration of the centrifugal sprays, corresponding to the two parts of the sprays. The dashed lines represent the nonrotating part and the solid lines represent the rotating part. Figure 22 (c) shows that the two parts of the spray have distinct cores. After they have broken up, the distribution of the fuel in the sprays improves considerably.

The popularity of the centrifugal-type nozzle is apparently decreasing. Their very low coefficients of discharge (reference 6), low rate of spray penetration, and poor atomization of the fuel (reference 11) make them less suitable for high-speed, compression-ignition engines than other types of nozzles. They are suited to spark-ignition engines using fuel-injection systems, but other types of high-dispersion nozzles serve as well and are less complicated. A comparison of the discharge weights from the centrifugal nozzle and from a plain nozzle of the same orifice area (see table I) indicates the large difference in the discharge coefficients of the two types.

Nozzles that are combinations of two types (figs. 7, 9, 18, 27, and 28).—Photographs of sprays from plain and multiple-orifice nozzles show that very little fuel is delivered to the air near the nozzle, most of it going to the farther side of the combustion chamber. Among the injection nozzles tested at this laboratory in an attempt to correct this situation there have been three in which plain orifices were combined with nozzles having low penetration and high dispersion.

Photographs of sprays from a combination of multiple-orifice and slit nozzles are shown in figure 27, the plane of the slit and the axes of the cylindrical orifices being coincident. It is apparent from the photographs that this nozzle delivers more fuel to the air near the nozzle than does the multiple-orifice type, especially at the higher air densities. As both the photographs and a comparison of figure 22 (a) and figure 22 (d) will show, the angle between the jets from the cylindrical orifices has been altered even though the angles between the orifices themselves remained the same. Several nozzles of the multiple-orifice and slit type were made and tested on an engine having a quiescent combustion chamber of the vertical-disk form. Preliminary test results were not encouraging and further test work was postponed.

A nozzle containing both multiple orifices and impinging jets is described in reference 16, which also contains photographs of sprays produced by it. Two impinging and two nonimpinging jets were used, the discharge area of the latter being 2.25 times that of the former. The photographs showed that the spray produced by the impinging jets became entrained in the higher velocity sprays from the nonimpinging jets so that little fuel remained near the nozzle. Tests made with this nozzle in a compression-ignition engine having a vertical-disk form of combustion chamber gave inferior results as compared with those when multiple-orifice nozzles were used. The engine detonated readily and the performance was poor.

A nozzle having helical grooves cut in the walls of its cylindrical orifice was made and tested to determine whether such grooves would impart sufficient rotation to the fuel jet to increase its cone angle. If such were the case, the principle might be of use in multiple-orifice nozzles, the construction of which prevents whirling the fuel before it reaches the orifices. The spray photographs in figure 28 and the photographs of the Plasticine targets (fig. 22 (e)) show that the spray did not rotate as a whole and that, although the cone angle is somewhat greater than for sprays from grooveless orifices of the same dimensions, the difference is due rather to increased turbulence of the fuel than to centrifugal force. The small sprays at the base of the main sprays are the discharges from the ends of the two helical grooves. The rate of spray-tip penetration was reduced by the presence of the grooves, as the curves of figure 7 (m) show. The dashed line of that figure shows, for comparison, the tip penetration of a spray from a grooveless orifice of the same dimensions in air at a density of 14 atmospheres.

SOME OTHER NOZZLES AND INJECTION VALVES

The nozzles and injection valves herein described include representatives of most of the types commonly used at the present time. A great many variations of the pintle and annular-orifice types of nozzles have been used, as well as of the impinging-jets, slit, and centrifugal types. (See reference 26.) Injection valves have been used in which steel diaphragms took the place of springs, either allowing the nozzle to move away from the stationary stem (reference 25) or allowing the stem to move away from the nozzle (reference 26). An injection valve having two concentric lapped stems set to open at different fuel pressures and opening up separate orifices in the nozzle has been made and tested at this laboratory (reference 27).

EFFECT OF AIR FLOW

All the spray photographs shown in this report were made with the air motionless. The air in some combustion chambers may, for practical purposes, be considered motionless but in many other cases the sprays are injected into air having a high velocity. Tests of the effect of air velocities up to about 60 feet per second on fuel sprays are reported in reference 28. Other tests using air velocities up to 800 feet per second are reported in references 29 and 30, and the effect of air velocities up to 27 feet per second on the distribution of fuel following injection cut-off is reported in reference 31. The tests showed that air moving at 60 feet per second or less will blow the envelops away from the cores of sprays during the injection period and will help to distribute all the fuel throughout the combustion chamber after injection cut-off. Air velocities of the order of 300 feet per second were necessary, however, to break up the spray cores during the injection period.

EFFECT OF AIR AND FUEL TEMPERATURES

All the photographs shown in this report were made with the air and fuel at room temperature. Some photographs showing the effects of air and fuel temperatures on fuel sprays, at an air density of 1 atmosphere, are reproduced in reference 32. Photographs of fuel sprays in the N. A. C. A. spray-combustion apparatus (reference 29) show their behavior in air at engine temperatures and pressures. The rate of spray-tip penetration is decreased slightly by heating the air and considerably more so by heating the fuel (reference 32). Raising the temperature of the air assists in the dispersion of the fuel throughout the combustion chamber and causes an appreciable amount of the fuel to be vaporized during the injection period. (See reference 33.)

EFFECT OF DIFFERENT FUELS

The fuel used for all the sprays shown in this report was a commercial diesel fuel. Spark photographs of sprays of gasoline, kerosene, diesel oil, and heavy fuel oil from both plain and centrifugal-type nozzles have been made at this laboratory, and the results are given in reference 4. The spray penetration was found to increase slightly and the spray cone angle to decrease slightly with increasing specific gravity of the fuel. Photographs of diesel-fuel and gasoline sprays made at low injection pressures and air densities (reference 34) show little difference in penetration rates or general appearance. Photographs of diesel-fuel and safety-fuel sprays in the N. A. C. A. spray-combustion apparatus (reference 29) show that the diesel fuel penetrated faster than the safety fuel. Photomicrographs of sprays of six different liquids are shown in reference 35. Measurement of the drop sizes led to the conclusion that the average drop diameter increases with increases in fuel viscosity or surface tension.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *December 4, 1934*.

REFERENCES

1. Rothrock, A. M., and Marsh, E. T.: Penetration and Duration of Fuel Sprays from a Pump Injection System. T. R. No. 455, N. A. C. A., 1933.

   Two photographs of fuel sprays from a plain nozzle used with a pump-injection system are shown, one in air at atmospheric density and the other in air at a density of 14.5 atmospheres. Curves are given to show the effects of pump speed, valve-closing pressure, injection-tube length and diameter, pump-load control setting, nozzle orifice diameter, and the presence of a check valve in the discharge tube on the penetration of the spray tip.

2. Rothrock, A. M.: Pressure Fluctuations in a Common-Rail Fuel Injection System. T. R. No. 363 N. A. C. A., 1930.

3. Beardsley, Edward G.: The N. A. C. A. Photographic Apparatus for Studying Fuel Sprays from Oil Engine Injection Valves and Test Results from Several Researches. T. R. No. 274, N. A. C. A., 1927.

Nine photographs of fuel sprays from both plain and centrifugal nozzles are reproduced, showing the effect of chamber air density and orifice size on the spray characteristics. The injection pressure was 8,000 pounds per square inch in each case, and the density of the chamber air was either 1 or 14.6 atmospheres. Curves are given which show the effects of injection pressure, gas density, and specific gravity of the fuel on the penetration of sprays from a plain cylindrical nozzle; other curves show the effects of groove helix angle and ratio of orifice area to groove area on the penetration, distribution, and cone angles of sprays from centrifugal-type nozzles.

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

Photographs of fuel sprays from a plain and a centrifugal-type nozzle are shown, the injection pressure and chamber air density being 8,000 pounds per square inch and 14.6 atmospheres, respectively, in each case. Curves are given for both types of nozzles showing the effects of the fuel and cylinder gas densities on the spray-tip penetration, and the effects of the fuel density on the spray angle and dispersion. Other curves are given only for the centrifugal-type nozzle showing the effects of the gas density on the spray-tip velocity and the volumetric growth.

5. Lee, Dana W.: Experiments on the Distribution of Fuel in Fuel Sprays. T. R. No. 438, N. A. C. A., 1932.

The distribution of the fuel in sprays was investigated by photographing them under a wide variety of conditions and also by injecting them against Plasticine targets. Photographs of sprays from plain nozzles are shown injected into an evacuated chamber, into the atmosphere, into compressed air, and into transparent liquids. Pairs of identical sprays injected counter to each other under a variety of conditions are also shown. Small high-velocity air jets were directed normally to the axes of sprays, and the photographs show the spray envelop being blown aside, exposing the spray core. Few quantitative results are presented, but the photographs are discussed in detail.

6. Gelalles, A. G.: Coefficients of Discharge of Fuel Injection Nozzles for Compression-Ignition Engines. T. R. No. 373, N. A. C. A., 1931.

7. Gelalles, A. G.: Effect of Orifice Length-Diameter Ratio on Fuel Sprays for Compression-Ignition Engines. T. R. No. 402, N. A. C. A., 1931.

One photograph of a fuel spray from a plain nozzle is reproduced to show the method of measuring the spray-tip penetration and spray cone angle. Curves are given which show the effect of the orifice length-diameter ratio on the spray characteristics, for orifice diameters from 0.008 to 0.040 inch, with and without helical grooves to give the fuel a whirling motion. Injection pressures from 2,000 to 8,000 pounds per square inch and chamber air densities from 5.0 to 17.7 atmospheres were used. Some data on the variation of spray-tip deceleration with velocity are given in a table.

8. Rothrock, A. M.: Hydraulics of Fuel Injection Pumps for Compression-Ignition Engines. T. R. No. 396, N. A. C. A., 1931.

9. Miller, Harold E., and Beardsley, Edward G.: Spray Penetration with a Simple Fuel Injection Nozzle. T. R. No. 222, N. A. C. A., 1926.

Retouched photographs of fuel sprays from a 0.015-inch orifice plain nozzle, injected by pressures from 3,000 to 8,000 pounds per square inch into air having densities from 1 to 21.4 atmospheres, are shown. Curves are given to show the effects of injection pressure and chamber air density on the velocity and penetration of the spray tip.

10. DeJuhasz, Kalman J., Zahn, O. F., Jr., and Schweitzer, P. H.: On the Formation and Dispersion of Oil Sprays. Penn. State Coll. Eng. Exp. Sta. Bull. No. 40, 1932.

11. Lee, Dana W.: The Effect of Nozzle Design and Operating Conditions on the Atomization and Distribution of Fuel Sprays. T. R. No. 425, N. A. C. A., 1932.

Data on the sizes and the distribution of the drops in fuel sprays from several different types of nozzles were secured by catching the sprays on smoked-glass plates and then measuring and counting the impressions made by the drops in the lampblack. The principal factors investigated were injection pressure, air density, orifice diameter, and orifice length-diameter ratio.

12. Sass, Friedrich: Kompressorlose Dieselmaschinen. Julius Springer (Berlin), 1929.

13. Kemper, Carlton: Improving the Performance of a Compression Ignition Engine by Directing Flow of the Inlet Air. T. N. No. 242, N. A. C. A., 1926.

14. Spanogle, J. A., and Moore, C. S.: Considerations of Air Flow in Combustion Chambers of High-Speed Compression-Ignition Engines. T. N. No. 414, N. A. C. A., 1932.

15. Gardiner, Arthur W.: A Preliminary Study of Fuel Injection and Compression Ignition as Applied to an Aircraft Engine Cylinder. T. R. No. 243, N. A. C. A., 1926.

16. Spanogle, J. A., and Hemmeter, G. T.: Development of an Impinging-Jet Fuel-Injection Valve Nozzle. T. N. No. 372, N. A. C. A., 1931.

Two photographs of a fuel spray from a two impinging jet nozzle, and two of a spray from a nozzle having two nonimpinging jets in addition to two impinging ones, are shown. In each case the photographs show two views of the sprays at right angles to each other. Spray-tip penetration against time curves are given for air densities of 1 and 14.6 atmospheres.

17. Spanogle, J. A., and Whitney, E. G.: A Description and Test Results of a Spark-Ignition and a Compression-Ignition 2-Stroke-Cycle Engine. T. R. No. 495, N. A. C. A., 1934.

18. Joachim, William F., Hicks, Chester W., and Foster, Hampton H.: The Design and Development of an Automatic Injection Valve with an Annular Orifice of Varying Area. T. R. No. 341, N. A. C. A., 1930.

Three photographs of fuel sprays from an annular-orifice injection valve, injected by pressures of 6,000, 8,000, and 10,000 pounds per square inch into air at a density of 15.3 atmospheres, are shown. Curves are given that show the effect of injection pressure, valve-opening pressure, and chamber-air density on the spray-tip penetration.

19. Taylor, C. F., Taylor, E. S., and Williams, G. L.: Fuel Injection with Spark Ignition in an Otto-Cycle Engine. S. A. E. Jour., March 1931, vol. XXVIII, no. 3, pp. 345–352.

20. Marsh, E. T., and Waldron, C. D.: Some Characteristics of Sprays Obtained from Pintle-Type Injection Nozzles. T. N. No. 465, N. A. C. A., 1933.

Two photographs of fuel sprays from pintle injection nozzles are shown, one nozzle having a pintle angle of 8° and the other 30°. An injection pressure of 1,500 pounds per square inch and a chamber-air density of 18 atmospheres were used in each case. Spray-tip penetration against time curves are given for sprays from both nozzles at injection pressures from 1,500 to 4,000 pounds per square inch and chamber-air densities from 11.2 to 18 atmospheres.

21. Spanogle, J. A., and Foster, H. H.: Basic Requirements of Fuel-Injection Nozzles for Quiescent Combustion Chambers. T. N. No. 382, N. A. C. A., 1931.
22. Spanogle, J. A., and Foster, H. H.: Performance of a High-Speed Compression-Ignition Engine Using Multiple Orifice Fuel Injection Nozzles. T. N. No. 344, N. A. C. A., 1930.

    Six photographs of fuel sprays from various multiple-orifice nozzles are shown. The injection pressures ranged from 3,200 to 6,800 pounds per square inch, the air density was 13.6 atmospheres, and the spray chamber was equipped with a glass and wood insert that confined the sprays to a space similar to the combustion chamber of the engine with which the nozzles were used.
23. Spanogle, J. A., Hicks, C. W., and Foster, H. H.: Increasing the Air Charge and Scavenging the Clearance Volume of a Compression-Ignition Engine. T. R. No. 469, N. A. C. A., 1933.
24. Beardsley, E. G.: Some Factors Affecting the Reproducibility of Penetration and the Cut-off of Oil Sprays for Fuel Injection Engines. T. R. No. 258, N. A. C. A., 1927.

    Four photographs of fuel sprays from centrifugal-type nozzles, injected by a pressure of 8,000 pounds per square inch into air at densities of 1 to 28.2 atmospheres, are shown. Curves are given to show the effect of the magnitude and uniformity of the initial pressure in the injection-valve tube and of the injection-tube length on the spray-tip penetration. Some data on the effect of the injection period, injection-tube length, and type of valve on secondary discharges are included.
25. Joachim, W. F., and Beardsley, E. G.: Factors in the Design of Centrifugal Type Injection Valves for Oil Engines. T. R. No. 268, N. A. C. A., 1927.

    Fourteen photographs of fuel sprays from centrifugal-type nozzles are shown, injected into air having densities of from 1 to 42 atmospheres. Curves are given that show the effect of air density on the penetration of sprays from nozzles having different helix angles, the effect of groove helix angle on spray-tip velocity and deceleration and on spray cone angle and volume, the effect of valve-seat position on spray penetration, the effect of orifice length-diameter ratio on spray penetration and cone angle, and the effect of the ratio of orifice area to groove area on spray penetration, cone angle, volume, and dispersion.
26. Büchner, Dr.: The Fundamental Principles of High-Speed Semi-Diesel Engines. Part I. T. M. No. 356, N. A. C. A., 1926.
27. Spanogle, J. A., and Whitney, E. G.: The Effectiveness of a Double-Stem Injection Valve in Controlling Combustion in a Compression-Ignition Engine. T. N. No. 402, N. A. C. A., 1931.
28. Rothrock, A. M., and Beardsley, E. G.: Some Effects of Air Flow on the Penetration and Distribution of Oil Sprays. T. N. No. 329, N. A. C. A., 1929.

    Photographs of fuel sprays from a multiple-orifice nozzle and from plain nozzles having orifice diameters of 0.006, 0.012, and 0.022 inch, injected into air having a density of 13.6 atmospheres by an injection pressure of 6,000 pounds per square inch, are shown. Sprays from each nozzle are shown in air having no movement and in air moving at a velocity of 60 feet per second. Curves of spray-tip penetration against time are given for sprays from each of the plain nozzles for the same conditions.
29. Rothrock, A. M.: The N. A. C. A. Apparatus for Studying the Formation and Combustion of Fuel Sprays and the Results from Preliminary Tests. T. R. No. 429, N. A. C. A., 1932.

    Diesel-fuel and safety-fuel sprays were injected into the glass-walled combustion chamber of a modified test engine while it was being motored, combustion of the fuel being controlled by regulating the temperature of the engine. Spark photographs of the sprays without combustion are reproduced to show the results of changes in the injection-valve position, air temperature, and engine speed. Several photographs showing the burning of the fuel in the combustion chamber are also shown.
30. Rothrock, A. M.: Effect of High Air Velocities on the Distribution and Penetration of a Fuel Spray. T. N. No. 376, N. A. C. A., 1931.

    Photographs of fuel sprays injected normal to and counter to air at atmospheric temperature and pressure, but having velocities from 0 to 800 feet per second, are shown. The plain nozzle used had an orifice diameter of 0.020 inch, and the injection pressure was 3,500 pounds per square inch.
31. Rothrock, A. M., and Spencer, R. C.: Effect of Moderate Air Flow on the Distribution of Fuel Sprays after Injection Cut-Off. T. R. No. 483, N. A. C. A., 1934.

    A large number of photographs of fuel sprays show the effect of air velocities up to 27 feet per second on the distribution of the fuel in the sprays for about 0.05 second after cut-off. The air was driven counter to the sprays by a fan, air densities from 1 to 13 atmospheres were used, and the fuel-injection pressures were 2,000, 4,000, and 6,000 pounds per square inch. A 0.020-inch orifice plain nozzle was used for most of the tests, but photographs are also shown of sprays from an 0.008-inch orifice plain nozzle, a multiple-orifice nozzle, and a two-impinging-jets nozzle.
32. Gelalles, A. G.: Some Effects of Air and Fuel Oil Temperatures on Spray Penetration and Dispersion. T. N. No. 338, N. A. C. A., 1930.

    Photographs of fuel sprays from a 0.004-inch orifice plain nozzle, injected by pressures of 4,000 and 8,000 pounds per square inch into air at atmospheric density, are shown. For each injection pressure one photograph is shown with the fuel and air at room temperature, and another with fuel and air temperatures of 110° and 1,100° F. Curves of spray-tip penetration against time, derived from the published photographs, are also included.
33. Rothrock, A. M., and Waldron, C. D.: Fuel Vaporization and Its Effect on Combustion in a High-Speed Compression-Ignition Engine. T. R. No. 435, N. A. C. A., 1932.
34. Rothrock, A. M., and Waldron, C. D.: Some Characteristics of Fuel Sprays at Low Injection Pressures. T. N. No. 399, N. A. C. A., 1931.

    Photographs of gasoline sprays from plain open nozzles with 0.008- and 0.020-inch orifices are shown. The injection pressures were 100, 300, and 500 pounds per square inch, and the air densities were 1 and 4.2 atmospheres. Curves of spray-tip penetration against time are given for both gasoline and fuel-oil sprays, using the nozzles, injection pressures, and air densities listed.
35. Lee, Dana W., and Spencer, Robert C.: Photomicrographic Studies of Fuel Sprays. T. R. No. 454, N. A. C. A., 1933.

    A large number of photomicrographs of fuel sprays are shown, taken at magnifying powers of 2.5, 3.25, and 10. Several types and sizes of nozzles were used with different fuels, a wide range of injection pressures was employed, and the density of the air into which the sprays were injected ranged from 14 atmospheres to 0.0013 atmosphere. The photomicrographs are discussed and explained, and atomization data from a few of them are compared with data from other sources.

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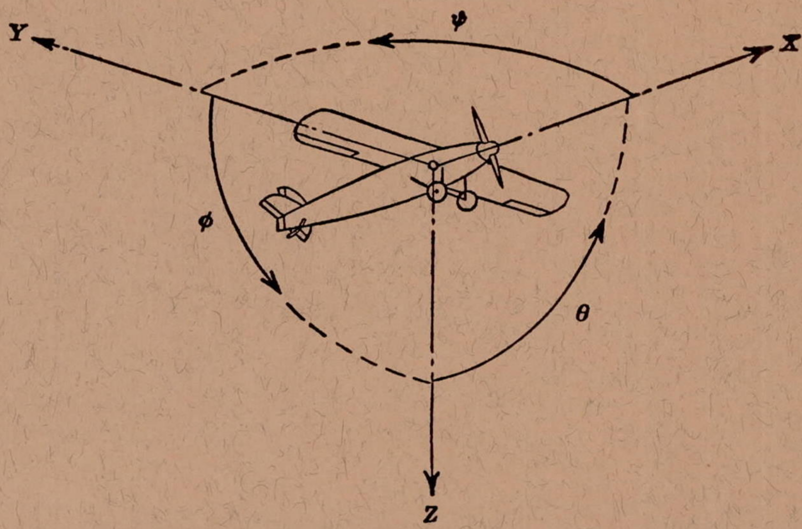

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l = \frac{L}{qbS}$ (rolling) $C_m = \frac{M}{qcS}$ (pitching) $C_n = \frac{N}{qbS}$ (yawing)

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

4. PROPELLER SYMBOLS

D, Diameter
p, Geometric pitch
p/D, Pitch ratio
V', Inflow velocity
V_s, Slipstream velocity
T, Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$
C_s, Speed-power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$
η, Efficiency
n, Revolutions per second, r.p.s.
Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp. = 76.04 kg-m/s = 550 ft-lb./sec.
1 metric horsepower = 1.0132 hp.
1 m.p.h. = 0.4470 m.p.s.
1 m.p.s. = 2.2369 m.p.h

1 lb. = 0.4536 kg.
1 kg = 2.2046 lb.
1 mi. = 1,609.35 m = 5,280 ft.
1 m = 3.2808 ft.