NACA–TR–440

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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REPORT No. 440

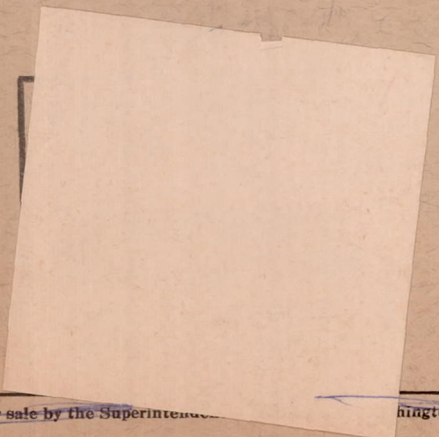# THE MECHANISM OF ATOMIZATION ACCOMPANYING SOLID INJECTION

By R. A. CASTLEMAN, JR.

1932

AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length_____	l	meter_____	m	foot (or mile)_____	ft. (or mi.)
Time_____	t	second_____	s	second (or hour)_____	sec. (or hr.)
Force_____	F	weight of one kilogram____	kg	weight of one pound____	lb.
Power_____	P	kg/m/s_____	_____	horsepower_____	hp
Speed_____	_____	$\begin{cases} \text{km/h} \\ \text{m/s} \end{cases}$ _____	k. p. h. / m. p. s.	mi./hr._____ / ft./sec._____	m. p. h. / f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight $= mg$

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

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

ρ, Density (mass per unit volume).

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

Specific weight of "standard" air, 1.2255 kg/m^3 $= 0.07651$ lb./ft.^{3}.

mk^2, Moment of inertia (indicate axis of the radius of gyration k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord.

$\dfrac{b^2}{S}$, Aspect ratio.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) pressure $= \dfrac{1}{2}\rho V^2$.

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

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

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

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

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

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

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.

$\rho\dfrac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord 40 m/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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THE MECHANISM OF ATOMIZATION ACCOMPANYING SOLID INJECTION

By R. A. CASTLEMAN, Jr.

Bureau of Standards

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

NAVY BUILDING, WASHINGTON, D. C.

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SUMMARY

A brief historical and descriptive account of solid injection is followed by a detailed review of the available theoretical and experimental data that seem to throw light on the mechanism of this form of atomization. It is concluded that this evidence indicates that (1) the atomization accompanying solid injection occurs at the surface of the liquid after it issues as a solid stream from the orifice; and (2) that such atomization has a mechanism physically identical with the atomization which takes place in an air stream, both being due merely to the formation, at the gas-liquid interface, of fine ligaments under the influence of the relative motion of gas and liquid, and to their collapse, under the influence of surface tension, to form the drops in the spray. This simple theory, previously proposed by the author, is the most satisfactory and fits the observations the best of any yet advanced. It is recommended that use of the term "atomization" be restricted to a certain definite range, in which its use is sound, etymologically and physically.

INTRODUCTION

In two former papers (references 1 and 2) the atomization of liquids was treated as a phenomenon due to the relative motion of gas and liquid at their interface, this motion causing the formation of ligaments of liquid extending into the gas. It was also shown that these ligaments are so fine that they will collapse, under the influence of surface tension alone, with sufficient rapidity to account for the observed sizes of the drops in the atomized spray. Air-stream atomization only was specifically considered in the latter paper; satisfactory theoretical and experimental evidence was presented in that case.

Another method of atomization—apparently the only other method found useful to date—was invented by James McKechnie (reference 3) in 1910. In this method, now called for obvious reasons "solid injection," the liquid is injected under rather high pressure [1]

into comparatively still air and is thereby finely atomized. The spray (see fig. 5) takes the form of a cone with the orifice as vertex. It has been shown by the National Advisory Committee for Aeronautics that this spray is very inhomogeneous as to drop size.

Both methods of atomization (air-stream atomization and solid injection) involve a very high relative motion of gas and liquid at their interface. This requirement is easily met in the carburetor engine, which compresses an air-fuel mixture to a temperature well *below* that at which it will ignite spontaneously, ignition being caused by the passage of an electric spark at the desired instant. Since the air may therefore be carbureted with atomized fuel before it enters the engine, all that is necessary is to introduce fuel in proper quantity at a constricted section of the intake air stream.

The compression-ignition engine, as its name indicates, depends for ignition on the temperature developed by the approximately adiabatic compression of pure air. Hence a very high compression ratio is needed, ignition being timed by fuel injection, so that the fuel can only be introduced into the cylinder near the end of compression. In large, low-speed engines (for stationary or marine service) an arrangement devised by Diesel has been found useful—an air stream from an auxiliary compressor passes over the surface of the liquid fuel and into the engine, the fuel thus being atomized and introduced into the cylinder at the proper instant.

To adapt this type of engine to automotive uses, it was desirable to reduce its bulk and weight. An obvious means of accomplishing this was the elimination of the air compressor. Since McKechnie's device substitutes a compact lightweight fuel pump for the compressor and offers other advantages for high-speed operation, it is used almost universally in high-speed practice. Hence, much interest is attached to the explanation of the atomization which results from solid injection.

It was previously suggested (reference 2) that solid injection seemed to be so similar to air-stream atomization as regards relative motion at the gas-liquid interface that an identical physical mechanism might be expected. However, it has been pointed out that in the case of solid injection such forces as those due to fluid friction in the nozzle passages might deter-

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[1] McKechnie was under the impression that sudden release from very high pressure would, in combination with the very high temperature of the air suddenly compressed in a Diesel engine, immediately vaporize the liquid, but it seems that this will lead mainly to atomization. He did not specify this pressure, merely calling it "extremely high"; Kuehn used up to 40 atmospheres in his 1924 experiments; Wöltjen and Sass experimented with pressures ranging from 50 to 350 atmospheres; while the National Advisory Committee for Aeronautics has experimented with pressures ranging from about 3,500 to about 8,000 pounds per square inch (238 to 545 atmospheres) (lower pressures are, however, considered in some of their recent work). In most modern practice pressures of 200 to 600 atmospheres are used, depending on circumstances and on the effects desired.

mine the break-up of the larger mass of liquid. So it seems important to consider to what extent the theory advanced for air-stream atomization applies to solid injection.

AVAILABLE DATA

Technische Hochschule, Danzig.—In the experiments performed at the Danzig Technische Hochschule and reported by Kuehn (reference 4), the liquid was forced, at comparatively low pressures (maximum around 40 atmospheres), into the open atmosphere, where a sample of the spray was caught on a smoked glass plate, weighed, the drops counted, and their mean size thus found, careful corrections for evaporation, etc., being made. Kuehn also describes the "atomization" process as the injection pressure is increased from zero to about 40 atmospheres. The following points are of particular interest here.

Descriptive—Atomization.—In describing the phenomenon at very low injection speeds, Kuehn says (reference 4, Technical Memorandum No. 330, p. 40) that, as the liquid's speed is gradually increased, "* * * a slight fraying of the stream begins. This effect is produced by the separation of individual drops at first, followed by constantly increasing numbers, until it seems as though the surface were were being peeled off. This peeling continues until the stream is entirely dispersed in drops. * * *" This is in accord with the theory of ligament formation.

Location of stream break.—As the injection pressure was increased, the point at which the jet broke was figuratively represented as moving toward the orifice, but apparently it could not be made to reach the orifice, even under the most intense pressure available (about 40 atmospheres). This is required by any surface theory.

Absolute size of drops.—The mean size found seemed at that time surprisingly large, the diameter being about 70 microns at an injection pressure of 40 atmospheres. This value agrees roughly with the trend of the AEG results obtained at higher injection pressures, since the mean size approaches the maximum as the injection pressure is lowered.

Technische Hochschule, Graz.—Work done at the Graz Technische Hochschule has been reported by Triebnigg (reference 5) who, arguing that the friction of the air and the surface tension of the liquid would cause the solid stream to become unstable, deduced the size of the resultant droplets in terms of such quantities as surface tension, air density, coefficient of friction between air and liquid, effective injection pressure, etc. Theoretical, as well as experimental evidence has, however, been produced both by Sass (reference 6) and by Lee (reference 7) to show that Triebnigg's work must be either incorrect or incomplete, or both.

Technische Hochschule, Darmstadt.—Wöltjen[2] (reference 8), working at the Darmstadt Technische Hochschule, devised a method for measuring the size of the drops formed under the approximate conditions of air density and fuel injection used in the engine. The liquid was injected into an air-tight chamber which could be held at any desired pressure. Here it was "atomized" and the drops caught in a gelatinous tanning extract, where they remained approximately stationary in spherical form while being examined microphotographically. Wöltjen gives results for various liquids, air densities, injection pressures, etc., for both solid injection and "high-pressure" air atomization.

Allgemeine Elektricitäts-Gesellschaft (AEG).—In certain experiments performed under the auspices of the AEG, on which a preliminary report has been made by Sass (reference 6, pp. 45–49), the sizes of the drops formed in the solid injection of gas oil were measured. Wöltjen's method, slightly modified, was used. Curves were given showing the distribution of the sizes of the drops[3] and some of these seem particularly apropos in the present connection:

Absolute size of drops.—The variation in size was surprisingly great, the largest drops being, in some cases, over ten times as large as the smallest. The diameter of the smallest drops recorded was about 4 microns when an injection pressure of 280 atmospheres and a chamber pressure of 10 atmospheres were used. This indicates life periods of the order of from 2 to 5 microseconds for the ligaments from which those drops were formed, so that these ligaments would collapse within less than a millimeter of their origin, which is quite consistent with observations. The collapse of the ligaments from which the largest drops were formed would require from 120 to 300 microseconds for similar initial conditions and degree of instability, so that the ligaments would remain solid for about an inch. In such cases other factors besides surface tension might affect the collapse. It may be of interest

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[2] Wöltjen's dissertation has been published in abstract form only. Some of his photographs are reproduced by Hausfelder (reference 9), and some of his numerical results by Lee (reference 7). A photostat copy of the dissertation is on file at the office of the National Advisory Committee for Aeronautics.

[3] The spray was aimed vertically down at the "catching liquid" (in this case glycerin, at the surface of which the drops of gas oil would float). In endeavoring to avoid the "splintering" of the large drops which might occur at the surface of the liquid if the spray struck this with too great velocity, this liquid was placed 20 centimeters below the nozzle. This arrangement, however, may appear to introduce two other possible sources of error. Since the time required by Stokes' law (reference 10) for drops of 4 microns diameter to fall this distance in still air is of the order of 8 minutes, it might seem that (a) some of the smaller drops might not reach the "catching dish" before this was removed for microscopical examination; (b) there would be a serious volume change in the smaller drops due to evaporation during their fall. While the time allowed for this fall was not specifically mentioned by Sass, only a very small fraction of a second would be needed for the spray tip to reach the "catching dish," so that it seems probable that not more than a few seconds were allowed before the dish was removed. As to (a), that Sass recorded drops this small (even slightly smaller in some cases), seems due to the fact that they did not fall in still air, but were pushed or pulled by the larger drops, so that a very much shorter time of fall would be needed. As to (b), it appears that the very short time of fall needed in this case would not permit much vaporization.

to note that Lee (reference 11) has produced evidence which seems to indicate that a liquid injected at 4,000 pounds per square inch (272 atmospheres) into air at 215 pounds per square inch (14.7 atmospheres) must be disintegrated in slightly less than 1 inch from the nozzle.

Diameters of 7 to 8 microns were found for the smallest droplets of gas oil *atomized* by solid injection into air of atmospheric density. The size of these drops is practically independent of injection pressure. This compares favorably with the mean diameter of about 7 microns found by Sauter (reference 12) in the *high*-speed air-stream atomization of kerosene, a liquid of surface tension about the same as that of gas oil. Since a spray becomes more homogeneous the higher the relative air speed, it is seen that in Sauter's observation the mean would approach the minimum. This evidence that the size of the *atomized* drops is the same in the two cases favors a similarity in the mechanism of their formation.

Effect of changes in injection pressure.—Distribution curves of drop size are given for each of the injection pressures of 150, 220, 280, and 350 atmospheres, the chamber pressure being held constant at 10 atmospheres. Results reproduced in Figure 1[4] show that, with each increase in injection pressure, (*a*) the absolute sizes of the smallest drops formed remain about constant; (*b*) there is a decided increase in the number of small drops formed; (*c*) the sizes
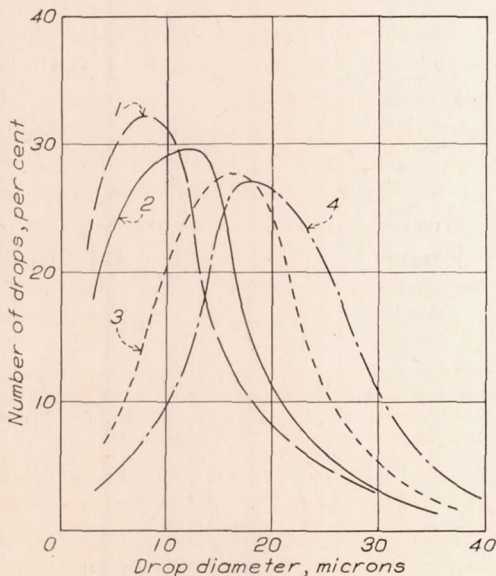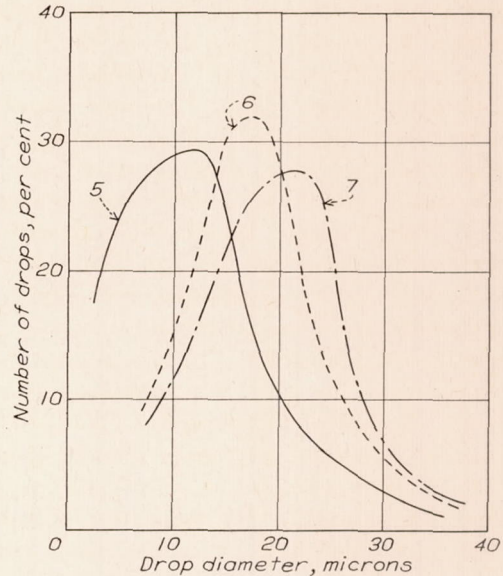

Orifice diameter, 0.57 mm
Chamber pressure, 10 atm.
Injection pressure for curve 1=350 atm. (5,150 lbs./sq. in.)
Injection pressure for curve 2=280 atm. (4,110 lbs./sq. in.)
Injection pressure for curve 3=220 atm. (3,230 lbs./sq. in.)
Injection pressure for curve 4=150 atm. (2,200 lbs./sq. in.)
FIGURE 1.—Dependence of frequency on injection pressure (Sass)

of the larger drops decrease. All three results are consistent with the ligament-formation theory. The

4 Figures 1, 2, and 3 taken from Kompressorlose Dieselmaschine, by F. Sass.

smallest drops being truly "atomized" (in the sense defined below) can not get much smaller when the relative speed is increased, but more of these will be formed before this speed drops to a value too low for atomization. Also, the length of path, over which this relative speed remains high enough to cause

Orifice diameter, 0.57 mm
Injection pressure, 280 atm.
Chamber pressure for curve 5=10 atm. (147 lbs./sq. in.)
Chamber pressure for curve 6=5 atm. (73.5 lbs./sq. in.)
Chamber pressure for curve 7=atmospheric.
FIGURE 2.—Dependence of frequency on chamber pressure (Sass)

ligaments to be drawn from the main mass, increases with the injection pressure, so that the size of the ligaments which break up into the larger drops, their life periods, and the size of these drops themselves, are all decreased.

Effect of changes in air density.—Gas oil was injected at a pressure of 280 atmospheres into air held at pressures of 1, 5, and 10 atmospheres, and size-distribution curves, reproduced in Figure 2, are given for the spray produced in each case. These curves are seen to show consistent decrease in the size of both the smallest and the largest drops as the air density is increased, which connotes dependence of their formation on surface forces.

Effect of changes in orifice diameter.—With injection and chamber pressures held constant at the respective values of 280 and 10 atmospheres, the orifice size was varied in three steps. While the results, reproduced in Figure 3, do not indicate any great change in the absolute sizes of the smallest drops, they do show that, as the orifice size is decreased, the small drops become more frequent and the large drops less frequent. These changes in distribution indicate that drop formation takes place at the surface, since the chief effect of decrease in orifice size is increase in the ratio of surface to volume of the jet as it emerges.

Bureau of Standards.—As the result of work started in 1921, it was concluded that the mechanism of air-stream atomization consists merely in the formation of fine ligaments under the influence of the relative motion of gas and liquid at their interface. These ligaments subsequently collapse, to form the drops in the spray, under the influence of the liquid's surface tension, in a manner indicated in Rayleigh's analysis. (Reference 13.) Quantitative check could, however, only be obtained after the sizes of the ligaments had been found, and spark photographs by Scheubel (reference 14) indicated that, when the relative air speed is high enough for atomization, the ligaments
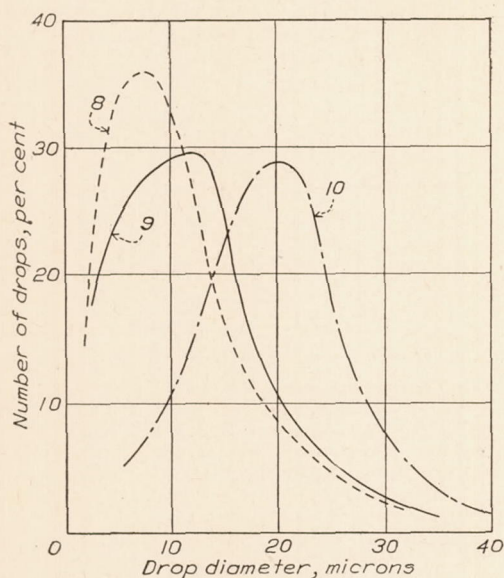
Injection pressure, 280 atm.
Chamber pressure, 10 atm.
Orifice diameter for curve 8=4 by 0.40 mm (0.0157 in.)
Orifice diameter for curve 9=2 by 0.57 mm (0.0224 in.)
Orifice diameter for curve 10=1 by 0.80 mm (0.031 in.)
FIGURE 3.—Dependence of frequency on orifice diameter (Sass)

collapse so quickly that they can scarcely be observed, much less measured. It was necessary, then, to estimate the ligament sizes from those of the drops observed in the spray. While satisfactory technique had been outlined by Sauter in 1926 (reference 15), the drop-size measurements which he then gave were very uncertain. In 1928 he reported (reference 12) extended technique, and gave results of measurements of drop sizes from which a very definite estimate could be made of the probable drop size under conditions of true atomization. An analysis of the phenomenon of atomization was then published (references 1 and 2) which showed quantitative agreement with the observations of Scheubel (reference 14). Air-stream atomization only was specifically treated, but it was pointed out that solid injection, in which the *relative* motion at the gas-liquid interface is identical, appeared to have a similar physical background.

Work of Weber.—A theoretical analysis of the disintegration of a liquid jet under the influence of air motion has been made by C. Weber. (Reference 16.) He found that many of his theoretical deductions agreed with Haenlein's observations, to which his treatment may be regarded as complementary.

Technische Hochschule, Dresden—Description of program.—An investigation of the disintegration of small round jets of liquid launched as solid streams into the atmosphere is being conducted at the Dresden Technische Hochschule. The jet velocity is being varied over quite a wide range in the case of a number of liquids of different viscosity, thus extending the work of Rayleigh (reference 13), who investigated only the effect of surface tension.

Results.—An interim report, in the form of a dissertation, has been made by Haenlein. (Reference 17.) A series of shadow spark photographs obtained with gas oil is reproduced in Figure 4. It is seen that the relative motion of liquid and air produces a wavy surface, thus causing the main jet to become unstable and hence to disintegrate sooner than it would under the influence of surface tension only. Although this effect increases with the relative air speed and apparently atomization ultimately results at high speeds, it is to be noticed that there is a distinct step (fig. 4, *f*) intermediate between the disintegration of the whole stream and its atomization into spray, and that this intermediate step involves a distortion of the surface to form elongated threads. While Haenlein's statement of the problem seems to indicate that increase in waviness is a sufficient explanation of atomization, it seems important to point out that the complete explanation involves the intermediate formation and collapse of fine ligaments. According to Haenlein, the work is to be continued. It is certainly aimed at a very important phase of the atomization problem—preatomization phenomena.

Some interesting observations—Relative speed at atomization.—Haenlein's pictures indicate that surface atomization of gas oil starts at an injection velocity (see fig. 4) of somewhere between 40 and 73 meters per second. Scheubel (reference 14) found that ethyl alcohol with slightly lower surface tension is atomized *in an air stream* at about 55 meters per second. These observations might be taken to indicate a similarity between air stream atomization and solid injection.

Effect of viscosity of liquid.—While Haenlein obtained waviness with all the liquids tested, he was unable, with the relative speeds available, to obtain atomization, or even the separation of comparatively coarse droplets from the surface of the jet, with liquids of high viscosity such as glycerin and castor oil. This is to be expected, since high viscosity would seriously interfere with the growth of a dent in the ligament surface. In explaining the detachment of droplets
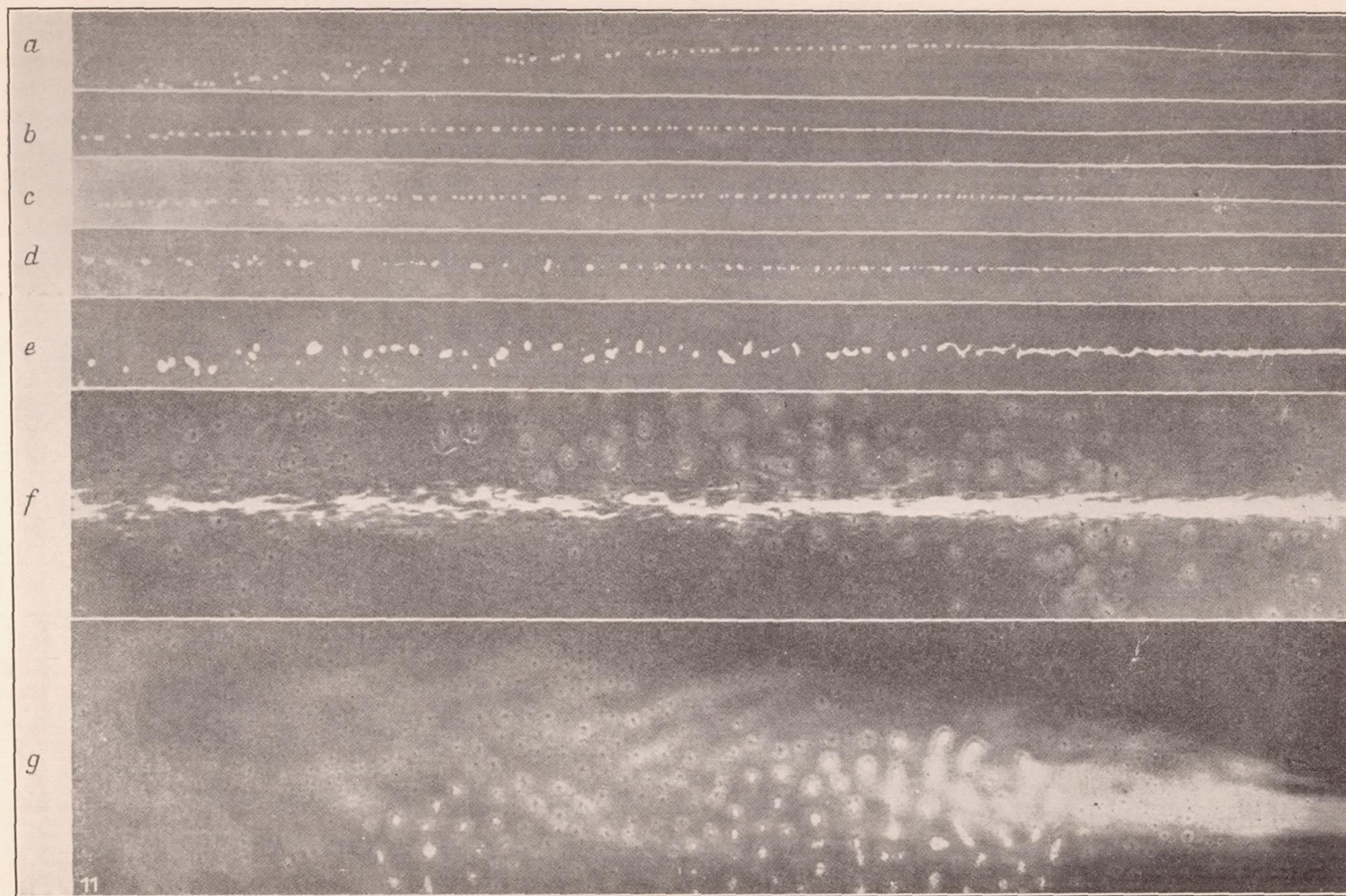
a, Nozzle diameter=0.51 mm; jet velocity= 5.1 m/s
b, Nozzle diameter=0.51 mm; jet velocity= 6.6 m/s
c, Nozzle diameter=0.51 mm; jet velocity= 7.5 m/s
d, Nozzle diameter=0.51 mm; jet velocity=15.6 m/s
e, Nozzle diameter=1.04 mm; jet velocity=18.0 m/s
f, Nozzle diameter=1.04 mm; jet velocity=40.0 m/s
g, Nozzle diameter=1.04 mm; jet velocity=73.0 m/s

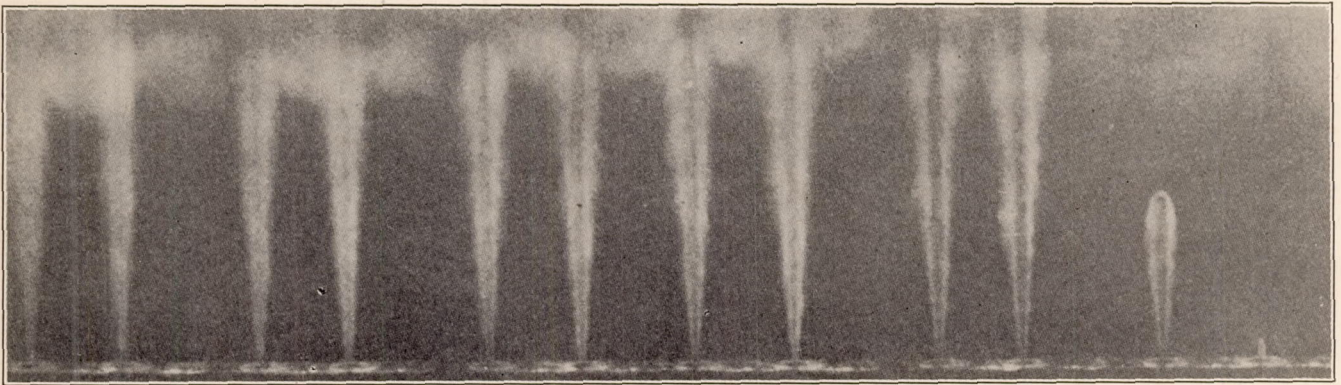FIGURE 4.—Collapse of gas-oil jet—reproduced from shadow spark photos by Haenlein

from the surface of the jets of water and of gas oil, Haenlein says: "* * * with water and gas oil, due to their small viscosity, the air can not cause the development of a very pronounced wave form. Separate liquid particles are thrown off (werden abgeschleudert), and form a cone-shaped mantle around the core of the jet. * * *" If "thrown off" is changed to "drawn off," this view of atomization is seen to agree well with the ligament-formation theory. Haenlein, however, gives no positive explanation of the mechanism of drop detachment.

Pennsylvania State College.—Results of experiments conducted at the Pennsylvania State College have been

developed at all, which would stand on their own feet, without the continuous support of experiments.

"For this reason in the researches at the engineering experiment station it was not attempted to develop a spray theory. Nevertheless, a few experiments were made with the purpose of clearing up which physical forces do or do not participate in the atomization * * * processes. The results are of sufficient interest to merit brief mention.

"The purpose of one experiment was to determine whether atomization is due to the friction of jet with the air. Sprays were injected into an evacuated chamber, the air pressure being one-fiftieth atmos-

a, Injection pressure 8,000 lbs./sq. in. (545 atm.); chamber pressure atmospheric
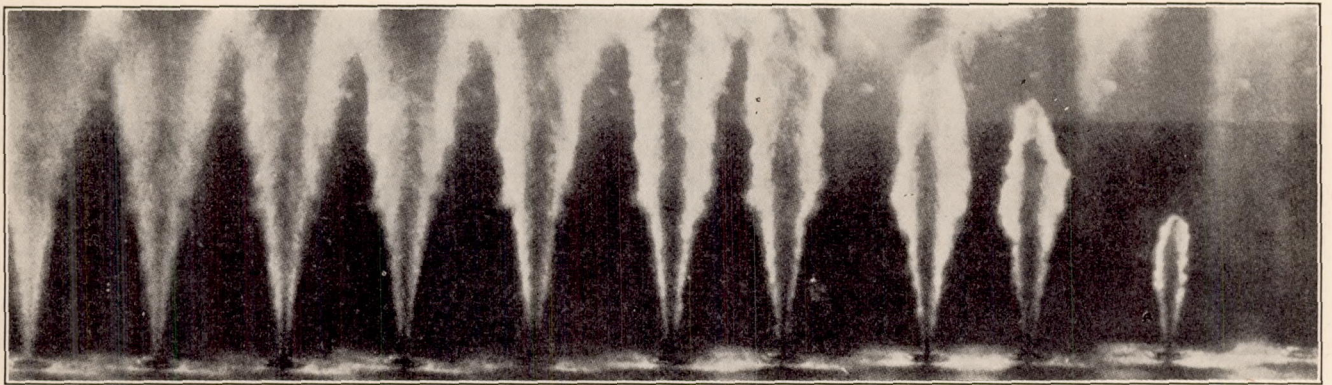
b, Injection pressure 8,000 lbs./sq. in. (545 atm.); chamber pressure 200 lbs./sq. in. (13.6 atm.)
FIGURE 5.—Effect of air density on spray formed by solid injection N. A. C. A. spray photographs

reported by DeJuhasz (reference 18), who, after reviewing several atomization theories, says with regard to the atomization that results from solid injection:

"The theoretical investigations mentioned refer to primitive forms of jet under low pressure or have been evolved, of necessity, under drastic simplifying assumptions. For oil-engine use the sprays are produced under complicated conditions to which the theories mentioned can not be applied directly and, indeed, are likely to result in misleading conclusions. In view of the complex nature of the oil-injection sprays it is doubtful whether sufficiently accurate theories can be

pheric pressure (about 0.6 in. Hg. abs.), and thereby the air resistance was reduced to a very low value. In spite of this it was found that the spray was atomized and dispersed to approximately the same extent as in air of atmospheric density. Further increasing air density to multiples of atmospheric, however, had the effect of widening the spray angle, making the distribution pattern more even, and reducing the penetration. This result seems to be strong evidence against the supposition that the atomization and dispersion are due solely to air-friction forces.

*   *   *   *   *   *

"These evidences lend support to the view that (under the conditions of oil-engine injection) the liquid emerges from the nozzle in an already atomized, or at least disgregated state, that it already possesses the ability to disperse and, therefore, that in the atomization and dispersion process the flow phenomena in the nozzle are the main influencing factors."

The opinion of DeJuhasz regarding the place where the liquid is atomized seems by no means far-fetched, being derived probably from Diesel's old form of high-pressure air atomization, in which most of the liquid is atomized within the nozzle. Lee, however, by showing that no measurable change in drop size results from changes in nozzle design, has proved that other factors than those introduced by the nozzle must be responsible for the break-up of the jet.
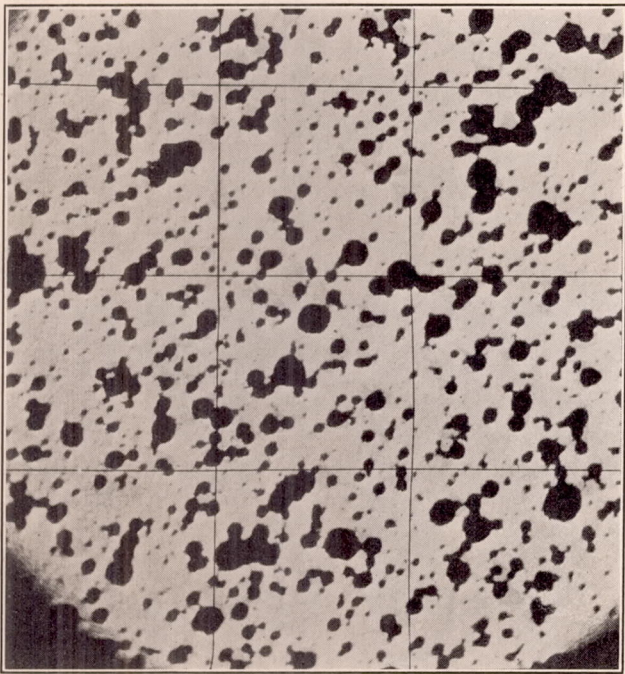
(b) Plain 0.020-inch nozzle.   Mean injection pressure, 4,120 lbs./sq. in.   Position on record A–14

FIGURE 6.—Drops in spray formed by solid injection.   N. A. C. A. photomicrograph

DeJuhasz implies that effects on cone angle are criteria of atomization. However, previous N. A. C. A. observations have shown that measurements of cone angle at low-air density are rather uncertain criteria from which to draw any conclusion, and that it is impossible to judge the quality of the atomization from unmagnified spark photographs of sprays.

National Advisory Committee for Aeronautics (N. A. C. A.).—This committee has for a number of years been conducting, at its experimental laboratory at Langley Field, a study of the compression-ignition heavy-oil engine with the object of adapting it to aeronautic use. Most of the earlier work, however, was directed at the technology of the utilization of oil sprays, and only comparatively recently has much attention been paid to the structure of these sprays. Some of this later work seems particularly apropos in the present connection.

Outer form of sprays and effect of air density.—Figure 5 is reproduced from a report by Joachim and Beardsley. (Reference 19.) A "noncentrifugal" (plain round hole) nozzle with orifice diameter of 0.022 inch (0.56 mm) was used. Group (a) shows successive views of a spray of gas oil injected at a pressure of 8,000 pounds per square inch (545 atmospheres) into the open atmosphere. The spray is seen to take the form of a cone with the orifice as vertex. The size of the drops can not be determined from such photographs, but a coarse central core surrounded by a thin veil of drops might be suspected. Group (b) shows successive views of a spray injected into air at 200 pounds per square inch (13.6 atmospheres) but under otherwise identical conditions. It is seen that the cone angle has increased to more than twice the original value.

Physical structure of sprays.—The National Advisory Committee for Aeronautics has recently conducted some experiments on the physical structure of the sprays formed by solid injection.

Drop size.—A series of drop-size measurements have been made by Lee (reference 7), using a modification of Wöltjen's method. The chief changes in method were as follows: (1) The spray was directed horizontally, the drops falling under gravity to the catching dish; (2) the catching dish consisted of a smoked glass plate, the impressions of the drops being recorded microphotographically. As had been done by Wöltjen and by Sass, chamber and injection pressure were varied over wide ranges. The four nozzles used varied as regards internal design, orifice diameter, and length diameter ratio. A typical record is reproduced in Figure 6.

Results are given in the form of "atomization curves," with "group mean diameter" as abscissas and "percentage by number" or "percentage by volume" as ordinates. The absolute sizes of the drops, the effect of changes in injection pressure, and the effect of changes in orifice size were in qualitative agreement with Sass's results, mentioned above. Lee concludes that the fineness and uniformity of atomization depends principally (1) on efflux velocity, as determined by injection pressure and by nozzle design; and (2) on orifice size. Such factors as internal nozzle design and air density were found to have, *per se*, negligible effects. The conclusion regarding the effect of air density appears contradictory to Sass's results, but it should be pointed out that the two methods of measuring drop sizes and of recording results are not directly comparable.

Distribution of fuel.—Rothrock recently reported (reference 20) the results of studies which throw some light on the distribution of fuel in sprays formed by

solid injection. He directed a high-speed stream of air normal to the axis of a spray injected into the open atmosphere. As shown in Figure 7, the outer

sions were obtained from impressions in clay, and the cone dimensions from a spray photograph. Lee also obtained evidence that the core was composed of

Injection pressure 3,500 lbs./sq. in. (238 atm.); chamber pressure atmospheric

FIGURE 7.—Effect of air stream normal to axis of jet (250 to 600 ft.-sec., estimated). N. A. C. A. spray photographs

veil was easily turned aside, but the core was little deflected, thus proving that the momentum of the outer veil is negligible compared with that of the inner core. Hence a drop in the outer spray has either a size or a velocity, or both, enormously less than one in the inner core.

In a well-conceived and carefully executed series of tests, Lee recently has proved (reference 11) that most of the fuel is concentrated in the inner core. He determined the dimensions of the core by directing the jet against soft modeling clay placed at different distances from the orifice and measuring the dimensions of the impressions made. A picture of the core and of the outer cone constructed from measurements given by Lee, for an injection pressure of 4,000 pounds per square inch (272 atmospheres) and a chamber
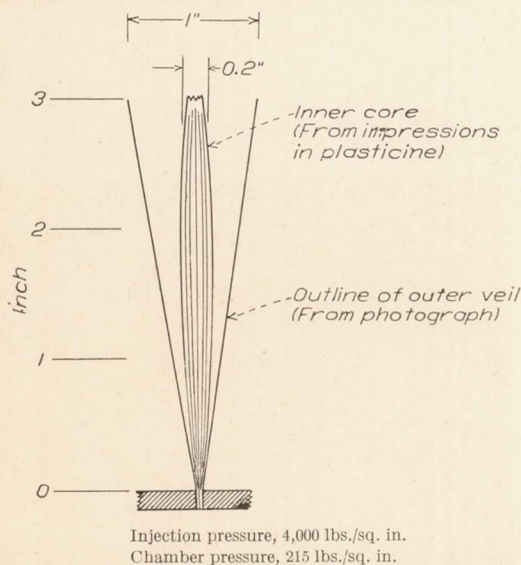
Injection pressure, 4,000 lbs./sq. in.
Chamber pressure, 215 lbs./sq. in.

FIGURE 8.—Reconstruction of spray picture from impressions in plasticine and from photograph (dimensions given by Lee)

pressure of about 215 pounds per square inch (14.7 atmospheres), as shown in Figure 8. The core dimen-

discrete drops, by showing that the cores of two oppositely directed jets penetrated each other.

Jet disintegration.—Several series of magnified spray photographs, obtained by Lee [5] and Spencer during February, 1932, shed further light on the manner in which a solid liquid stream flowing continuously from an orifice breaks up at various injection pressures. Representative views of two such jets are reproduced in Figure 9. The photographs seem to support the ligament-formation theory and are particularly interesting in the following respects: (1) They all indicated ligament formation as an intermediate step in the detachment of a small drop from a large mass of liquid, the ligaments extending from the unatomized mass in the direction of relative motion and appearing to decrease in size and length as the relative air speed is increased, as was shown by Scheubel (reference 14) in air-stream atomization. (2) While the ligaments persist to much higher injection velocities than was found by Haenlein, this is to be expected because some air would be entrained by the continuous spray used by the National Advisory Committee for Aeronautics in this particular test and the actual relative velocity, while difficult to determine, would surely be less than in Haenlein's case. (3) While waviness was obtained, it is clear from the N. A. C. A. photographs that the small drops are formed only by means of ligaments torn from the main mass, so that Haenlein's implied explanation (loc. cit.) seems insufficient.

University of Cambridge.—Flow experiments conducted at the University of Cambridge were reported by A. L. Bird (reference 21), who showed that under the conditions used in oil-engine injection, the flow in an orifice of 0.013 inch diameter is intermediate between the streamline and the turbulent condition. This has suggested as an explanation of spray formation the increase in turbulence as the liquid emerges from the orifice. That this explanation is insufficient
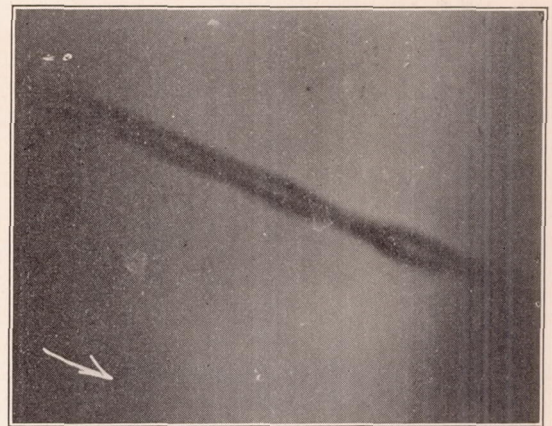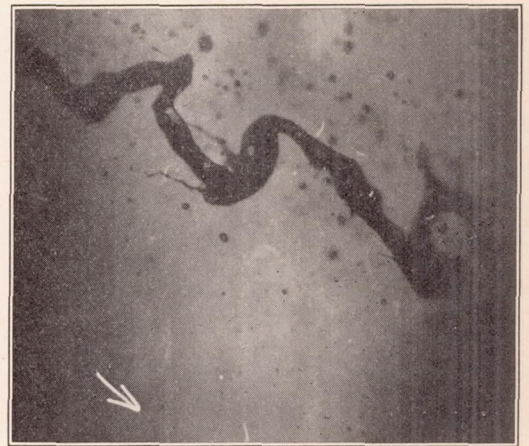
[5] Refer to TN on microphotographs.
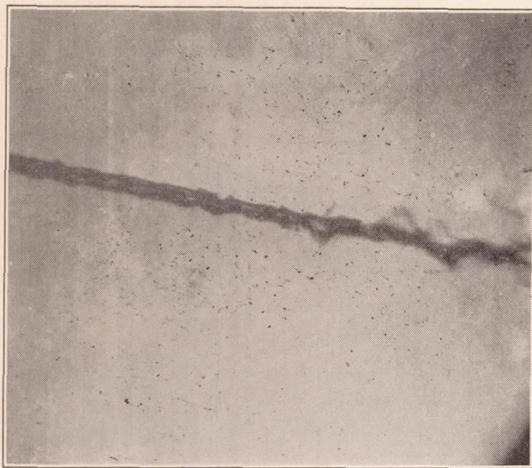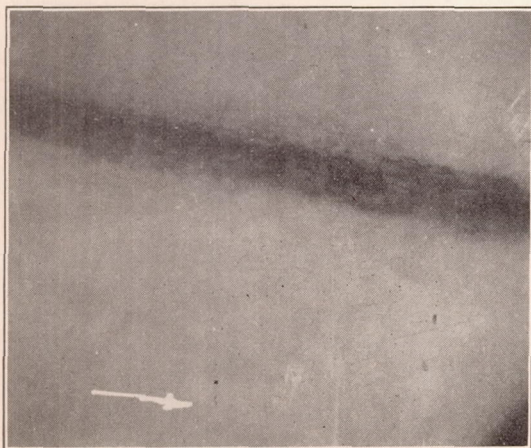
Injection pressure 100 lbs./sq. in.

Injection pressure less than 30 lbs./sq. in.

Injection pressure 750 lbs./sq. in.

Injection pressure 200 lbs./sq. in.

Injection pressure 1,500 lbs./sq. in.
0.008 in. (0.02 mm) orifice diameter
1 5/16 in. (2.4 cm) from orifice

Injection pressure 700 lbs./sq. in.
0.020 in. (0.51 mm) orifice diameter
4¾ in. (12. cm) from orifice

FIGURE 9.—Continuous spray, magnified 10 diameters. N. A. C. A. spark photographs

is shown by the photographs of Lee and Spencer (reference 22), for turbulence would be most effective close to the orifice, whereas the N. A. C. A. investigators observed droplet formation as much as 4 inches from the orifice.

CONCLUSION

Close examination of the evidence so far produced shows that much of it supports the view that the atomization accompanying solid injection is a surface phenomenon. There appears to be little difference in physical mechanism between air-stream atomization and that which accompanies solid injection. Both can be explained by the formation of ligaments at the liquid-gas interface, under the influence of the *relative* motion of gas and liquid, and by the collapse of these ligaments under the influence of surface tension.

The difference in results in the two cases can be attributed to the difference in the way in which the forces at the interface are constrained to act. In solid injection it seems to be more difficult to adjust the conditions so that the surface of the liquid shall be continually exposed to an air stream of relative velocity high enough for atomization. For this reason air-stream atomization should yield more uniformly fine drops than solid injection.

Much of the existing confusion in the literature is due to indefiniteness in the use of the term "atomization." Etymologically, the term implies the formation of drops so fine as to be indivisible. Such a concept has a definite physical significance in the case of liquid jets, for it has been shown that for a particular liquid injected into a given atmosphere the drop size approaches a lower limit as the relative air-liquid speed is increased. A liquid therefore may be considered as truly atomized when the drop size has reached the limiting value. On the other hand, a liquid may be considered as disintegrated when the drop sizes are larger than the limiting value.

The mechanism of true atomization can be explained simply by the ligament theory, and in cases where the time intervals are so short as to preclude appreciable evaporation, it is difficult to picture any other mechanism for atomization. While the ligament theory is applicable to many cases of disintegration, it is not necessarily a complete explanation, for other factors may enter to cause the formation of large drops.

BUREAU OF STANDARDS,
WASHINGTON, D. C., *January 6, 1932.*

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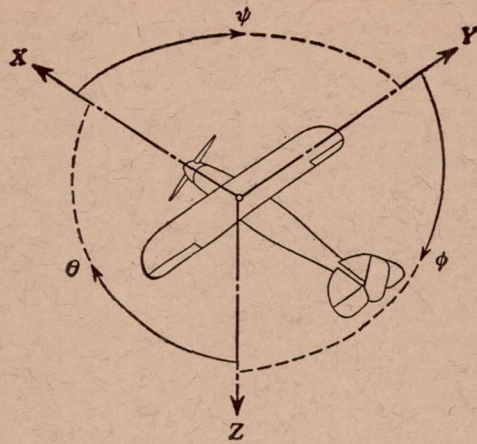
Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Sym-bol		Designation	Sym-bol	Positive direction	Designa-tion	Sym-bol	Linear (compo-nent 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

$$C_l = \frac{L}{qbS} \qquad C_m = \frac{M}{qcS} \qquad C_n = \frac{N}{qbS}$$

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 $C_T = \dfrac{T}{\rho n^2 D^4}$

Q, Torque, absolute coefficient $C_Q = \dfrac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P = \dfrac{P}{\rho n^3 D^5}$.

C_S, Speed power coefficient $= \sqrt[5]{\dfrac{\rho V^5}{Pn^2}}$.

η, Efficiency.

n, Revolutions per second, r. p. s.

Φ, Effective helix angle $= \tan^{-1}\left(\dfrac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg/m/s = 550 lb./ft./sec.

1 kg/m/s = 0.01315 hp

1 mi./hr. = 0.44704 m/s

1 m/s = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg.

1 kg = 2.2046224 lb.

1 mi. = 1609.35 m = 5280 ft.

1 m = 3.2808333 ft.

13