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ON AERODYNAMIC BREAKUP OF LIQUID DROPS

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SANDIA LABORATORIES

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ON AERODYNAMIC BREAKUP OF LIQUID DROPS

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ABSTRACT

A critical survey of the literature on the aerodynamic breakup of liquid drops yields the parameters currently most appropriate for characterizing the breakup process. The threshold conditions for breakup were found to be determined by the critical Weber number and the Ohnesorge number.

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SUMMARY

The stability of liquid drops under aerodynamic loading is vital to the safety assessment of the space application of systems for nuclear auxiliary power (SNAP). A critical survey of the literature on the breakup of liquid drops is presented.

The Weber number $(\rho_g V^2 D / 2\sigma)$ emerges as the best current means to estimate the breakup potential of a liquid drop. Weber numbers between 1 and 10 are typical for incipient breakup of low-viscosity liquids. For high-viscosity liquids, Weber numbers up to 30 may be appropriate. The Ohnesorge number $([\mu_L^2 / \rho_L \sigma D]^{1/2})$ is found to be useful as a measure of the influence of viscosity. For Ohnesorge numbers much less than 1, viscous effects are secondary. For values larger than 1, the effect of viscosity is to increase the value of the critical Weber number required for breakup.

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TABLE OF CONTENTS

	<u>Page</u>
Nomenclature	6
Introduction	7
General Description of the Breakup Phenomena	9
Nondimensional Parameters	12
Drop Breakup Experiments	15
Theories for Drop Breakup	21
Conclusion	27
Bibliography	35
APPENDIX--Dimensional Analysis	39

LIST OF ILLUSTRATIONS

<u>Figure</u>		
1.	Vibrational breakup of a water drop	29
2.	Bag breakup of a water drop	30
3.	Shear breakup of a propellant drop	31
4.	Chaotic breakup of a water drop	33
5.	Transitional breakup: stripping to chaotic	34
6.	Bag and stamen breakup of a water drop	34

NOMENCLATURE

a	acceleration
Bo	Bond number $\rho L^2 a / \sigma$
Ca	Capillary number $\mu V / \sigma$
C_D	drag coefficient
D	diameter of drop
Fr	Froude number V^2 / aL
L	characteristic dimension
On	Ohnesorge number $[\mu^2 / \rho L \sigma]^{1/2}$
R	radius of drop
Re_M	mixed Reynolds number $\rho_g VL / \mu_\ell$
Re	Reynolds number $\rho VL / \mu$
t	time
V	relative velocity
We	Weber number $\rho V^2 L / 2 \sigma$
Δ	deformation of drop surface
μ	dynamic viscosity
$\bar{\mu}$	viscosity ratio μ_g / μ_ℓ
ν	kinematic viscosity
ρ	density
$\bar{\rho}$	density ratio ρ_g / ρ_ℓ
σ	surface tension

Subscripts

g	gas phase
ℓ	liquid phase

ON AERODYNAMIC BREAKUP OF LIQUID DROPS

Introduction

The breakup of liquid drops due to aerodynamic forces has been studied extensively for the last three decades. Before this active period, the number of investigations of drop breakup per decade was only 1 to 5 percent of the current rate. Most of these early efforts were concerned with the breakup of rain droplets in free fall, a phenomenon still under study.

Chemical processes involving mixing of gas-liquid systems, the formation of rain, wholesale spraying of crops and insects, supersonic flight through rain, liquid-fueled rocket combustion instabilities, and more recently the reentry of molten materials originally constituting space systems have prompted this intensification of research efforts.

In each of these problem areas the integrity of a liquid drop under the effect of aerodynamic forces is crucial to the success or failure of a system or operation. For example, to minimize rocket combustion instability owing to the nonuniform heat release from fuel breakup, the fuel droplets must not break up in the flow field. On the other hand, drop breakup is desirable to ensure good coverage in spraying operations or to prevent rain damage to aircraft structures during supersonic flight. In the case of reentry of radioactive fuels from SNAP systems, it may be desirable either to ensure or to prevent breakup of molten fuel drops.

One method proposed for the disposal of a SNAP generator is to have the generator "burn up" on reentry into small particles with long-term atmospheric residence. Thus dangerous radioactive nuclides will decay through several half-lives before reaching the inhabited part of the atmosphere. An alternative method is to design the generator for the reentry environment so that either the nuclear material is completely contained or the fuel is released and kept in a form not hazardous to man.

Since SNAP devices must be designed to provide the minimum possible power-to-weight ratio, the margin of safety for assured performance on reentry may be small. If a SNAP device does burn up on reentry, either by design or by system malfunction, it is essential to have some knowledge of the final particulate size of the radioactive material in order to evaluate the biological hazards resulting from the incident. One means for estimating the size is to examine the stability of a liquid drop exposed to a high-speed gas stream. Although this is only a hydrodynamic approach, it does permit one to set boundaries on the regions of the atmosphere where a liquid drop of given size and velocity will or will not break up as a result of aerodynamic forces. In addition, one can also estimate the spectrum of particle

sizes produced if a liquid drop does break up. In the reentry of a SNAP system, liquid drops conceivably can be produced in either of two ways: (1) a melting and coalescence of small particles into one drop or (2) the stripping of molten drops directly from a reentry generator. In either case, the character and size of the debris in the atmosphere will be determined by the mode of drop breakup.

Many investigations of the droplet breakup phenomena have been completed or are in progress. This critical review of the literature on aerodynamic breakup of liquid drops was undertaken to define the extent of previous and current work and, especially, to determine its applicability to the problems of the Aerospace Nuclear Safety Program. The review contains five main sections. The first two sections, "General Description of the Breakup Phenomena" and "Nondimensional Parameters," are intended to indicate the more general aspects of the breakup process. The third and fourth sections treat specific experimental and analytical investigations of drop breakup. The fifth and final section is an attempt to summarize what is already known about drop breakup, what applicability this information has in the ANS program, and what additional information is necessary to improve understanding of the phenomena.

General Description of the Breakup Phenomena

The breakup of liquid drops in a gas stream is a complex process of coupled mechanical and fluid mechanical phenomena. The driving potential for breakup is the aerodynamic pressure, proportional to $\rho_g V^2$, acting on the drop and results from the relative velocity, V , between the drop and its surroundings. Four rather well defined breakup modes, described below, have been observed. They are, in order of increasing relative velocity (other factors constant):

1. vibrational or rotational breakup,
2. bag breakup,
3. shear or stripping breakup, and
4. chaotic breakup.

The vibrational form of breakup occurs when the drop is flattened by the gas stream and oscillation develops at the drop's natural frequency. If the frequency of oscillation and the liquid properties are such that the interaction between the flow field and the drop tends to increase the amplitude of oscillation, the drop can break up (Figure 1). Blanchard and others¹⁻⁹ have observed phenomena in which a vibrating drop ultimately breaks into two smaller drops. The natural frequencies for droplet vibration were first investigated by Rayleigh¹⁰ and are discussed by Levich.¹¹ This type of breakup can be observed only where the relative velocity is sufficiently small and is of sufficient duration to allow adequate time for the disruptive amplification of drop oscillations to occur.

The second mode of breakup is bag breakup; it has been observed during experiments with the drop immersed in both steady^{7,9,12,13} and transient¹⁴⁻²¹ flow fields. Again, the gas stream increasingly flattens the drop. However, instead of oscillating, the center portion of the drop's front surface first becomes concave and then is blown out downstream to form a hollow bag attached to a toroidal rim (Figure 2). The bag finally bursts, producing many fine drops; later the heavy rim divides into much larger drops, which constitute about 75 percent of the liquid originally in the drop.¹⁴ The physical reasons for bag breakup are not clear at this time, but two explanations are found in the literature. The classical approach is to assume that this form of breakup occurs from the action of the pressure difference between the front and back of the drop.²¹⁻²⁵ The pressure difference causes the center to be blown out into a bag which grows and breaks up. The other approach is to explain the growth of the ring and bag on the basis of the growth of a ring vortex in the drop.^{26,27} Circulation patterns which might indicate the formation of such a vortex have been observed in liquids by Winnikow and Chao²⁸ and others.^{2,29,30} The growth of vortex rings and bags in liquid-liquid systems has been reported by O'Brien.²⁶ It has not been shown positively that circulation patterns exist in a liquid drop undergoing bag breakup in a gas stream; consequently, it is difficult to assess the validity of the ring vortex theory. More recently it has been suggested by W. Reynolds³¹ that bag breakup results from a Taylor instability of an axisymmetric disturbance whose wavelength is the order of the drop diameter.

At still higher relative velocities, the third mode of breakup is observed. In this case the drop deforms in a manner nearly opposite to that of bag breakup; that is, the drop flattens on the rear side and becomes convex on the front or upstream side. Then, after a period of time, the drop loses mass from the upstream surface either in the form of thin sheets, filaments, or droplets depending on the liquid properties and relative velocity (Figure 3). This form of drop breakup, termed shearing or stripping breakup, has been observed only during transient flow experiments.^{14,16,18,19,21,25,32-35} The qualitative physical interpretation of this phenomenon is fairly clear. Motion of the liquid on and near the drop's front surface is caused by shear forces resulting from gas flowing over the liquid surface. When the shearing force is slightly larger than the resisting force of surface tension, cylindrical sheets or ligaments of fluid are removed from the drop at the downstream edge of the convex surface. Subsequently ligaments divide into small drops. For greater aerodynamic shear, the initial deformation process is unchanged, but mass removal is accomplished by wave crest stripping. It is well known that a gas stream flowing over a liquid surface will contribute to the generation of surface waves and that the higher the relative velocity between the gas and the liquid, the more pronounced is this effect. An increase in the size of the disturbance results finally in detachment of liquid from the surface and ultimately in disruption of the drop.

At extremely high relative velocities, the fourth breakup mode, the chaotic type, is observed. This phenomenon has been reported by several investigators (References 14-16, 21, 32-38). In each case the liquid drop was subjected to rapid acceleration by the gas flow, and the drop was observed to shatter, almost immediately, into a cloud of small droplets (Figure 4). This type of breakup is probably due to the instabilities discussed by Taylor.³⁹ Taylor showed theoretically that when two superposed fluids of different densities are accelerated in a direction perpendicular to their interface, the interface is unstable if the acceleration is directed from the less dense to the more dense fluid. Lewis⁴⁰ has shown experimentally that a layer of water driven by compressed air is unstable and that small disturbances introduced into the interface between air and water develop large amplitudes in an extremely short time. Under conditions of high acceleration, the front surface of a liquid drop is subject to the same phenomenon. The surface is unstable and the drop immediately breaks into a spray of small droplets.

While the types of breakup just described are clearly defined, the transitions from one breakup mode to another are not always sharp. There have been experiments which gave combined breakup modes or even a distinct transitional mode. An example of the former is a drop which begins breakup in the shear mode and completes the process in the chaotic mode²¹ (Figure 5). An example of the latter is the bag and stamen mode²⁰ (Figure 6) which occurs as a transition between the bag and shear types of breakup. In this example of transitional breakup a small cylinder of liquid, termed the stamen, forms on the inside of the back wall of the bag and appears to remain nearly motionless while the toroidal rim and bag are blown past it (Figure 6). The amount of material contained in the stamen and therefore its size increase with increasing relative velocity between the gas and the drop.²¹

While the modes of breakup are relatively well defined; the factors which enable one to predict what mode of breakup will occur are not at all clear. It is obvious, therefore, that the breakup phenomena is a very complex fluid dynamic process.

Nondimensional Parameters

Previous experimental and analytical work on the problem of liquid drop breakup have uncovered the physical variables affecting the breakup process. Dimensional analysis can be used to determine ways of grouping the variables into dimensionless parameters which may be used to characterize the breakup process. It should be emphasized that not all the parameters found by dimensional analysis are automatically significant to the process under study. Their significance and functional dependence for a process can be determined only by experiment, analysis or a combination of the two.

A dimensional analysis of the drop-breakup problem performed by Nicholson and Figler³⁵ yielded several variables such as the Weber and Reynolds numbers which are known to apply. However, the analysis did not include the drop's acceleration, which may be a governing factor in producing some forms of breakup. An extension of their dimensional analysis (details are given in Appendix A), including the drop's acceleration, yielded the set of dimensionless parameters given below (note that the drop diameter, D , is taken as the characteristic dimension):

$$\frac{V^2}{Da} = Fr, \text{ the Froude number}$$

$$\frac{\rho_g V^2 D}{2\sigma} = We, \text{ the Weber number}$$

$$\frac{\rho_g VD}{\mu_g} = Re, \text{ the Reynolds number}$$

$$\frac{\rho_g}{\rho_l} = \bar{\rho}, \text{ a density ratio}$$

$$\frac{\rho_g VD}{\mu_l} = Re_M, \text{ a mixed Reynolds number grouping.}$$

This is not a unique set of dimensionless parameters. Because there are eight variables having only three dimensions (mass, length, and time), there are other groups of parameters, given in Appendix A, which can be formed. The fact that other groups can be formed is easily demonstrated. Multiplication of all parameters in the group above by any one of the group will form a new group of variables. Other dimensionless parameters formed which are found in drop-breakup literature are:

$$\frac{\mu V}{\sigma} = Ca, \text{ the Capillary number}$$

$$\left[\frac{\mu_{\ell}^2}{\rho_{\ell} D \sigma} \right]^{\frac{1}{2}} \quad \text{On, the Ohnesorge number}$$

$$\frac{\rho_{\ell} D^2 a}{\sigma} \quad \text{Bo, the Bond number}$$

$$\frac{\mu_g}{\mu_{\ell}} = \bar{\mu}, \text{ a viscosity ratio.}$$

Dimensionless numbers are usually discussed in terms of the ratio of forces or effects relating to material properties, system geometry, and flow properties. For example, the Reynolds number is stated to be the ratio of the inertial forces (of order ρV^2) to the viscous forces (of order $\mu \frac{V}{D}$) for a fluid of viscosity μ moving at velocity V in or near a body whose characteristic dimension is D . The Reynolds number, $\rho V D / \mu$, or any other dimensionless group, has meaning only when its magnitude is compared with some characteristic value at which something is known to happen. For example, when the Reynolds numbers for pipe flow is greater than 2000 the flow is generally turbulent. With the limitations on the interpretations of dimensionless parameters in mind, it is appropriate now to discuss the dimensionless groupings found by dimensional analysis.

The Froude number is encountered when a free surface exists between fluids of greatly different densities. The Froude number is the ratio of aerodynamic forces tending to distort a free surface to the acceleration forces tending to stabilize it. However, on a droplet, the acceleration vector is from the liquid to the gas, and the effect of the acceleration is to destabilize the free surface. A better dimensionless number when dealing with the destabilizing effect of acceleration is the Bond number. This number arises naturally from studies of Taylor instabilities⁴¹⁻⁴³ and is the ratio of the forces resulting from drop acceleration, which act to increase the amplitude of a disturbance of dimension L ($\rho_{\ell} L a$), to the forces of surface tension (σ/L) which act to reduce the disturbance. When the Bond number ($\rho_{\ell} L^2 a / \sigma$) is greater than 1, it is expected that Taylor instabilities will be prominent in the breakup process. For large accelerations, the wavelength, L , of the amplified disturbance will be relatively small compared to the drop diameter and the chaotic mode of breakup will predominate. For small acceleration, L may be on the order of the drop diameter. The growth of a single axisymmetric disturbance of this size may be the cause of the bag or bag and stamen mode of breakup.

The Weber number is defined as the ratio of the aerodynamic forces acting to disrupt a drop ($\rho_g V^2$) to the surface tension forces ($2\sigma/D$) resisting disruption. It is the dimensionless parameter encountered most often in discussions of drop breakup.

The appearance of the standard fluid dynamic similarity parameter, the Reynolds number, in the dimensionless group is not surprising and needs no further discussion. However, the grouping $\rho_g VD/\mu_L$ (mixed Reynolds number, Re_M) while similar to Re , is formed instead with the droplet's viscosity. This parameter can be interpreted as the ratio of the inertial force of the gas to the viscous forces within the drop. A more consistent parameter may be formed by multiplying by the density ratio to substitute ρ_L for ρ_g . The resultant parameter, $\rho_L VD/\mu_L$, while more consistent, is still difficult to assign physical meaning to, since a velocity of order V within the drop is lacking. If, however, a significant circulation is generated within the drop, a finite liquid velocity and, hence, a significant parameter could result.

The remaining three parameters, the Capillary number, Ohnesorge number, and viscosity ratio are obtained from other combinations of the relevant physical variables. Each is known to have some effect on the breakup process.^{10,22,23,29} The Ohnesorge number physically may be considered the ratio of the viscous forces to the product of the inertial and surface tension forces of the drop. It can also be considered as the ratio of the square root of the Weber number (We) to the mixed Reynolds number (Re_M). Thus the Ohnesorge number can be derived from the original set of five dimensionless parameters. The Capillary number, which is the ratio of the viscous forces to the surface tension forces, appears from considerations of wave growth stability criteria for cylinders and sheets of fluid. This parameter, therefore, has some correlation with the particle sizes produced during breakup. The viscosity ratio, $\bar{\mu}$, and the density ratio, $\bar{\rho}$, can be considered as ratios of viscous forces and inertial forces, respectively, for the fluids comprising the drop and its surroundings. They are related in a parameter $b = [2 + 3/\bar{\mu}] \{1 + [\bar{\rho}\bar{\mu}]^{-1/2}\}^{-1}$, found by Chao²⁹ to determine the ease with which a vortex may be started in a liquid drop. When b is small (less than order 1), a vortex develops easily.

As stated previously, dimensional analysis only provides groupings of physical variables into nondimensional parameters. Functional dependence or importance of the parameters is not a product of the analysis. However, discussion of the meaning of the groups is important for two reasons. First is the understanding of the relative magnitudes of the forces causing and opposing distortion of the drop. Second is the fact that these parameters appear in the literature relating to drop breakup. Thus, understanding drop breakup phenomena requires sorting and studying of the dimensionless parameters to decide which are relevant.

Drop Breakup Experiments

A great volume of experiments dealing with aerodynamic break of liquid drops has been performed. As the need has grown for more refined information on the breakup process, apparatus has ranged from equipment for very simple falling drop experiments to that for complex shock-tube experiments. For the purposes of this discussion, the experiments will be divided into two groups; the few experiments performed before 1945 and those performed thereafter. To allow comparisons of the various experiments in this latter group, the experiments are presented in tabular form following the review of the early experiments.

The early works relating to drop breakup were performed to obtain information on the processes involved in the formation of rain. The experiments were limited in scope and only two of the works found are of real interest. Lenard¹ in 1904 attempted to use a vertical wind tunnel to support water drops, but he could not suspend them for longer than a second. His measurements of gravitational fall rates obtained by adjusting the air speed to hold the drops motionless were in error, but his description of the vibrational breakup process, which he attributed to centrifugal forces, seems correct. Hochshwender,¹² in a dissertation presented in 1919, described bag-type breakup resulting from free fall of large water drops. He is credited by some to be the first to describe the bag breakup mode. While these works are the ones most pertinent to breakup, other early works such as Rayleigh's study of capillary waves and liquid-drop oscillation,¹⁰ which are factors in the breakup process, provided a background for the post-1945 experiments summarized in Table A.

Discussion of Experiments

The post-1945 experiments provide insight into the complexity of the drop-breakup process. For many cases the results of an experiment or the conclusions based thereon are of special interest or may be in apparent conflict with the other experiments. It is appropriate, therefore, to discuss these aspects of the experiments in greater detail.

Modes -- Each of the four modes of breakup--vibrational, bag, shear, and chaotic--has been seen by several investigators. The vibrational mode has been noted only when a drop could be observed for times on the order of tens or hundreds of seconds, as in the experiments of Blanchard,^{2,5,6} Koenig,⁹ and Magarvey and Taylor.⁷ Bag, shear, and chaotic breakup require significantly shorter times, on the order of milliseconds or less. This permits the observation of these modes in most transient breakup experiments conducted in shock tubes and wind tunnels. Because of the limited velocity attainable in a drop-tower experiment, only vibrational and bag-type breakup has been observed. Lane^{15,16} performed the first experiments in which bag, shear, and chaotic breakup were observed. Experiments in a wind tunnel produced bag breakup but in the experiments in a shock tube he could

TABLE A

Summary of Experiments after 1945

Reference	Experiment	Observations
Beal, J. L., et al. (44) 1963-65	Molten zirconium drops were released into horizontal Mach 7 stream in a shock tunnel. High-speed films were made, and attempts were made to determine the size spectrum of the resultant particles from craters in impact targets.	Experiments at $We = 7.2$ and 24 showed breakup apparently occurring in the chaotic mode. Because Zr explodes during combustion in air, the results (particularly the size of particles formed from breakup) are questionable.
Blanchard, D. C. (2,5,6) 1948, 49, 50	Water drops were supported in a vertical wind tunnel. Strobe pictures of droplets undergoing breakup were obtained. Internal circulation was visualized using alumina and graphite powders. Experiments were repeated with water treated to lower surface tension.	<ol style="list-style-type: none"> 1. Water drops greater than 5-mm dia broke in the vibrational mode. 2. Interruption of flow or turbulence reduced the critical We from 4.7 to 1.5. 3. Reduced surface tension made the drops break up more easily. 4. Circulation perceptible only with graphite tracer.
Chapman, D. R. and Larson, H. K. (45) 1963	A jet of molten glass was ejected at various velocities into a chamber evacuated or at atmospheric pressure. Viscosity of the glass was changed by controlling its temperature.	<ol style="list-style-type: none"> 1. Low-speed injection gave either spheres or teardrops at low and high viscosity, respectively. 2. High-speed injection gave disks flattened or concave on the stagnation point side. 3. For $\mu = 2$ to 3 poise and $\sigma \cong 360$ dyne/cm, $We = 2.6$ for impending breakup.
D'Albe, E. M. F. and Hidayetulla (46) 1955	Drops of water fell under the influence of gravity. Measurements were made of drop sizes produced by breakup.	<ol style="list-style-type: none"> 1. Critical We was a function of turbulence level. 2. The largest number of fragments had diameters of 0.1 to 0.2 of the original drop diameter.
Engel, O. G. (32) 1958	Water drops in a horizontal shock tube were subjected to a shock and subsequent high-speed flow. Single-frame photographs of drops undergoing breakup were made.	<ol style="list-style-type: none"> 1. Drops flattened on their rear surface and breakup proceeded by stripping and chaotic modes. 2. She postulated Taylor instability for the chaotic mode and Helmholtz instability for the stripping mode.
Haas, F. C. (25) 1964	Drops of mercury fell vertically into an opposing high-velocity free jet of air. High-speed movies of the breakup process were taken.	<ol style="list-style-type: none"> 1. Critical We for breakup was observed to be between 5 and 6. 2. The breakup mode determined from the pictures appears to be stripping instead of the bag mode usually observed at low Weber numbers. This may be due to the drop diameter being of the same order as the jet diameter.
Hanson, A. R., Domich, E. G. and Adams, H. S. (17,20) 1963, 1965	Drops were supported by acoustic levitator in a horizontal shock tube and subjected to shock and high-speed air flow. Five different fluids of widely varying viscosity ($0.6 < \nu < 100$ cstks) were used for experiments. Single-frame pictures were made of as many as 7 drops per run.	<ol style="list-style-type: none"> 1. The bag or bag and stamen breakup mode was observed for all fluids. 2. Large viscosity effect noted only for $\nu \geq 10$ centistokes. ($On > 1$) 3. Critical velocity for breakup correlates best with one-third power of surface tension. 4. Critical Weber numbers varied from 4.8 to 24.
Koenig, L. R. (9) 1965	Drops suspended in a vertical wind tunnel similar to that used by Blanchard. Several drops and their interaction observed simultaneously.	<ol style="list-style-type: none"> 1. Single drops broke up in vibrational mode as observed by Blanchard. 2. Bag or vibrational breakup mode was observed for one drop following in the wake of another.

TABLE A (cont)

Reference	Experiment	Observations
Lane, W. R., <u>et al.</u> (15,16) 1949, 51	Water drops were dropped in vertical wind tunnel, dropped into horizontal shock tube, or suspended on a wire below a vertical blast gun. Movies and individual photographs were made of the breakup process.	<ol style="list-style-type: none"> 1. Bag mode observed only in wind tunnel. Shear, then chaotic breakup modes were observed as velocities were increased in the shock tube and blast gun. 2. Spray produced by breakup became finer as the air velocity increased, but above sonic velocity there was no appreciable increase in fineness.
Magarvey, R. H. and Taylor, R. W. (7,13) 1956	Large water drops (smaller than 20 mm) fell free for a distance of 15 meters. Single-frame photographs of the drops were taken along with measurements of the size of some fragments.	<ol style="list-style-type: none"> 1. Vibrational and bag breakup of drops was observed. 2. During bag breakup, the heavy rim deformed into 2, 3, or 4 lobes, each lobe forming a large drop. 3. The largest number of fragments had diameters less than 0.2 of the parent drop's diameter.
Nicholson, J. E. and Figler, B. D., (35) 1966	Water drops fell into horizontal shock tube and were subjected to shock wave and high-velocity air-stream. High-speed movies were made of the breakup process.	<ol style="list-style-type: none"> 1. The breakup mode observed was shear and then chaotic as velocity increased. 2. The time to breakup was correlated by $\rho_g/\rho_d(Vt/D)^2 = \text{constant}$.
O'Brien, V. (26,27) 1961	Liquid drops fell into a volume of another liquid. No attempt was made to scale the experiments by similarity arguments. Single still pictures were taken of the drops.	<ol style="list-style-type: none"> 1. A ring vortex was generated by the drop falling through another liquid, and this was postulated to be analogous to a drop falling in air; the vortex was taken to be the reason for bag breakup.
Rabin, E., <u>et al.</u> (18,19) 1959-60	Drops of various liquid propellants suspended in a horizontal shock tube. High-speed photographs were made of the breakup process for burning and nonburning propellants. Test time was varied by altering the length of the shock-tube driver.	<ol style="list-style-type: none"> 1. Bag and shear breakup modes were noted for near-critical drops, but only the shear mode was observed for drops well above critical conditions. 2. The critical condition for breakup was a function of flow duration. 3. Critical conditions were best fit by $We/Re^{-\frac{1}{2}} = \text{constant}$. 4. In the same experiment, bag and shear breakup were observed for small and large drops, respectively.
Ranger, A. A. and Nicholls, J. A. (38) 1966	Drops of water fell into a shock tube and were subjected to a shock wave and airflow at shock Mach numbers of 1.5 to 4. ($We > 1100$). Single-frame photographs of the breakup process were made with an image converter camera.	<ol style="list-style-type: none"> 1. Chaotic breakup occurs very soon after shock passage. 2. The mass loss rate of a drop is obtained by fitting the drop motion to the momentum equation with empirical constants.
Wilcox, J. D., June, R. K., Brown, H. A., Jr., and Kelley, R. C., Jr. (34) 1961	Drops, 3-mm diameter, of Newtonian and non-Newtonian liquids were introduced into a vertical shock tube. The viscosity of the Newtonian liquids was varied over a wide range. Spark photographs were taken of the breakup process in airstreams moving at 220 and 366 m/sec.	<ol style="list-style-type: none"> 1. Drop breakup was observed to take place in the shear or chaotic modes. 2. For viscoelastic liquids breakup was delayed and occurred by the formation of ligaments rather than by surface shearing. 3. At these supercritical conditions, $We \gg 100$, no significant effect of viscosity was observed on the mechanics of breakup of drops of Newtonian liquids.
Wolfe, H. W. and Anderson, S. H. (21) 1964	Drops of several fluids having diverse properties were dropped into a vertical or horizontal shock tube. High-speed movies were taken of breakup process. Particles produced by breakup were sampled by impaction on microscope slides.	<ol style="list-style-type: none"> 1. Bag, bag and stamen, shear and chaotic breakup were observed as the relative velocities increased over the critical conditions for breakup. 2. Few particles were collected less than 10 microns in diameter due to sampler inadequacies.

obtain only shear and chaotic breakup. He concluded, therefore, that bag breakup could be attained only in wind-tunnel or drop-tower experiments. However, Hanson et al.,^{17,20} Wolfe and Anderson,²¹ and others showed that bag-type breakup could be produced in shock-tube experiments. There is no obvious reason for Lane's inability to produce bag breakup in his transient experiments.

Experiments on the breakup of a drop in the wake of another were performed by Koenig.⁹ In his apparatus he found vibrational breakup was predominant for single drops, but the breakup of drops in a wake of another drop often occurred in the bag mode. It is not known whether turbulence or distortion of the velocity profiles caused the anomalous behavior of the following drop; clearly, the possible influence of the wake should be investigated further.

Critical Parameters -- A great deal of effort has been expended in the performance of experiments to determine the "critical parameter" for breakup of liquid drops. At least three different critical parameters have resulted. First is the critical Weber number which, based on Haas' experiments with mercury,²⁸ is a constant whose value is about 6. Magarvey and Taylor,⁷ using free-falling water drops having diameters between 1 and 2 cm, found breakup occurring in the bag mode. The approximate critical Weber number range for these experiments is calculated to be between 3.5 and 14. Taylor,⁴⁷ in interpreting the experiments of Lane, Prewett and Edwards,¹⁵ found the average critical Weber number was 2.7 for the breakup of water drops under widely varying conditions. Unfortunately the critical Weber number appears to be a function of liquid properties other than surface tension. Hanson et al.,²⁰ using fluids of widely varying viscosity, found critical Weber numbers between 4.8 and 24. Hanson thus proposed that the critical conditions for each material be represented by $U^n D = \text{constant}$. Here the constant and the exponent were found to be different for each fluid, with $n = 2$ for low-viscosity fluids and $n \leq 2$ for high-viscosity liquids. Rabin et al.,^{18,19} found critical Weber numbers for relatively low-viscosity fluids to vary between 4 and 20 depending on the drop diameter. Weber numbers greater than 9 were observed only during experiments using a short shock-tube driver. The resulting short test time might have been the cause of the high critical Weber numbers. In attempts to correlate this data for critical conditions, they found $We/Re^{-1/2}$ constant to be most satisfactory, but the same correlation fails when applied to Hanson's data.

Besides showing that bag breakup could be produced in a shock-tube experiment, Hanson et al. first observed the existence of the bag and stamen sequence in the transition from bag to shear breakup. Wolfe and Anderson concluded that the amount of material in the stamen increased as the difference between test conditions and the critical condition for bag breakup increased. Hanson et al. also showed that the viscosity of the liquid affected not only the critical Weber number but also produced changes in the appearance of the drop during breakup. As the viscosity of the liquid increased, there was an increasing tendency for the liquid films constituting the bags to form filaments of liquid and then drops, rather than to break up directly into drops. The apparent effect of the filaments was the formation of larger drops, a tendency noted in the atomization literature.^{48,49}

Other interesting transitional effects were noted by Rabin et al.^{18,19} who, instead of seeing a bag and stamen effect, discovered an experimental condition in which apparently similar experiments would produce either bag or shear breakup. It should be made clear that Rabin's experiments did not completely cover the entire range of variables; thus, the bag and stamen region could have been missed. The reason for the overlap of the bag and shear modes is not obvious, but it may have been a result of the initial deformation of the drop when the wire holding it was jerked from the flow path.

Flow Duration and Turbulence -- Another interesting effect which has been seen in several experiments is the influence of flow duration on the breakup process and/or the mode of breakup. The simplest example of the influence of flow duration is the absence of vibrational breakup for flow durations less than tens of seconds. Likewise, a flow duration less than the time required for any given mode of breakup to occur may be expected to preclude the appearance of that mode of breakup. However, the most significant effect of flow duration is the change in the critical conditions necessary for breakup. For example, Rabin et al.^{18,19} used drivers of different lengths in his shock tube to change the test time of his experiment. They found a significant increase in velocity was necessary to cause breakup as the test time decreased. Similar results were found by Morrell^{50,51} for experiments dealing with the disintegration of a liquid jet in a high-speed air stream.

Also stated as an influence on the breakup process is turbulence of the stream in which the drop is immersed. The influence of turbulence on the breakup process has not been adequately determined, although Blanchard² and D'Albe⁴⁶ state that air-stream turbulence decreases the velocity necessary to cause breakup. However, no specific experiments have been performed to test the effect of turbulence, and apparently no one has measured the turbulence level in their apparatus in an attempt to determine its effect. If turbulence is shown to have an effect, the breakup process for drops traveling in the turbulent wake of larger bodies will have to be examined in a new light.

Breakup Products -- Sampling of the drops formed when a drop breaks up has been attempted during at least four experiments. D'Albe and Hidayetulla⁴⁶ and Magarvey and Taylor¹³ both sampled the particles formed by bag breakup of free-falling water drops. The results of the two sampling experiments, which consisted of catching the particles formed, were consistent and indicated that the diameter of the largest number of drops was 0.1 to 0.2 of the original drop's diameter.

Two other sampling experiments^{21,44} were performed in conjunction with drop breakup in a shock-tube flow. In each case, targets were placed downstream of the location at which the drop broke up. The small drops were expected to impact on the targets as a result of the drop's being carried along at or near the local gas velocity. The efficiency of such an impaction process has been found to be a function of an impaction parameter, P , where $P \propto U \rho_L D / \mu_g L$.⁵² L is the characteristic

dimension of the body on which particles having velocity (U), density (ρ_p), and diameter D are to impact. For P below a certain value (of order 1, but a function of geometry) the efficiency of capture for particles becomes very small. It is easily seen that the smaller the particle, the larger the velocity and/or the smaller the characteristic dimension of the catcher must be.

The configuration used by Beal et al.⁴⁴ to catch particles was a 1/4-inch-wide electropolished lead target. Because of the high values of U and small L , his sampling efficiency was probably quite good down to the limit of experimental resolution (≈ 1 -micron-diameter particles). However, the particles sampled may have been the product of a combustion explosion⁵³ rather than an aerodynamic breakup process, and the application of the results to breakup processes is therefore doubtful. Wolfe and Anderson²¹ attempted to sample the products of breakup using a 4 x 6-inch array of microscope slides. However, the velocity and density of the particles was low enough that the collection of particles smaller than diameters on the order of 30 microns probably was impaired severely. Their data confirms that few particles smaller than 15 microns were collected. It appears, therefore, that the size spectrum of the particles collected by Wolfe and Anderson is not reliable for particles smaller than 30 microns.

Theories for Drop Breakup

There are at least three different classes of theories which are applied to the aerodynamic breakup of liquid drops. They are, in order of complexity, "critical parameter" theories, time-to-breakup theories, and resultant particle size theories. All theories are based on an assumed mode of distortion and flow of liquid within the drop. Thus it is unlikely that any one theory could be applied to all of the various modes of breakup observed experimentally. Since no universally applicable method has been advanced to predict the mode of breakup experienced under the large range of possible conditions, the theories are, therefore, rather limited in their applicability to the breakup problem.

Critical Parameter Theories

Least dependent on the assumed mode of breakup are the "critical parameter" theories. Here it is assumed that when some parameter, usually the Weber number, reaches a critical value, the drop will begin to break up. Usually no time is implied at which the breakup will occur. When the Weber number, the ratio of aerodynamic to surface tension forces, is smaller than some critical value, breakup can never occur; when larger, breakup can occur. The concept of a critical Weber number was based on experimental observations, described above, and also on early analyses, similar to that given below, equating surface tension forces and mean aerodynamic pressure.⁵⁴

$$\text{Aerodynamic pressure} = C_D \frac{1}{2} \rho_g V^2$$

$$\text{Surface tension} \quad 2\sigma/D$$

$$We_{crit} = 2/C_D$$

Since $0.05 < C_D < 1.0$ for a sphere, the critical value of We could be between 2 and 40.

Hinze,^{22,23} in 1949, confirmed analytically the critical Weber number criterion by solving the linearized hydrodynamic equation for the flow within the drop subject to an approximation of the measured external aerodynamic pressure on a sphere. He found the maximum deviation Δ_{max} from the spherical shape was of the form

$$(\Delta/R)_{max} = C We.$$

The symbol C is a constant whose value depends on the liquid viscosity and the velocity history of the particle. It should be noted that the expression does not define a critical value of the Weber number but merely states that the deformation is proportional to Weber number. Since linearized equations were used, the expression may not be correct for large deformations. Hinze determined values of C for

high- and low-viscosity fluids (large and small values of the Ohnesorge number, $[\mu^2/\rho\sigma D]^{1/2}$) under suddenly applied flows and free-fall velocity histories. Using experimental values of the critical Weber number, $(\Delta/R)_{\max}$ was determined to be of order 1 for breakup. Using a value of 1 for $(\Delta/R)_{\max}$, the following values for the critical Weber numbers can be found:

For a suddenly applied velocity,

low-viscosity liquids, $We_{\text{crit}} = 5.9;$

high-viscosity liquids, $We_{\text{crit}} = 10.5.$

For free-fall velocity,

high- or low-viscosity liquids, $We_{\text{crit}} = 10.5.$

Other researchers have used Hinze's methods to derive expressions for the deformation of drops subject to flow fields less approximate than that assumed by Hinze. Haas²⁵ used the measured pressure distribution on a sphere in a flow at a fixed Reynolds number to obtain another estimate of the constants in Hinze's equation. However, the increased accuracy is probably pointless, since the drop does not remain spherical. Again assuming breakup to occur when $(\Delta/R)_{\max} = 1$, a critical Weber number of 7.7 was obtained for the low-viscosity case. Morrell^{50,51} performed a similar analysis for a circular liquid jet and obtained the same expression for the deformation, $(\Delta/R)_{\max}$, indicating that the breakup criteria for a jet and a sphere may be similar. Morrell also attempted to account for differences in flow duration by postulating that if the flow duration is large with respect to the natural period of oscillation of the drop, the drop will be deformed or broken up by the vibration or bag mechanism. If, however, the flow time is short compared to the natural period, a stripping mode of breakup characterized by a constant critical value of $\rho_g V^2$ will be dominant. By matching the two critical theories at a flow duration equal to the natural period, satisfactory agreement with some experimental data was attained.

Golovin^{55,56} analyzed the vibrational motions of a drop's surface under the assumption that a rotational motion existed within the drop. For a water drop falling at terminal velocity in air, the analysis predicts the drop will be stable up to a Weber number of 6.

Dodd⁵⁷ in 1960 published a paper relating drop breakup to the velocity field generated by a body moving at subsonic velocity through a cloud of drops. His approach was to formulate the drop equation of motion and dynamic equations for bag growth including constants which could be determined from experiment. Using Lane's¹⁵ results, the constants were evaluated and applied to drop breakup resulting from a body moving through a cloud of drops. A critical Weber number of 12 can be inferred from the expression. Data are presented on the size velocity a body must have to break up a drop before the drop actually impacts on the body.

It seems apparent that while the critical parameter concept is attractive because of its simplicity, the effects of viscosity and flow duration, among others, preclude the definition of a single parameter which describes potential breakup of a drop. In addition, the experiments and analytical studies discussed above do not suggest or indicate the existence of a single critical parameter breakup theory.

Time-to-Breakup Theories

Littaye⁵⁸ proposed that the time for liquid globules to break up was on the same order as their vibrational period. Hinze,²³ however, pointed out that this could only be the case if the driving force (aerodynamic pressure) was relatively small--that is, for Weber numbers near the critical value. He proposed instead that the time to breakup was of the order

$$t = \frac{R}{V} \left(\frac{1}{0.75} \frac{(\Delta/R)_{\max}}{\bar{\rho}} \right)^{1/2}$$

based on the analysis described in the previous section. This expression is based on the assumption that the drop is composed of a low-viscosity fluid having a large Weber number in an impulsively started stream. For high-viscosity fluids ($On \gg 1$), the following time was found:

$$t \approx \frac{\mu_l}{\rho_g V^2} \left(\frac{\Delta}{R} \right)_{\max}.$$

Curiously, this expression does not explicitly contain the diameter of the drop. In regard to the latter case of high-viscosity fluid, Hinze notes that if the breakup is forestalled by viscous effects, the relative velocity between the drop and its surroundings may decay to the point where the drop is stable. As discussed above, Haas²⁵ repeated the analysis of Hinze and obtained results identical in form but with different constants.

In 1949 Gordon²⁴ used a relatively simple model to obtain times for breakup of a drop. He assumed that a cylindrical plug of fluid is extruded from the drop under the influence of aerodynamic, surface-tension, and viscous forces. Equations for the acceleration were written, integrated twice, and solved for the time required for the displacement to equal the drop radius. The result of these operations is an expression which cannot be solved explicitly for the time to breakup. However, when $We = 8$, an infinite time is required for breakup, implying a critical Weber number of 8. For low- and high-viscosity and large Weber number, the times to breakup are respectively

$$t = \left(\frac{2D}{V} \right) \left(\bar{\rho} \right)^{-1/2} \quad \text{for low-viscosity liquids,}$$

and

$$t = \frac{32\mu_{\ell}}{\rho_g V^2} \quad \text{for high-viscosity liquids.}$$

Both expressions, it can be noted, are of the same form as those found by Hinze. Two shortcomings of Gordon's theory are:

1. It is not clear that bag-type breakup occurs in the manner assumed.
2. The viscous resistance assumed is for fully developed flow in a long pipe, a condition not fulfilled by the assumed model.

Using an approach similar to Gordon's, Wolfe and Anderson²¹ derived an expression for the time to breakup for stripping and bag modes. By assuming that the plug of fluid was not accelerating but was moving at some average velocity, they obtained a result which could be solved explicitly for the time to breakup. Also included in the analysis was an arbitrary constant, K, whose value was dependent on the mode of breakup, i.e., stripping or bagging. Since Wolfe and Anderson attribute bag breakup to pressure drag and stripping breakup to skin friction, the value used for K is proportional to the drag force component compared to the total aerodynamic force. The results of the calculation are as follows:

$$t = \frac{D}{\left(A^2 + BP \right)^{1/2} - A}$$

where

$$A = 16 \mu/D\rho_1 \quad B = 2/\rho_1$$

$$P = 1/2 \rho_g V^2 C_D - K\sigma/d$$

Note that when $P = 0$, t goes to infinity; this occurs when $We = K/C_D$. For $K = 1$ and $0.05 < C_D < 1$, the critical value of We can be between 1 and 20. The limiting forms of the expression for large and small viscosity are the same as those found by Hinze and Gordon, i.e.,

$$t = \left(\frac{D}{V} \right) \left(\bar{\rho} \right)^{-1/2} \quad \text{for low-viscosity liquids,}$$

and

$$t = \frac{32\mu_{\ell}}{\rho_g V^2} \quad \text{for high-viscosity liquids.}$$

This theory has the same limitations as stated above for the Gordon theory plus the additional shortcoming of neglect of the acceleration of the fluid plug.

The works of Morrell,⁵⁹ Morrell and Povinelli,⁶⁰ and Clark⁶¹ have been devoted to studies of liquid jet breakup resulting from exposure to shock-driven gases and high-velocity flows. As indicated earlier, Morrell assumes that the breakup behavior of a liquid jet is a function of action time of the gas on the liquid. For long and short action times (compared to the drop's natural period of vibration), vibrational and stripping modes of breakup, respectively, occur. While it is true that the results obtained for jets are not directly applicable because of nongeometric similarity between a drop and a jet, the dependence of time to breakup on physical variables is of interest. For the stripping mode they find an expression for the time to breakup,

$$t = 0.536 \bar{\rho}^{-2/3} \bar{\mu}^{-1/3} \frac{R}{V} \left(\frac{Re}{1 + 2 We/Re^{1/2}} \right)^{1/2}.$$

This expression is obtained by assuming that the shearing effect of the gas flow is confined to a thin layer of liquid, or boundary layer, at the drop's surface. This layer is subsequently stripped off because the shear and inertial forces tending to remove the layer are greater than the surface-tension forces acting to prevent removal. Note that the exponent of the density ratio is 2/3 rather than 1/2 as found by Hinze et al. The viscosity dependence of the expression is of interest since it implies that the more viscous the liquid, the faster breakup occurs in a given gas! Morrell and Povinelli note that as the liquid viscosity increases, agreement between theory and experiment deteriorates.

Theories on Particle Sizes Resulting from Breakup

The product of the drop breakup process is a spectrum of smaller-diameter particles, which, in turn, may again break up if conditions are still favorable. While the literature is scant on the specific subject of particle-size spectra resulting from the breakup of a single drop, the literature dealing with particle sizes produced by atomization processes is voluminous. These works may be applicable to drop breakup, since aerodynamically unstable drops are considered to be an intermediate stage in the atomization process. But because of the volume of atomization literature and the difficulty in relating it directly to drop-breakup condition, no attempt is made here to review it. Rather the reader is referred, as a starting point, to one of the bibliographies dealing with atomization processes.⁴⁹

Wolfe and Anderson²¹ proposed a method of calculating the average particle size resulting from shear- or bag-type breakup. Basically the theory assumes that a cylindrical sheet of fluid produced early in the breakup process breaks into circular annular strips whose thickness is derived from the aerodynamic shear on the liquid and whose width is determined from Squire's⁶² analysis of film stability.

Each strip is subsequently assumed, according to Rayleigh's theory,¹⁰ to pinch off droplets through the action of surface tension. The result is an expression for the average particle diameter, D_a .

$$D_a = \left[\frac{136 \mu_1 \sigma^{3/2} D^{1/2}}{\rho_g^2 \rho_1^{1/2} V^4} \right]^{1/3}.$$

The expression agrees functionally with Mayer's theory,⁶³ with Weiss and Worsham's experimental data for jet breakup,⁴⁸ and with drop breakup experiments performed by Wolfe and Anderson.

Conclusion

The aerodynamic breakup of liquid drops is a very complex process. Widely different types of breakup occur under different flow conditions. Theories on breakup do exist, but no one theory describes or predicts the drop-breakup mechanism or the ultimate particulate size produced by breakup. Consequently, to predict the behavior of liquid drops one must rely primarily on experimental correlations. In considering the analyses and experiments reviewed here, a critical Weber number criterion emerges as the current best means to estimate whether a liquid drop will or will not break up. Since critical Weber numbers ranging from 1.5 to 25 have been reported for incipient liquid drop breakup, it should be recognized that a single critical Weber number criterion is neither a unique nor an adequate description of the phenomena. The criterion is merely a useful guide.

Since critical Weber numbers greater than about 10 are observed only for viscous liquids, it is apparent that viscosity has a definite role in the drop breakup process. However, the effects of viscosity are most important near the critical conditions for incipient breakup; as determined from experiments, the effects are to increase the Weber number required for breakup and to alter the mechanics of the breakup process in a direction favoring production of larger droplets. This role of viscosity is also confirmed by theory. It has been shown that if the Ohnesorge number, which physically may be considered as the ratio of the viscous forces to the product of the inertial forces and surface-tension forces of a drop, is of order 1, viscous effects are important in the droplet breakup process, and critical Weber numbers for incipient drop breakup up to about 25 may have to be considered. However, in any situation where the Ohnesorge number is much less than 1, viscous effects may be neglected and a critical Weber-number range between 1 and 10 should be utilized in droplet-breakup calculations.

Since there is a wide variation in observed critical Weber numbers, it is not certain that a given drop with a Weber number in the critical range will break up. All that can be said definitely is that the drop may be on the verge of breaking up and that breakup may or may not occur. More exact data dealing with the response of a specific liquid in the particular environment of interest would be needed to apply the Weber number criteria more specifically. But even then, small variations in initial deformations, duration of velocity pulse, and stream turbulence, together with flow field interaction with other bodies, will still cause uncertainties in predicting the breakup behavior of drops.

In applying the results of the experiments and analysis reviewed here to drops of molten materials, as might occur in the reentry of a SNAP device, one must appreciate all of the uncertainties in the results. Most of the experiments to date have been conducted in subsonic flows, and all of the quantitative experiments have been performed under continuum-flow conditions. Therefore the extrapolation of these results to the low-density, high-velocity flow regimes typical of reentry may be questioned. Detailed experimental work needs to be performed in the reentry

environment to determine possible effects of this environment on the mode of breakup and the size of particulate formed as a result of breakup. In particular, an experiment where there is adequate time to continuously observe the breakup process at high Mach numbers and low densities is required. The experiment should begin with a study of the effects of the drop injection technique in order to insure that the observed breakup is not the result of the injection process but rather a result of the aerodynamic processes alone. This is particularly important if bag or vibrational breakup is expected. Detailed information on the mode of breakup, surface deformation, and size spectrum of particulate produced is necessary to gain insight into the breakup process and to permit extrapolation of laboratory experiments to the reentry environment.

Until further quantitative experiments have been performed, the following conclusions can be drawn:

1. Critical Weber-number criteria remain the best acceptable means for estimating drop stability.
2. Critical Weber numbers are affected by viscosity.
3. The Ohnesorge number may be used as an indicator of viscous effects.
 - a. For Ohnesorge numbers much less than 1, viscous effects are secondary, and a critical Weber number range between 1 and 10 should be utilized.
 - b. For Ohnesorge numbers of order 1 or larger, viscous effects are important, and critical Weber numbers up to at least 25 are possible.
4. Drops having Weber numbers in the critical range may or may not break up. Breakup of a drop at near-critical conditions will take place in the vibrational or bag modes.
5. If a drop breaks up in the vibrational mode, two large drops and several small drops are usually found.
6. If a drop breaks up in the bag mode, up to approximately 75 percent of the drop's original mass may exist in sizes $1/10$ to $1/5$ of the original drop's diameter.
7. Liquid drops having Weber numbers greatly in excess of the critical value will break up in the shear or chaotic modes. A spray of fine particulate having diameters considerably smaller than $1/10$ of the original drop's diameter will be produced.

Figure 1. Vibrational breakup mode. Stroboscopic pictures of water drops; (a) 8.8 mm (spherical diameter), strobe frequency 80/sec; (b) 8 mm (spherical diameter), strobe frequency 90/sec; (c) 9.4 mm (spherical diameter), strobe frequency 70/sec; Blanchard.⁶

(a)

(c)

(b)

(d)

Figure 2. Bag breakup mode--photographs of the breakup of a free-falling 15-mm water drop; Magarvey and Taylor.⁷

Figure 3. Shear breakup mode--shattering of 1.4 mm diethylcyclohexane drop; flow velocity, 5.3 m/sec; framing rate, 6770 frames/sec; Rabin, Schallennmuller and Lawhead.¹⁹

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Figure 3. (continued)

Figure 4. Chaotic breakup of 2.7-mm diameter water drop; Engle,³²

Figure 5.

Stripping to chaotic transitional breakup of a 3-mm drop of 2 ethylhexyl hydrogen phosphate; airstream velocity 866 m/sec; (a) 0 μ sec; (b) 70 μ sec; (c) 150 μ sec; (d) 250 μ sec; (e) 490 μ sec; (f) 850 μ sec; Wilcox *et al.*³⁴

Figure 6.

Bag and Stamen breakup of water drops; initial drop diameters, from top to bottom, 720, 840, 990, and 930 μ air velocity 25.4 m/sec; Hanson, Domich, and Adams.²⁰

BIBLIOGRAPHY

1. Lenard, P., "Ueber Regen," Meteorological Z, 21, 247-262 (1904).
2. Blanchard, D. C., "Observations on the Behavior of Water Drops at Terminal Velocity in Air," GE-OR-7, Project Cirrus, General Electric Res. Lab., (1948).
3. Volynskii, M. S., "On the Breakup of Droplets in an Airstream," Doklady Akad Nauk SSSR, 62, 301-304 (1948).
4. Volynskii, M. S., "Investigation of Drop Disintegration in a Gas Stream," Doklady Akad Nauk SSSR, 68, pp. 237-240 (1949).
5. Blanchard, D. C., "Experiments with Water Drops and the Interaction Between Them at Terminal Velocity in Air," GE-OR-17, Project Cirrus, GE Res. Lab. (1949).
6. Blanchard, D. C., "The Behavior of Water Drops at Terminal Velocity in Air," Trans. Am. Geo. Un., 31, 836-42 (1950).
7. Magarvey, R. H. and Taylor, B. W., "Free Fall Breakup of Large Drops," Journal of Applied Physics, 27, 1129-35 (1956).
8. Komabayasi, M., Gonda, T., and Isono, K., "Lifetime of Water Drops Before Breaking and Size Distribution of Fragment Droplets," Met. Soc. of Japan, Journal, Ser. 2, 42, 330-340 (1964).
9. Koenig, L. Randall, "Drop Freezing Through Drop Breakup," J. of the Atmos. Sci, 22, 448-51 (1965).
10. Rayleigh, Lord, Theory of Sound, Vol. II, Dover (1945).
11. Levich, V. G., Physicochemical Hydrodynamics, Prentice Hall, Inc. (1962).
12. Hochschwender, E., Dissertation, Heidelberg (1919).
13. Magarvey, R. H. and Taylor, B. W., "Shattering of Large Drops," Nature, 177, 745-746 (1956).
14. Jenkins, D. C., "Note on the Possibility of Raindrops being Shattered by the Air Disturbances Caused by a Moving Body," Royal Aircraft Establishment, Tech. Note No. Mech. Eng. 239, RAE-TN-ME-239 (1957).
15. Lane, W. R., Prewett, W. C., and Edwards, J., "Some Experiments on the Shatter of Drops by Transient Blasts of Air," Porton Technical Paper No. 115 (1949).
16. Lane, W. R., "Shatter of Drops in Streams of Air," Industrial & Engineering Chemistry 43, 1312-1317 (1951).
17. Hanson, A. R., Domich, E. G., and Adams, H. S., "An Experimental Investigation of Impact and Shock Wave Breakup of Liquid Drops," U. of Minn., Inst. of Tech, Rosemont Aeronautical Labs., Final Report to U.S. Bur. of Aeronautics (1955).
18. Rabin, E. and Lawhead, R., "The Motion and Shattering of Burning and Non-Burning Propellant Droplets," Rocketdyne Report AFOSR TN 59-129 (1959).
19. Rabin, E., Schallenmuller, A. R., and Lawhead, R. B., "Displacement and Shattering of Propellant Droplets," Rocketdyne Report AFOSR TR 60-75 (1960).
20. Hanson, A. R., Domich, E. G., and Adams, H. S., "Shock Tube Investigation of the Breakup of Drops by Air Blasts," Phys. of Fluids, 6, 1071-80 (1963).
21. Wolfe, H. E. and Anderson, W. H., "Kinetics, Mechanism and Resultant Droplet Sizes of the Aerodynamic Breakup of Liquid Drops," Aerojet-General Corp. Report 0395-04(18)SP (1964).

22. Hinze, J. O., "Forced Deformations of Viscous Liquid Globules," Applied Scientific Research, A1, 263-272 (1949).
23. Hinze, J. O., "Critical Speeds and Sizes of Liquid Globules," Applied Sci. Res., A1, 273-288 (1949).
24. Gordon, G. D., "Mechanism and Speed of Breakup of Drops," J. of Appl. Physics 30, 1759-61 (1959).
25. Haas, Fred C., "Stability of Droplets Suddenly Exposed to a High Velocity Gas Stream," AIChE J, 10, 920-4 (1964); also Cornell Aeronautical Lab. Report I 108-100 (1963).
26. O'Brien, V., "Why Raindrops Breakup--Vortex Instability," J. of Meteorology, 18, 549-552 (1961).
27. Blanchard, D. C., "Comments on the Breakup of Raindrops," J. of Atm. Sci., 19, 119-120 (1962).
28. Winnikow, S. and Chao, B. T., "Droplet Motion in Purified Systems," Phys. of Fluids, 9, 50-61 (1966).
29. Chao, B. T., "Motion of Spherical Gas Bubbles in a Viscous Liquid at Large," Reynolds Numbers, Physics of Fluids 5, 69-79 (1962).
30. Bond, W. N. and Newton, D. A., "Bubbles, Drops and Stokes Law," Phil. Mag., 5, 794-804 (1928).
31. Reynolds, W. C., private communication (November 1966).
32. Engel, O. G., "Fragmentation of Waterdrops in the Zone Behind an Air Shock," J. of Research of the N.B.S., 60, 245-280 (1958).
33. Wilcox, J. D. and June, R. K., "Apparatus for Study of the Breakup of Liquid Drops by High-Velocity Airstreams," J. of the Franklin Institute, 271, 167-183, (1961).
34. Wilcox, J. D., June, R. K., Brown, H. A., Jr., and Kelley, P. G., Jr., "The Retardation of Drop Breakup in High-Velocity Airstreams by Polymeric Modifiers," Journal of Applied Polymer Science, 5, 1-6 (1961).
35. Nicholson, J. E and Figler, B. D., "Complementary, Aerodynamic Test Techniques for Rain Erosion Alleviation Studies," Paper 66-766 AIAA Aerodynamic Testing Conf., Los Angeles, California (Sept. 21-23, 1966).
36. Rojec, E. A., "Photographic Investigation of Shear Type Droplet Breakup," Rocketdyne Research Rept. 63-39 (1963).
37. Dabara, E. K., Ragland, K. W., Ranger, A. A., and Nicholls, J. A., "Two-Phase Detonations and Drop Shattering Studies," U. of Mich. Rept. 0632+-2-T (1966).
38. Ranger, A. A. and Nicholls, J. A., "Aerodynamic Breakup of Liquid Drops," 3rd Combustion Conference, ICRPG, JFK Space Flight Center, Coco Beach, Florida, (Oct. 17-21, 1966).
39. Taylor, G. I., "The Instability of Liquid Surfaces when Accelerated in a Direction Perpendicular to Their Planes I," Proc. Royal Soc., A 201, 194-202 (1950).
40. Lewis, D. J., "The Instability of Liquid Surfaces when Accelerated in a Direction Perpendicular to Their Planes II," Proc. of Royal Soc. (London), A 202, 81-96 (1950).
41. Keller, J. B. and Kolodner, I., "Instability of Liquid Surfaces and Formation of Drops," J. Applied Physics, 25, 918-21 (1954).
42. Chang, I. D. and Russell, P. E., "Stability of a Liquid Layer Adjacent to a High Speed Gas Stream," Phys. of Fl., 8, 1018-26 (1965).

43. Lang, S. B. and Wilke, C. R., "Illustrations of a Method for Determining Hydrodynamic Stability Criteria," J. of Colloid and Interface Sci., 21, 153-8 (1966).
44. Beal, J. L. et al., "Dispersal of Reactor Core Materials by Re-entry Processes," Cornell Aeronautical Laboratory, Inc., Repts. 110-900-1 (1964), and 114-080-2 (1965).
45. Chapman, D. and Larson, H. K., "The Lunar Origin of Tektites," NASA TN D 1556, (1963).
46. D'Albe, E. M. F. and Hidayetulla, "The Breakup of Large Water Drops Falling at Terminal Velocity in Free Air," Quart J. Royal Met. Soc., 81, 610 (1955).
47. Taylor, Geoffrey, "Shape and Acceleration of a Drop in a High Speed Airstream," Chemical Defense Est. G. B. 1956 PTN./660/5278/49, The Scientific Papers of Sir Geoffrey Ingram Taylor, Vol III, G. K. Batchelor, ed., Cambridge Univ. Press (1963).
48. Weiss, M. A. and Worsham, C. H., "Atomization in High-Velocity Airstreams," ARS Journal, 29, 252-259 (1959).
49. Miesse, C. C., "Recent Advances in Spray Technology," Applied Mechanic Rev., 9, 321-3 (1956).
50. Morrell, Gerald, "Breakup of Liquid Jets by Transverse Shocks," 8th International Symposium on Combustion, Calif. Inst. of Tech., 1059-68 (1960).
51. Morrell, G., "Critical Conditions for Drop and Jet Shattering," NASA TN D-677 (1960).
52. Ranz, W. E. and Wong, J. B., "Impaction of Dust and Smoke Particles on Surface and Body Collectors," Ind. and Eng'g. Chem., 44, 1371-80 (1952).
53. Nelson, L. S., "The Combustion and Explosion of Zirconium Droplets Ignited by Flash Heating," Sandia Corporation Report SC-RR-65-569 (1965).
54. Triebnigg, H., Der Einblase und Einspritzvorgang bei Dieselmotoren, Springer Verlag, Vienna (1929).
55. Golovin, A. M., "The Theory of the Vibration and Breakdown of Droplets in a Gas Stream in the Presence of Rotational Motion Inside the Droplets, I.," Bull. Acad. Sci. USSR Geophys. Ser. (USA) No. 8, 658-662 (1964).
56. Golovin, A. M., "On the Theory of Oscillations and Fractioning of a Drop in a Gas Stream with a Potential Movement Within the Drop, II.," Bull. Acad. Sci. USSR Geophys. Ser. (USA) No. 8, 769-771 (1964).
57. Dodd, K. N., "On the Disintegration of Water Drops in an Airstream," J. Fl. Mech., 9, 175-82 (1960).
58. Littaye, G., "Sur La'atomisation d'un Jet Liquide," Comptes Rendus Acad. Sci., 217, 99-105 (1943).
59. Morrell, G., "Rate of Liquid Jet Breakup by a Transverse Shock Wave," NASA TN D-1728 (May 1963).
60. Morrell, G. and Povinelli, F. P., "Breakup of Various Liquid Jets by Shock Waves and Applications to Resonant Combustion," NASA-TN-D-2423 (1964).
61. Clark, B. J., "Breakup of a Liquid Jet in a Transfer of Gas," NASA TN D-2424 (1964).
62. Squire, H. B., "Investigation of the Instability of a Moving Liquid Film," Brit. J. App. Phys., 4, 167-9 (1953).
63. Mayer, E., "Theory of Liquid Atomization in High-Velocity Gas Streams," ARS Journal, 31, 1783-1781 (1961).

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APPENDIX

Dimensional Analysis

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Dimensional Analysis

In order to determine the basic sealing parameters for the drop-breakup problem, a dimensional analysis of the physical variables known to effect breakup was performed. The physical variables are D , V , ρ_g , μ_g , μ_ℓ , ρ_ℓ , σ , a . Their definition and units are as follows (L is length, M is mass and T is time):

Drop diameter	D	L
Relative velocity	V	LT^{-1}
Gas density	ρ_g	ML^{-3}
Gas viscosity	μ_g	$ML^{-1}T^{-1}$
Liquid viscosity	μ_ℓ	$ML^{-1}T^{-1}$
Liquid density	ρ_ℓ	ML^{-3}
Surface tension	σ	MT^{-2}
Drop acceleration	a	LT^{-2}

It is assumed that some quantity relevant to the breakup process can be related to the physical variables in terms of a series expansion. Additionally, it is assumed that the quantity, such as the time to breakup or mass loss rate, is already nondimensionalized. The quantity, Q , therefore has dimensions of $M^0 L^0 T^0$. Thus

$$\begin{aligned}
 Q = & a_1 D^\alpha V^\beta \rho_g^\gamma \mu_g^\Delta \mu_\ell^\epsilon \rho_\ell^\lambda \sigma^\nu a^\kappa + \\
 & a_2 D^{2\alpha} V^{2\beta} \rho_g^{2\gamma} \mu_g^{2\Delta} \mu_\ell^{2\epsilon} \rho_\ell^{2\lambda} \sigma^{2\nu} a^{2\kappa} + \\
 & a_3 D^{3\alpha} \dots \dots \dots
 \end{aligned} \tag{1}$$

Substituting the dimensions of the corresponding physical variables, neglecting terms of higher order, and equating the exponents of each dimension in the left- and right-hand members of the equations gives the following three equations.

1. Equating exponents of the length

$$\alpha + \beta - 3\gamma - \Delta - \epsilon - 3\lambda + \kappa = 0 \tag{2}$$

2. Equating exponents of the time

$$\beta + \Delta + \epsilon + 2\nu + 2\kappa = 0 \tag{3}$$

3. Equating exponents of the mass

$$\gamma + \Lambda + \epsilon + \lambda + \nu = 0 \quad (4)$$

If there were as many equations as there are unknowns,⁸ all the exponents could be determined uniquely. This cannot be achieved. However, it is possible to determine three exponents in terms of the remaining five by solving the three equations given above. Thus, solving for α , β , and γ , one obtains:

$$\begin{aligned} \alpha &= \kappa - \nu - \epsilon - \Lambda \\ \beta &= -[2\kappa + 2\nu + \epsilon + \Lambda] \\ \gamma &= -[\nu + \lambda + \epsilon + \Lambda]. \end{aligned}$$

Substituting these quantities in expression (1) above and neglecting the higher-order terms, the following results:

$$G = D^{+\kappa-\nu-\epsilon-\Lambda} V^{-2\kappa-2\nu-\epsilon-\Lambda} \rho_a^{-\nu-\lambda-\epsilon-\Lambda} \mu_a^\Delta \mu_\ell^\epsilon \rho_\ell^\lambda \sigma^\nu a^\kappa.$$

By combining the physical variables having the same exponent, an expression for G in terms of dimensionless groups is obtained:

$$G = \left(\frac{Da}{V^2}\right)^\kappa \left(\frac{\sigma}{DV^2 \rho_g}\right)^\nu \left(\frac{\mu_\ell}{DV \rho_g}\right)^\epsilon \left(\frac{\mu_g}{V \rho_g D}\right)^\Delta \left(\frac{\rho_\ell}{\rho_g}\right)^\lambda.$$

In terms of the variables defined in the nomenclature, this is

$$G = Fr^{-\kappa} (2We)^{-\nu} \bar{R}^{-\epsilon} Re^{-\Delta} \bar{p}^{-\lambda}.$$

This particular grouping is not unique, since by solving Eqs. (2), (3), and (4) for a different set of three exponents, say λ , ν , and κ , a different set of dimensionless parameters results,

$$G = On^{-\alpha} Ca^\beta \bar{p}^\gamma \bar{\mu}^\Delta \left(\frac{\mu_\ell}{\rho_\ell \sigma^3}\right)^\kappa.$$

Successive solutions of Eqs. (2), (3), and (4) for other exponents yields other groups of parameters including the Bond number. However, this procedure is not really necessary, since the other dimensionless groups can be formed as products of the original five parameters.

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