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AN EXPERIMENTAL STUDY OF THE DRAG COEFFICIENT  
OF BURNING ALUMINUM DROPLETS

BY

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INTRODUCTION

A knowledge of the dynamics of motion of burning particles and droplets is important in heterogeneous combustion in multi-phase flow systems. In this paper the dynamics of 200-500 micron aluminum droplets which burn as they fall through stagnant ambient air are examined. The starting hypothesis was that the effective drag force experienced by a burning droplet should be quite different than that predicted for an equivalent non-burning droplet falling in the same medium.

C. T. Crowe, J. A. Nicholls and R. B. Morrison<sup>1</sup> summarized the earlier experimental results on the drag coefficients of burning particles. Since these data largely pertain to burning hydrocarbon droplet systems, which differ in many respects from the burning aluminum system, the extrapolation of results to the present study is highly questionable. In their experiments Crowe, et al examined burning gun powder particles accelerating in a gas stream, and found an increase in the drag coefficient as compared to the standard drag curve for spheres. Leont'yeva<sup>2</sup> measured the drag coefficients of burning carbon spheres and found an increase in the drag. The drag of burning metal droplets appears to have been largely neglected.

The effect of combustion upon drag can be seen from the development of the momentum equation for a variable mass. Consider a mass  $M$  traveling along a straight line with velocity  $V$  at time  $t$ . At time  $t+dt$  suppose mass  $M$  ejects mass  $-dM$  at a velocity  $u$  along the same straight line. The time rate of change of momentum for this system can be derived<sup>3</sup> as

$$\frac{dG}{dt} = M \frac{dV}{dt} + (V - u) \frac{dM}{dt} \quad 1$$

Equating the time rate of change of momentum to the summation of external forces we have the momentum equation for a system of variable mass.

$$\Sigma F = M \frac{dV}{dt} + \frac{dM}{dt} (V - u) \quad 2$$

Applying this equation to a droplet falling in air and neglecting the buoyant force, the equation for drag force is then

$$D = Mg + M \frac{dV}{dt} + D_M \quad 3$$

where  $M$ ,  $g$ ,  $V$ ,  $dV/dt$  are the particles mass, acceleration of gravity, velocity and the particles acceleration respectively.  $D_M$  is the force component in the direction of fall resulting from the integration of  $[(V - u) dm/dt]$  over the particle surface. Thus the drag force differs from the non-burning steady-state case by terms which account for the mass exchange and the resulting acceleration. The drag coefficient is then given by

$$C_D = \frac{D}{1/2 \rho V^2 A} \quad 4$$

where  $\rho$  is the density of the stagnant medium and  $A$  is the projected frontal area of the particle.

#### Experimental Technique

Experiments to measure the influence of combustion on the drag of burning aluminum droplets have a unique set of requirements. First, a clean and rapid high temperature ignition must be achieved. Secondly, an accurate history of the droplet's relative velocity and acceleration must be determined. Thirdly, the burning rate must be measured, and the nature of burning must be characterized. Nelson<sup>4</sup> used a flash-heating technique to ignite high specific

area foils to study the combustion of zirconium droplets in a gaseous media. Prentice<sup>5</sup> adapted the technique to study certain aspects of aluminum combustion. A similar technique of ignition was employed in the present study. Here small aluminum foils of predetermined mass were dropped along the axis of a helical xenon flashtube. When the foil reached the center of the helix, 24,000 joules stored in a 1140 microfarad capacitor bank was discharged through the flashtube and the resulting thermal radiation caused rapid melting and ignition of the foil. With the exclusion of the small period of time that the burning droplet was in the helix of the flashtube its displacement history was observed by high speed cameras over the entire trajectory. By intercepting the particle at some point in the trajectory, the value of  $dM/dt$  may then be obtained by reweighing and comparing to the original foil mass. Since the flashtube is separated from the gaseous oxidizer, the chemical composition, temperature, pressure, and relative velocity (zero in this case) of the test gas can be controlled to permit an idealized examination of the drag coefficient.

The higher reflectivity of untreated aluminum, as compared to zirconium in Nelson's studies, necessitated the output of a substantially higher irradiance from the flashtube. To achieve this it was necessary to include a spark gap and induction coil into the electrical circuit so that the 1140 microfarad capacitance bank could be charged above the 4000 volt breakdown voltage of the General Electric FT-625 flashtube. This bank was usually charged to 6500 volts which represents a total power input of 24,000 joules. Ignition of the foils was not obtained at energy values much lower than this.

### Behavior of the Aluminum Droplet

The primary objective of the experiment was to obtain numerical values of the drag coefficient as a function of Reynolds number for different burning aluminum droplet sizes. It has been pointed out by Prentice<sup>5</sup> that when aluminum burns in air it has a tendency to form oxide caps, to spin, to jet and to fragment. Some of these phenomena as observed in the NASA-LRC studies are illustrated in the still plate streak photograph of Figure 1. The most obvious event is that of fragmentation. Approximately three quarters along the trajectory of the burning droplet a primary puffing event was observed. These events introduce uncertainties, and if the values of the drag coefficient and corresponding Reynolds number are to be meaningful, the behavior of the particle, its flame zone and the sequence of events that these quantities undergo must be well characterized.

The results reported in this paper are for falling droplets in the 200-500 micron range combusting in air at atmospheric pressure. The relative humidity was approximately 50 percent and the temperature approximately 77°F.

In many of the experiments in which still plate streak photographs were taken, events could be observed but not characterized. Some insight into this problem was obtained when a chopping disk was incorporated as a rapid shutter and timing device. Figure 2 is typical of these pictures taken at a relatively high exposure. The indicated events were observed repeatedly. In general, as the particle leaves the flashtube it burns with no noticeable irregularities. It continues to fall until it reaches the point of the primary puff where there is a sudden increase in brightness. The brightness

rapidly decreases and then the particle will generally start to spiral. The spiraling ceases and as the particle continues to fall it will suddenly fragment, usually producing one major particle.

Additional details of droplet appearance and flame structure of free-falling burning droplets were obtained by high speed Fastax motion pictures. Figure 3 is a sequence of frames of a burning aluminum droplet impinging upon a glass slide. These pictures were taken early in the combustion history and show the particle preceded by a highly luminous crescent shaped flame with no evidence of particle spin. The details of these Fastax photographs show the ratio of the crescent shaped flame diameter to droplet diameter to be approximately 2.7:1. The combustion of the droplet began to terminate when the flame first struck the slide; part of the surrounding oxide smoke particles were deposited on the slide and a portion upon the particle.

One of the difficulties in calculating the drag coefficient and Reynolds number is estimating the change in the droplet diameter that occurs when a particle is heated to its boiling point. Assuming that the particle is still a sphere on the glass slide, the ratio of the diameter immediately after the vapor diffusion flame was extinguished to the diameter when the particle was cool was calculated to be 1.16. This is in agreement with values obtained by a formula Prentice used to calculate density changes. This correction was applied to values of Reynolds number and drag coefficients calculated later.

A photomicrograph of the quenched droplet of Figure 3 is shown in Figures 4 and 5. Figure 4 shows the oxide pattern deposited on the slide.

It is important to note that the ratio of the diameter of the outer oxide smoke to the particle diameter is approximately 5:1 which is very much greater than 2.7:1 observed prior to particle quench. This suggests that flame to particle diameter ratios inferred from slide interception must be carefully interpreted.

Figure 5 is a photomicrograph of the same particle in which the slide has been rotated  $90^\circ$  to show a side view. The purpose of this was to show how the larger particles were squashed on impact.

High speed high magnification Fastax movies of the type shown in Figure 3 are certainly informative but they are limited by representing only a small portion of the complete particle history in each experiment. What was really needed for the drag coefficient study was a complete trajectory history of the burning droplet and its flame zone. Figure 6 is a single still plate film on which multiple exposures of a single burning aluminum droplet were photographed while it was falling. Certain portions of this picture have been enlarged to show detail of the droplet and flame structure.

In the initial portion of the trajectory the droplet was burning in a manner similar to that shown on the slide of the Fastax movie in Figure 3. As the particle continued to burn the intensity of the flame and the particle decreased somewhat with time. Suddenly the particle brightened, then the crescent flame rapidly expanded, contracted and disappeared. The luminosity of the particle then began to decrease before fragmentation.

### Drag Coefficient and Reynolds Number

Examination of the equation for the drag force indicated that accurate measurements of  $V$ ,  $dV/dt$ ,  $M$  and  $dM/dt$  were necessary to calculate the drag coefficient. In the experiment the displacement as a function of time of the burning droplet was recorded by a high speed camera. This datum was then curve fitted and differentiated to yield  $V$  and  $dV/dt$ . In these experiments the particle injection apparatus imparted an initial velocity to the droplet. After leaving the flashtube small droplets which had not accelerated to their terminal velocity would do so very quickly, whence they would then start to decelerate. Accurate values of the mass of large droplets was not easily obtained by slide interception, and at this writing the data is still in the process of reduction.

Figure 7 is a graph of the drag coefficient and Reynolds number on which the standard drag curve and values of  $C_D$  and  $R_E$  for burning gun powder have been shown for reference. The burning aluminum droplet data are preliminary values for the smallest particles studied, since their mass could be accurately estimated for photomicrographs. In the expression for the drag force the value of  $dM/dt$  was small for the burning rate encountered and the surface integral was neglected. The terminal velocity had been reached by the time of interception so that  $dV/dt \approx 0$ . The results indicate that the terminal velocity was less than that of a non-burning sphere of the same size and density and that there was a corresponding increase in the drag coefficient.

## SUMMARY

Examination of the results of these experiments indicate the following.

1. An aluminum droplet burning in ambient (50 percent relative humidity) air generally follows a set sequence of events: the particle will puff, spiral and then fragment.
2. The motion of the droplet relative to the stagnant gas created a crescent shaped flame zone.
3. A rapid expansion of the vapor-phase diffusion flame is associated with the primary puff after which the vapor phase diffusion flame disappears.
4. Measurements to calculate the drag coefficient and Reynolds number should be made above the primary puffing event.
5. Values of the drag coefficient and Reynolds number calculated indicate a several-fold increase in the drag coefficient resulting from combustion in air.

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## NOMENCLATURE

A	Projected Area of Droplet ( $\text{cm}^2$ )
$C_D$	Coefficient of Drag
d	Particle Diameter (cm)
D	Drag Force (dyne)
$D_M$	Drag Force Resulting from Integration of $(V-u) \, dM/dt$ over Droplet Boundary (dyne)
F	External Force (dyne)
G	Droplet Momentum ( (Gram - cm)/Sec)
M	Mass (Gram)
Re	Reynolds Number
t	Time, (sec)
u	Velocity of Mass Leaving Droplet (cm/sec)
V	Velocity of Droplet (cm/sec)
$\rho$	Density of Medium (Grams/cc)
$\mu$	Dynamic Viscosity of Medium (gm/cm sec)

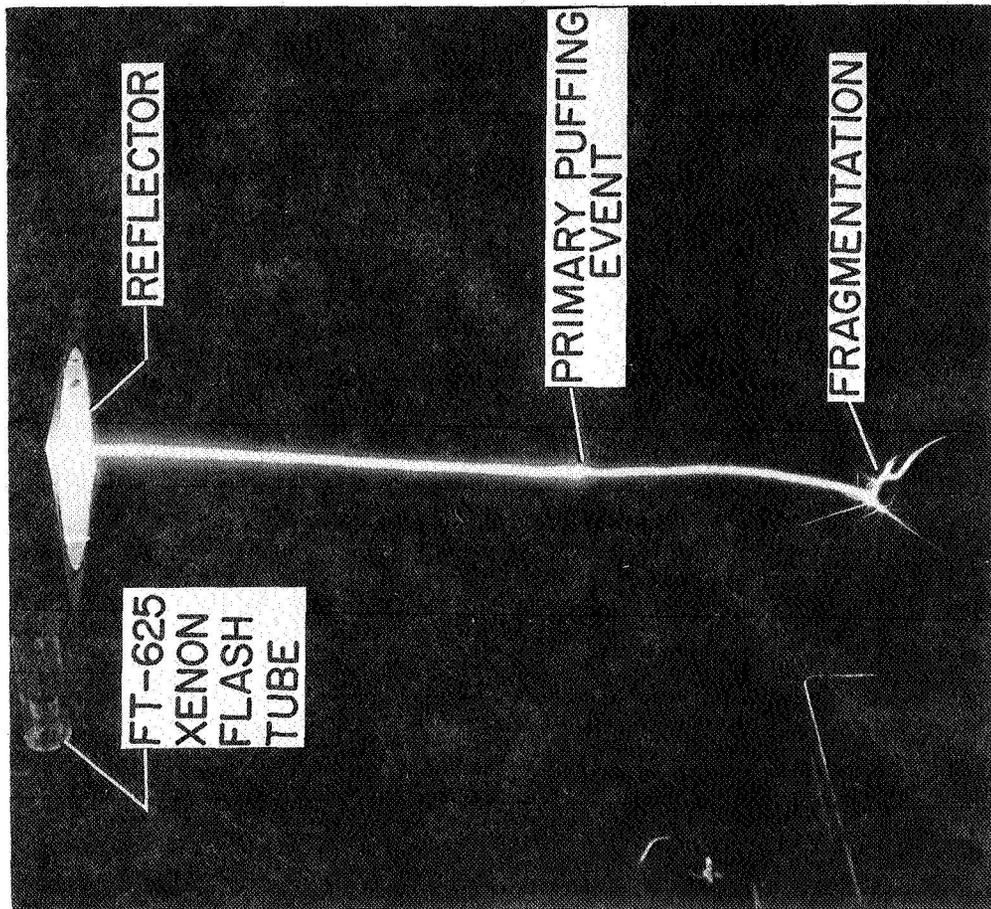


Figure 1.- Still-plate photograph of a burning aluminum droplet.

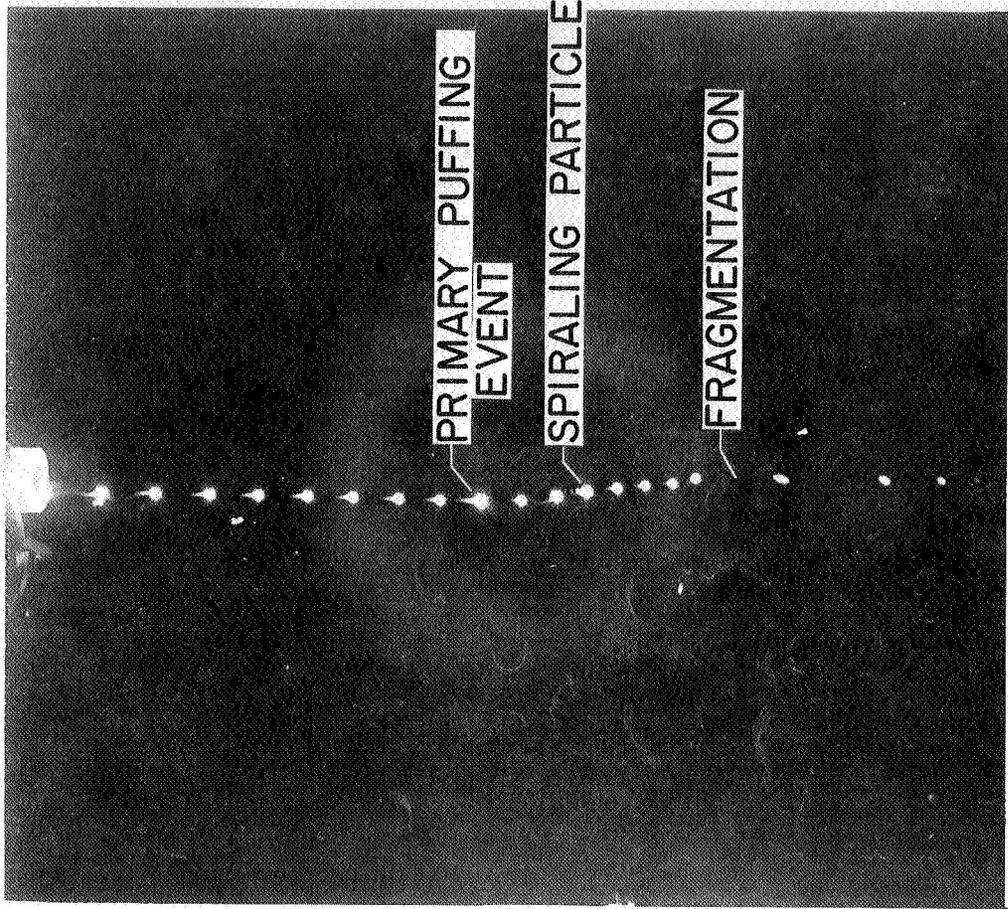


Figure 2.- Chopped still-plate photograph of a 350 $\mu$  burning aluminum droplet.

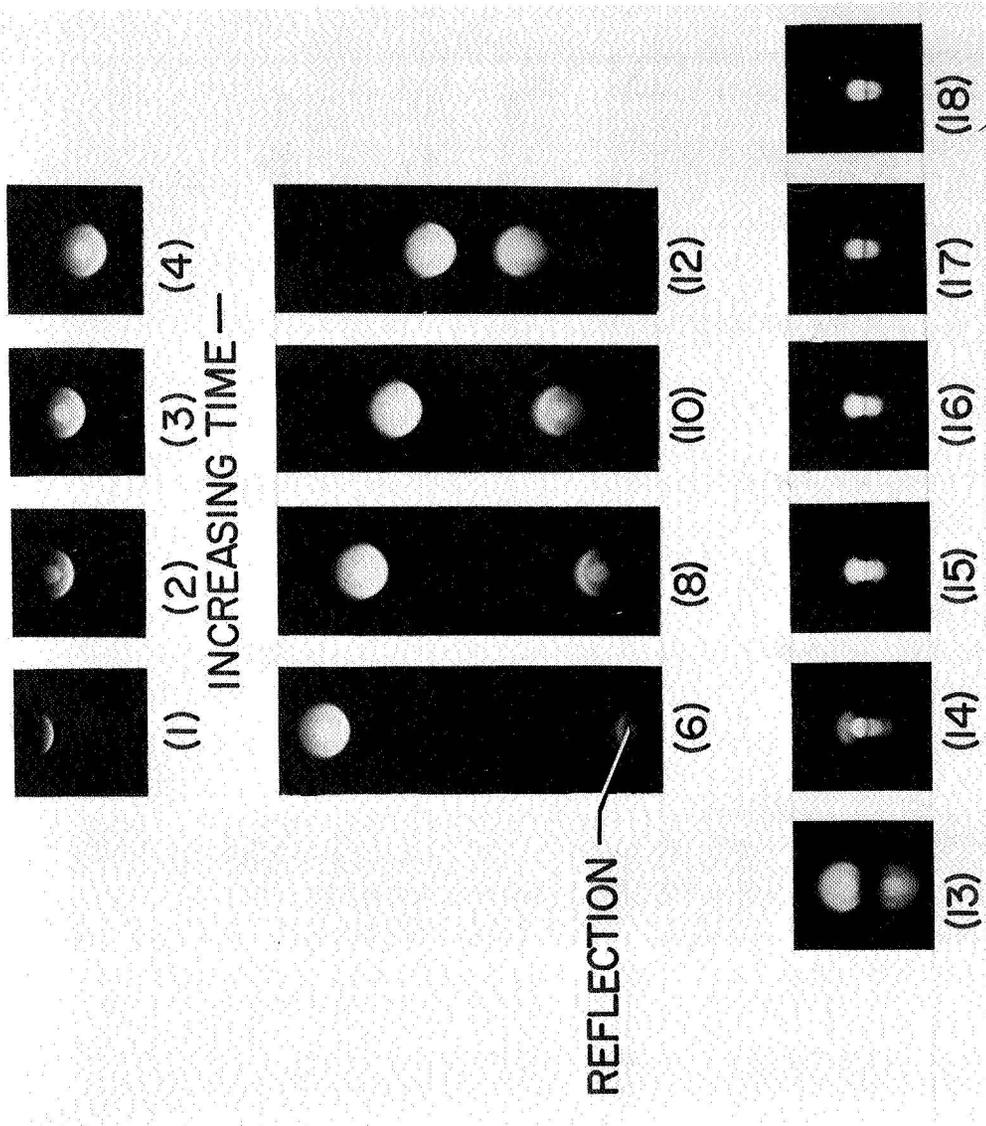


Figure 3.- Burning aluminum droplet impinging on glass slide fastax framing rate 3600 fps, ( ) indicates frame number.

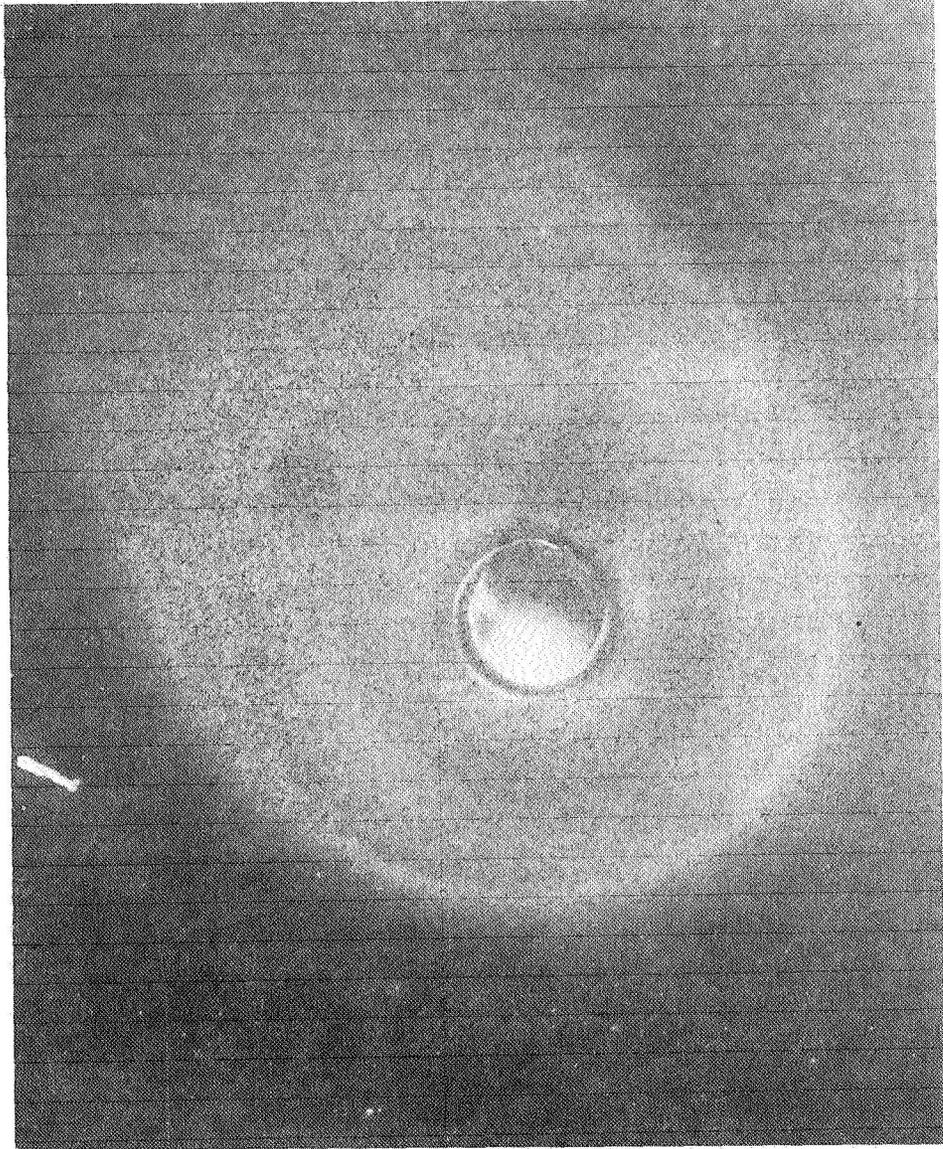


Figure 4.- Quenched aluminum particle (top view).

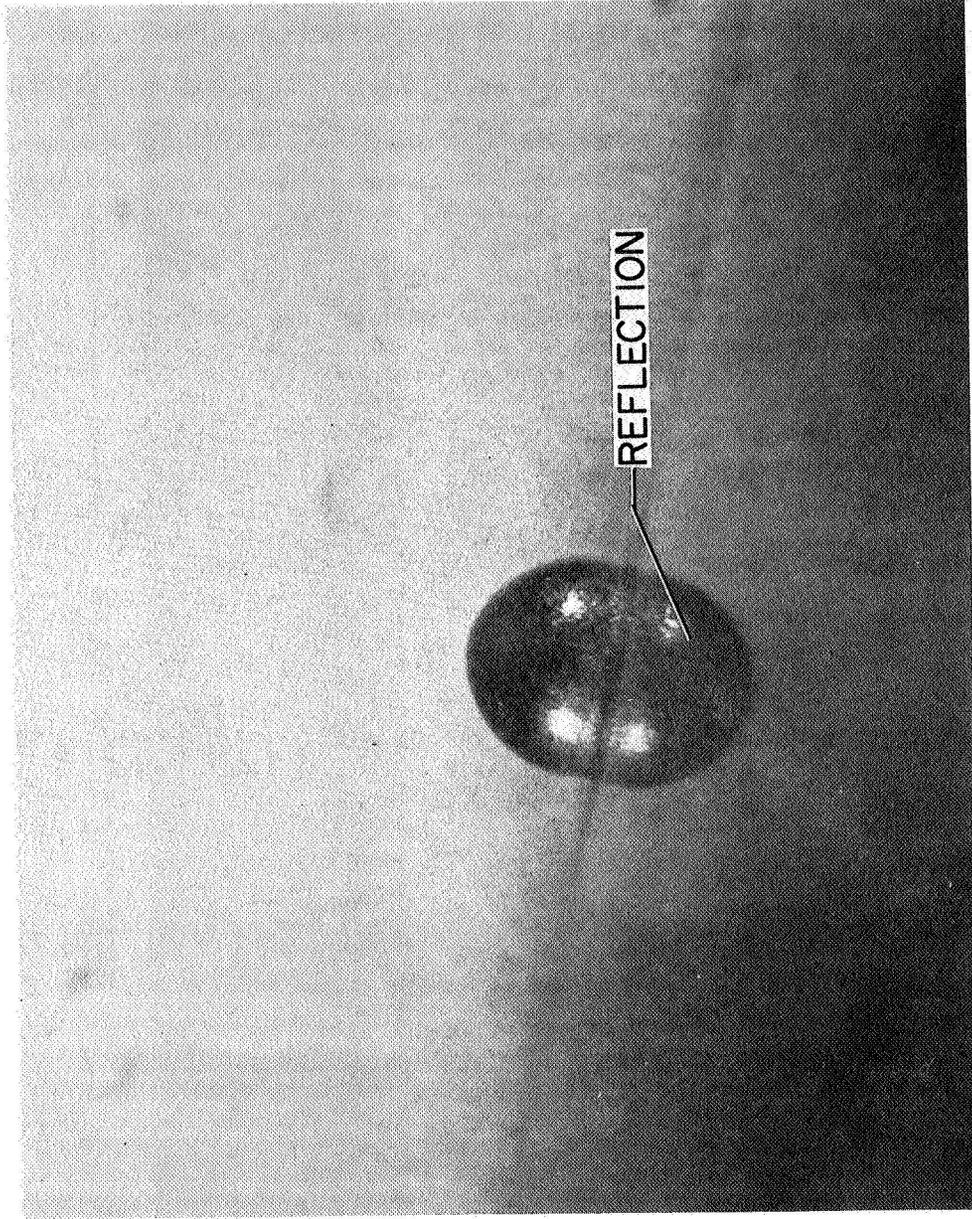


Figure 5.- Quenched aluminum particle (side view).

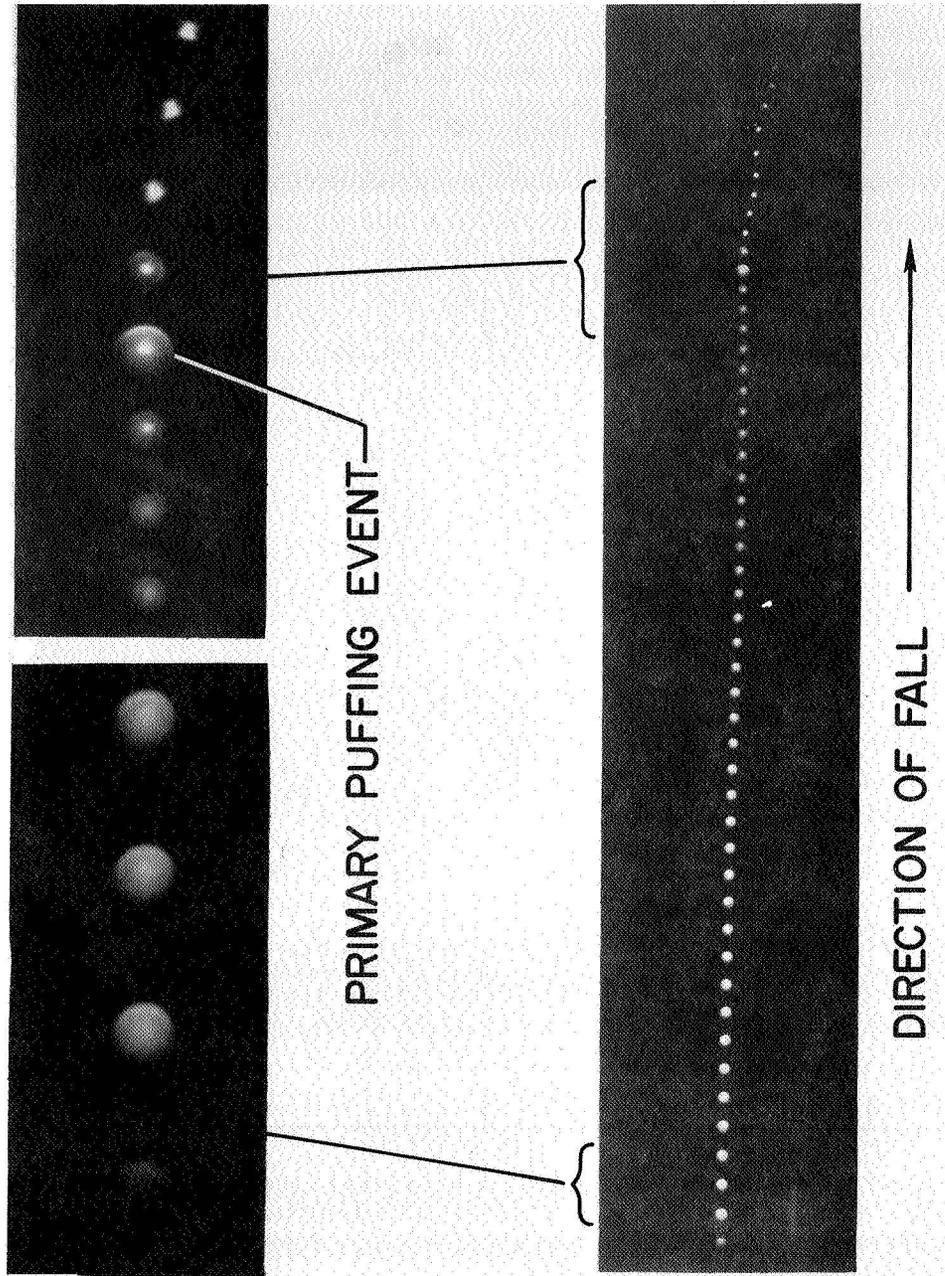


Figure 6.- Time resolved history of a burning aluminum droplet and associated flame zone.

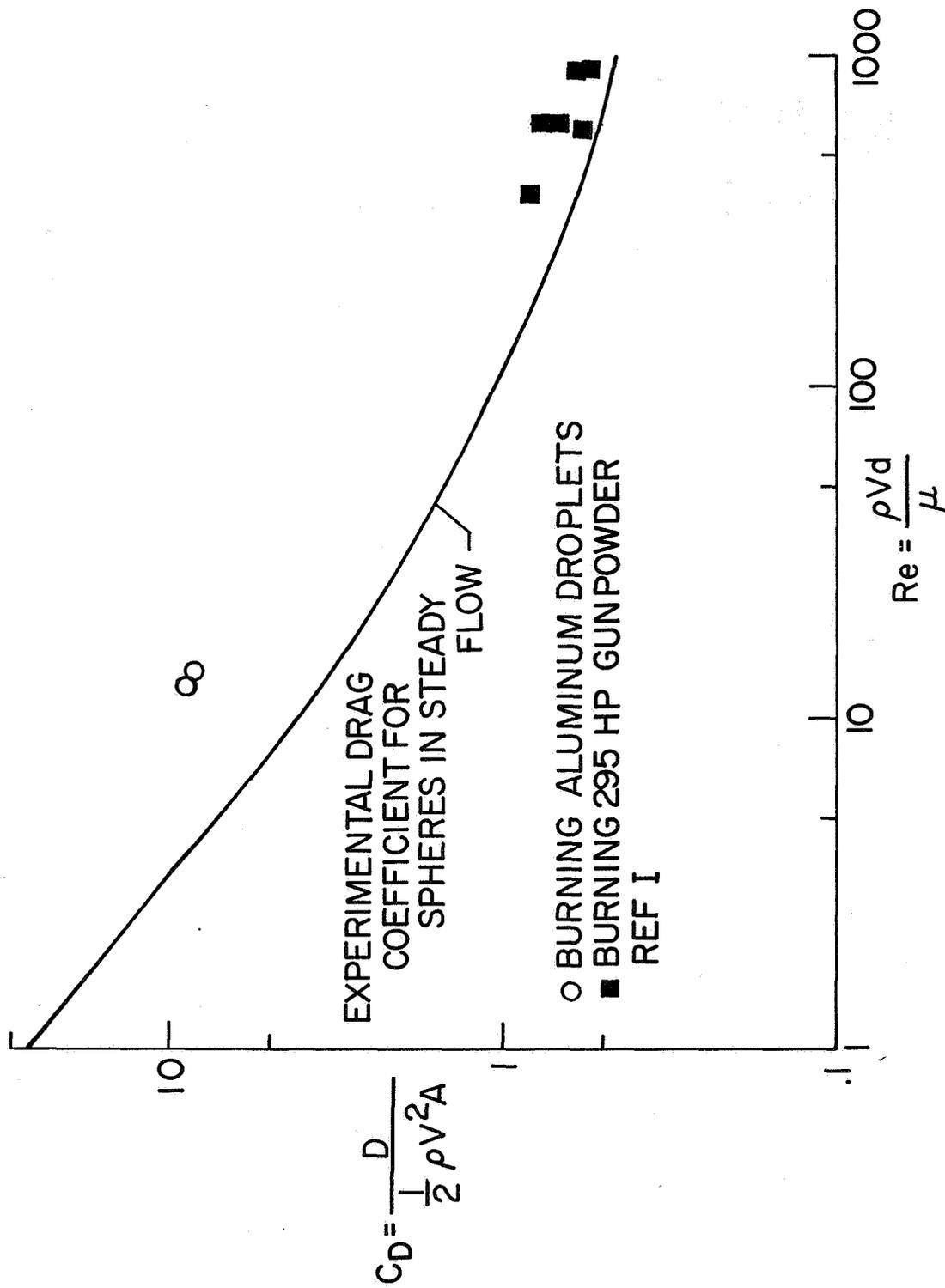


Figure 7.- Drag coefficient versus Reynolds number for burning particles.