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HYPERVELOCITY IMPACT JET FORMATION

James A. ANG

Sandia National Laboratories, Experimental Impact Physics 1543, Albuquerque, New Mexico 87185-5800*

The hypervelocity impact of a particle on a surface generates a jet of shocked material which is thrown from the impact site. A simple analytic model has been developed to obtain expressions for the evolution of this jet of ejecta. The analysis is based on applying the conservation equations of mass and momentum to the problem of a normal impact of a sphere against a semi-infinite flat target. Expressions are developed for the evolution of the jet velocity, jet release point and the locus of points which describe the ejecta envelop. These analytical ejecta profiles are compared with high speed photographs of impact jet formation.

1. INTRODUCTION

It is well known that hypervelocity impacts can give rise to jetting phenomena. The oblique impact of flat surfaces is a simple geometry which has yielded analytical conditions for jet formation[1] and simple test configurations for high speed photography[2]. While this geometry is useful for the analysis and testing of linear shaped charges, there is an important class of problems which may be approximated by the impact of a sphere into a flat plate. The study of the jetting and ejection of material from such hypervelocity impacts has been used to explain meteorite genesis from Lunar and Martian surfaces[3,4], to develop plasma generation-based micrometeoroid detectors[5] and to investigate impact flash formation[6].

While the impact of a spherical particle into a flat target gives rise to a continuously varying impact angle, it is characterized by simple trigonometric relations and thus is only slightly more complicated than the constant impact angle from the oblique impact of flat surfaces. In a recent study by the author, a simple analytical model for the jet initiation and release point was developed for the spherical particle into flat plate impact configuration[6]. In an extension of that earlier study, a simple analytic model has been developed to obtain expressions for the evolution of the jet of ejecta.

2. ANALYSIS: JET EVOLUTION MODEL

The Jet Evolution Model (JEM) is based on applying the conservation equations of mass and momentum to the normal impact of a spherical particle against a semi-infinite flat plate target as shown in Figure 1. Modeling results include; the determination of explicit expressions for the speed, direction, and release point of the ejected jet. These expressions are used in a simple kinematic analysis to determine the locus of points which describe the jet profile evolution and provide a basis for comparison to high speed photographs of the impact generated jets.

The particle is assumed to be the same material as the target and this material is assumed to be incompressible and inviscid. A further assumption is that the

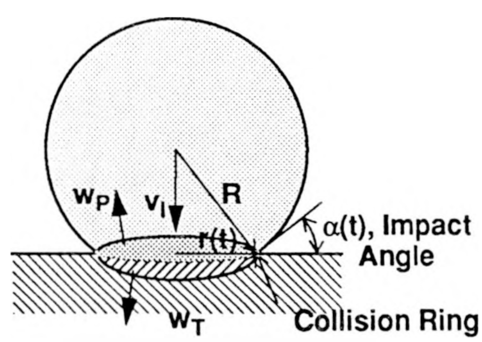

Figure 1. Schematic of the impact area for the normal impact of a particle of radius, R onto a flat target. The impact velocity is v_I, shock velocity in the target and particle, w_T and w_P, respectively.

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particle and target surfaces do not experience deformation. With these assumptions, the instantaneous collision ring radius and impact angle are given by:

$$r(t) = R\sin(\alpha(t)), \tag{1}$$

$$\alpha(t) = \cos^{-1}\left(1 - \frac{v_I t}{R}\right), \tag{2}$$

where R is the particle radius and v_I is the impact velocity.

It is useful to introduce a reference frame fixed at the stagnation point to describe the evolution of the impact-generated jet, as illustrated in Figure 2. The impact is assumed to have proceeded to the point where a quasi-steady jet is released. Continuity is applied to the differential region of volume at the collision ring. The instantaneous flux of material into the ring is given by,

$$\Phi_{in}(t) = \rho_P \frac{v_I}{2}\pi r^2(t) + \rho_T \frac{v_I}{2}\pi r^2(t), \tag{3}$$

where v_I is the impact velocity and $\rho_P = \rho_T = \rho$. Assuming this flux is balanced by a flux of ejecta,

$$\Phi_{out}(t) = 2\pi\rho v_j(t)\, r(t)\, w(t), \tag{4}$$

where $v_j(t)$ is the jet velocity and $w(t)$ is the jet width, the following condition is derived:

$$v_I r(t) = 2 v_j(t)\, w(t) \tag{5}$$

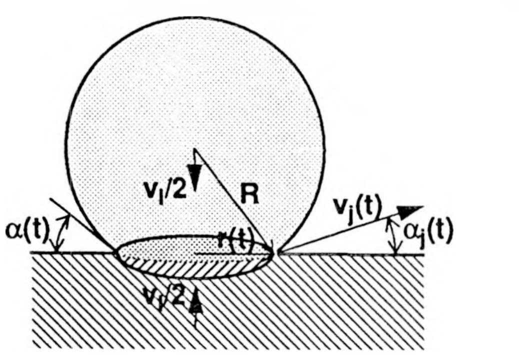

Figure 2. Schematic of the impact area in the jet formation reference frame. This is the reference frame where it is assumed that the jet release angle, $\alpha_j(t) = 1/2\alpha(t)$. $v_j(t)$ is the jet release velocity in this reference frame.

The jet release point is fixed to the expanding collision ring. Therefore, the jet origin is equal to the collision ring radius, $r(t)$, which moves out over the face of the target as the impact proceeds. In this reference frame, the jet release angle is assumed to be equal to half the impact angle

$$\alpha_j(t) = \frac{1}{2}\alpha(t) \tag{6}$$

To determine the jet release velocity, a momentum balance is performed in the particle reference frame illustrated in Figure 3. In this reference frame, the following momentum balance is made along the impact axis. Momentum carried into the ring from the target media is given by,

$$M_{in}(t) = \rho\pi v_I^2 \int_{t_r}^{t} r^2(t)\, dt, \tag{7}$$

where t_r is the jet release time. This is balanced by the momentum out of the ring due to the jet,

$$M_{out}(t) = m_j(t)\left[v_j(t)\sin(\alpha_j(t)) + \frac{v_I}{2}\right] \tag{8}$$

where,

$$m_j(t) = \rho\pi v_I \int_{t_r}^{t} r^2(t)\, dt \tag{9}$$

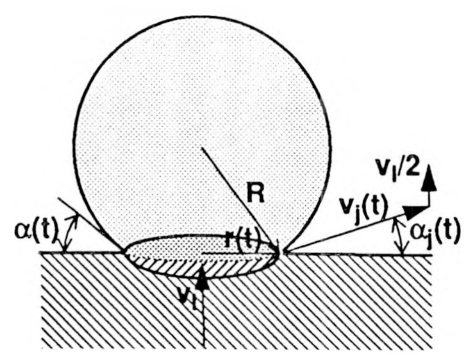

Figure 3. Schematic of the impact area in the particle reference frame. In this reference frame, the jet release velocity is the vector sum of $v_j(t)$ and $v_I/2$.

is the mass of the jet. Combining Eqns. (7)-(9) yields:

$$v_j(t) = \frac{v_I}{2\sin(\alpha_j(t))} \quad (10)$$

recalling Eqn. (5) again, the following expression for the jet thickness is found:

$$w(t) = r(t)\sin(\alpha_j(t)) \quad (11)$$

The set of relations given by Eqns. (1), (6), (10) and (11) define the release point, direction, speed and thickness of the impact-generated jet as a function of time.

The evolution of the jet is governed by the following dimensionless time scale,

$$T = \frac{tv_I}{R} \quad (12)$$

In general, the impact interval time covered by the relations developed in this analysis are for T between 0 and 1. Substituting the dimensionless time, T into Eqns. (1), (6),(10) and (11), plots may be generated which illustrate the evolution of the jet. Figures 4a-d show the evolution of the jet release point, jet release angle, jet velocity and jet thickness versus T. It should be noted again, that the jet initiation condition will determine the true jet release time, so the singularity in jet velocity at T=0 is not an issue.

3. JET PROFILES

The expressions for the jet release point, angle and velocity may be combined to determine the locus of points which define the jet profile for any point in dimensionless time T^* such that $T_r<T_j<T^*<1$. Where, T_r is the initial dimensionless jet release time, T_j is any later jet release time and T^* is a later point in time at which the jet profile is determined. Furthermore, it is possible to determine the profile for the segment of the jet which is released between T_r and $T = 1$, for any point in time $T > 1$.

A shift in the jet velocity by $v_I/2$ is made in the following relations to plot the jet trajectory in the laboratory frame. The envelop of ejecta is given by the following parametric relations,

$$\frac{x}{R}(T_j, T) = \frac{T - T_j}{2\tan(\alpha_j(t))} + 1 \quad (13)$$

$$\frac{y}{R}(T_j, T) = T - T_j \quad (14)$$

The profiles generated with these relations are shown in Figure 5 for the 2 km/s impact of a 6.35 mm steel sphere into a steel target. These profiles include the specification of a jet release time T_r, from the Jet Initiation Model presented in Ref. 6.

High speed photographs of hypervelocity impact jet formation were obtained and the Sandia National Laboratories Terminal Ballistics Facility. This small two-stage light gas gun is used to launch a variety of saboted projectiles at 2-8 km/s. Figure 6 illustrates the jet evolution for a 6.35 mm steel sphere into steel impact at 2 km/s.

4. DISCUSSION

The analysis presented in this paper is based on a number of assumptions. However, the key conclusion is that the simple geometry of a sphere impacting a flat plate may be analyzed with these rather crude assumptions. The jet profile which is generated in a hypervelocity impact is governed by some rather simple relations which follow from the kinematics of the problem.

The late time jetting for the continued penetration beyond T=1 is not covered in the present analysis. There is continued jetting and displacement of matter from the impact site beyond this point in time. The assumption of similar materials was necessary to specify a simple stagnation point reference frame.

Within some limits, it may be possible to extend this simple analysis to consider the impact of dissimilar materials.

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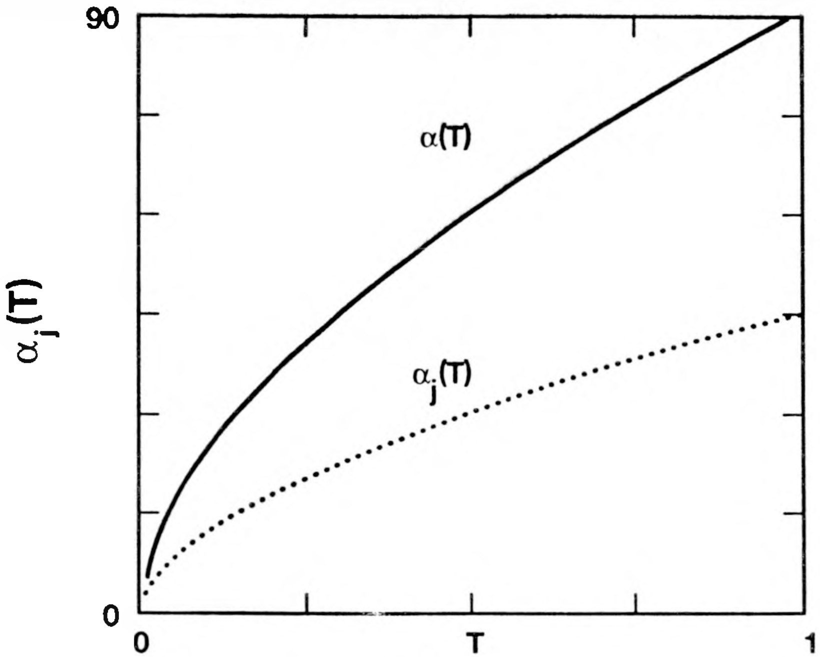

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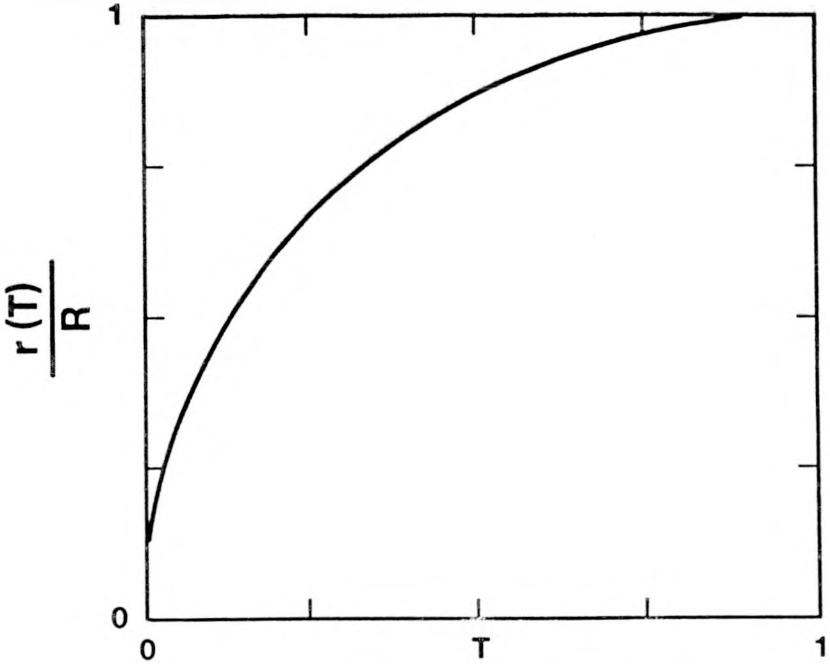

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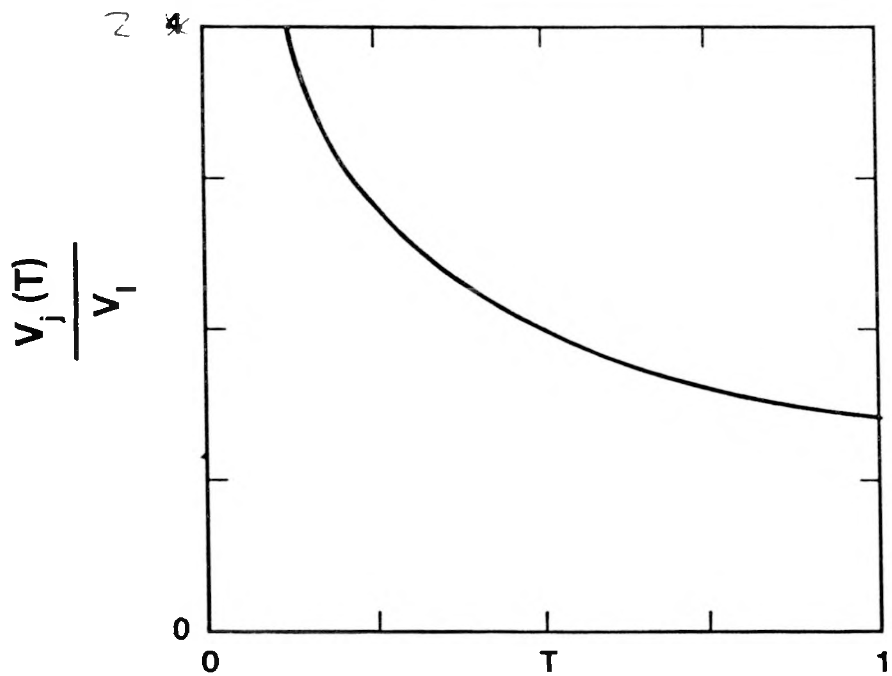

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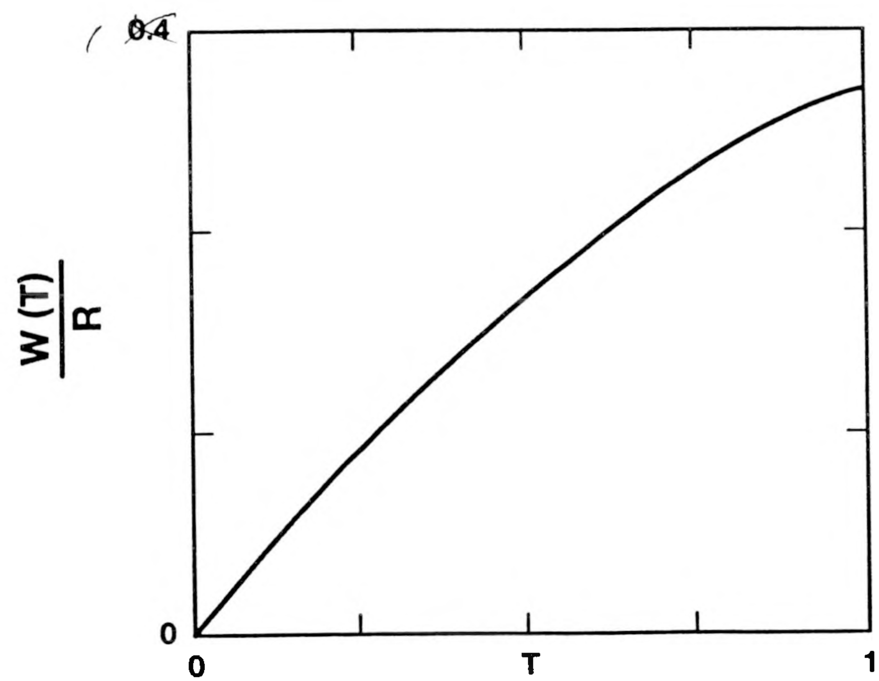

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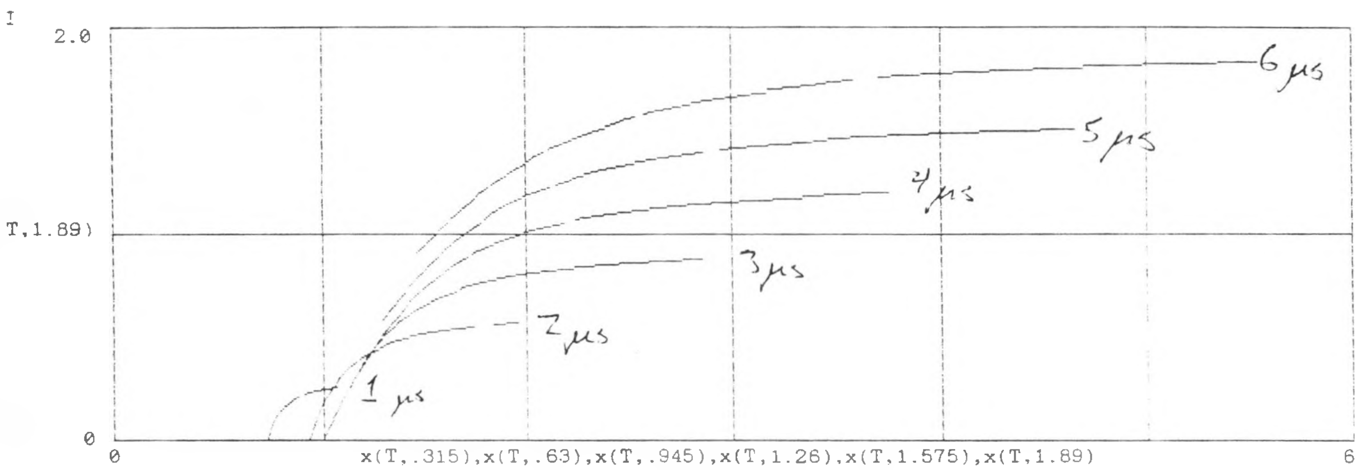
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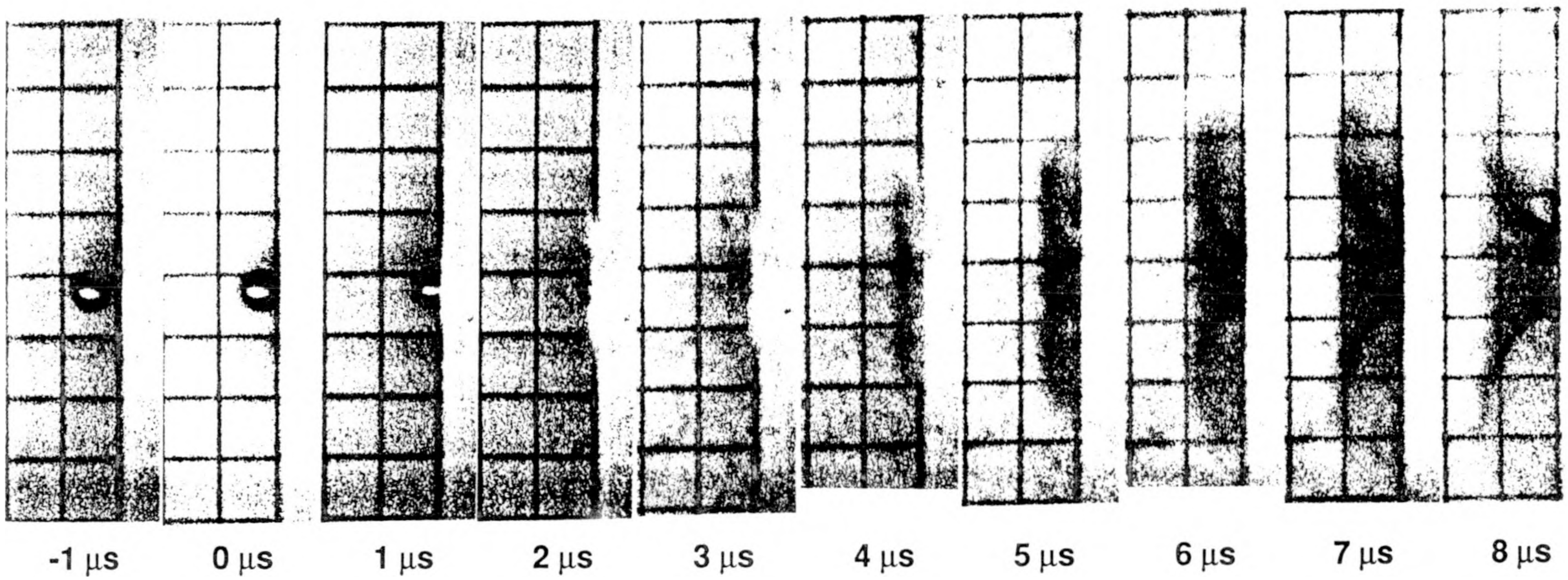
Fig 5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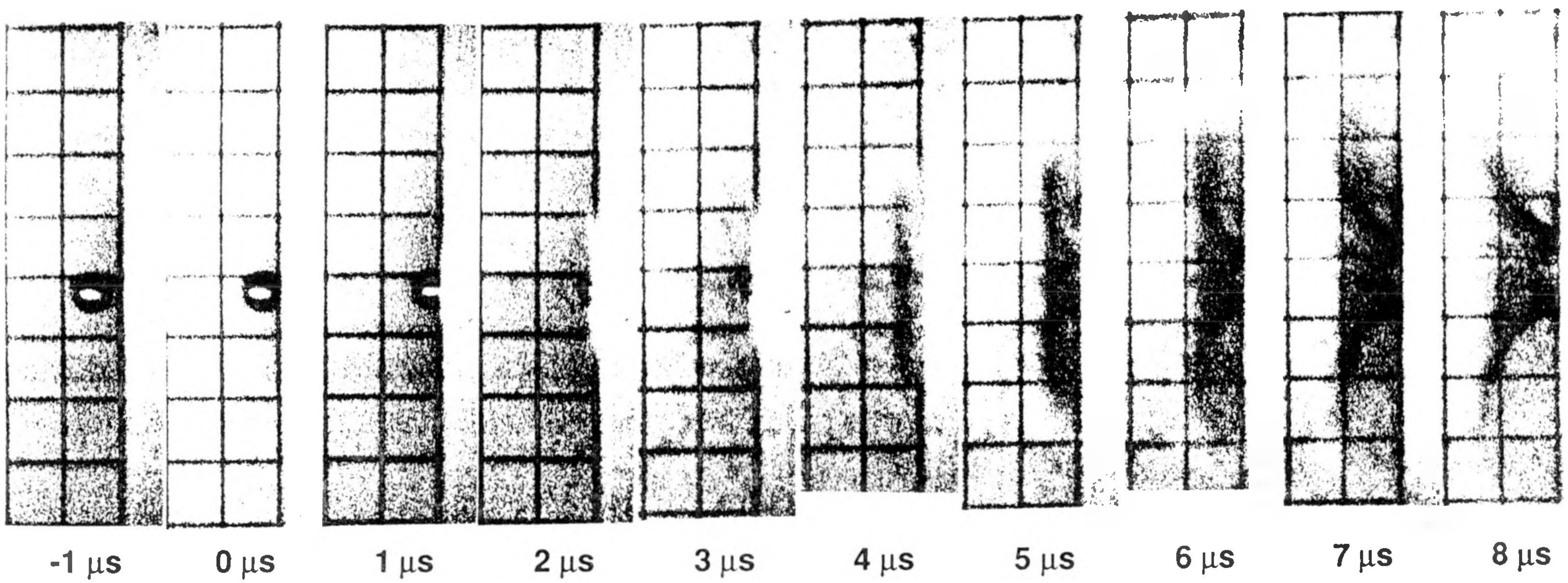
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