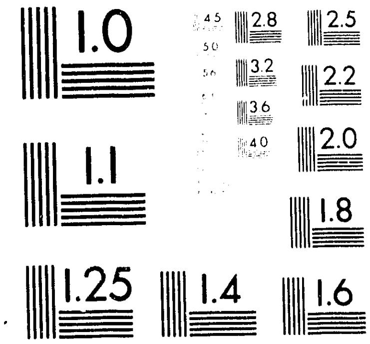
1.0
4.5
5.0
5.6
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

1 of 1

DEBRIS CLOUD CHARACTERIZATION AT IMPACT VELOCITIES OF 5 TO 11 KM/S

L. C. Chhabildas, M. B. Boslough, W. D. Reinhart and C. A. Hall
Experimental Impact Physics Department 1433
Sandia National Laboratories
Albuquerque, New Mexico, USA 87185-5800

A series of experiments has been performed on the Sandia Hypervelocity Launcher to impact a 1.25-mm thick aluminum bumper by an aluminum flier plate 17-mm diameter by 0.92-mm thick over the velocity range of 5 km/s to 11 km/s. Radiographic techniques were employed to record the debris cloud generated upon impact. The shape of the debris cloud is found to depend on the flier plate tilt. Generally—the data indicate a central core of higher density surrounded by a diffused layer. These experiments allow measurements of debris cloud expansion velocities as the material undergoes a phase change from solid fragments at impact velocities of 5 km/s to a mixture of liquid and vapor phase at higher impact velocities. The expansion velocity of the debris cloud increases with increasing impact velocity, with the high-density leading edge travelling faster than the impact velocity. There is a difference between the X-ray and photographic measurements of expansion velocities at higher impact velocities. This is believed to be due to the presence of very low-density vapor in the photographic records that are not detected using X-ray techniques.

INTRODUCTION

There is considerable interest in characterizing debris clouds that are generated upon impact of a projectile on a target plate. When the target is thin compared to the size of the projectile the geometry approximates the Whipple bumper shield configuration. If the target is thick then it can represent an armor configuration. The debris cloud that is generated upon impact depends on several factors, including the velocity, size and shape of the projectile [1, 2], and the relative thickness of the target to the projectile dimensions. In this paper, the results of a systematic study conducted to characterize debris clouds generated upon impact of a thin aluminum plate on a thin aluminum bumper shield are summarized. The experiments were performed over an impact velocity range of 5 km/s to 11 km/s. Aluminum was chosen in this study, since it is representative of aerospace materials. The experiments allow measurements of debris cloud properties as the material undergoes a phase change from solid/liquid fragments at impact velocities of 5 km/s to a mixture of liquid and vapor phase at higher impact velocities.

EXPERIMENTAL TECHNIQUE

Sandia's newly developed HyperVelocity Launcher, HVL, [3] was used to conduct these experiments. The HVL is based on the principle that structured, time-dependent (shockless), megabar driving pressures are needed to launch a flier plate without inducing melt or fracture in the flier plate. This is accomplished by using a graded-density material to impact a stationary flier plate at high velocities on a two-stage light-gas gun. Two-stage light-gas gun impact velocities over the range of 3 to 6.9 km/s will launch a nominally 1-mm thick aluminum flier plate to velocities over the range of 5 to 11 km/s [3]. The mass of the flier plate is controlled by the diameter of the impacting plate. The velocity of the flier plate is measured using radiographic techniques. Due to two-dimensional effects and the large deformation that the flier-plate undergoes upon acceleration, the flier plate is generally bowed after long flight distances.

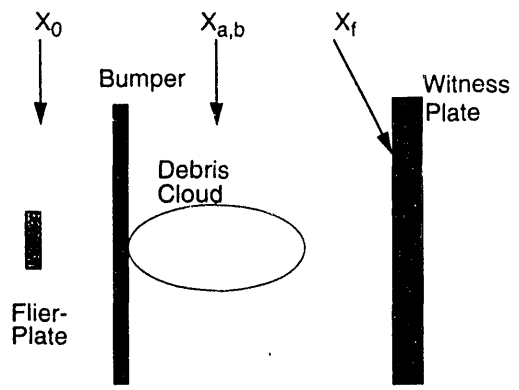

Figure 1. Experimental Impact Configuration

The experimental configuration used to generate debris clouds upon impact is indicated in Figure 1. Aluminum flier plates 17-mm diameter by 0.92-mm thick impacted 1.27 mm thick aluminum bumper plates. Aluminum witness plates 3.18 mm thick were positioned 203 mm behind the bumper plate. The debris cloud is viewed between the bumper shield and the witness plate using flash X-ray radiographic techniques. The back surface of the witness

Table 1. Summary of Debris Cloud Experiments

Shot No	Impact Velocity (km/s)	Time after bumper impact (μs)	Debris Length f (mm)	Debris Diameter d (mm)	Aspect Ratio f/d	Front Velocity f/t (km/s)	Lateral Velocity d/t (km/s)	Bumper hole h_b (mm)	Plate hole h_p mm x mm
hal5	4.99	8.63	43.2	34.2	1.26	5.09	2.0	27.2	45 x 58
hal4	7.43	7.44	55.8	40.3	1.38	7.5	3.2	26.8	26 x 31
hal2	9.56	6.27	62.9	42.1	1.49	10.2	4.0	26.2	-
hal6	11.1	5.1	57.9	42.2	1.37	11.4	5.3	42.7	11 x 15

Figure 2. Radiographs of the debris cloud formed upon impact of an aluminum flier plate (F) with an aluminum bumper plate at (a) 5 km/s, (b) 7.43 km/s, (c) 9.56 km/s, and (d) 11.1 km/s.

plate was also radiographed at an angle to determine the effect of subsequent loading by the impact-generated debris cloud. The X-ray measurements of the debris cloud are indicated in Figure 2. Only those X-rays that are not absorbed by the debris cloud *i.e.*, the relatively higher density material within the cloud is being imaged. A sensitivity analysis on the minimum areal density of the debris cloud that can be imaged using current radiographic capabilities has not been performed for these studies.

RESULTS

Results of experiments performed to characterize the debris cloud are summarized in Table 1. The impact velocity of the flier plate is determined very accurately using multiple radiographic measurements over distances of 350 mm. The X-ray of the flier plate shown in Figure 2 is taken ~ 250 mm prior to impact. The flier plate appears to be severely deformed for experiment hal6 prior to impact. This is because the temperature of the flier plate material is very close to the melt boundary. The debris cloud dimensions indicated in Table 1 are those measured from the radiographs that are shown in Figure 2. Both the debris front location (its length) and the maximum debris diameter is given in the table. The ratio of the debris front length dimension to its diameter, defined as the aspect ratio, should be a very accurate estimate. The variation of aspect ratio with impact velocity is shown in Figure 3.

The impact time on the bumper is defined to be zero in this study. The debris exposure time, which is the time after impact in the table when the X-ray is taken, is accurate to within an uncertainty of three hundred nanoseconds, due to the uncertainty in estimating the impact time on the bumper. This will introduce ~ 6% uncertainty in estimating the debris front and lateral velocities indicated in Table 1. The variation of both the debris front velocity and the lateral velocity with impact velocity is indicated in Figure 4. The debris front velocity for experiment hal5 is very accurate because multiple X-rays (not shown) over long distances were used to estimate the velocity. The lateral velocity of the debris cloud is calculated assuming that the debris expands linearly from its pre-impact diameter of 17 mm to the diameter measured at the exposure time. Multiple X-ray exposures are needed to verify this assumption.

The hole size in the bumper plate is determined by averaging the "width" of the debris cloud from both front

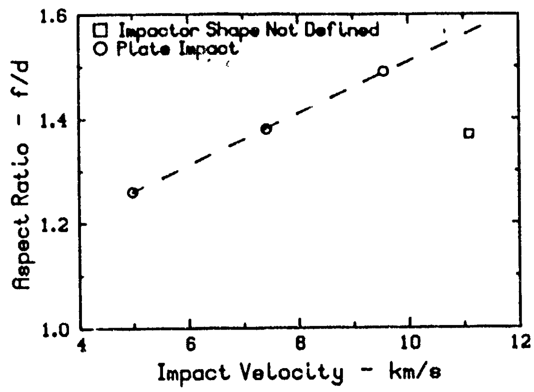

Figure 3. The ratio of the leading edge of the debris front to its diameter f/d *versus* impact velocity.

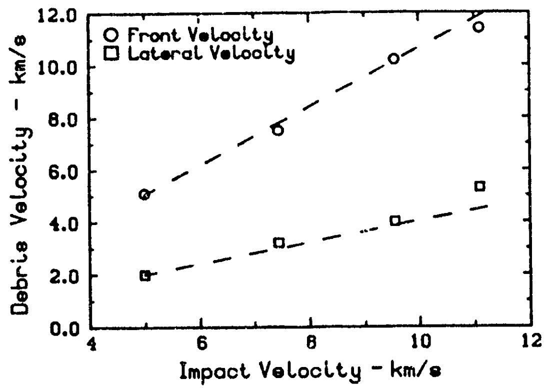

Figure 4. Debris front and lateral velocity variation with impact velocity.

and back surface ejection at the bumper plate. Since an orthogonal view is absent, it is assumed for current discussions that the hole in the bumper plate is symmetrical and circular. This assumption is especially reasonable for normal impact by a plate into thin bumper plates.

The hole size in the witness plate is determined experimentally using an oblique X-ray source. Pre-calibration of the experimental set up is necessary to estimate the hole size. The witness plate radiograph is generally taken approximately 50 µs after impact interaction of the debris cloud with the witness plate. It is taken sufficiently early to eliminate interactions from the arrival of the slower moving two-stage light-gas gun projectile debris. Although the measurement of a rupture in the witness plate was not successful in experiment hal2, previous experiments [5] conducted at similar impact conditions have indicated a backwall rupture.

DISCUSSIONS

Thermodynamic States

Assuming a flat-plate impact, the peak stress states in the aluminum flier and the bumper will be ~ 58 GPa, 102 GPa, 150 GPa, and 190 GPa at impact velocities of 4.99, 7.43, 9.56, and 11.1 km/s, respectively. Accordingly, the corresponding release temperatures of aluminum [4] shocked to 60 GPa will be very close to the melt temperature of 930 K, while the release temperature of aluminum that has been shocked to 190 GPa will be over 3000 K, which is well above its boiling temperature of 2700 K. Therefore, the aluminum debris will be in the solid/liquid phase at an impact velocity of 5 km/s, liquid phase at 7.43 km/s, and liquid phase with increased quantity of vapor fraction at the higher impact velocities of 9.56 and 11.1 km/s, respectively.

Debris Cloud Shape

The flier plate mass used in this study is ~ 0.53 g, and its undeformed *aspect ratio i.e.*, thickness-to-diameter ratio is ~ 0.05. After impact, the free-surface stress relief dominates. The diameter of a sphere representing an equivalent mass of the flier plate would be 7.2 mm. The wave interaction time for a plate impact will be one-eighth the time compared to a spherical impact. Therefore, one-dimensional effects control the impact interaction. This is indicated by the shape of the debris cloud observed in the radiographs. The leading edge of the debris cloud in all instances has the highest density mass. The shape of the debris cloud generated upon impact is found to depend on the flier plate tilt. The data indicate a central core of higher density surrounded by a diffused layer. The variation of the aspect ratio with impact velocity is shown in Figure 3. The ratio of the debris front dimension to its diameter, defined as the aspect ratio, is an accurate estimate. If the debris propagation effects are influenced strictly by one-dimensional processes then this ratio is expected to increase with time. For spherical propagation this ratio is expected to be close to unity. Note in experiment hal6, where the flier plate impactor is not well defined, the aspect ratio is lower than the expected result.

Solid fragments are observed in Figure 2a for the impact experiment at 5 km/s. It is surprising to observe a disc shaped leading edge for the two experiments at 7.44 km/s and 9.56 km/s, considering that the bumper material is expected to be completely molten. Any low density vapor preceding the debris cloud is not observable on the radiographs. Since the flier plate is significantly deformed in experiment hal6 (Figure 2d), its shape prior to impact is not well defined. Consequently, the debris cloud in figure 2d is not similar to those indicated in Figures 2a, 2b, and 2c. It can be shown that low density debris of approxiamtely 0.008 g/cm^3 would fill uniformly into a cylinder having an aspect ratio of 1.42. In all instances, low energy X-ray sources would be more accurate and precise in defining the true "shape" of the debris cloud.

Debris Velocities

The debris front and lateral velocities of the experiments (shown in Figure 2) are indicated in Figure 4. As indicated in the figure, the high density leading edge of the debris front is travelling faster than the impact velocity. Previous impact experiments at 10 km/s diagnosed using fast framing photographic techniques [5] have indicated a vapor front (preceding the debris cloud) travelling at velocities of 14 km/s. It is, therefore, crucial that both X-rays and photography be used if possible to obtain a detailed description of the debris cloud. An alternate approach is to develop low energy X-rays to allow the imaging of the entire debris cloud. The lateral velocity of the debris cloud resulting from plate impact also increases with impact velocity; when expressed as a fraction of the impact velocity the lateral velocity appears to be relatively constant and ~ 40% of the impact velocity. Note the radial expansion velocity will be ~ 20% of the impact velocity. In experiment hal6 the impactor is not well defined; the debris front velocity appears to be lower than anticipated, while the lateral velocity appears to be higher than the expected measurement.

SUMMARY

A series of experiments has been performed to characterize the debris generated from plate impacts over the velocity range of 5 km/s to 11 km/s. Radiographic techniques were employed to record the debris clouds generated. The shape of the debris cloud is found to depend on the flier plate tilt, but the data also indicate a central core of higher density material surrounded by a diffused layer. These experiments allow measurements of debris cloud expansion velocities as the material undergoes a phase change from solid fragments at impact velocities of 5 km/s to a mixture of liquid and vapor phase at higher impact velocities. The expansion velocity of the debris cloud appears to increase with increasing impact velocity. At higher impact velocities there is a discrepancy between the present X-ray and previous photographic measurements [5] of expansion velocities. This is believed to be due to the presence of very low-density vapor in the photographic records that are detected using X-ray techniques.

Although not discussed above, the hole size in the bumper plate is estimated to be ~ 26.5 mm, and is independent of the impact velocity when the integrity of the flier plate is maintained. When compared to the original flier plate dimensions of 17 mm, this is an amplification by a factor of 1.5 to 1.6 in these studies.

The rupture damage to the witness plate is listed in Table 1. It should be noted that although there is presence of molten and vaporized aluminum in the debris cloud, the backwall is still ruptured—mainly because of the high-density leading edge and the presence of what appears to be a central high density core.

Studies in the past have concentrated on impacting spheres onto thin bumper plates at lower velocities than this study, because the capability to launch spheres is available. Spherical impact also provides well-controlled boundary conditions for numerical analysis of the experiments. Our experiments, primarily due to their plate geometry, will also serve to validate hydrodynamic codes in the impact regime where very few experiments are available.

ACKNOWLEDGMENTS

This work performed at Sandia National Laboratories supported by the U.S. Department of Energy under contract DE-AC04-76DP00789. We would also like to acknowledge Tom Tsai and John Connell, Defense Nuclear Agency, for their interest in this work.

. REFERENCES

[1] E. S. Hertel, L. C. Chhabildas, L. Yarrington, "Computational Determination of Ballistic Limits for a Simple Whipple Bumper Shield," in *Proceedings of the Workshop on Hypervelocity Impacts in Space-1991,* ed. by J. A. M. McDonnell, 1992, pp. 15-18.

[2] C. H. Konrad, L. C. Chhabildas, M. B. Boslough, A. J. Piekutowski, K. L. Poormon, S. A. Mullin, D. L. Littlefield, "Dependence of Debris Cloud Formation on Projectile Shape," this volume.

[3] L. C. Chhabildas, J. E. Dunn, W. D. Reinhart, J. M. Miller, *Intl. J. Impact Engng.*, V14, 1993.

[4] G. I. Kerley, *Intl. J. Impact Engng.*, V5, pp. 441-449, 1987.

[5] L. C. Chhabildas, E. S. Hertel, S. A. Hill, *Intl. J. Impact Engng.*, V14, 1993.

DISCLAIMER

DATE
FILMED
10/27/93

END