# EXPERIMENTAL TECHNIQUE TO SIMULATE ORBITAL-DEBRIS IMPACT ON SPACE SHIELDS AT IMPACT VELOCITIES OVER 10KM/S

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## ABSTRACT

With the development of a new HyperVelocity Launcher, HVL, at Sandia, it is now possible to perform experiments over the velocity range of 7 to 12 km/s. This velocity range has not been previously accessible for gram-size plates. This meets the requisite mass-velocity criteria established for the orbital debris environment. In this paper, the technique employed to launch thin flier plates to velocities not previously accessible on a two-stage light-gas gun is reported. In particular, this technique has been used on a two-stage light-gas gun to launch nominally 0.5 to 1.0-mm thick aluminum, titanium, and magnesium flier plates intact to velocities up to 12.2 km/s. Since the mass-velocity capability of the newly developed HVL meets the average specifications of the space debris environment, it is expected to be a useful tool to evaluate the effects of debris impact on space structures and debris shields. Examples of a plate impact *i.e.,* orbital debris impact on a thin Whipple shield are presented in this paper.

## 1. INTRODUCTION

In the early sixties, when space became accessible for manned missions, micrometeoroids were the principal impact threat to space voyagers. The micrometeoroid environment is composed of dust-type 100–μm size silicate particles, and the impact hazards associated with this natural debris was considered remote and accepted as a hazard associated with any space mission. Protection sheets now commonly referred to as Whipple bumper shields (Ref. 1) were designed for deployment with the early spacecraft and tested using electro-thermal gun facilities (Ref. 2). Specifically, these launcher capabilities were well matched with the micrometeoroid environment, *i.e.,* the ability to propel 50-μm to 75-μm size borosilicate particle at velocities of 15 to 18 km/s, and were used to evaluate the various Whipple bumper shield designs proposed for spacecraft (Ref. 3). It is now recognized that the current impact threat to space structures results not from naturally occurring meteoroids, but from man-made artificial space debris (Refs. 4,5). The space debris environment, also referred to as orbital debris (or space junk), is characterized as gram-size millimeter or centimeter diameter metallic plate-like "particles" with average impact (interaction) velocities of 8 to 15 km/s (Refs. 4,5). The impact threat to space mis-

sions resulting from orbital debris is no longer considered remote due to the abundance of the debris (~ 4 million pieces), its relatively large size, and also because its population is growing. There is a need, therefore, for a launcher which has the requisite mass-velocity capability to study impact problems that are related to current space applications, *i.e.,* over the currently inaccessible velocity range of 7 to 15 km/s. In this paper, a brief description of the recently developed HyperVelocity Launcher (HVL) (Refs. 6-9) at Sandia Laboratories is reported. The HVL can launch 1.0-mm-thick aluminum, titanium, and magnesium flier plates (gram-size) intact to velocities of 10.4 km/s, and 0.5-mm-thick aluminum and titanium plates intact to 12.2 km/s (Refs. 8,9). A few selected examples of plate impacts *i.e.,* simulated orbital debris impacts on a thin Whipple shield are also presented and discussed in this paper. Additional results of orbital debris impact simulations on single or multiple shields are published in the literature (Refs. 10-15).

## 2. TECHNIQUE TO LAUNCH FLIER PLATES

This section briefly describes the experimental techniques employed to augment the launch capabilities of Sandia's 28.6 mm bore two-stage light-gas gun. The experimental impact configuration is indicated in Figure 1. As indicated in the figure, a two-stage light-gas gun projectile, which has a graded-density impactor facing with a tantalum backing, is made to *impact* a thin flier plate located at the muzzle end of the barrel. The graded-density material is fabricated so that a smooth variation in its shock impedance occurs through its thickness. The shock impedance of the impacting surface of the graded-density impactor is that of a plastic, while the shock impedance of the back surface resembles tantalum. When this graded-density material is used to impact a titanium alloy flier plate at ~ 6.4 km/s, an initial shock of approximately 50 GPa, followed by a ramp wave to over 100 GPa, is introduced into the flier plate (Refs. 8,9). At higher impact velocities the input pressure profile would result in a higher peak pressure pulse resulting in launching flier plates to yet faster velocities. The final velocity of the flier plate is dependent on the impact velocity of the graded-density material with the stationary flier plate (Refs. 8,9). An intervening plastic buffer between the graded-density impactor and the flier plate is usually used to further tailor the time-dependent pressure pulse to minimize fracture of the flier plate.

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As shown in Figure 1, the flier plate used in these experiments consists of a center plate made to fit exactly into a concentric guard ring. 6061-T6 aluminum alloy, AZ31 magnesium alloy, and Ti-6Al-4V titanium alloys have been used as flier plate materials. The outside diameter of the guard ring used in these studies was 28.6 mm, while the inner diameter of the guard ring and the diameter of the center plate was ~ 19 mm. Two-dimensional effects due to radial release waves (generated upon impact) emanating from the edges of the plate will cause a velocity gradient across the radius of the plate. Large velocity gradients across the radius of the plate would cause the flier plate to bend and, therefore, fragment. The guard ring geometry indicated in Figure 1 allows a controlled separation of the center plate from its edges without causing the entire flier plate to fragment.
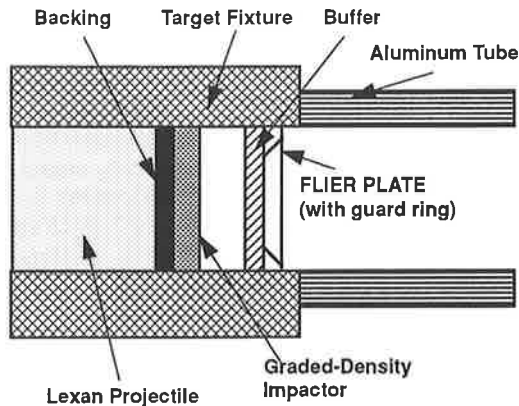


**Figure 1.** A graded-density impactor/flier-plate experiment

Following impact, flash X-rays are taken to determine the velocity of the flier plate and also to check for its integrity following impact and subsequent acceleration by the shockless pressure pulse. Four of these flash X-rays are taken while the flier plate is in the aluminum barrel extension, usually a few microseconds after impact. The other 3 X-rays are taken after
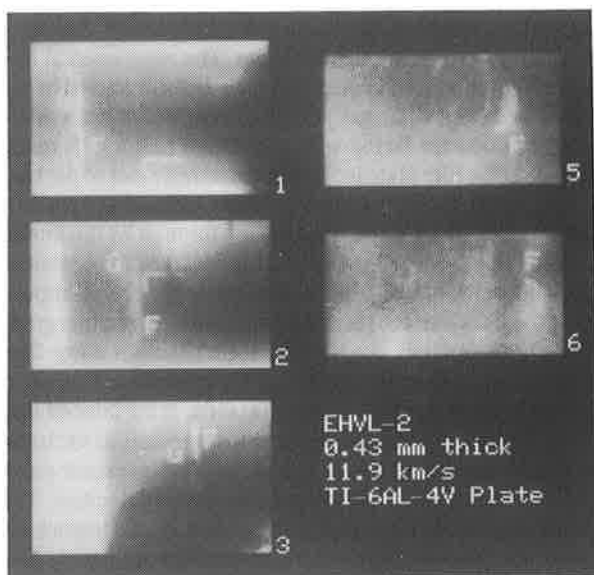


Figure 2. The titanium flier plate is moving from left to right at a velocity of 11.9 km/s. The sequence of radiographs shown on the left is taken over the first 60 mm; the radiographs on the right are taken after a travel distance of 90 mm and 160 mm.

the flier plate has exited from the muzzle and are located ~ 80 mm, 170 mm, and 350 mm from the impact position. Radiographs of the flier plate taken in flight over these large distances allow an accurate measurement of its velocity. The flier plate velocity is determined to within 1% (Ref.13). Figure 2 shows the results of a Ti-6Al-4V flier plate launched at 11.9 km/s. To achieve such high velocities the graded-density material impacted the buffered-flier-plate at ~ 7.4 km/s. A 1.25 mm thick TPX plastic buffer was used in this experiment, while the Ti-6Al-4V alloy plate thickness was 0.43mm. A similar experiment at an impact velocity of 7.4 km/s with a 0.42 mm thick aluminum flier plate propels it at a velocity of 12.2 km/s. Due to two-dimensional effects and the large deformation that the flier plate undergoes upon acceleration, the flier plate is generally bowed during long flight distances.

## 3. BUMPER SHIELD TESTS

In this section, the results of a few selected tests performed on a simple single Whipple sheet of aluminum are highlighted. Detailed analysis of Whipple single sheet tests and the results of impact tests on advanced shields such as multi-shock multi-layered Nextel ceramic sheets and mesh double bumper are published in References 10 to 15.

### 3.1. Experiment JSC9

Figure 3 shows the high speed photographic results of an aluminum plate 19-mm diameter and 1-mm thick impacting a 0.3 mm thick aluminum bumper at a velocity of 9.5 km/s. Notice the formation of an outer *'transparent'* looking debris cloud with an inner darker cloud. The transparent debris cloud front is travelling faster than the impact velocity *i.e.*, at a velocity of ~ 12 km/s, and is presumed to be low density vapor preceding the higher density liquid cloud. The symmetric features of the debris cloud suggests a relatively symmetric impact on the bumper by a bowed flier plate. Although not indicated in the figure, a 4-mm thick aluminum backwall located ~ 300 mm away from the bumper ruptures as a result of impulsive loading by the entire impact debris. The timing for the rupture of the backwall is consistent with the impact of the higher-density darker cloud.
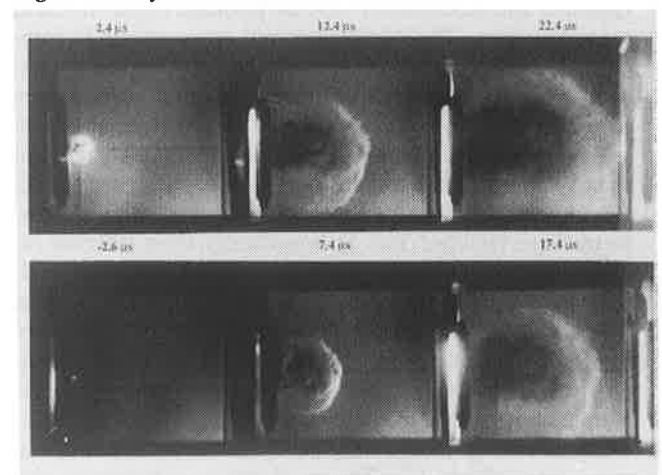


Figure 3. Fast framing photographic records of the debris cloud generated upon impact of a 1-mm thick 19-mm diameter aluminum plate on a 0.3-mm thick aluminum bumper. Debris is propagating from left to right. 1-cm grid marks are indicated in the figure. The time sequence for the pictures are -2.6, 2.4, 7.4, 12.4, 17.4, and 22.4 µs, from impact respectively.

## 3.2. Experiment WS12

As the thickness of the bumper sheet is increased to ~ 1.25 mm, the debris cloud appears to be no longer transparent in this example. Results of a similar experiment performed at an impact velocity of 10.2 km/s, are shown in Figure 4. The nearly spherical debris cloud front propagates at a velocity of ~ 14 km/s, while the radial expansion velocity is ~ 7 km/s. This, however, does not mean that the entire debris cloud is propagating at this velocity. The structure of the debris cloud at 7 μs after impact suggests an approximate dispersion of 50 mm suggesting a velocity distribution from a maximum front velocity of 14 km/s to ~ 7 km/s. The debris cloud is over 120 mm in diameter prior to impacting the backwall. The symmetric features of the debris cloud suggest a relatively symmetric impact on the bumper by the flier plate.
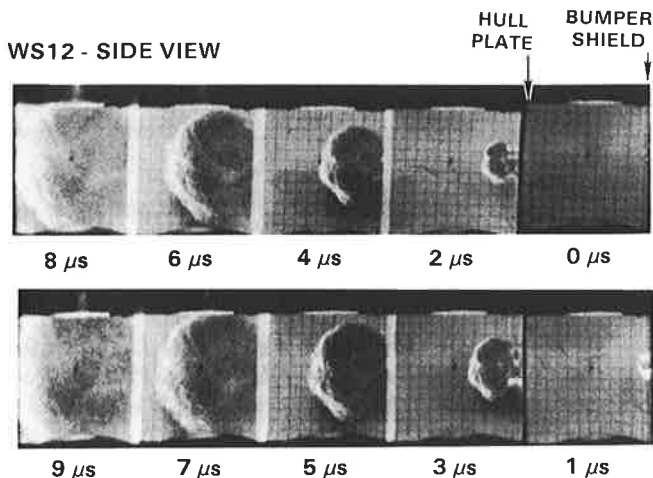
**WS12 - SIDE VIEW**



Figure 4. Fast framing photographic records of the debris cloud generated upon impact of a 1-mm thick 19-mm diameter aluminum plate on a 3.2-mm thick aluminum bumper. Debris is propagating from right to left in these sequence of pictures. 1-cm grid marks are indicated in the figure.

Figure 5 indicates the results of impulsive loading on a 3.2-mm thick aluminum backwall located ~ 112 mm away from the bumper. The first frame is taken at 8 μs (after impact at the bumper by the flier plate), the time at which the leading edge of the debris cloud arrives at the rear backwall. A deformation bulge is observed in the frame at ~ 13 μs, while the perforation is indicated by the frame at ~ 18 μs. The timing for the rupture of the backwall is consistent with the impact of a slower moving debris cloud traversing at ~ 8 km/s. Notice that rupture of the backwall occurs at the center of the backwall.

The above two experiments are examples of debris cloud propagation resulting from impact of a thin bumper shield by a thin flier plate simulating an orbital debris impact. Fast framing photographic records suggest a very nearly spherical evolution of the debris cloud propagation. In general, the photographic records indicate an opaque cloud preventing the observations of a detailed structure within the debris. In both cases, the leading front is propagating at velocities considerably faster than impact velocities. Based on the timing of the rupture of the back wall, the experiments suggest very low-density vapor-like material traversing at very fast velocities with a higher-density liquid-like material traversing at velocities comparable to impact velocities. The density distribution

of the debris cloud, however, cannot be quantitatively estimated from the existing photographic records. Based on the location of the rupture/perforation of the backwall *i.e.,* along the center axis of the debris cloud, the high density mass appears to be concentrated along the center axis.
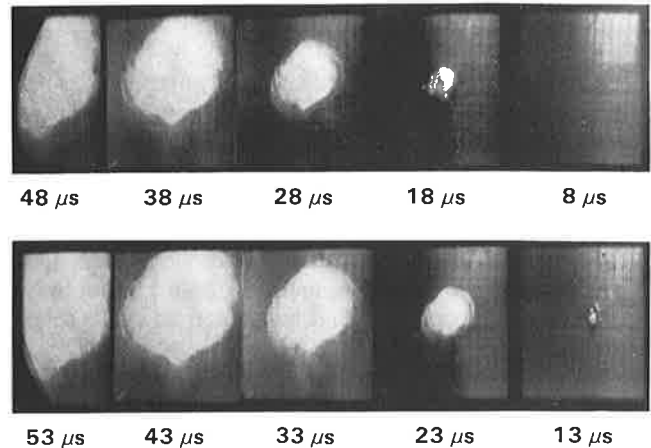
**WS12 - BACK SURFACE VIEW**



Figure 5. Fast framing photographic records of the backwall indicates rupture at the center of the backwall as a result of loading of the debris cloud depicted in Figure 4.

## 3.3. Experiment HAL2

In this experiment, a 0.93-mm thick, 17-mm diameter aluminum plate impacts a 1.27-mm aluminum bumper at 9.6 km/s. Radiographic measurements of the debris cloud are taken at ~ 5 and 6 μs after impact. The faster moving lower density material is transparent to X-rays; the debris front does not appear to be spherical as indicated in the photographic records; the
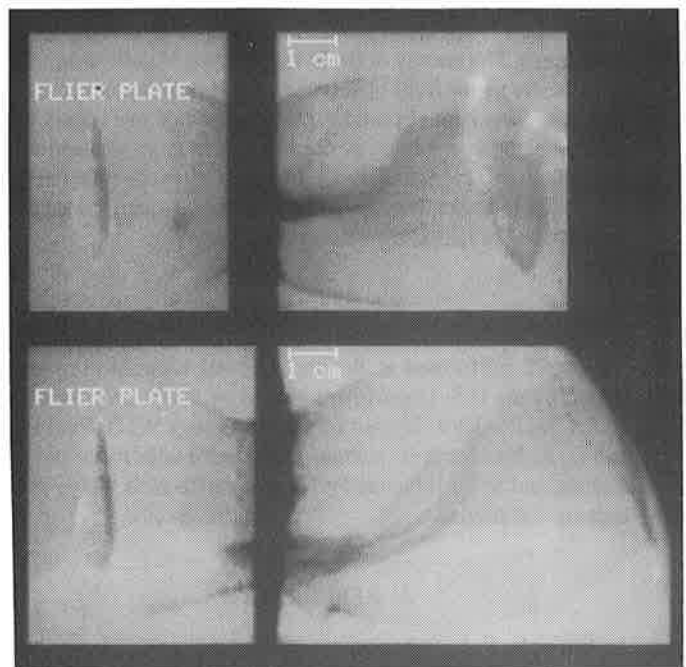


Figure 6. Radiographs of an impact experiment at 9.6 km/s. The flier plate is ~ 0.93 mm thick, while the bumper is 1.27 mm thick. The leading edge of the debris appears to be concentrated and plate-like even though it is expected to be molten.

higher density mass from the bumper sheet appears to be concentrated, plate-like, and is moving at a velocity of about 10 km/s. The one-dimensional column-like features of the debris (indicated in Figure 6) is a lot more damaging to the back wall since it does not disperse efficiently in the lateral direction. Although not shown in this figure, a 3.2 mm thick backwall located ~ 200 mm away from the bumper is perforated.

## 4. SUMMARY

An impact technique using graded-density materials has been described which allows launching of gram-size plates to hypervelocities. Nominally 0.5 mm to 1-mm thick 6061-T6 aluminum, Ti-6Al-4V, and AZ31 magnesium alloy flier plates have been launched intact to velocities over 12 km/s. In particular, the mass-velocity capability of the newly developed HVL meets the average specifications of the artificial space debris environment, and has, therefore, been a useful tool to evaluate the effects of space debris impact on debris shields (Refs. 10-15).

In general, the photographic records indicate an opaque cloud which prevents the observations of a detailed structure within the debris. In both cases the leading front is propagating at velocities considerably faster than impact velocities. Based on the timing of the rupture of the backwall, the experiments suggest very low-density vapor-like material traversing at very fast velocities with a higher-density liquid-like material traversing at velocities comparable to impact velocities. The density distribution of the debris cloud, however, cannot be quantitatively estimated from the existing photographic records. Based on the location of the rupture/perforation of the backwall *i.e.*, along the center axis of the debris cloud, the high-density mass appears to be concentrated along the center axis.

Radiographic records, however, do indeed indicate the details of the debris cloud that are not observable using photographic techniques. The energy of the X-rays are too high to image the low density vapor front observed in the photographic records. The one-dimensional column-like features of the debris resulting from plate impact as observed in radiographs and hydrodynamic CTH-simulations of these experiments (Refs. 10,15) is a lot more damaging to the backwall since it does not disperse in the lateral direction very efficiently.

## 5. ACKNOWLEDGMENTS

## 6. REFERENCES

1. Whipple, F. L. "Meteorites and Space Travel." *Astronomical J.*, No. 1161:131, 1947.

2. Posever, F. C., and Scully, C. N., "Investigation of Meteoroid Impacts on Two-Sheet Configurations." AFFDL-TR-65-196. *Wright-Patterson Air Force Base*, Ohio.

3. Cour-Palais, B. G., "Hypervelocity Impact in Metals, Glass and Composites." *Intl. J. Impact Engng.*, Vol 10, p. 221-237.

4. 1990 Report on Orbital Debris by Interagency Group(Space) for National Security Council, Washington, D. C., 1989.

5. Kessler, D. J., Reynolds, R. C. and Anz-Meador, P. D. "Orbital Debris Environment for Spacecraft Designed to Operate in Low Earth Orbit." NASA TM 100-471, 1989.

6. L. C. Chhabildas, Barker, L. M., Asay, J. R., Trucano, T. G., Kerley, G. I. "Sandia's New HyperVelocity Launcher-HVL." *Sandia National Laboratories Report* SAND91-0657, May 1991.

7. Chhabildas, L. C., Barker, L. M., Asay, J. R., Trucano, T. G., Kerley, G. I. and Dunn, J. E. "Launch Capabilities to Over 10 km/s." in *Shock Waves in Condensed Matter-1991*, ed. by S. C. Schmidt, J. W. Forbes and R. Dick, Elsevier Science Publishers, 1992.

8. Chhabildas, L. C. "Hypervelocity Launch Capabilities to Over 10 km/s." *Proceedings of the XIII AIRAPT Conference on High Pressure Science and Technology*, - 1992, Bangalore, India ed. by A. K. Singh.

9. Chhabildas, L. C., Dunn J. E., Reinhart, W. D., Miller, J. M., "An Impact Technique to Accelerate Flier Plates to Velocities over 12 km/s," *Intl. J. Impact Engng.*, V14, 1993.

10. Chhabildas, L. C., Hertel, E. S., Hill, S. A. "Whipple Bumper Shield Tests at Over 10 km/s." in *Shock Waves in Condensed Matter-1991*, ed. by S. C. Schmidt, J. W. Forbes and R. Dick, Elsevier Science Publishers, 1992.

11. Chhabildas, L. C., Hertel, E. S., Hill, S. A. "Experimental and Numerical Simulations of Orbital Debris Impact on a Simple Whipple Bumper Shield." in *Proceedings of the Hypervelocity Impact Symposium-1991*, University of Kent at Canterbury, Kent, U.K., ed. by J. A. M. McDonnel.

12. Ang, J. A., Chhabildas, L. C., Cour-Palais, B. G., Christiansen, E. C. and Crews, J. L., "Evaluation of Whipple Bumper Shields at 7 and 10 km/s." AIAA Paper 92-1590, *Space Programs and Technologies Conference*, 1992.

13. Boslough, M. B., Ang, J. A., Chhabildas, L. C., Cour-Palais, B. G., Christiansen, E. C., Crew, J. L., Reinhart, W. D., Hall, C. A., "Hypervelocity Testing of Advanced Shielding Concepts for Spacecraft Against Impacts to 10 km/s," *Intl. J. Impact Engng.*, V14, 1993.

14. Hertel, E. S., Chhabildas, L. C., "Orbital Debris Impact on a Simple Whipple Bumper Shield," *Aerospace Testing Seminar Series, Proceedings*—Institute of Environmental Series, 1993.

15.. Hertel, E. S., and Chhabildas, L. C., "Computational Determination of the Ballistic Limits for a Simple Whipple Bumper Shield," in *Proceedings of the Hypervelocity Impact Symposium-1991*, University of Kent at Canterbury, Kent, U.K., ed. by J. A. M. McDonnel.