Experimental technique to launch flier-plates representing orbital debris to hypervelocities

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ABSTRACT

Very high driving pressures (tens or hundreds of GPa), are required to accelerate flier plates to hypervelocities. This loading pressure pulse on the flier plates must be nearly shockless to prevent the plate from melting or vaporizing. This is accomplished by using graded-density impactors referred to as ''pillows''. When this graded-density material is used to impact a flier-plate in a modified two-stage light gas gun, nearly shockless megabar pressures are introduced into the flier plate. The pressure pulses must also be tailored to prevent spallation of the flier-plate. This technique has been used to launch nominally 1-mm-thick aluminum, magnesium and titanium (gram-size) intact plates to 10.4 km/s, and 0.5-mm-thick aluminum and titanium (half-gram size) intact plates to 12.2 km/s. This is the highest mass-velocity capability attained with laboratory launchers to date, and should open up new regimes of impact physics and lethality studies related to space sciences for laboratory investigations. In particular, the mass-velocity capability of this newly developed hypervelocity launcher meets the average specifications of the space debris environment, and is therefore expected to be a useful tool to evaluate the effects of debris impact on space structures and debris shields.

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[1] were designed for deployment with the early spacecrafts and tested using electro-thermal gun facilities[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 km/s to 18 km/s, and were used to evaluate the various Whipple bumper shield designs proposed for spacecrafts[3]. It is well recognized now that the principal impact threat to space structures results not from naturally occurring meteoroids, but from man-made artificial space debris[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 km/s to 15 km/s[4,5]. The impact threat to space missions resulting from orbital debris is no longer considered remote due to the abundance of the debris (over 3.6 million pieces), its relatively large size, and also because its population is growing[4,5]. 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 km/s to 15 km/s. It is the purpose of this paper to describe the recently developed HyperVelocity Launcher (HVL)[6,7] which 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[7,8]. In particular, the mass-velocity capability of the newly developed HVL meets the average specifications of the space debris environment, and has therefore been a useful tool to evaluate the effects of debris impact on space structures and debris shields[9-14].

0-8194-1187-6/93/$6.00

2. EXPERIMENTAL TECHNIQUE

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. A summary of experimental impact conditions to achieve hypervelocities are summarized in Table 1 for a selected few experiments. Results of many other experiments are summarized elsewhere[6-8]. The experimental impact configuration is indicated in Fig. 1. As indicated in the figure, a two-stage light-gas gun lexan projectile, which has a facing of a graded-density material[15,16] backed by tantalum 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. 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. This is indicated in Table 1. The diameter of the graded-density impactor facing and its tantalum backing used in this study was ~ 27 mm.

Table 1: Summary of HVL Experiments

Experiment No.	Graded-Density Impactor Thickness (mm)	Flier-Plate Material	Buffer/Flier-Plate Thickness (mm)	Impact Velocity (km/s)	Flier-Plate Velocity (km/s)
MG1	5.58	Ti-6Al-4V	1.5/1.00	6.4	9.4
HVL2	2.21	Ti-6Al-4V	1.21/0.43	7.4	11.9

As shown in Fig. 1, the flier plate used in these experiments consists of a center plate made to fit exactly into a 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 emanating from the edges of the plate upon impact would cause a velocity gradient across the radius of the plate. Large velocity gradients across the radius of the flier plate would cause it to bend and, therefore, fragment. The guard ring geometry indicated in Fig.1 allows a *controlled* separation of the center plate from its edges without causing the entire flier plate to fragment.

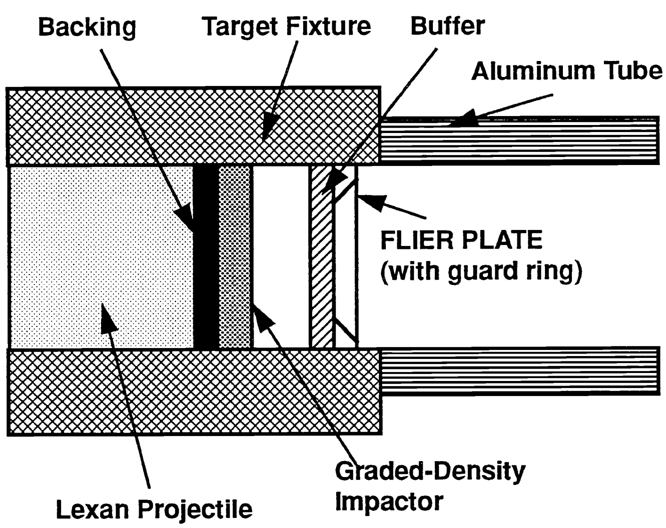

Fig. 1. A graded-density impactor/flier-plate experiment

Following impact, seven flash X-rays are taken of the flier plate while it is in motion over a flight distance of 350 mm. They are used 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 the flier plate has exited from the muzzle and are located ~ 80 mm, 170 mm, and 350 mm from the impact position. Radiographic pictures 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%.

3. RESULTS

In the experiment shown in Fig. 2, the graded-density material impacts the buffered/titanium alloy flier plate at a velocity of 6.4 km/s. (The impact velocities indicated in Table 1 are not measured but are estimates based on the gun performance data and are accurate to ~ 2%). A 1.5 mm thick lexan buffer was used in this experiment to further cushion the launch[7,8,17]. The lexan buffer also reduces the magnitude of the tensile states generated in the flier plate material[17]. The Ti-6Al-4V alloy plate launched at 9.4 km/s, and the radiographs of the titanium flier plate are shown in Fig. 2. Titanium and aluminum alloy flier plates are commonly used in these studies, because of their high-fracture resistant property[15]. A similar graded-density impact experiment at an impact velocity of 6.4 km/s using a 6061-T6 aluminum flier plate, propels the flier plate at a velocity of 10.4 km/s[7,8,17].

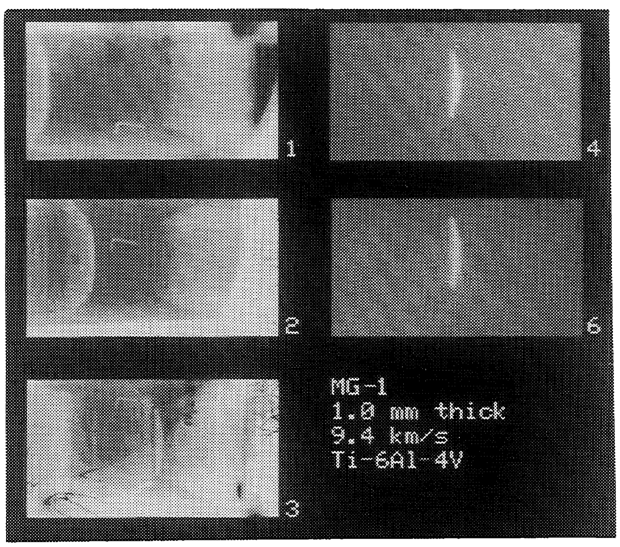

Fig. 2. The titanium flier plate is moving from left to right at a velocity of 9.5 km/s. The sequence of radiographs shown on the left is taken over the first 60 mm; the radiographs on the right are taken after a travel distance of 90 mm and 350 mm from impact, respectively. The mass of the center plate is 1.3 gram.

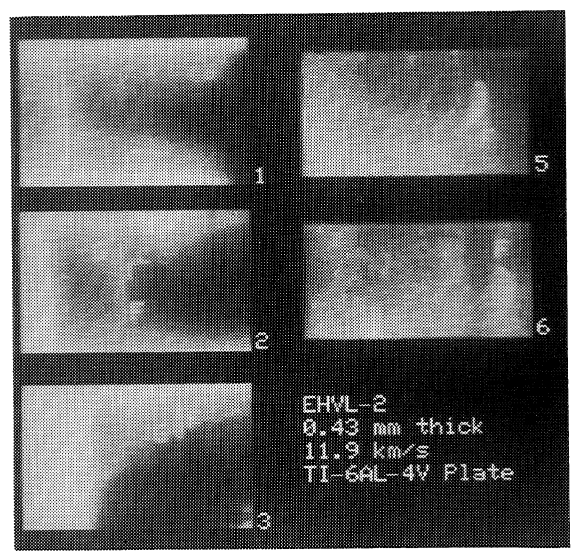

Fig. 3. The titanium flier plate is moving from left to right at a velocity of 11.9 km/s. The sequence of radiographs shown on the left is taken over the first 60 mm; the radiographs on the right are taken after a travel distance of 180 mm and 350 mm from impact, respectively. The mass of the center plate is 0.55 gram.

Fig. 3 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 a velocity of ~ 7.4 km/s. A 1.25-mm thick TPX buffer was used in this experiment, while the Ti-6Al-4V alloy plate thickness was 0.43 mm. A similar experiment at an impact velocity of 7.4 km/s with a 0.42-mm-thick 6061-T6 aluminum flier plate propels the aluminum flier plate at a velocity of 12.2 km/s.

4. APPLICATION TO DEBRIS SHIELDS

We have made extensive use of the hypervelocity launch capability to test various debris shielding concepts[9-14]. In this section, the results of one selected test is summarized to give an overview of the type of information that can be obtained. In experiment XH-9, a 1 mm-thick, 12.7 mm diameter Ti-6Al-4V flier weighing about 0.53 g was launched to a velocity of 9.72 km/s. The flier impacted on a bumper consisting of a single sheet of 0.74 mm-thick Ti-6Al-4V. A 4 mm-thick backwall of aluminum was located about 150 mm beyond the bumper sheet. The two principal diagnostic techniques that were used to characterize the impact generated debris cloud were: 1) fast framing photography, and 2) flash x-ray radiography. The framing photography collects light reflected, scattered and radiated from the expanding debris cloud, whereas the flash x-ray images are exposed by x-rays that are not absorbed by the debris cloud. For this reason, the photographs tend to be sensitive to the low-density, hot, vapor part of the cloud, and the radiographs are sensitive to the higher-density material within the cloud. Combining these two complementary techniques provides a comprehensive set of image data that is necessary to characterize the impact generated debris cloud.

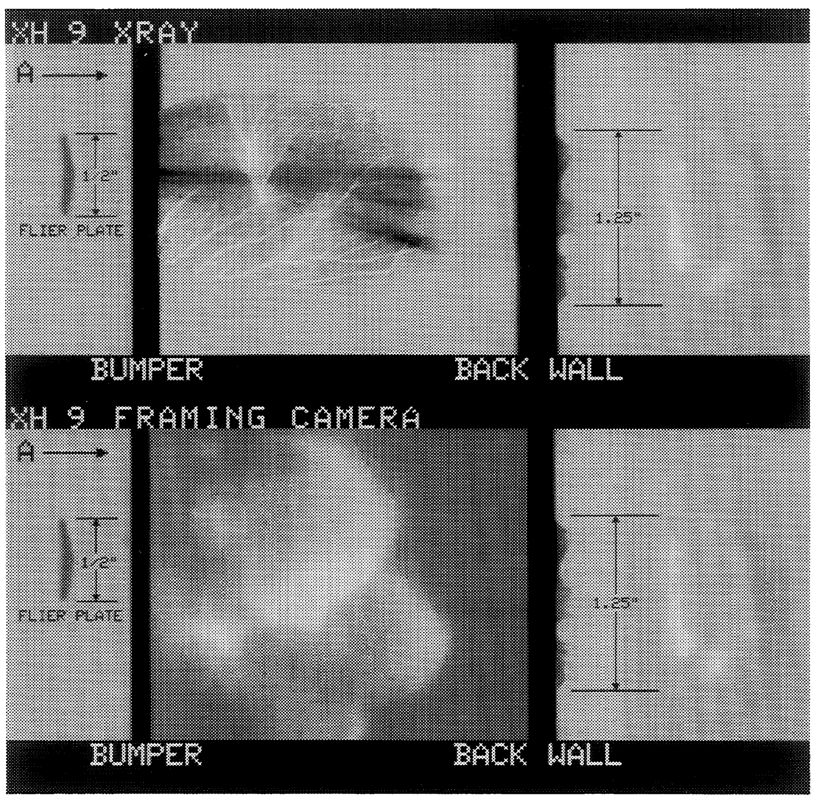

Fig. 4. Radiographic image of a debris cloud generated upon impact of a titanium flier plate with a titanium bumper shield at a velocity of 9.72 km/s. The titanium flier plate prior to impact is indicated on the left. The corresponding photographic image using fast framing photograhy is also shown in the picture. The photographic image shows evidence of low density vapor front while x-ray imaging exposes relatively higher density material. Notice the coulmn like nature of the debris cloud in the x-ray radiographs. The static electrical discharge is also evidenced in the x-rays.

An example of such a set of data for experiment XH-9 is depicted in Fig. 4. The left-hand image is a flash x-ray radiograph of the flyer just before impact, showing it to be intact and slightly bowed. In the upper center, a flash x-ray image is shown that was exposed about 5.8 μs after impact. It is apparent that most of the mass in this image is moving in three narrow columns all parallel to the impact direction. In the lower center is depicted a framing camera image, also showing the debris cloud about 5.8 μs after impact. The central columnar streams of high density material are no longer visible, but diffuse clouds of low-density vapor dominate the image. Note that the photographic debris cloud has propagated farther than the one imaged by the x-ray debris cloud indicating that the low density vaporized debris front is travelling faster than the relatively higher density cloud imaged using X-rays. An analysis of these photographs suggest that the leading edge of the debris cloud determined from photographic records is travelling at over 11 km/s while the x-ray radiograph yields a velocity of ~ 10 km/s. Similar results have been reported for aluminum flier plates impacting aluminum bumpers[9-14,18].

5. FLIER-PLATE ENHANCEMENT - VELOCITY AND MATERIAL

The flier plate velocities can be further enhanced either by using explosives, plastics, or hydrogen as a first layer of the graded-density impactor or on the flier plate itself. Calculations have indicated that as a result of high-pressure compression and decompression these materials behave "energetically," in that the expansion velocities of these materials are extremely high. This results in an efficient "push" on the flier plate and can further enhance the flier plate velocity. If the impact velocity is further increased to 8 km/s, a 10-mm layer of liquid hydrogen buffer is predicted to increase the velocity of the aluminum flier to 14 km/s, Hence hydrogen buffers in combination with higher impact velocities appear to offer a way to achieve even higher flier velocities[7,8,17].

Although the technique is being used currently to launch AZ31 magnesium alloy, Ti-6Al-4V titanium alloy and 6061-T6 aluminum alloy plates, one-dimensional hydrodynamic calculations suggest that this technique can be extended to include other (high-density) materials[7,8,17].

6. SUMMARY

A systematic study has been described which allows launching of gram-size plates to hypervelocities. In particular, nominally 1-mm thick 6061-T6 aluminum, Ti-6Al-4V, and magnesium alloy flier plates have been launched intact to velocities in excess of 10 km/s. This has been achieved by using a graded-density material to impact a stationary flier plate at a velocity of 6.4 km/s on the two-stage light-gas gun. Upon impact, a shockless, time-dependent, high pressure (100 GPa) pulse is produced at the flier-plate/impact interface. This allows shockless acceleration of the flier plate to hypervelocities without causing excessive heating leading to melt or vaporization. The pressure pulse must be tailored, however, to prevent spall fracture of the plate. To obtain higher flier-plate velocities, the graded-density impactor velocity was increased to 7.4 km/s. This resulted in launching ~ 0.4-mm- thick titanium and aluminum flier plates to velocities of 11.9 and 12.2 km/s, respectively. In particular, the mass-velocity capability of the newly developed HVL meets the average specifications of the artificial space debris environment, and is therefore expected to be a useful tool to evaluate the effects of space debris impact on space structures and debris shields. Results of some of these experiments have been summarized in other publications[9-14].

An example of using this technology to evaluate debris shields is provided in this paper. Further studies describing the results of an evaluation of both simple and advanced spacecraft shielding concepts are summarized in Refs. 9 through 14. The combined use of both X-ray radiographic techniques combined with framing cameras pictures[18] is necessary for an accurate description of the debris cloud. There is evidence of a lower density vaporized cloud propagating much faster than anticipated velocities. Radiographic techniques are, however, indicating lower speeds (when compared to those obtained using photographic techniques) for the impact generated higher density debris clouds.

7. ACKNOWLEDGMENTS

This work performed at Sandia National Laboratories supported by the U.S. Department of Energy under contract DE-AC04-76DP00789. The able technical assistance provided by W. D. Reinhart, and C. A. Hall is gratefully acknowledged.

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