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Calculations Supporting Hypervelocity Launcher Development

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Sandia National Laboratories has developed a HyperVelocity Launcher (also referred to as HVL) in which a thin flier plate (nominally 1 mm thick) is launched to velocities in excess of 12 km/s. The length-to-diameter ratio of these launched flier plates varies from 0.02 to 0.06. The launch technique is based upon using structured, time-dependent, high-pressure, high-acceleration pulses to drive the flier plates. Such pulses are achieved by using a graded-density material to impact a stationary flier. A computational and experimental program at Sandia seeks to extend this technique to allow launching thick plates whose length-to-diameter ratio is 10 to 20 times larger than thin plates. Hydrodynamic codes are used to design modifications to the basic impact technique to allow this extension. Two-dimensional effects become more important for launching chunks with this technique. We have controlled and used these effects to successfully launch a chunk-flier, consisting of 0.33 gm of titanium alloy, 0.3 cm thick by 0.6 cm in diameter, to a velocity of 10.2 km/s. This is the largest chunky size ever launched at this velocity from a gas gun configuration.

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INTRODUCTION

Sandia has developed a HyperVelocity Launcher, HVL, which is capable of launching gram-size plates to velocities not to date accessible on smooth-bore guns such as the two-stage light-gas gun. The interest in increased velocity launch capabilities in part was motivated by Strategic Defense Initiative research, and concern regarding impact of orbital debris particles on space voyagers. This has led to the development of an impact technique [1,2] in which a time-dependent structured pressure pulse is generated to launch 0.5 mm to1.0 mm thick flier plates to velocities up to 12.2 km/s.

There are two main requirements in order to launch thin flier plates to hypervelocities. First, very high loading pressures are required. Second, this loading must be nearly *shockless* and *uniform* over the entire impact surface. To achieve both these requirements, a multi-layer, graded-density material [3] is used to impact the thin flier plate. With this graded-density impactor nearly shockless 100 GPa pressure pulses [4] are created in the flier. Since the loading on the flier is shockless, excessive heating is minimized, preventing melting of the flier. The method has been used [5] to launch a 0.5 mm thick titanium alloy (Ti-6Al-4V) plate intact to 12.2 km/s. With further improvements to this technique we expect that launch velocities approaching 14 km/s can be achieved.

As indicated above, the loading that is necessary to launch flier plates must be nearly ***shockless*** (***i.e., ramp***) and ***uniform*** during the acceleration process. When a material is subjected to ramp loading, constitutive behavior causes the compressive ramp wave to steepen as it traverses the material. This, in effect, increases the loading rate within the sample until the compression wave achieves a steady "high-pressure shock" profile. This shock produces high temperatures that can lead to melting. We thus require the flier plate to be *thin* in order to prevent shock up and melting. The current aspect ratio *i.e.*, the length to diameter ratio, of thin fliers launched on the Sandia HVL is approximately 0.05 to 0.1 It is the purpose of this report to describe a technique that has been developed to launch an intact "chunk", *i.e.* a 0.3 cm thick by 0.6 cm diameter cylindrical titanium alloy (Ti-6Al-4V) flyer, to approximately 10.2 km/s. The experimental techniques used to accomplish this launch were similar but not identical to techniques developed for the Sandia HyperVelocity Launcher (HVL). One key to the success of this experiment was pretest design work that was performed using the **CTH** [6] multi-dimensional hydrodynamic code. Although, many pretest calculations were necessary to achieve the final design, only a subset of these will be reported here to highlight the technical issues associated with the launch of a chunk flier. In particular, the calculations presented in this paper have been tailored to indicate the path that led to the experimental conditions that were finally selected. These **CTH** calculations are reported in the next section, while the experimental results are discussed in the final section.

TECHNICAL ISSUES

As indicated earlier, to launch plates to hypervelocities a high-pressure quasi-isentropic loading wave is necessary to prevent the flier plate from melting. To achieve this criterion, a multi-layer graded-density material is used to impact the thin flier plate. When this graded-density material is used to impact a thin flier plate at high velocities of over 6 km/s on a two-stage light-gas gun, nearly shockless 100 GPa pressure pulses are introduced into the flier plate.

If one wants to launch a thicker flier, then it is clearly necessary for the graded-density impactor to be scaled proportionately to produce loading of the thick *chunk* by a scaled time-dependent high-pressure pulse. This cannot be arbitrarily accomplished for the following reasons. Thickening the graded-density impactor will add considerable mass to the two-stage light-gas gun projectile, lowering the required impact velocity to less than 6 km/s. This will reduce the high pressures that are necessary to launch the larger mass. Also, the loading pressure pulse resulting from a thicker impactor will scale proportionately and will be of a *longer* duration. Two-dimensional effects emanating from the edges of the thick chunk will become important and possibly create a severe velocity gradient over a larger radius of the flier. This may cause the flier to bend and even fragment.

From previous experience, we know that 2-D axisymmetric **CTH** calculations accurately simulate the impact of a multi-layer impactor and subsequent acceleration of a thin flier plate. We have therefore used **CTH** to simulate and evaluate the technical issues related to launching thicker flier plates. This approach is quite important to the experimental program, because it allows us to reduce the need to perform parameter variations in the laboratory in order to optimize the experimental configuration.

In all the calculations discussed here, a graded-density impactor which is approximately three times thicker than that used in a conventional HVL experiment is assumed. The exact dimensions of the graded-density impactor layers used in the experiment described in this report is indicated in Table 1. In all the calculations reported in this paper an impact velocity of 5.8 km/s for the graded-density impactor is used. This is the impact velocity at which the reported experiment was performed.

Table 1: Graded-Density Impactor Dimensions

Material Layer	Thickness (mm)	Diameter (mm)
TPX	3.00	12.7
Magnesium	1.803	12.7
Aluminum	1.499	12.7
Titanium	1.194	12.7
Copper	6.375	12.7
Titanium*	0.792	26.97

We report four different CTH calculations here. In all the calculations (as well as the experiment) a TPX buffer ~4 mm thick lies on the impact side of the flier. The flier consists of a central portion, isolated from the barrel by a guard ring assembly. (See Figure 1 for the configuration used in the experiment and in calculation #4.) The term "flier" in the following discussion **ALWAYS** refers to the central portion. The use of guard rings with fliers is standard in our previous HVL experiments.

First, we performed a 1-D **CTH** calculation (#1) to confirm that the impactor assembly tabulated in Table1 will launch a flier without melting or fracturing it during the acceleration phase, and also to predict the final velocity. The velocity *vs* time of a 3 mm thick titanium alloy flier is presented in Figure 2. The predicted terminal velocity is ~ 8.8 km/s. The driving pulse in the simulation is observed not to melt or fracture the flier. This experiment cannot be performed because the resulting two-stage gun projectile would be too heavy to obtain the required impact velocity of 5.8 km/s.

The calculation #2 is a two-dimensional simulation (see Figure 3) in which the barrel and radial response of the impactor and flier are modeled. The impactor and the flier have the same diameter as the tungsten barrel (~ 29 mm) that is generally used in Sandia HVL experiments. This experiment is still not feasible because of the impactor mass, but it is interesting to see the differences that the simulated 2-D effects create. The loading pulse is three times longer than in the usual thin flier case. A velocity gradient over the face of the flier is created by the resulting 2-D effects. The flier is predicted to bend and fracture in the simulation in response to this non-uniform loading. The velocity *vs* time of the center of the flier is plotted in Figure 2. The peak velocity is only 8 km/s, a reduction of 9% in velocity from the 1-D calculation.

This is directly due to 2-D effects.

In calculation #3 the graded-density impactor diameter is reduced to 12.7 mm to reduce its mass. This makes it possible to achieve an impact velocity of 5.8 km/s in an experiment. The barrel and flier diameters are left unchanged (see Figure 3). The loading pulse has the same duration as that of #2. It is observed in calculation #3 that 2-D edge effects are even more severe in this geometry This causes increased bending of the flier, as compared to #2, and a further reduction of the peak velocity in Figure 2 to ~ 6 km/s (70% of the 1-D calculation).

Our final calculation, #4, replicates the conditions of the experiment that was performed. See Figure 4. Our reasoning behind this calculation is as follows. One reason 2-D effects cause reduction of the flier velocity is because edge effects emanating from the impactor/flier boundary are *release waves*. The high pressure drive therefore decays too quickly. If we could maintain the driving pressure, even with 2-D distortions in the impact region, then we would not suffer the observed velocity reductions.

This can be achieved by using a step-down barrel of 10 mm diameter as indicated in Figure 4. An equal diameter flier is inserted in the barrel. The diameter of the impactor is 12.7 mm to maintain the 5.8 km/s impact velocity. Tungsten is used as a barrel material because of its high-impedance and relatively low sound speed. Upon impact, the stress states at the tungsten/flier boundary are higher than those in the sample itself. This prevents the release of the driving pressure, creating a longer duration acceleration phase for the flier. We also find that flier bending is reduced by maintenance of the high pressures. A potential trade-off is the radial "squeezing" that the flier and impactor undergo.

Optimizing this final configuration is obviously what a joint experimental/computational program is really about. That our insight is correct is seen in Figure 2, where the peak velocity observed for #4 is 9.4 km/s (actually, it is still increasing at the final time of the calculation). This is an increase of 7% over the ideal 1-D behavior. This is dramatic evidence that 2-D effects actually work in our favor now, and create accelerations that are greater than we could achieve in idealized 1-D geometries. This is quite different from the thin flier situation. The calculation suggests that bending of the flier is minimal and that melting does not occur. (We show an illustration of the predicted deformation of the flyer past peak acceleration in Figure 4.) Thus, we predict an intact flier for #4.

Conclusion - A Successful Experiment

The geometry of calculation #4 was shot in an experiment at the Sandia two-stage light gas gun. An impact velocity of 5.8 ± 0.1 km/s was estimated for the experiment. The mass of the central flier (not including the guard ring) is 0.33 g, while the mass of the guard ring is 0.7 g.

Radiographic measurements of the flier and the guard ring are taken along their flight path after exit from the tungsten barrel and up to a flight distance of ~ 1.4 meters. These measurements yield an average flier velocity of 10.2 km/s, 16% greater than the 1-D simulation. The chunky projectile appears to be tumbling as it traverses, rotating approximately half a turn over this flight distance. These radiographic measurements are shown in Figure 5.

In conclusion, we observe that the interior ballistics for a chunk-flier HVL launch are considerably different than for a thin flier HVL experiment. Calculations have proven to be important for design and interpretation of experiments. Results of these calculations provide understanding the behavior of the launch system that would be difficult to achieve in other ways. They are also effective in reducing the number of experiments in the program.

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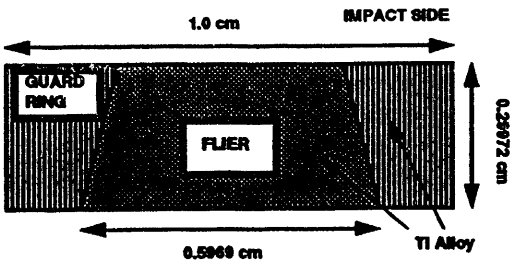

Figure 1. Guard ring used in experiment.

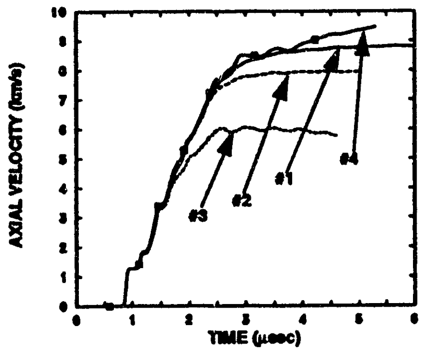

Figure 2. Flier velocity histories for calculations #1 - #4.

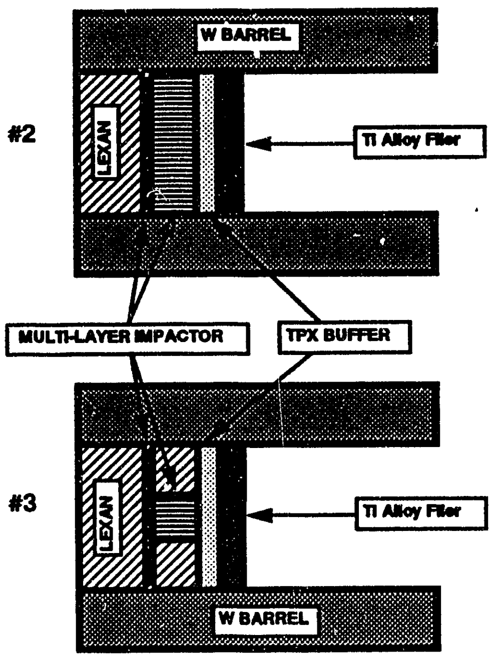

Figure 3. Schematics for #2 and #3 (not to scale).

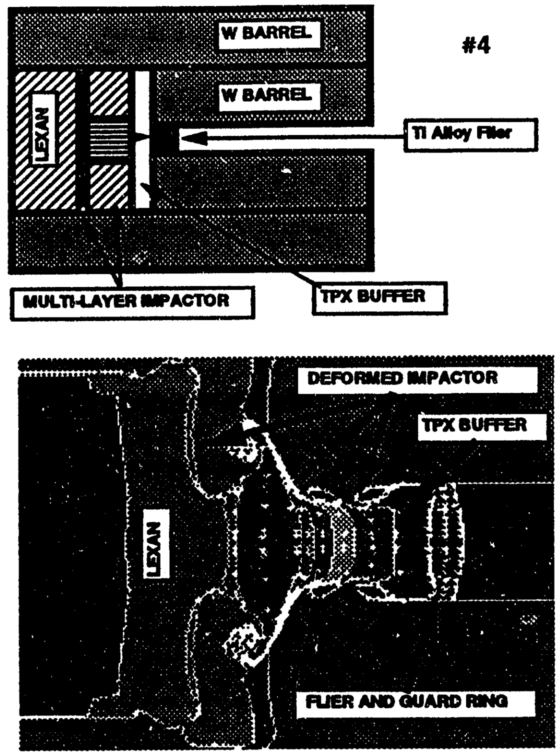

Figure 4. Schematic of #4 and a representative calculated configuration at t=3.5 μsec.

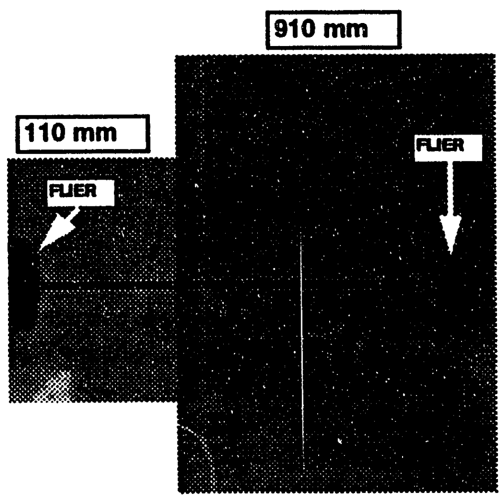

Figure 5. Experimental radiographs at 110 mm and 910 mm from the impact location. The scale is not the same in the two radiographs.

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