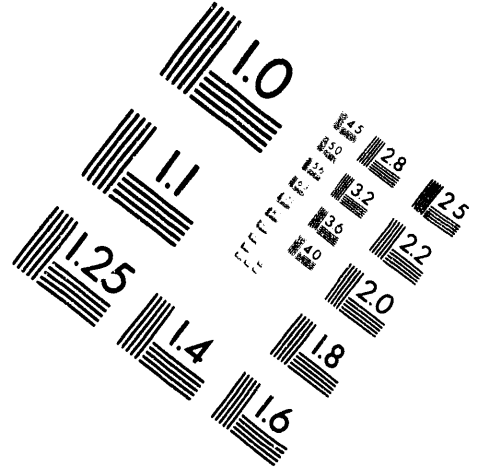
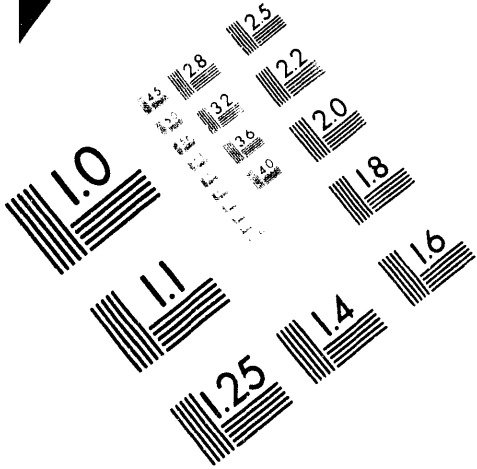




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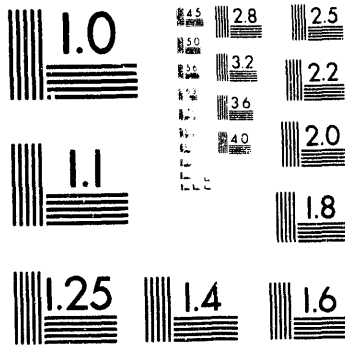
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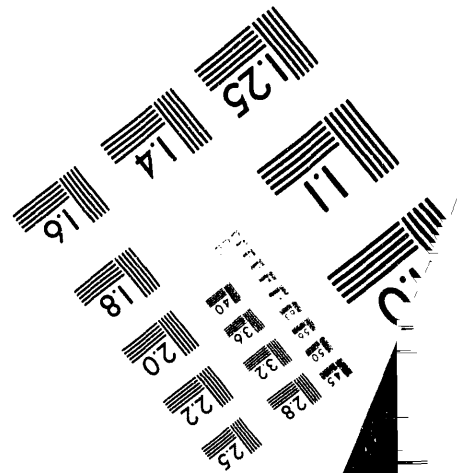
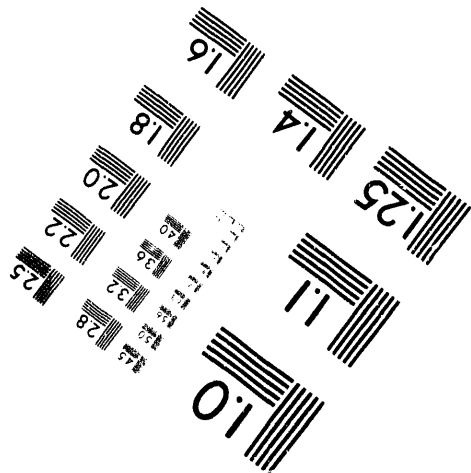
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EFFECT OF PHASE CHANGE IN A DEBRIS CLOUD ON A BACKWALL STRUCTURE¹

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The physical state of a debris cloud generated upon impact of a thin flier plate with a thin bumper depends on the impact velocity. At impact velocities of 10km/s, the debris cloud is expected to be primarily molten with some vapor present. A series of calculations using the finite-difference code CTH has been used to evaluate the effect of phase change (*i.e.*, higher concentrations of vapor) in debris clouds and their subsequent impact on a backwall structure. In these calculations, the higher concentrations of vapor is achieved by increasing the initial temperature of the impactor and the bumper material while keeping the same impact velocity. The nature of the interaction of the debris cloud and the subsequent loading on the backwall depends on its thermophysical state. This interaction (with a backwall) can cause either spallation, rupture, or simply bulging of the backwall structure. These results will be discussed and compared with an impact experiment performed at ≈ 10 km/s on the Sandia hypervelocity launcher. In the experiment, the debris cloud was generated by the impact of a titanium plate with a titanium bumper.

INTRODUCTION

Protection sheets, commonly referred to as Whipple bumper shields, were proposed for deployment with early spacecraft. In the early sixties, these sheets were designed to protect the spacecraft from micrometeoroid debris, which is primarily dust-type 100 μ m-size silicate particles. It is recognized that the threat to spacecraft has progressively increased due to the abundance of man-made space-debris in the environment. The space-debris environment, also referred to as orbital debris, is presumed to be gram-mass mm- or cm-diameter metallic plate-like particles with average impact interaction velocities of ≈ 10 km/s. The possibility of impact on spacecraft by these heavier plate-like objects is not negligible. The requirements for an adequate bumper shield are quite demanding for a variety of reasons, including the uncertainty in the size, shape, and density of the orbital debris particulate and the high interaction velocities.

At higher impact velocities, *i.e.* at velocities in excess of 7km/s, most of the impact generated debris (from the Whipple shield) will consist of molten liquid with some vaporized material present. There is considerable speculation that, for Whipple shields to be effective, there should be a greater mass fraction of vaporized debris in the debris cloud. It is the purpose of this paper to use the results of an experiment conducted at ≈ 10 km/s [1] to validate the use of the CTH hydrodynamics code [2] for these types of problem, and further evaluate the effect of having more vapor in the impact-generated debris cloud and of changing the density of the bumper material on the physical integrity of the backwall structure. Results of this study indicate that it is not merely sufficient to have more vaporized debris in an impact-generated debris cloud for the survival of a backwall structure; the density and

relative kinetic energy of the debris also have an effect on determining the integrity (*i.e.*, the survivability) of a backwall structure.

PROBLEM DESCRIPTION

Experiment XH-9 Base Case

In the XH-9 experiment, a thin, flat flier plate impacted a thin, flat bumper shield at a velocity of 9.66km/s. The flier plate material was Ti-6Al-4V and the geometry was a circular disk 12.629mm in diameter and 0.98mm thick, with a mass of 0.529gm. The bumper shield was 0.7366mm thick, and also made of Ti-6Al-4V. The backwall was 4.0132mm thick, and separated from the bumper shield by a distance of 15.24cm. The backwall was made of 6061-T6 aluminum. More details on the experiment procedure and results can be found in [1].

Sensitivity Studies

Three different studies were done on the problem described above. In the first study, the materials, dimensions and impact velocity were left unchanged, while the initial temperatures of the flier plate and/or bumper shield were varied as shown in Table 1 (to increase the vapor content in the debris cloud):

Table 1. Initial Temperature Variations

Case ID	Flier Temperature	Bumper Temperature
Base Case	300K	300K
"Hot Bumper"	300K	1923K
"Hot"	1923K	1923K
"Very Hot"	3513K	3513K

¹This work performed at Sandia National Laboratories supported by the U. S. Department of Energy under contract DE-AC04-76DP00789.

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where the melting temperature of Ti-6Al-4V is 1943K and the vaporization temperature is 3533K. In the second study, the materials, dimensions and initial temperatures were unchanged, but the impact velocity was progressively increased to ≈ 20 and ≈ 30 km/s. In the third study, the flier material, dimensions and the impact velocity were unchanged but the bumper shield material was changed to plexiglass and to cadmium. These materials were selected as lower- and higher-density materials than Ti-6Al-4V but with similar, low melt points. The thickness of the bumper shield was adjusted to maintain constant areal densities, so the cadmium bumper was 0.381mm thick and the plexiglass bumper 2.667mm thick. (The backwall was identical in all cases.)

CTH INPUT MODELS

The CTH calculations were performed using a two-dimensional, cylindrical geometry. These impact calculations were run in two stages.

The impact of the flier plate onto the bumper shield was simulated first, using fine resolution. The x -direction (radial) mesh was started at $x=0$, the axis of symmetry, while the y -direction (axial) mesh was started at $y=-0.5$ cm with the initial contact surface between the flier plate and the bumper shield defined to be $y=0$. A subgrid of 400×750 0.01cm-square cells was used in an initial interaction region 8cm in diameter and 7.5cm in length (with additional cells growing at a 5% rate used outside this subgrid).

The initial impact calculation was run until the debris cloud had expanded to fill nearly the entire 400×750 square-cell subgrid which, for impacts of ≈ 10 km/s, took $\approx 6\mu$ s. The material distribution at that time was then manually rezoned into a larger, coarser mesh which included the backwall. This mesh used a larger subgrid of 100×474 0.04cm-square cells in a larger, later interaction region 8cm in diameter but 19cm in length (again with additional cells growing at a 5% rate used to model further regions). This second part of the calculation was run until backwall bulging and/or rupture was predicted.

RESULTS

Base Case Results vs Experiment

Photographs from the XH-9 experiment [1] at $\approx 5.8\mu$ s show the leading edge of the debris cloud travelling at ≥ 11 km/s while radiographs at the same time give a velocity of ≈ 10 km/s; this indicates that the low-density vaporized debris front is travelling faster than the relatively higher density cloud imaged using X-rays. The base case CTH analysis predicts the leading edge of the debris cloud ($\rho \geq 10^{-6}$ gm/cm³) to be travelling at ≈ 12 km/s and the higher-density inner core ($\rho \geq 10^{-1}$ gm/cm³) to be travelling at ≤ 11 km/s, in reasonable agreement with test data.

Initial Temperature Variations

The debris cloud propagation seen in the first set of calculations (increasing the initial temperature of the flier plate and/or bumper shield) differs due to the varying amounts of molten and vaporized material produced in the initial impact. Figure 1 shows the debris cloud extent predicted by CTH at 5μ s after initial impact of the flier plate with the bumper shield, for the base case problem and for the three sensitivity studies as identified in Table 1. Contours showing order-of-magnitude changes in the density are included to highlight the debris cloud internal structure.

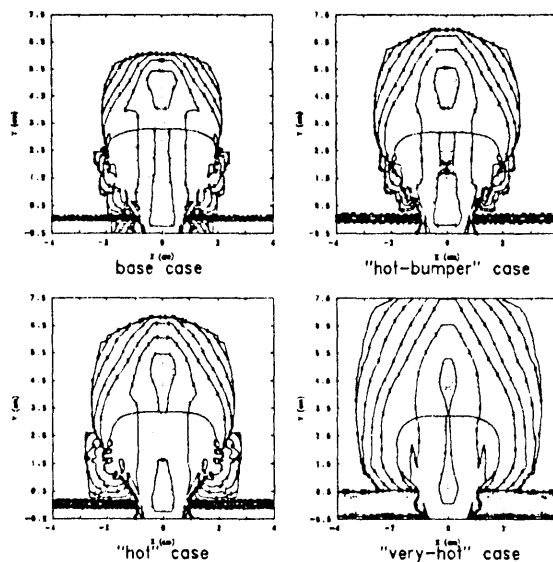


Figure 1. Debris Cloud with Density Contours at 5μ s for Base Case and Initial-Temperature Variations

At 5μ s after impact, the flier-plate debris consists of about equal amount of molten and vaporized material in the base case analysis; in the "very-hot" calculation, in contrast, the flier plate debris is about 67%-vapor at this time, due to the higher initial temperatures. (Note that the fraction of material molten or vaporized is estimated simply based upon the amount of material above the melt or vaporization temperature.)

The debris cloud in the base case analysis travels the slowest and has dispersed the least, while the debris cloud in the "very-hot" case travels the fastest and has dispersed the most.

As a result, the impulse imparted to the backwall is distributed differently in each of these four cases, in both space and in time, as shown in Figure 2 for a typical point in the backwall 0.25cm from the impact centerline. For all distances ≤ 0.5 cm from the impact, the impulse is significantly higher in the base case, and most of that impulse is accumulated in a relatively brief period (from $\approx 12.5\mu$ s to $\approx 17.5\mu$ s). In the "very-hot" calculation, due to the higher fraction of vaporized material, the impulse is significantly lower and is accumulating slowly. In the two intermediate cases, the final impulse in the region

$\leq 0.25\text{cm}$ from the impact centerline is $\approx 65\text{-}80\%$ lower than in the base case, and is accumulated over a somewhat longer period (from $\approx 12.5\mu\text{s}$ to $\approx 22.5\mu\text{s}$).

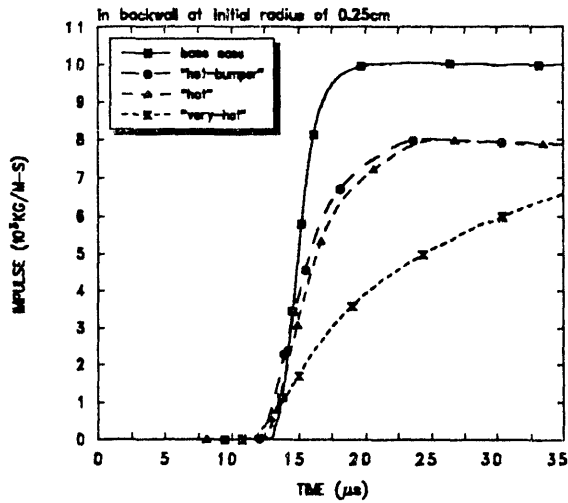


Figure 2. Impulse on Backwall for Base Case and Initial-Temperature Variations

The final configuration of the backwall in these four cases is shown in Figure 3. The greater, more localized and more rapid impulsive loading predicted by the base case results in late-time rupture of the backwall, while the lower and slower loadings predicted by the other three, elevated-temperature cases merely flex or bulge the backwall slightly.

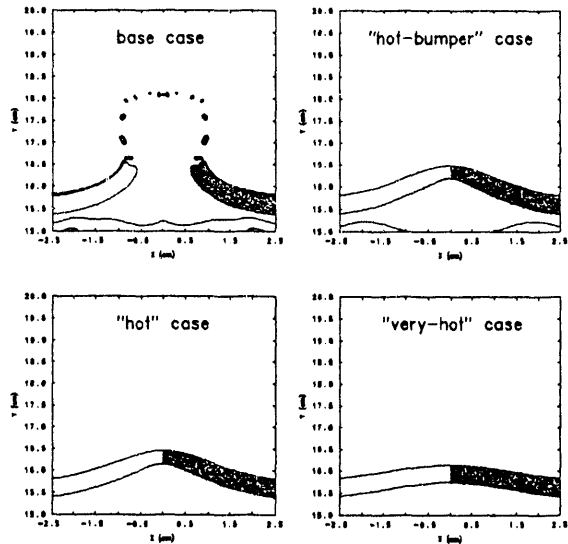


Figure 3. Backwall Configuration at $35\mu\text{s}$ for Base Case and Initial-Temperature Variations

Impact Velocity Variations

An alternate way to generate more vaporized material in a debris cloud is to have the initial impact occur at

higher velocities. Figure 4 shows the debris cloud resulting from a $\approx 20\text{km/s}$ impact at a time ($2.5\mu\text{s}$) corresponding to the debris cloud at $5\mu\text{s}$ in the base case $\approx 10\text{km/s}$ impact. The flier plate material in this debris cloud is $\approx 78\%$ vapor, compared to $\approx 50\%$ vapor in the basecase. However, since the leading edge of the vapor is travelling much faster in this case, it does not have sufficient time to disperse the debris as efficiently as in the initial-temperature variations. Therefore, a greater impulse is imparted to the backwall more rapidly for higher initial impact velocities, as shown in Figure 5 for a typical point in the backwall.

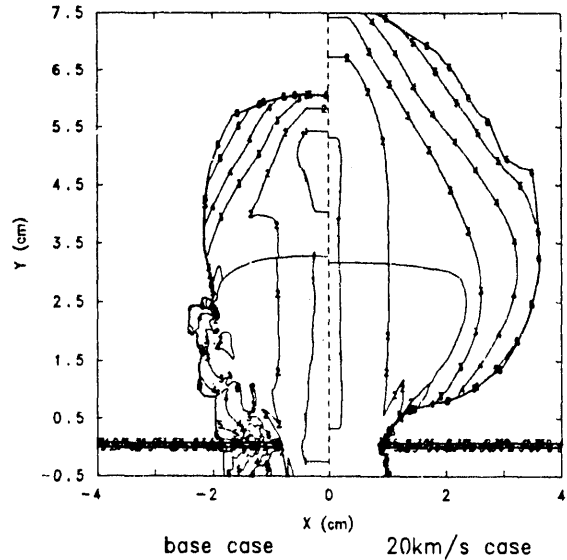


Figure 4. Debris Cloud at $5\mu\text{s}$ for $\approx 10\text{km/s}$ Impact (Base Case) and at $2.5\mu\text{s}$ for $\approx 20\text{km/s}$ Impact

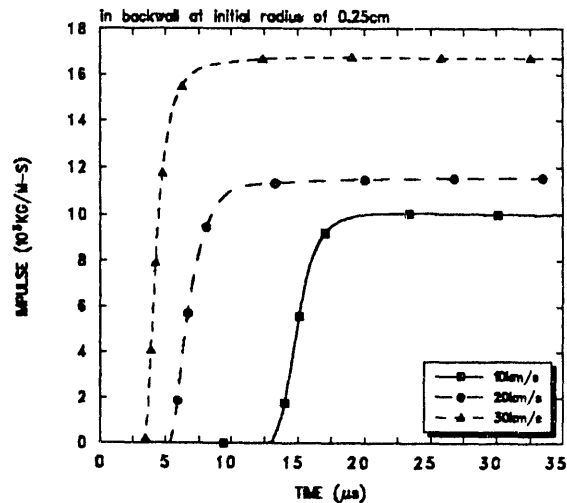


Figure 5. Impulse on Backwall for Base Case and Impact-Velocity Variations

Thus, although the thermal state of debris clouds resulting from higher-velocity impacts may be such that more vapor is present, the debris cloud has sufficient

concentrated kinetic energy to rupture the back wall. The diameter of the resulting hole was predicted to be 2.06cm and 3.10cm, respectively, for initial impact velocities of $\approx 20\text{km/s}$ and $\approx 30\text{km/s}$, compared to a final hole diameter of 1.25cm in the base case analysis.

Bumper Material Variations

Figure 6 shows the debris cloud structure predicted at $5\mu\text{s}$ assuming equal-mass bumper shields made of cadmium and plexiglass instead of titanium alloy. At the time shown, the debris cloud produced by impact with a thin, high-density, cadmium bumper has propagated slightly further both radially and axially and is slightly more spherical in shape than the debris cloud in the base case analysis; the debris cloud produced by impact with a thick, low-density, plexiglass shield has propagated much further axially and is much more elongated. With the cadmium shield, $\approx 55\%$ of the flier material is vapor at this time (compared to $\approx 50\%$ in the base case). With the plexiglass bumper, almost all of the flier material is molten by this time.

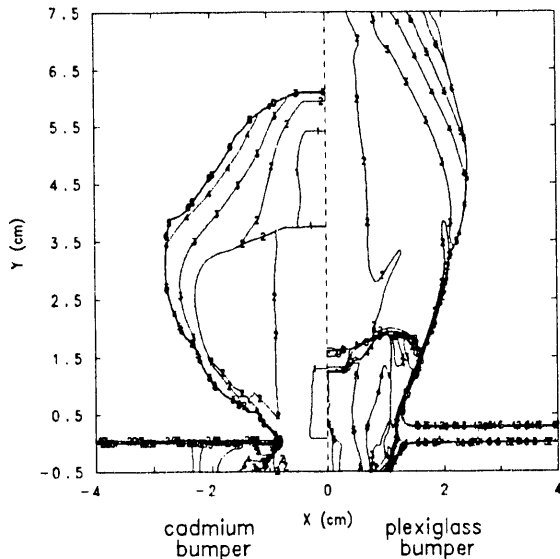


Figure 6. Debris Cloud with Density Contours at $5\mu\text{s}$ for Bumper-Material Variations

The more-rapidly expanding debris cloud generated by impact with a plexiglass bumper reaches the backwall earliest, while the leading edges of debris clouds generated by impacts with titanium and with cadmium shields arrive at about the same time, as shown in Figure 7 for a typical point in the backwall. All of these debris clouds have enough concentrated kinetic energy to rupture the backwall, with the hole size roughly proportional to the impulse loading delivered to the backwall in each case (as would be expected). The diameter of the resulting hole was predicted to be 1.75cm and 1.05cm, respectively, for the cadmium and plexiglass bumper shields, compared to a final hole diameter of 1.25cm in the base case analysis.

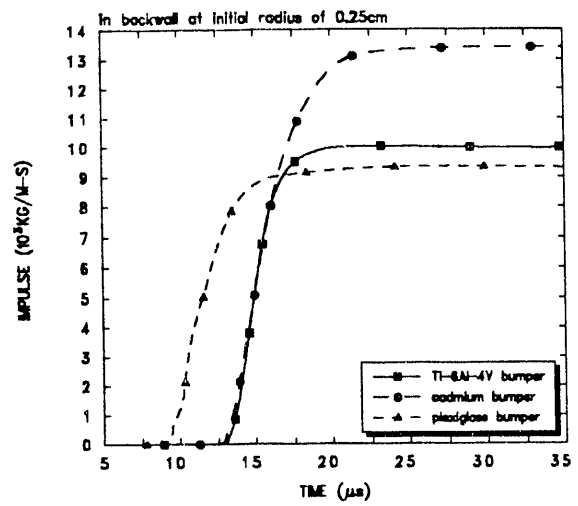


Figure 7. Impulse on Backwall for Base Case and Bumper-Material Variations

CONCLUSIONS

A series of calculations using the finite difference code CTH has been used to evaluate the effect of phase change (*i.e.*, higher concentrations of vapor) in a debris cloud and subsequent impact on a backwall structure. In these calculations, higher concentrations of vapor were achieved by increasing the initial temperature of the impactor and the bumper material while keeping the same impact velocity. The results showed that generating more vapor in the debris cloud did assist in backwall survival, by distributing the impact load over a wider surface area and longer time frame. The results of other calculations, assuming higher impact velocities, showed that the presence of a higher proportion of vaporized material in the debris cloud is not a sufficient condition for backwall survival, if the vaporized debris does not have enough time and/or space to disperse adequately before loading the backwall. Finally, calculations with different bumper shield materials indicate that individual material properties also affect debris cloud propagation and backwall damage.

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2. J. M. McGlaun, S. L. Thompson, L. N. Kmetyk, M. G. Elrick, "A Brief Description of the Three-Dimensional Shock Wave Physics Code CTH", Sandia National Laboratories, SAND89-0607, July 1990.

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