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Effect of Phase Change in a Debris Cloud on a Backwall Structure

L. N. Kmetyk, L. C. Chhabildas, M. B. Boslough, R. J. Lawrence

Prepared by
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Effect of Phase Change in a Debris Cloud on a Backwall Structure

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Abstract

The physical state of a debris cloud generated upon impact of a thin flier plate with a thin bumper depends on the impact velocity and material properties. 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 concentration of vapor is achieved *artificially* 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 with, and the subsequent loading of, the backwall depends on the thermophysical state of the debris cloud. 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 ~10km/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.

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1 Introduction

It is well known that the principal threat to orbiting space structures results from impact damage caused by orbiting space debris [1, 2]. Presently, conventional laboratory facilities are not available for evaluating damage mechanisms or the effectiveness of protective structures against this debris. Although analytic methods [3, 4] for predicting impact damage and hydrodynamics code [5] simulations of impact events have progressed to the point of providing realistic damage assessments, these analyses and/or models have not been validated over the velocity range of 7 to 10km/s, primarily due to lack of experimental capabilities to launch gram-size plates or particles over that velocity range.

A requirement for an effective debris shield is that it must protect the spacecraft from impacts both from the micrometeoroid and orbital debris environment. The micrometeoroid environment is thought to result from dust-size particles having an average velocity of 20km/s, while the orbital debris environment is believed to be millimeter- or centimeter-size particles weighing approximately a gram with average velocities of 10km/s. It is generally assumed that the average density of orbital debris in the environment [1, 2] is $\sim 2.8\text{g/cm}^3$, and therefore can be represented by the material properties of aluminum. The orbital debris, *i.e.*, the man-made space debris, is more hazardous than the micrometeoroid environment because of its abundance and relatively large mass and particle size. This makes the design requirements for an adequate bumper shield difficult to establish. In addition, the requirements for an adequate bumper shield are demanding due to:

1. The uncertainty in the size, shape and density of the orbital debris particulates,
2. The inability of hydrodynamics codes to accurately represent impact phenomena due to uncertainties in material properties and computational difficulties associated with the propagation of fragmented (molten and partially vaporized) debris, and
3. The lack of an impact test capability with launcher mass-velocity capabilities of approximately a gram and in excess of 7km/s to test design concepts.

With the development of a hypervelocity launch capability [6, 7] at Sandia, it is now possible to perform experiments over the velocity range of 7 to 12km/s [8], a velocity range not previously accessible for gram-size plates. This approximates the mass-velocity criteria established for the orbital debris environment, but not the shape.

A previous study [9] summarized test results performed to evaluate the integrity of a simple aluminum Whipple bumper shield located at 114mm from the space structure at impact velocities of $\sim 10\text{km/s}$; the mass of the aluminum flier plate, which is supposed to represent the orbital debris particle, was varied from 0.32g to 1.3g. Numerical simulations of those experiments were performed using the Eulerian finite-difference code CTH [10], results of which are also summarized in that report [9]. Results of those experiments

indicated that the thin aluminum bumper completely disintegrated into a debris cloud upon impact at $\sim 10\text{km/s}$ by the aluminum flier plate. The debris cloud front propagated at velocities in excess of 14km/s , and expanded radially at a velocity of $\sim 7\text{km/s}$. Photographic techniques were used to determine the propagation characteristics of the debris clouds in these experiments. Subsequent loading on the hull structure by the debris cloud penetrated the substructure completely. However, when the mass of the flier plate was reduced to 0.32g the substructure (although "damaged") was not punctured over the duration of the experiment. CTH simulations of those experiments predicted the results of the experiments qualitatively in that the penetration or lack of penetration of the substructure was correctly predicted; however, the propagation characteristics of the debris cloud were not replicated quantitatively.

In this report, test results performed to evaluate the integrity of a titanium-alloy Whipple bumper shield located at 152mm from the space structure at impact velocities of $\sim 10\text{km/s}$ are presented, together with CTH simulations of this experiment; in this case, the mass of the titanium-alloy flier plate was $\sim 1\text{g}$. This study determines the "mass" requirements of the orbital debris for the integrity of a backwall structure. It is the purpose of this report, however, to evaluate other methods to protect the backwall structure. This has led to an evaluation of the effect of increased vapor concentration in a debris cloud for a mixed mass of the orbital debris to protect a backwall structure. The results of this study are summarized in this report.

The experimental technique used to obtain hypervelocity launch characteristics has been described elsewhere [11]; the experimental setup used to simulate orbital debris impact conditions is described here only briefly, followed by a discussion and summary of the experimental results. The CTH input model is described briefly, followed by results of our basecase calculations with comparison to experimental data. Three computational sensitivity studies were done starting from that basecase, investigating the effect of initial temperature variations, impact velocity variations, and bumper material variations on debris cloud conditions and backwall damage.

2 Experimental Technique and Results

The experimental technique used to obtain hypervelocity launch characteristics has been described elsewhere [11]. The experimental setup used to simulate orbital debris impact conditions is described here briefly, followed by a discussion and summary of the experimental results in the next section.

The experimental impact configuration used to simulate orbital debris impact is indicated in Figure 2.1. In experiment XH-9, a 1mm-thick, 12.7mm-diameter Ti-6Al-4V flier weighing about 0.53g was launched to a velocity of 9.7km/s. The flier impacted on a bumper consisting of a single sheet of 0.74mm-thick Ti-6Al-4V. A 4mm-thick backwall of 6061-T6 aluminum was located about 150mm 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.

Such data for experiment XH-9 are presented in Figure 2.2. The left-hand image is a flash x-ray radiograph of the flier just before impact, showing it to be intact and slightly bowed. In the upper center is a flash x-ray image that was exposed about $5.8\mu\text{s}$ 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 $5.8\mu\text{s}$ 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. Analysis of these images suggests that the leading edge of the debris cloud determined from photographic records is travelling at over 11km/s, while the x-ray radiograph yields a velocity of $\sim 10\text{km/s}$. (Similar results have been reported previously for aluminum flier plates impacting aluminum bumpers [12-18].)

Figure 2.1. Experimental Impact Configuration used to Simulate Orbital Debris Impact on a Whipple Bumper Shield Design

Figure 2.2. Radiograph (Top) and Photograph (Bottom) of Debris Cloud Generated in Experiment XH-9

3 CTH Input Model

The CTH calculations were performed using a two-dimensional, cylindrical, geometry, and with the nonequilibrium, multi-material temperature and multi-material pressure modelling options and with the high-resolution interface tracker. Velocity was specified to be convected conserving momentum exactly and discarding any kinetic energy discrepancies. Artificial viscosity was used, with default values for the linear and quadratic coefficients, and the shear artificial viscosity increased to 0.1. The region around the flier plate, bumper shield and backwall was modelled as void.

The flier plate, bumper shield and backwall were all specified to be modelled by ANEOS equations of state [19], and as elastic-perfectly plastic materials. For Ti-6Al-4V in the flier plate and bumper shield we used Poisson's ratio $\nu=0.322$ and a yield stress $Y=12\text{kbar}$; for the 6061-T6 aluminum backwall we assumed Poisson's ratio $\nu=0.33$ and a yield stress $Y=5\text{kbar}$. The ANEOS parameters used in the basecase CTH analyses are given in Table 3.1 [20].

These impact calculations were run in two stages, as described below. Input listings used for the two stages for the base case calculation are given in the appendices, for reference.

3.1 Bumper Impact

First, the impact of the flier plate onto the bumper shield was simulated, using fine resolution. The x-direction (radial) mesh was started at $x=0$, the axis of symmetry in the cylindrical coordinates used, while the y-direction (axial) mesh was started at $y=-0.5\text{cm}$ 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 both axially and radially).

3.2 Backwall Impact

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 $\sim 10\text{km/s}$, took $\sim 6\mu\text{s}$. The material distribution at that time was then rezoned into a larger, coarser mesh which included the backwall. As in the first part of the calculation, the x-direction (radial) mesh was started at $x=0$, the axis of symmetry in the cylindrical coordinates used, and the y-direction (axial) mesh was started at $y=-0.5\text{cm}$ with the initial contact surface between the flier plate and the bumper shield defined to be $y=0$. However, this mesh used a subgrid of 100×474 0.04cm -square, larger, cells to model 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 and the backwall motion stopped.

Table 3.1. ANEOS Equation-of-State Parameters Used in CTH Base Case Calculation

ANEOS Parameter	Flier/Bumper (Ti-6Al-4V)	Backwall (6061-T6 Aluminum)
V1	3.	1.
V2	4.	4.
V3	4.42	2.7
V4	0.0	0.0
V5	0.0	0.0
V6	-4.99e5	7.63e11
V7	1.09	2.06
V8	0.036	0.0343
V9	0.80	-1.0
V10	2.	2.
V11	9.766e10	1.2e11
V12	0.1654	-6.639e9
V13	0.0	3.5e12
V14	0.0	0.8
V15	0.0	2.7e11
V16	0.0	0.043
V17	3.54671	0.0
V18	0.0	0.0
V19	0.0	0.0
V20	0.0	0.0
V21	0.0	0.0
V22	0.0	0.0
V23	3.225e9	3.98e9
V24	0.95	0.924
Z(1)	22.	13.
F(1)	0.9	1.
Z(2)	13.	
F(2)	0.06	
Z(3)	23.	
F(3)	0.04	

4 Basecase Results

Figure 4.1 shows the expansion of the debris cloud predicted at 1, 2, 3 and 4 μ s after impact of the flier plate with the bumper at 9.66km/s. The debris cloud configurations predicted at 5 and 6 μ s are presented in Figures 4.2 and 4.3, respectively. In these and subsequent debris cloud plots, contour lines show order-of-magnitude density variations, and dots highlight the higher-density core of the debris cloud. A high-density column, about equal in width to the original flier-plate diameter and travelling axially at about the original impact velocity, is visible in the debris cloud centerline; low-density material is seen expanding at higher velocity both laterally and axially from that central column. The material-interface lines indicate that the front half of the debris cloud consists of bumper-shield material, while the back half of the debris cloud consists of flier-plate material. The temperatures are highest in the center, with the column of higher-density material generally above the vaporization temperature, and most of the outer, low-density, material above the melt temperature.

Photographs from the XH-9 experiment (Figure 2.2) at $\sim 5.8\mu$ 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. Based upon the debris cloud shown in Figure 4.3, CTH 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, and are therefore qualitatively in reasonable agreement with test data.

The subsequent expansion of the debris cloud and its impact on the aluminum back-wall structure is illustrated in Figure 4.4, at 10, 15, 20 and 25 μ s after impact of the flier plate with the titanium-alloy bumper at 9.66km/s. The resulting hole in the backwall structure, at the end of the calculation at 35 μ s, is depicted in Figure 4.5; the predicted hole is unchanged between 30 and 35 μ s, indicating that it has stopped growing. (In these and subsequent backwall structure plots, only material interface lines and dot densities are used, to avoid visual clutter and highlight the condition of the back wall.) As expected, the rupture occurs on the centerline where the higher-density central column of debris impacts.

Figures 4.6 and 4.7 present pressure histories, and associated impulse delivered, for a number of history points embedded in the backwall structure at various distances radially outward from the impact centerline. The impact of the debris cloud causes a pressure rise, first visible on the centerline at $\sim 12.5\mu$ s and beginning later further out on the backwall. The pressure peaks at $\sim 15\mu$ s while there is yet no motion of the backwall (as seen in the upper right plot in Figure 4.4), and then falls as the back wall responds by bulging outward (as seen in the lower left plot in Figure 4.4). Both the pressures and the associated impulse drop off continuously with increasing distance from the centerline, where lower-density debris cloud material impacts the back wall.

Figure 4.1. Debris Cloud at $1\mu s$ (upper left), $2\mu s$ (upper right), $3\mu s$ (lower left), and $4\mu s$ (lower right) for Base Case Calculation

Figure 4.2. Debris Cloud at 5 μ s for Base Case Calculation

(Tim EOS) 2dc cth XN9 1mm TiAlV plate 9.66km/s on 29mil-TiAlv
 KBNCOR 11/02/92 15:28:59 CTH 1408 Time= 6.00204×10^{-6}

Figure 4.3. Debris Cloud at $6\mu\text{s}$ for Base Case Calculation

Figure 4.4. Debris Cloud and Backwall Structure at $10\mu s$ (upper left), $15\mu s$ (upper right), $20\mu s$ (lower left), and $25\mu s$ (lower right) for Base Case Calculation

Figure 4.5. Backwall Structure at $35\mu\text{s}$ for Base Case Calculation

Figure 4.6. Pressure on Backwall for Base Case Calculation

Figure 4.7. Impulse on Backwall for Base Case Calculation

5 Variational Studies

In Section 4, CTH simulations of tests performed to evaluate the integrity of a titanium-alloy Whipple bumper shield located at 152mm from the space structure at impact velocities of $\sim 10\text{km/s}$ were presented; that study helps determine the "mass" requirements of the orbital debris for the integrity of a backwall structure, and the reliability of using hydrocode simulations to represent these classes of investigations. The generally good agreement between calculations and experiments has allowed us to perform computational "gedanken" studies. This has resulted in an evaluation of the effect of increased vapor concentration in a debris cloud for a fixed mass of the orbital debris to protect a backwall structure, as a possible approach to a mitigating strategy. The results of this study are summarized in this section.

Three different variations were done on the problem described above in Section 4, to increase the vapor concentrations in the debris cloud.

- 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 5.1 (to increase the vapor content in the debris cloud); note that 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 $\sim 30\text{km/s}$.
- 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, as indicated in Table 5.2.

(The backwall was identical in all cases.)

5.1 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 5.1.1 shows the debris cloud extent predicted by CTH at $5\mu\text{s}$ after initial impact of the flier plate with the bumper shield, for the base case problem and for the three sensitivity studies identified in Table 5.1. Contours showing order-of-magnitude changes in the density and dot densities are included to highlight the debris cloud internal structure.

At $5\mu\text{s}$ after impact, the flier-plate debris consists of about equal amounts of molten and vaporized material in the base case analysis; in the "hot-bumper" and "hot" calculations, in contrast, the flier plate debris is between 50% and 60% vaporized at this

Table 5.1. Initial-Temperature Variation Study Input

Case ID	Flier Temperature	Bumper Temperature
Base Case	300K	300K
"Hot Bumper"	300K	1923K [†]
"Hot"	1923K [†]	1923K [†]
"Very Hot"	3513K [‡]	3513K [‡]

[†]1923K = $T_{MELT} - 20K$

[‡]3513K = $T_{VAP} - 20K$

Table 5.2. Bumper-Material Variation Study Input

Bumper Material	Density (gm/cm ³)	Thickness (cm)	T_{MELT} (K)	T_{VAP} (K)
Ti-6Al-4V (Base Case)	4.42	0.0762	1943	3533
Cadmium	8.92	0.0381	594	1040
Plastic	1.18	0.2667	300-400 [†]	

[†]decomposition

Figure 5.1.1. Debris Cloud at $5\mu s$ for Base Case Calculation (upper left), "Hot-Bumper" (upper right), "Hot" (lower left) and "Very-Hot" (lower right) Initial Temperature Variations

time and, in the "very-hot" calculation, 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 pressures and associated impulse imparted to the backwall are distributed differently in each of these four cases (when compared to the base case), in both space and in time, as shown in Figures 5.1.2 and 5.1.3 for points in the back wall at various distances from the impact centerline. For all distances $\leq 0.5\text{cm}$ 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 $\sim 12.5\mu\text{s}$ to $\sim 17.5\mu\text{s}$). 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 $\sim 65\text{-}80\%$ lower than in the base case, and is accumulated over a somewhat longer period (from $\sim 12.5\mu\text{s}$ to $\sim 22.5\mu\text{s}$).

The final configuration of the backwall in these four cases is shown in Figure 5.1.4. 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. This suggests, therefore, that a "hot" bumper sheet has the potential of "stopping" a hypervelocity projectile, when compared to a "cold" bumper plate, but needs to be substantiated experimentally.

5.2 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 5.2.1 shows the debris clouds resulting from a $\sim 20\text{km/s}$ impact at $2.5\mu\text{s}$ and from a $\sim 30\text{km/s}$ impact at $1.6\mu\text{s}$; these times correspond to the debris cloud location at $\sim 5\mu\text{s}$ for the base case $\sim 10\text{km/s}$ impact (presented in Figure 4.2). The flier plate material in these debris clouds is $\sim 78\%$ and $\sim 82\%$ vapor at the 20km/s and 30km/s impact velocities, respectively, compared to $\sim 50\%$ 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 discussed in Section 5.1. Therefore, a greater impulse is imparted to the backwall more rapidly for higher initial impact velocities, as illustrated in Figures 5.2.2 and 5.2.3 for a number of points in the backwall.

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 $\sim 20\text{km/s}$

Figure 5.1.2. Pressure on Backwall at Radial Distance of 0 (upper left), 0.2cm (upper right), 0.4cm (lower left) and 0.6cm (lower right) for Base Case Calculation and Initial Temperature Variations

Figure 5.1.3. Impulse on Backwall at Radial Distance of 0 (upper left), 0.2cm (upper right), 0.4cm (lower left) and 0.6cm (lower right) for Base Case Calculation and Initial Temperature Variations

Figure 5.1.4. Backwall Configuration at 35 μ s for Base Case Calculation (upper left), "Hot-Bumper" (upper right), "Hot" (lower left) and "Very-Hot" (lower right) Initial Temperature Variations

Figure 5.2.1. Debris Cloud at $2.5\mu\text{s}$ for 20km/s Impact (top) and at $1.6\mu\text{s}$ for 30km/s Impact (bottom)

Figure 5.2.2. Pressure on Backwall at Radial Distance of 0 (upper left), 0.2cm (upper right), 0.4cm (lower left) and 0.6cm (lower right) for Base Case Calculation and Impact-Velocity Variations

Figure 5.2.3. Impulse on Backwall at Radial Distance of 0 (upper left), 0.2cm (upper right), 0.4cm (lower left) and 0.6cm (lower right) for Base Case Calculation and Impact-Velocity Variations

and $\sim 30\text{km/s}$, as illustrated in Figure 5.2.4, compared to a final hole diameter of 1.25cm predicted in the base case analysis and shown in Figure 4.5. The results of the computational simulations are not surprising considering that the kinetic energy of the projectile is 4 and 9 times the kinetic energy of the basecase projectile.

5.3 Bumper Material Variations

Figure 5.3.1 shows the debris cloud structures predicted at $5\mu\text{s}$ assuming equal-mass (*i.e.*, equal areal density) 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, $\sim 55\%$ of the flier material is vapor at this time (compared to $\sim 50\%$ in the base case). With the plexiglass bumper, almost all of the flier material is molten by this time.

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 Figures 5.3.2 and 5.3.3 for typical points 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 final configuration of the backwall in these two cases is shown in Figure 5.3.4. 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. There appears to be a distinct correlation of the hole size with the density of the bumper material used in these studies. These concepts need to be evaluated further experimentally and theoretically.

Figure 5.2.4. Backwall Configuration at $35\mu\text{s}$ for 20km/s Impact (top) and for 30km/s Impact (bottom)

Figure 5.3.1. Debris Cloud at $5\mu\text{s}$ for Cadmium Bumper Shield (top) and for Plastic Bumper Shield (bottom)

Figure 5.3.2. Pressure on Backwall at Radial Distance of 0 (upper left), 0.2cm (upper right), 0.4cm (lower left) and 0.6cm (lower right) for Base Case Calculation and Bumper-Material Variations

Figure 5.3.3. Impulse on Backwall at Radial Distance of 0 (upper left), 0.2cm (upper right), 0.4cm (lower left) and 0.6cm (lower right) for Base Case Calculation and Bumper-Material Variations

Figure 5.3.4. Backwall Configuration at 35 μ s for Cadmium Bumper Shield (top) and for Plastic Bumper Shield (bottom)

6 Summary and 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. There is considerable speculation suggesting that the presence of an increased concentration of vapor states in a hypervelocity debris cloud would be sufficient to prevent the rupture of a backwall structure. The present study indicates that merely having an increased concentration of vapor in a debris cloud is not adequate to prevent the rupture of the structure upon which it impinges.

The use of these calculations is validated by comparing the results of CTH calculations with an experiment in which a titanium-alloy flier plate impacts a cold (room temperature) bumper sheet at 9.7km/s. The propagation characteristics of the resulting debris cloud determined calculationally agrees well qualitatively with the measured debris cloud and is noted to rupture a backwall structure both in the calculation and in the experiment.

Higher concentrations of vapor were achieved by increasing the initial temperature of the bumper material and the impactor at the same impact velocity of ~ 10 km/s. The results of these calculations may be summarized as follows:

- It is merely sufficient to increase the temperature of the bumper plate close to its melt temperature to prevent the rupture of the backwall structure.
- The debris cloud is sufficiently dispersed both spatially and temporally to result in distributing the impact load over a wider surface and a longer time frame.

Higher concentrations of vapor also can be achieved by increasing the initial impactor velocity to ~ 20 and ~ 30 km/s. The results of these calculations may be summarized as follows:

- The kinetic energy of the impacting projectile is now a factor of 4 and 9 times the kinetic energy of the projectile travelling at ~ 10 km/s.
- The resulting debris cloud propagates at much faster speeds when compared to the base case at 10km/s, resulting in a higher impulsive loading on the backwall structure located at the same standoff distance from the bumper.
- Since the debris cloud does not have enough time and/or space to disperse adequately before impinging on the backwall, it results in rupturing the structure.

In another set of calculations, higher concentrations of debris cloud vapor were obtained through the selection of low melting point bumper materials such as cadmium and a plastic plexiglass polymethylmethacrylate. In each case, the thickness of the bumper sheet was varied to ensure the same areal density as the base case. Results of these calculations may be highlighted as follows:

- Although a higher concentration of vaporized states do exist in the debris cloud, the backwall structure indeed ruptures upon loading.
- The hole size in the backwall appears to correlate with the density/impedance of the bumper material.
- This appears to be the result of a larger impulsive loading on the backwall structure when higher impedance materials are used as bumper sheets.

Based on this study it would appear that lower density materials would perform better as bumper shield materials when compared to higher density materials, for comparable masses. These computational results in each instance need to be evaluated further experimentally.

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A Bumper-Impact Input Deck

```
*
*eor*cgenin*
*
(Tim EOS) 2dc cth XH9 1mm TiAlV HOT-plate 9.66km/s on 29mil-TiAlv
*
control
  ep
  mmp
endcontrol
*
mesh
  block 1 geom 2dc type e
    x0 0.0
      x1 n 400 dxf 0.01 w 4.00
      x2 n 60 dxf 0.01 rat 1.05
    endx
    y0 -0.5
      y1 n 750 dyf 0.01 w 7.50
      y2 n 60 dyf 0.01 rat 1.05
    endy
    xact 0.0 2.00
    yact -1.0 0.0
  endblock
endmesh
*
insertion_of_material
  block 1
    package flyerplate
      material 1
      numsub 100
      yvelocity 9.66e5
      insert box
        x1 0.00000 x2 0.63145
        y1 -0.19800 y2 -0.10000
      endinsert
    endpackage
  package front-plate
    material 2
    numsub 100
    insert box
      x1 0.00000 x2 999.99999
      y1 0.00000 y2 0.07366
    endinsert
  endpackage
endblock
```

endinsertion

*

*

tracer

add 0.00000 -0.14800

add 0.10000 -0.14800

add 0.20000 -0.14800

add 0.25000 -0.14800

add 0.30000 -0.14800

add 0.40000 -0.14800

add 0.50000 -0.14800

add 0.60000 -0.14800

endtracer

*

eos num 2

mat1 -1

mat2 -1

*

*****

*

* DEFINE ANEOS TI-ALLOY

* -----

*

	NEOS	TITLE	LIB	TYPE	RHUG	THUG
ANEOS1	-1	'Ti-Al-V'			RHUG=-1	THUG=-1

	V1	V2	V3	V4	V5	V6	V7	V8
ANEOS2	3.	4.	4.42	0.	0.	-4.99e5	1.09	0.036

	V9	V10	V11	V12	V13	V14	V15	V16
ANEOS3	0.80	2.	9.766e10	.1654	0.0	0.0	0.0	0.0

	V17	V18	V19	V20	V21	V22	V23	V24
ANEOS4	3.54671	0.0	0.0	0	0.0	0.0	3.225e9	0.95

	Z(I)	F(I)
ANEOS5	22.	0.90

ANEOS5	13.	0.06

ANEOS5	23.	0.04

***** END OF DATA *****

*****

*

endaneos

*

endinput

*

*eor*cthin*

*

(Tim EOS) 2dc cth XN9 1mm TiAlV HOT-plate 9.66km/s on 29mil-TiAlv

*

control

```

mtrepo
tstop 6.0e-6
rdumpf 360000.0
cpshift 999.0
ntbad 100000
endcontrol
*
edit
  shortt
    time 0.0 dtfrequency 1.0e-6
  ends
  longt
    time 0.0 dtfrequency 1.0e-6
  endl
  plott
    time 0.0 dtfrequency 2.5e-7
  endp
  histc
    cycle 0 dcfrequency 5
    htracer1
    htracer2
    htracer3
    htracer4
    htracer5
    htracer6
    htracer7
    htracer8
  endh
ende
*
boundary
  bhydro
    block 1
      bxbot 0
      bxtop 2
      bybot 2
      bytop 2
    endb
  endh
endb
*
epdata
  matep 1 yield 12.e9 poisson 0.322
  matep 2 yield 12.e9 poisson 0.322
  mix 3
ende
*

```

```

fracts
  pressure
    pfmix -5.0e6
    pfvoid -5.0e6
    pfrac1 -10.0e9
    pfrac2 -10.0e9
endf
*
convct
  convection 1
  interface=high
endc
*
*eor* pltin
*
units cgsk
*
nlegend=off
*
contours,1.0e-6,1.0e-5,1.0e-4,1.0e-3,1.0e-2,1.0e-1,1.0
csymbols,'6','5','4','3','2','1','0'
*
limits x=-4.0,4.0,8 y=-0.5,7.5,8
flegend,c,d
left,contours,if
right,dots,if
2dplot mirror if dots=density=2.5 contours=density
*

```


B Backwall-Impact Input Deck

```
*
2d cth rezone debris cloud
*
prerezone
  file='rsctt'
  ofile='rezout'
  numsub=25
  time=6.0e-6
geom
  map=2dto2d
endg
endp
.
*
*eor*rezin*
*
(Tim EOS) 2dc cth XH9 1mm TiAlV plate 9.66km/s on 29mil-TiAlv
*
control
  ep
  mmp
  time 6.0e-6
endcontrol
*
mesh
  block 1 geom 2dc type e
    x0 0.0
      x1 n 100 dxf 0.04 w 4.00
      x2 n 50 dxf 0.04 rat 1.05
    endx
    y0 -0.5
      y1 n 475 dyf 0.04 w 19.0
      y2 n 25 dyf 0.04 rat 1.05
    endy
    xact 0.0 3.00
    yact -1.0 8.0
  endblock
endmesh
*
rezone
  file='rezout'
endr
*
insertion_of_material
  block 1
```

```

package back-plate
  material 3
  numsub 100
  insert box
    x1 0.00000 x2 999.99999
    y1 15.31366 y2 15.71498
  endinsert
endpackage
endblock
endinsertion
*
*
tracer
  add 0.00000 15.3200
  add 0.10000 15.3200
  add 0.20000 15.3200
  add 0.25000 15.3200
  add 0.30000 15.3200
  add 0.40000 15.3200
  add 0.50000 15.3200
  add 0.60000 15.3200
  add 0.70000 15.3200
  add 0.75000 15.3200
  add 1.00000 15.3200
  add 1.25000 15.3200
  add 1.50000 15.3200
  add 1.75000 15.3200
  add 2.00000 15.3200
  add 2.50000 15.3200
  add 3.00000 15.3200
  add 4.00000 15.3200
  add 5.00000 15.3200
  add 7.50000 15.3200
endtracer
*
eos num 3
  mat1 -1
  mat2 -1
  mat3 -2
*
*****
*
* DEFINE ANEOS TI-ALLOY
* -----
*
*      NEOS      TITLE      LIB      TYPE      RHUG      THUG
ANEOS1 -1      'Ti-Al-V'      RHUG=-1 THUG=-1

```

	V1	V2	V3	V4	V5	V6	V7	V8
ANEOS2	3.	4.	4.42	0.	0.	-4.99e5	1.09	0.036

	V9	V10	V11	V12	V13	V14	V15	V16
ANEOS3	0.80	2.	9.766e10	.1654	0.0	0.0	0.0	0.0

	V17	V18	V19	V20	V21	V22	V23	V24
ANEOS4	3.54671	0.0	0.0	0	0.0	0.0	3.225e9	0.95

	Z(I)	F(I)
ANEOS5	22.	0.90
ANEOS5	13.	0.06
ANEOS5	23.	0.04

***** END OF DATA *****

*

ANEOS -2 'Al' type=3 lib=6

*****

*

endaneos

*

endinput

*

*eor*cthin*

*

(Tim EOS) 2dc cth XN9 1mm TiAlV plate 9.66km/s on 29mil-TiAlv

*

control

mtrepo

tstop 35.0e-6

rdumpf 360000.0

cpshift 999.0

ntbad 10000000

endcontrol

*

restart

* time=30.0e-6

endr

*

edit

shortt

time 0.0 dtfrequency 5.0e-6

ends

longt

time 0.0 dtfrequency 5.0e-6

endl

plott

time 0.0 dtfrequency 1.0e-6

endp

histc

cycle 0 dcfrequency 5

```

htracer1
htracer2
htracer3
htracer4
htracer5
htracer6
htracer7
htracer8
htracer9
htracer10
htracer11
htracer12
htracer13
htracer14
htracer15
htracer16
htracer17
htracer18
htracer19
htracer20
endh
ende
*
boundary
  bhydro
    block 1
      bxbot 0
      bxtop 2
      bybot 2
      bytop 2
    endb
  endh
endb
*
epdata
  matep 1 yield 12.e9 poisson 0.322
  matep 2 yield 12.e9 poisson 0.322
  matep 3 yield 5.e9 poisson 0.33
  mix 3
ende
*
fracts
  pressure
    pfmix -5.0e8
    pfvoid -5.0e8
    pfrac1 -10.0e9
    pfrac2 -10.0e9

```

```

    pfrac3 -17.0e9
endf
*
convct
    convection 1
    interface=high
endc
*
*eor* hisplt
*
units cgsev
*
plot time cpu v2=dt
plot time mat-ek.1
plot time mat-ek.2
*
plot time mat-y-mom.1
plot time mat-y-mom.2
*
plot time yvelocity.1 legend='x0=0.0cm'
cplot time yvelocity.2 legend='x0=0.10cm'
cplot time yvelocity.3 legend='x0=0.20cm'
cplot time yvelocity.4 legend='x0=0.25cm'
cplot time yvelocity.5 legend='x0=0.35cm'
cplot time yvelocity.6 legend='x0=0.40cm'
cplot time yvelocity.7 legend='x0=0.55cm'
cplot time yvelocity.8 legend='x0=0.60cm'
legend,next
*
plot time xvelocity.1 legend='x0=0.0cm'
cplot time xvelocity.2 legend='x0=0.10cm'
cplot time xvelocity.3 legend='x0=0.20cm'
cplot time xvelocity.4 legend='x0=0.25cm'
cplot time xvelocity.5 legend='x0=0.35cm'
cplot time xvelocity.6 legend='x0=0.40cm'
cplot time xvelocity.7 legend='x0=0.55cm'
cplot time xvelocity.8 legend='x0=0.60cm'
legend,next
*
*eor* pltin
*
units cgsk
*
nlegend=off
*
contours,1.0e-6,1.0e-5,1.0e-4,1.0e-3,1.0e-2,1.0e-1,1.0
csymbols,'6','5','4','3','2','1','0'

```

```
*  
limits x=-4.0,4.0,8 y=-0.5,7.5,8  
flegend,c,d  
left,contours,if  
right,dots,if  
2dplot mirror if dots=density=2.5 contours=density  
*
```

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