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WHIPPLE BUMPER SHIELD SIMULATIONS

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The Whipple bumper is a space shield designed to protect a space station from the most hazardous orbital space debris environment. A series of numerical simulations has been performed using the multi-dimensional hydrodynamics code CTH to estimate the effectiveness of the thin Whipple bumper design. These simulations are performed for impact velocities of ~10 km/s which are now accessible by experiments using the Sandia hypervelocity launcher facility. For a ~10 km/s impact by a 0.7 gm aluminum flier plate, the experimental results indicate that the debris cloud resulting upon impact of the bumper shield by the flier plate, completely penetrates the sub-structure. The CTH simulations also predict complete penetration by the subsequent debris cloud.

1. INTRODUCTION

A requirement for an effective debris shield is that it must protect the spacecraft from impacts both from the micrometeoroid or orbital debris environment. The micrometeoroid environment is thought to consist of dust-size particles having an average velocity of 20 km/s, while the orbital debris environment is believed to be millimeter or centimeter size particles weighing approximately a gram with average velocities of 10 km/s. It is generally assumed that the average density of the orbital debris environment is ~2.8 gm/cm^3, and predominately consists of aluminum. The orbital debris environment, which is man-made space debris is considered to be more hazardous than the micrometeoroid environment because of its relatively large mass.

With the development of a hypervelocity launch capability at Sandia, it is now possible to perform experiments over the velocity range of 7 km/s to 10.4 km/s, a velocity range not accessible previously for gram-size projectiles. This mass-velocity capability coincides with an expected peak in the actual orbital debris environment[1]. In this paper, hydrodynamic simulations were performed using the multidimensional code CTH[2] to evaluate the integrity of a simple aluminum Whipple bumper shield located at 114 mm from the space structure at impact velocities of 10.1 km/s are summarized. The mass of the aluminum flier plate which is supposed to represent the orbital debris particle is 0.67 gm.

Results of this experiment which are discussed in detail in a companion paper[1] indicate that the thin aluminum bumper completely disintegrates into a debris cloud upon impact at ~10 km/s by an aluminum flier plate. The debris cloud front propagates at velocities in excess of 14 km/s, and expands radially at a velocity of ~7 km/s. Subsequent loading on the hull structure by the debris cloud penetrates the substructure completely. The CTH simulation qualitatively agrees with the experiment in that penetration of the hull structure is predicted by CTH. However, the CTH simulation does not predict a ~14 km/s debris cloud longitudinal velocity or a ~7 km/s radial velocity.

Although several hydrodynamics codes have thermodynamics models that are used to simulate strong shocks, the validity of these models for velocities in excess of 7 km/s has never been carefully evaluated, primarily due to lack of experimental studies at these velocities. At these impact velocities, materials are expected to melt and partially vaporize. Results of controlled experimental studies will allow a careful evaluation of thermodynamics models that are used in hydrodynamics codes to represent melting and vaporization.

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2. CTH HYDRODYNAMICS CODE

The CTH[2] code was developed to model a wide range of solid dynamics problems involving shock wave propagation and material motion in one, two, or three dimensions. A two-step Eulerian solution scheme is used; the first step is a Lagrangian step in which the cells distort to follow the material motion, the second step is a remesh step where the distorted cells are mapped back to the original Eulerian mesh. CTH has several thermodynamic models that are used for simulating strong shock, large deformation events. Both tabular and analytic equations-of-state are available. CTH can model elastic-plastic behavior, high explosive detonation, fracture, and motion of fragments smaller than a computational cell. The elastic-plastic model is linearly elastic-perfectly plastic with thermal softening. A programmed burn model is available for simulating high explosive detonation with ideal gas and Jones-Wilkins-Lee equation-of-state available for computing the thermodynamic properties of high explosive reaction products. A special model is available for moving fragments smaller than a computational cell with the correct statistical velocity. CTH has been carefully designed to minimize the dispersion generally found in Eulerian codes. It has a high-resolution interface tracker that prevents breakup and distortion of material interfaces. It uses second-order convection schemes to flux all quantities between cells.

3. PROBLEM SPECIFICATION

3.1 Experimental

The experimental impact configuration can be described as follows. The bumper shield material used was a 305 mm X 305 mm 6061-T6 aluminum alloy sheet, 1.2 mm thick. The space station hull structure was represented by a 305 mm X 305 mm 2219-T87 aluminum alloy panel, 3.20 mm thick. The stand-off distance between the bumper shield and the hull plate was 114 mm. The flier plate was constructed from 6061-T6 aluminum alloy sheet, 0.868 mm thick. The inner disk was 19 mm in diameter and had a mass of 0.667 gm. Diagnostics show the flier plate velocity to be 10.1 km/s. Front-lit photography was used to determine the structure of the debris cloud for at least 55 μs after the initial impact.

3.2 Computational

The actual experimental flier plate shape is not flat. Radiographs taken ~20 μs before impact appear to show a spherical cap of unknown obliquity and radius. The temperature of the flier plate is thought to be 600 K and the flier plate is intact prior to impact. Since the flier plate is initially flat, deformation has taken place during the shockless but rapid acceleration process[3]. We chose to bracket the experimental configuration with a flat plate (radius and thickness equal to that of the experimental flier plate) and a sphere of the same mass, both impacting normally. Since only normal impacts were considered, the computational geometry was two-dimensional axis-symmetric. The computational configuration used to simulate the experiment is indicated in Figure 1.

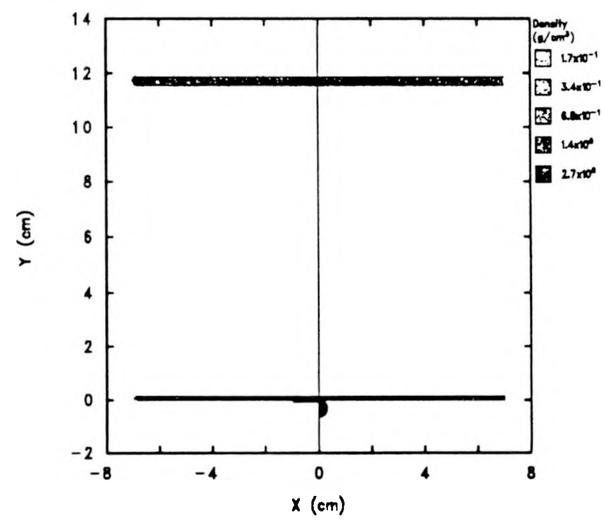

FIGURE 1

Initial Computational Configuration, Left Side, Flat Plate Right Side, Sphere

Our experience with CTH has shown that four computational zones across the thickness of a material is the minimum number necessary to resolve the shock structure in that material. For these simulations, we chose to increase the computational resolution to ~10 zones across the thickness of the bumper shield and the hull structure. In the region of initial impact, the zones are square (0.012 x 0.012 cm). The zones are gradually increased in size radially and longitudinally, so that, in the region of secondary impact, the zones are rectangular (0.012 X ~0.300 cm).

The two different aluminum modelled in this simulation are all treated using the elastic-plastic model with a Von Mises yield surface for material strength. Failure in tension is modelled by a simple cutoff scheme that relieves tension by introducing void into a computational cell when the mean principal stress exceeds the tensile strength. Table 1 lists the values used for the simulations reported here.

Table I : Material Strength Parameters

Aluminum	Yield Strength (dynes/cm^2)	Tension Limit (dynes/cm^2)
6061-T6	3.0×10^9	5.0×10^9
2219-T87	5.0×10^9	11.0×10^9

Aluminum was modelled with identical equations-of-state, namely, the SESAME table developed by Kerley[3].This table was scaled to take into account the higher density of the 2219 aluminum.

Finally, the multi-material pressure and temperature model was utilized in CTH. This model allow each material in a mixed cell to have a unique temperature and pressure. This model generally produces the "best" results, even though their are no mechanisms to allow for pressure relaxation and temperature equilibrium. In the time scales of the current simulations, the inability to model these phenomena is not expected to effect the results.

FIGURE 2

Experimental Debris Cloud at 7 μs after initial impact

In addition, a discard option was used to remove very low density vapor from the computational domain. When the flier plate and/or bumper material pressure and density dropped below 1×10^6 dynes/cm^2 and 1×10^{-4} gm/cm^3, that material was removed from the computational domain. This procedure tends to reduce the computation time by artificially removing material that does not effect the outcome of the simulation.

4. COMPUTAIONAL RESULTS

4.1 Material Locations and Qualitative Results

Figure 2 shows the debris cloud for the experiment[1] at 7 μs after initial impact which is ~1 μs prior to impacting the hull plate. This implies that the debris cloud front propagation velocity is ~14 km/s.

Figure 3 shows a representation of the CTH debris cloud at 11 μs after initial impact for a plate projectile on the left and for a spherical projectile on the right.

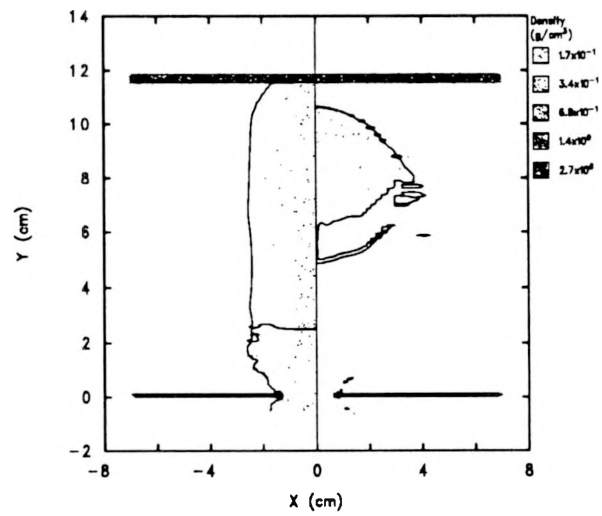

FIGURE 3

CTH Debris Cloud at 11 μs After Initial Impact

For both projectiles, the CTH debris cloud travels at approximately the same velocity as the projectile (~10 km/s). Radial expansion velocity of the debris cloud depends substantially on the projectile shape, for a flat plate the radial expansion velocity is ~1.3 km/s, for the spherical projectile it is ~3.4 km/s. Even for the spherical projectile, the predicted radial velocity is slower than what is determined experimentally. Figure 4 shows the hull structure at 20 μs after initial impact for a plate projectile on the left and for a spherical projectile on the right.

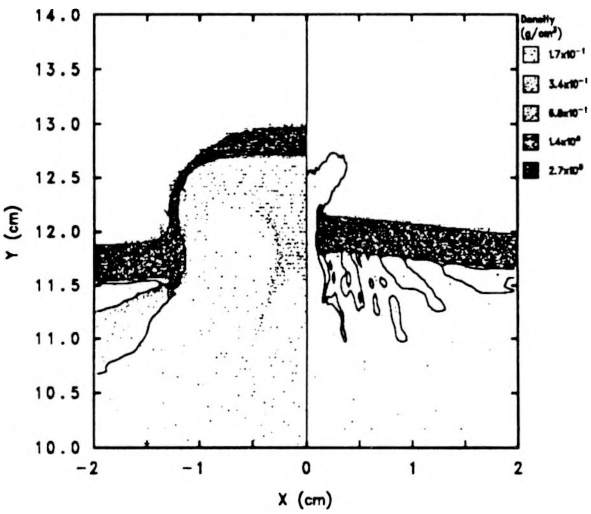

FIGURE 4

CTH Simulation of Hull Structure at 20 μs After Initial Impact

For both projectile assumptions, the hull structure is penetrated, although, the damaged area is larger for the flat plate assumption. Examination of the tensile state of the hull structure indicates that initial relief wave causes peak tensions of ~50×10^9 dynes/cm^2, in excess of any reasonable values for the tensile strength of aluminum.

4.2 Thermodynamic State of the Debris Cloud

Table 2 lists the percentage by mass of the bumper and projectile material in solid, liquid, and vapor state just prior to impact with the hull structure (11 μs). These estimates are based on CTH simulations and the equation-of-state of aluminum[4] which has been validated against shock induced vaporization experiments on aluminum[5].

Table II : Mass Fractions of the Debris Cloud

Material	Solid	Liquid	Vapor
Projectile (Sphere	0.00	0.87	0.13
Bumper (Sphere)	0.25	0.75	0.00
Projectile (Plate)	0.00	0.01	0.99
Bumper (Plate)	0.06	0.82	0.24

5. CONCLUSIONS

Results of the CTH simulations qualitatively agree with the experiment[1], in that penetration of the hull structure is predicted. The amount of damage or hole size predicted by CTH is between 0.5 and 2 cm in diameter, depending on projectile. The experimental photographs indicate that the hull structure hole is at least ~1.5 cm in diameter just after breaching. However, the increase in debris cloud front velocity over the impact velocity is not predicted. Very finely resolved one-dimensional simulations using an identical equation-of-state predict a debris front velocity of ~11.5 km/s. Similar calculations with a Lagrangian model also fail to predict debris front velocities in excess of ~11 km/s. Possible reasons for the observed discrepancy is thought to be due to: (1) the uncertainty in the equation-of-state for aluminum in expanded states, (2) the inability for the codes to model phase separation. Experimentally, it is believed that the low density vapor phase separates and travels much faster than the molten aluminum. The mechanisms and theories to represent phase separation are not available in CTH at this time. A phase separation effect should increase the debris cloud propagation velocity axially and radially and improve quantitative agreement between experiment and simulation.

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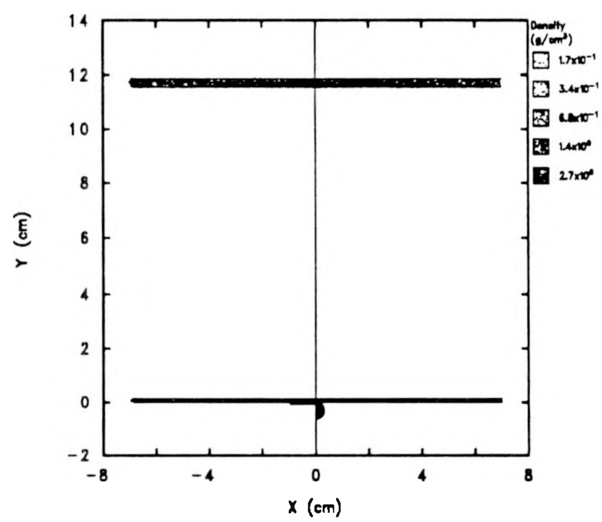

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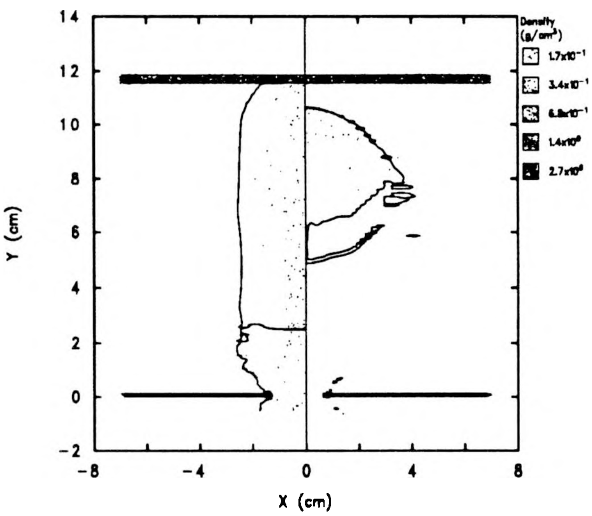

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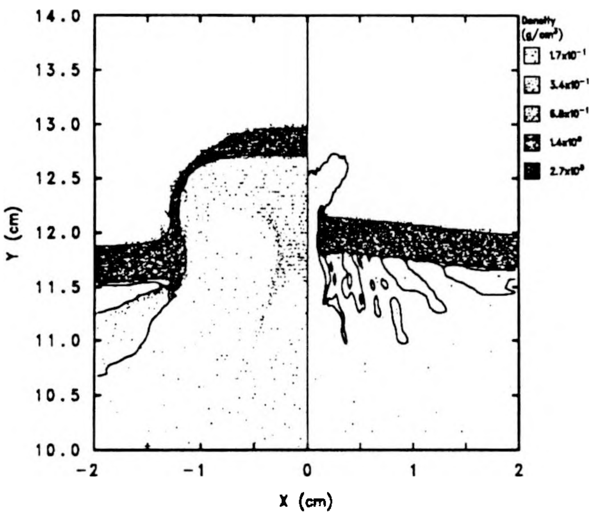

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