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HYPERVELOCITY IMPACT TEST FACILITY TO SIMULATE ORBITAL DEBRIS BY SHAPED CHARGE SINGLE PROJECTILES

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ABSTRACT

For the European Space Agency ESA as sponsor, Battelle at Frankfurt in Germany put a high explosive technology to work that permits to generate a single aluminium projectile with an impact velocity of 11.3 km/s, a cylindrical shape with an aspect ratio of 1.5 to 10, and a mass between 0.3 and 3 g. Primarily, the projectile is produced as the non-stretching tip particle of the metallic jet of a specifically designed shaped charge. Sophisticated explosive techniques were employed to get rid of the trailing jet particles and of the slug. The projectile is shortened to the desired length by consuming its leading portion during penetration of a PE plate of proper thickness. A special firing tank facilitates hypervelocity impact tests on targets of 500 mm diameter and up to a height of 900 mm under a vacuum of about 1 mbar. Via X-ray windows several flash X-ray pictures can be taken during each hypervelocity impact at differing times and at different locations of the target structure.

1. INTRODUCTION

For a space station orbiting at an altitude of 500 km and an inclination of 28,5°, by far most of the oncoming space debris particles have collision velocities in the range of 8.5 to 13.7 km/s. To investigate space debris protection shields under realistic conditions, hypervelocity impact tests are required that allow to study the impact behaviour of particles having a mass of about 1 g and a velocity > 10 km/s.

Different methods to accelerate particles are available. Each of them has particular limits in velocity and mass of the accelerated particles. The light gas gun is the standard tool for the simulation of orbital debris. By high performance light gas guns aluminium spheres can be launched to velocities of 10 km/s, but the mass is restricted to about 10 mg. Electrostatic dust accelerators can achieve velocities up to 60 km/s, but only in the mass range 10^{-15} g to 10^{-9} g. Electromagnetic plasma guns can accelerate masses in the range 10^{-8} g to 10^{-4} g to velocities up to 20 km/s. Electromagnetic guns are capable of launching a mass of more than 3 g up to a velocity of 11 km/s; but for that an enormous and costly experimental effort is required.

By shaped charge explosive accelerators of reasonable caliber, single aluminium projectiles with a mass between 0.1 g and 3 g can be generated and launched to a velocity of up to 12.3 km/s. The projectile is produced as the non-stretching tip particle of the jet of a specifically designed shaped charge. To get a single projectile, the trailing jet particles of lower velocity have to be removed. The slug at the end of the jet has to be blocked. The projectile itself generally has to be shortened to the needed aspect ratio. After passing through the shortening device the projectile travels to the target in the vacuum of a special firing tank. Thus, further degradation of the projectile by ablation in air is avoided, and no ablation products impinge on the target together with the projectile.

2. SHAPED CHARGE CONFIGURATION

The quasi-continuous mass distribution along its jet makes a conventional shaped charge unsuitable for orbital debris impact simulation. Based on experimental experience and supported by numerical simulations Battelle has designed a special shaped charge configuration (Figure 1) that provides a single non-stretching jet tip particle of large mass while the mass of the following jet particles is comparatively small. Velocity, length and diameter of the tip particle depend on the geometry of the explosive charge and the liner. They can be varied within certain limits. In particular, the speed of the tip particle is mainly determined by the

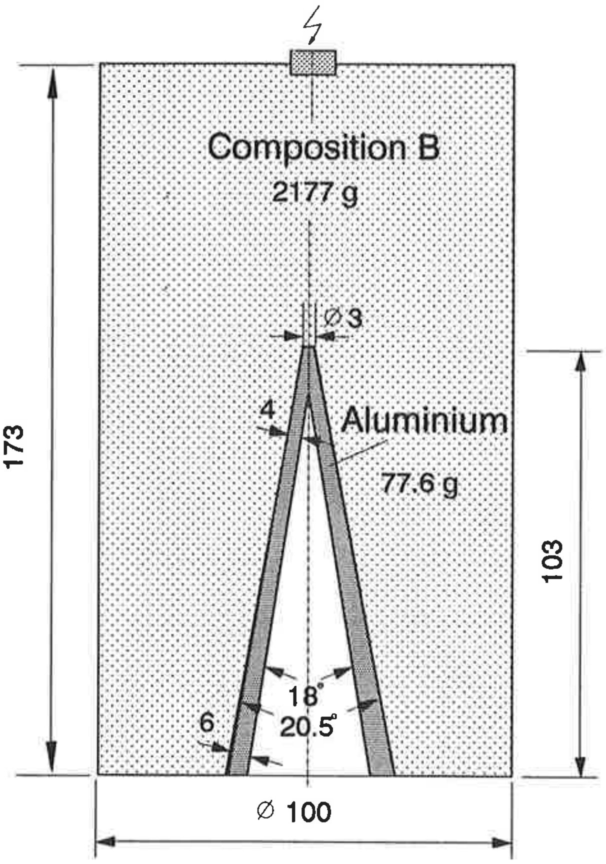

Figure 1. Shaped charge configuration

cone angle and the average thickness of the liner. The tip velocity is also determined by the type of high explosive employed for the charge. With Composition B which is a military high explosive containing 60% RDX, 39% TNT, and 1% wax and has a detonation velocity 7000 m/s, the shaped charge configuration of Figure 1 produces a tip particle speeding with 11.3 km/s. By using octogen as high explosive, a tip particle velocity of 12.3 km/s is achievable. To get a non-stretching tip particle that stays coherent and does not expand radially, the aluminium of the liner has to be of high purity, low grain size, and without texture.

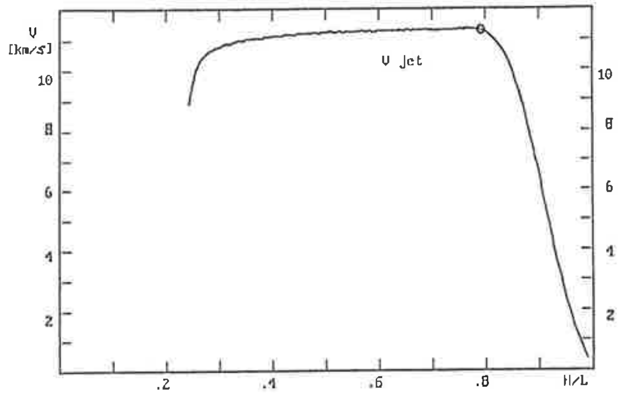

Figure 2. Velocity of liner elements

Numerical simulations were carried out with an one-dimensional analytical code for shaped charge computations (Ref. 1). Figure 2 shows the velocity of individual liner elements as a function of H/L, where L is the height of the liner and H designates the distance of the liner elements from the apex. There is an extended range with an inverse velocity gradient which leads to accumulation of a large mass in the hypervelocity tip particle of the jet.

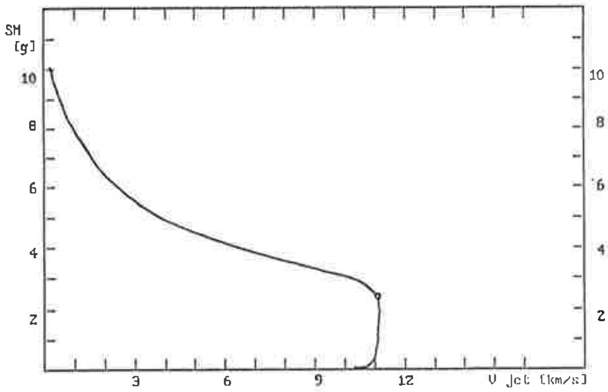

Figure 3. Cumulated mass of jet elements versus velocity

In Figure 3 the accumulated mass SM versus the jet velocity v_{jet} is displayed. A mass of about 2.5 g is added up within the 11.3 km/s fast tip particle.

A flash X-ray picture of the jet generated by a shaped charge according to Figure 1 is shown in Figure 4. The non-stretching tip particle has a velocity of 11.3 km/s. Its diameter is 4.7 mm, its length 34 mm (L/D = 7.2), and its mass amounts to 1.6 g. Small particles are trailing the tip particle with steadily decreasing velocity. The slug follows at the end of the jet with much less than 1 km/s.

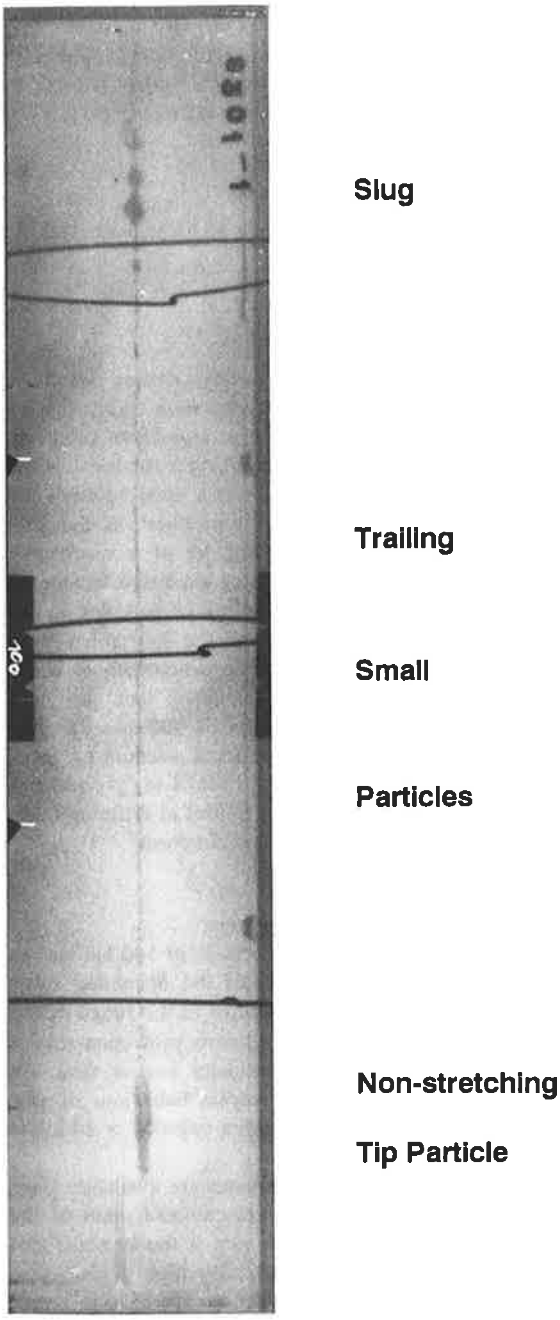

Figure 4. Shaped charge jet

3. FLYER PLATE CATCHERS; SHORTENING GADGET

To obtain a single hypervelocity projectile, the tip particle has to be isolated from the residual part of the jet. For hypervelocity impact tests on space debris protection shields in most cases an aspect ratio of the projectile L/D < 3 is requested. Therefore, the original particle has to be shortened to the proper length without degradation and loss of speed.

The final set-up of shaped charge, catchers, and shortening gadget is depicted in Figure 5. The catcher device which removes the small jet particles following the leading hypervelocity particle is a flyer plate accelerated by a body of high explosive that is close-fitting attached to the base of the shaped charge. Thereby the precise timing of the flyer

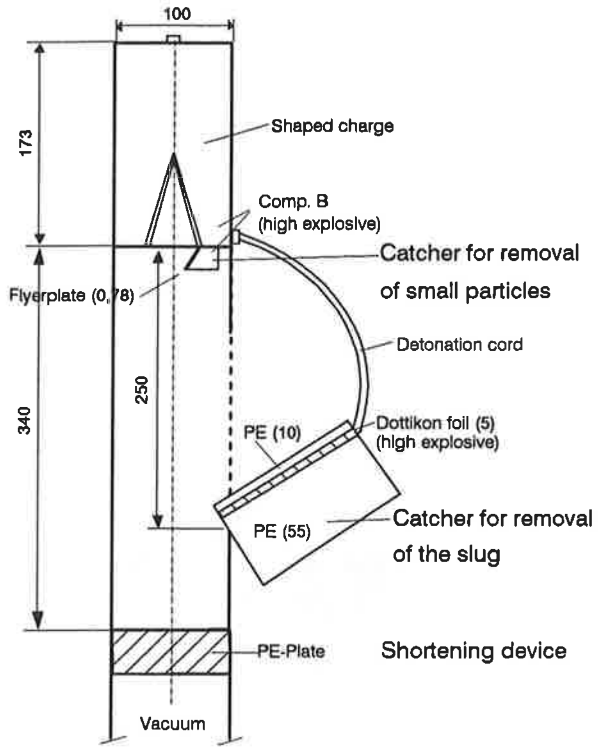

Figure 5. Set-up of shaped charge with catcher for trailing particles, slug catcher, and shortening gadget

plate is achievable so that its leading edge cuts through the jet axis exactly behind the tip particle. The catcher device for the removal of the slug is a sandwich consisting of a flyer plate, a high explosive sheet, and a backing plate. The high explosive sheet is initiated by the shaped charge via a detonation cord. The launching schedule of the flyer plate is adjusted by the length of the detonation cord.

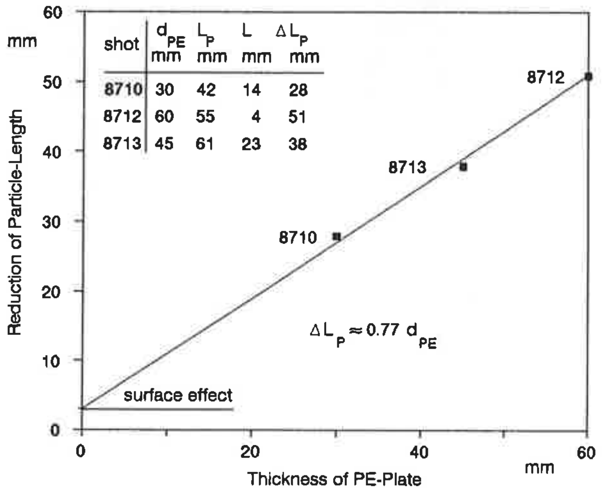

Figure 6. Reduction of projectile-length in relation to thickness of PE shortening plate

The shortening gadget is a simple PE plate which is penetrated by the hypervelocity projectile. In the hydrodynamic penetration process the leading portion of the particle is consumed while its rear part remains unaffected at the original speed. The minimum aspect ratio that is achievable is about L/D = 1. The reduction in length of the primary hypervelocity particle is rigorously determined by the thickness of the penetrated PE-plate (Figure 6). What is designated as "surface effect" in the graph corresponds to the acceleration of the polyethylene part of the kernel, which is a shock-compressed shock-heated "rigid" body that explodes upon exit from the back of the PE-plate (Ref. 2). Shielding is necessary to keep off these ejecta of the PE shortening plate from the target under hypervelocity impact test.

4. HYPERVELOCITY IMPACT TEST TANK

The specifically constructed firing tank facilitates hypervelocity impact tests on targets of lateral dimensions of 500 mm · 500 mm and an overall-length of up to 900 mm (Figure 7). The vessel can be evacuated to less than 10 mbar. The PE-shortening plate serves also as the vacuum seal at the entrance hole for the projectile. X-ray windows

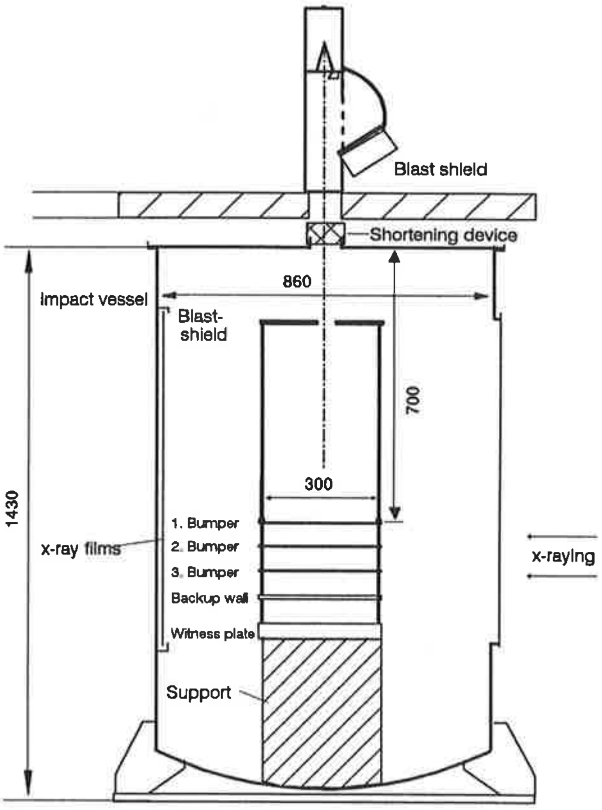

Figure 7. Set-up for hypervelocity impact tests on targets in evacuated test tank

are incorporated in the vessel and fixtures for packages of X-ray film and intensifier foils are provided on the opposite inside walls. With that, several flash X-ray pictures can be taken during each hypervelocity impact at differing times and at different locations of the target structure. Figure 8 is a photograph of the test chamber with outside blast shield and shaped charge arrangement; one of the X ray sources is also visible.

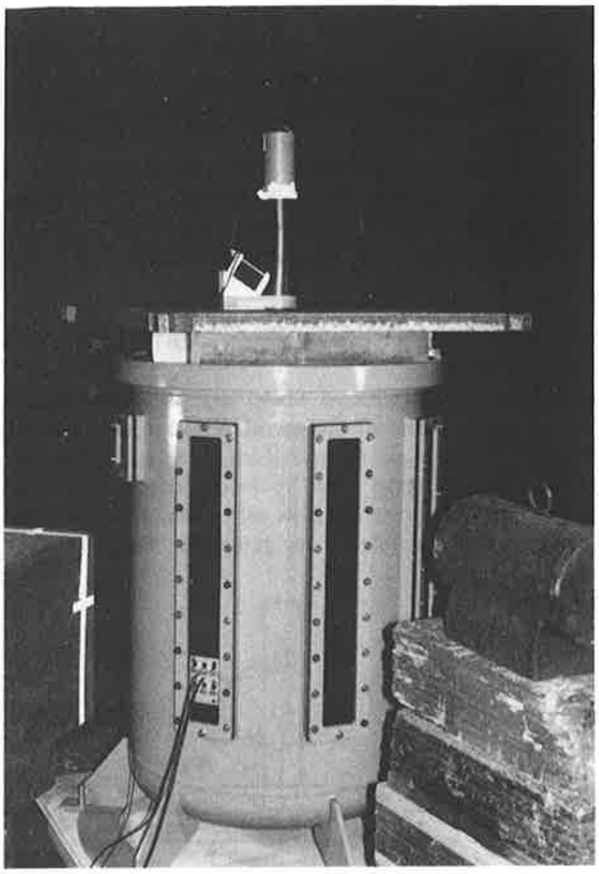

Figure 8. Test chamber with shaped charge arrangement and one of the X-ray sources

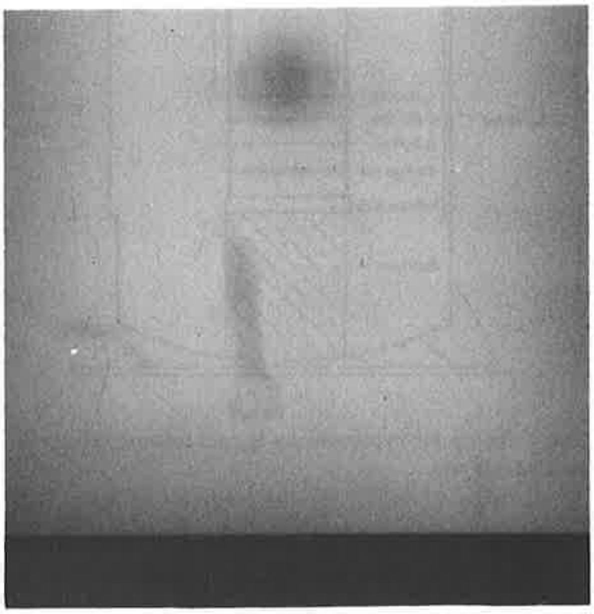

Figure 9. Flash X-ray picture of shaped charge single projectile (L/D = 5; 0.8 g) approaching a test shield with 11.1 km/s

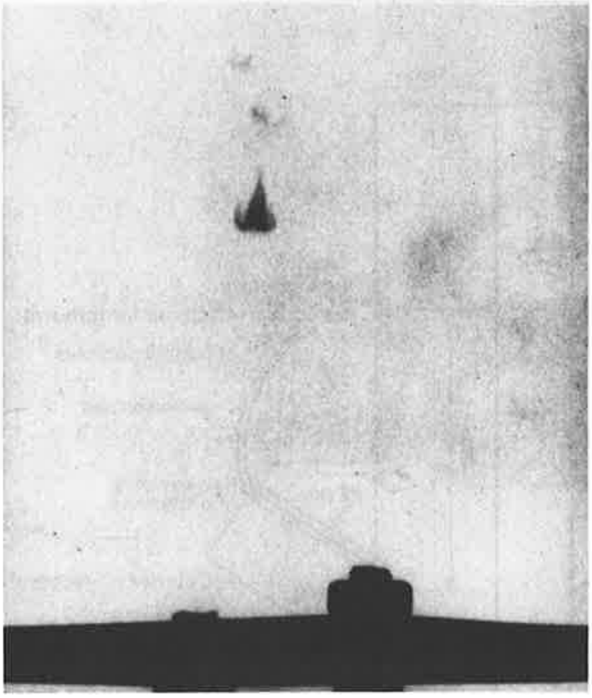

Figure 10. Flash X-ray picture of shaped charge single projectile (L/D = 1; 0.3 g) approaching a test shield with 11.3 km/s

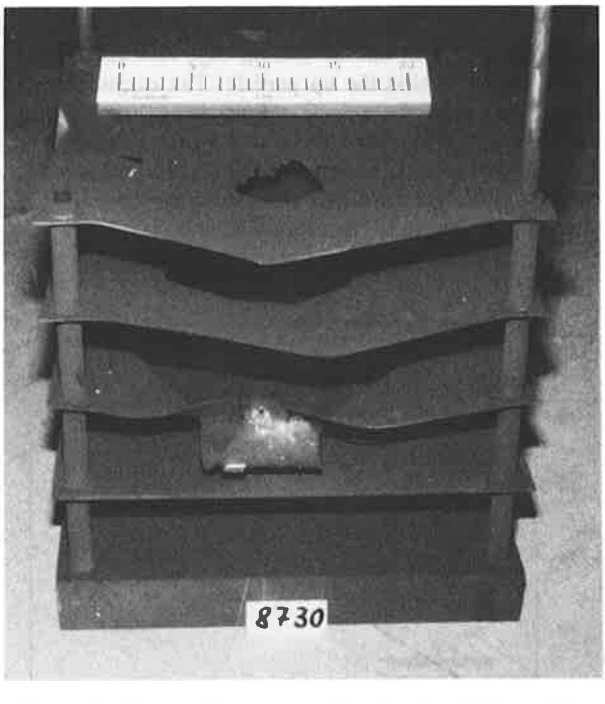

Figure 11. Target after impact of projectile of Figure 10

5. HYPERVELOCITY IMPACT TESTS

The feasibility of the test facility has been demonstrated by laboratory tests on targets resembling the anticipated COLUMBUS protection structure. The targets consisted of the main or back plate of 3.2 mm thick aluminium and of 2 or 3 bumper plates of 0.8 mm aluminium placed with a spacing of 60 mm in front of the back plate. The 3 flash X-ray pictures taken during each hypervelocity impact show the aluminium projectile as it approaches the first bumper plate (Figure 9; Figure 10), and the residual projectile and the ejecta after penetration of the first and of the second or third bumper plate. On the X-ray pictures aluminium fragments in the ejecta cloud down to sizes of about 0.3 mm ($\approx$ 0.3 mg) are distinctly discernible. That allows an adequate analysis of the hypervelocity impact and penetration. Figure 11 is a photograph of the target that was impacted by the projectile shown on the X-ray picture of Figure 10.

Without having the target in an evacuated vessel, target structures with dimensions of several meters can be investigated in Battelle's terminal ballistics facilities in Frankfurt by shaped charge single projectile hypervelocity impact tests.

6. CONCLUSIONS

The simulation of orbital debris impact by shaped charge single projectiles is so far the only one available for testing space debris protection shields by the impact of particles in the important mass range of about 1 g at velocities of more than 11 km/s.

Further improvement of the hypervelocity impact test method for simulation of orbital debris will be achieved by raising the velocity of the projectile to 12.3 km/s by means of employing RDX or HMX as high explosive for the shaped charge, and by perfection of the measures that protect the target effectively against all impacts other than of the hypervelocity projectile.

7. REFERENCES

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