SHAPED CHARGE TECHNIQUE FOR HYPERVELOCITY IMPACT TESTS AT 11 KM/S ON SPACE DEBRIS PROTECTION SHIELDS

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ABSTRACT

For a space station orbiting at 500 km, the most oncoming space debris particles have collision velocities in the range of 8 to 14 km/s. At impacts of aluminium on aluminium targets above 10 km/s melting and vaporization of target and projectile material affect the penetration process. Therefore, space debris protection shields have also to be investigated by impacts of well defined aluminium particles having a mass of about 1 g and a velocity well above 10 km/s, conditions that are not accessible for light gas guns.

Battelle has put to work for ESA/ESTEC a shaped charge technique being feasible to fulfil these requirements which has now been established as a standardized procedure. Eight hypervelocity impact tests on different target configurations yield the reproducibility of the impact conditions. The aluminium projectile has a velocity of (11.2 ± 0.1) km/s, a mass of (1.1 ± 0.15) g, and an aspect ratio of 3.7 ± 0.7.

1. INTRODUCTION

For a space station orbiting at 500 km, the most oncoming space debris particles have collision velocities in the range of 8 to 14 km/s. With aluminium as the typical debris material, actual system requirements lead to a critical particle dimension of the order of 10 mm corresponding to a mass of about 1 g for which protection is needed.

When an aluminium projectile impacts on an aluminium target, vaporization begins at about 10 km/s. As the damage mechanisms are drastically influenced by the material state, it is consequently necessary to test space debris protection shields by impacts in the velocity range well above 10 km/s. These conditions are not accessible for light gas guns.

Battelle developed for the European Space Agency ESA a shaped charge technique that permits to generate a single aluminium projectile having an impact velocity of 11.2 km/s, a cylindrical shape, an adjustable aspect ratio of 3 to 6, and a mass between 0.8 g and 2 g (Refs.1, 2).

In a recent study, the shaped charge technique, the test facilities, and the test procedures have been established as a standardized method.

2. THE SHAPED CHARGE TECHNIQUE

The shaped charge (Figure 1) was specifically designed to produce a non-stretching, and consequently not particulating, massive particle at the tip of its aluminium jet (Figure 2). The velocity of this tip particle is 11.2 km/s.

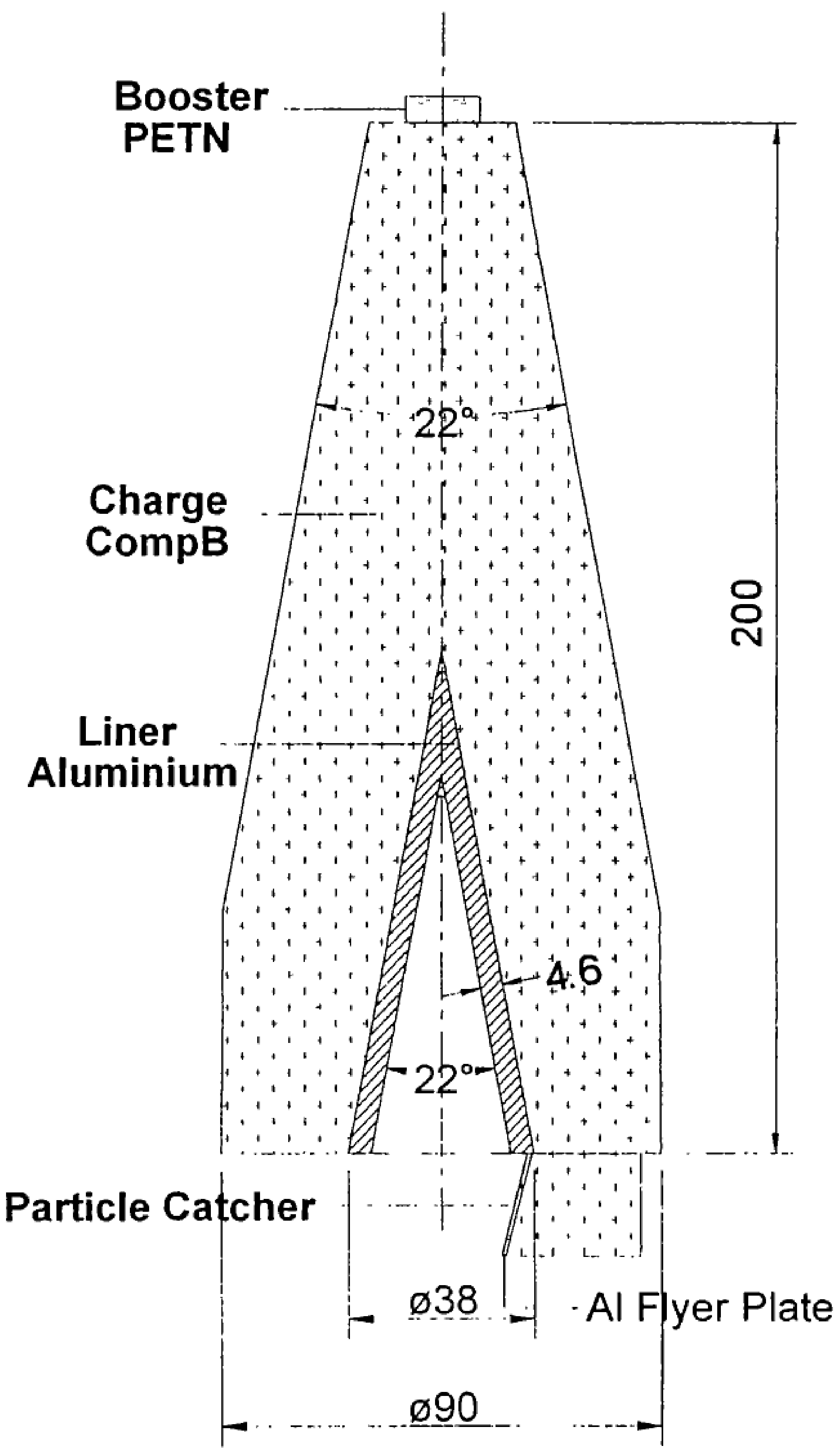

Figure 1. Shaped charge configuration.

The small jet particles trailing the leading hypervelocity particle are reliably removed by an explosively accelerated flyer plate (particle catcher). A different flyer plate deviates the heavy slug at the end of the jet (slug catcher).

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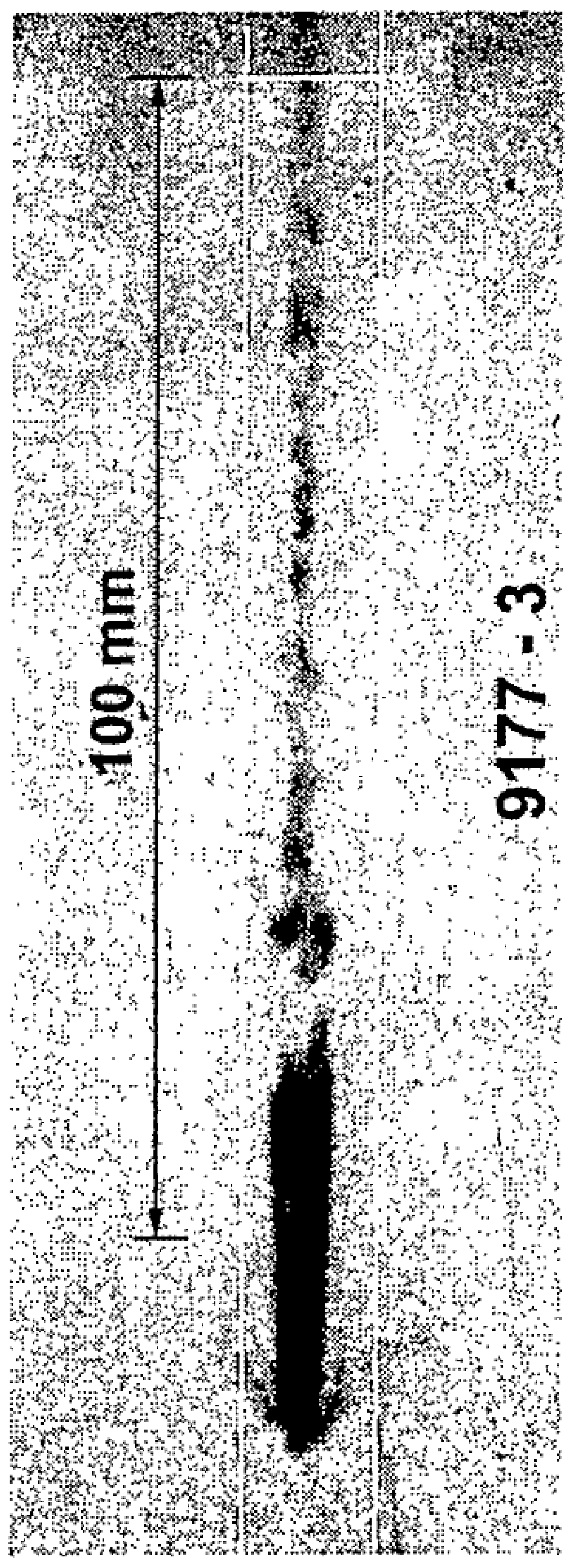


Figure 2. Non stretching tip particle with trailing jet particles.

Shaped charge, particle catcher, and slug catcher are assembled to a projectile launcher that can readily be handled (Figure 3).

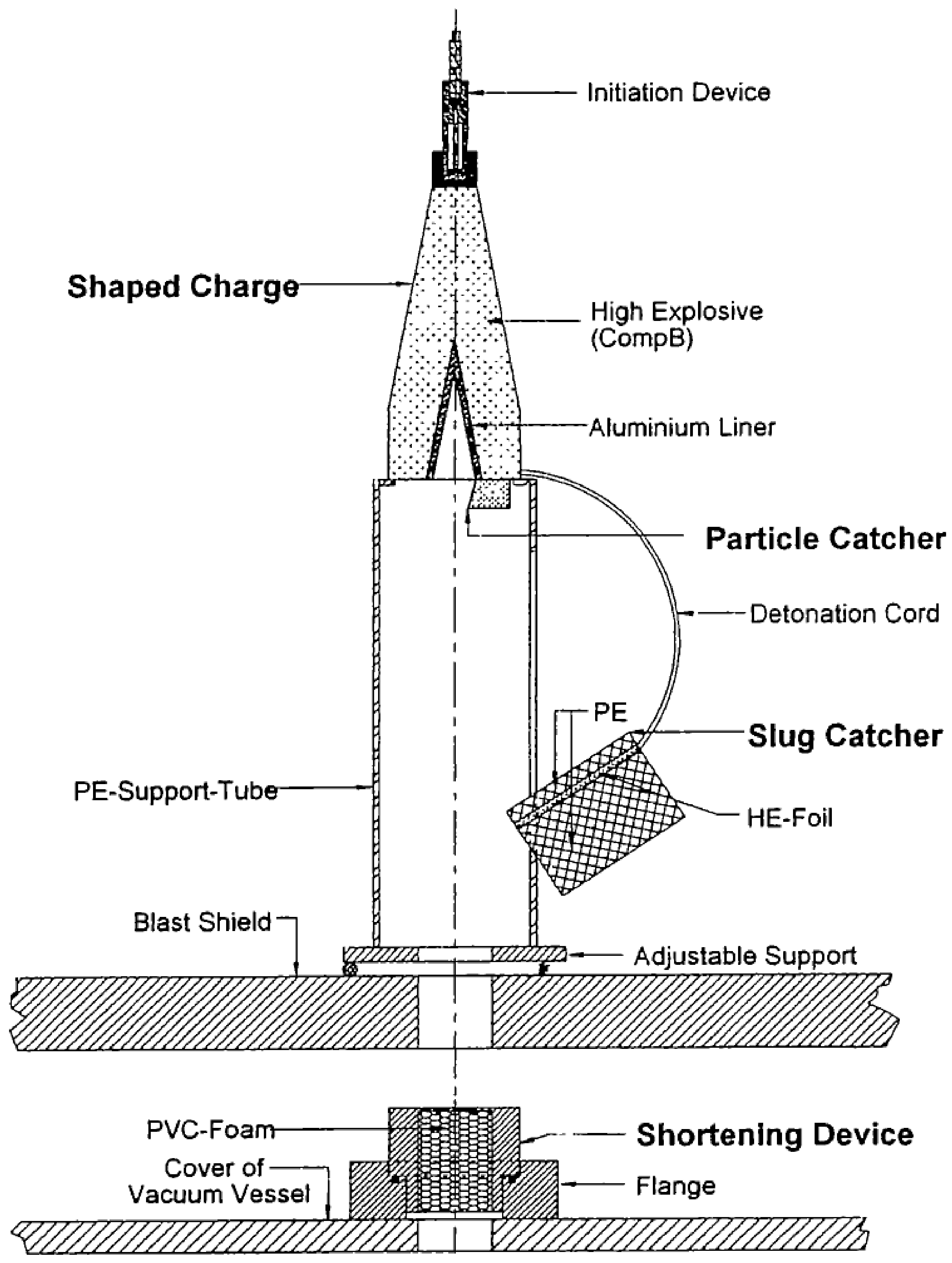


Figure 3. Projectile launcher.

The length of the isolated tip particle is adjusted to the desired aspect ratio by consuming its leading portion by perforation of a PVC-plate of proper thickness. The velocity of the projectile remains unchanged at 11.2 km/s.

The amount and size of solid fragments ejected out of the shortening plate can be diminished by using micro porous PVC-foam as the plate material.

3. THE TEST FACILITY

A specifically constructed test chamber facilitates hypervelocity impact tests on targets with dimensions up to 500 mm · 500 mm · 500 mm (Figure 4). The vessel can be evacuated to below 1 mbar. X-ray windows 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 preselected times and at different locations of the target structure.

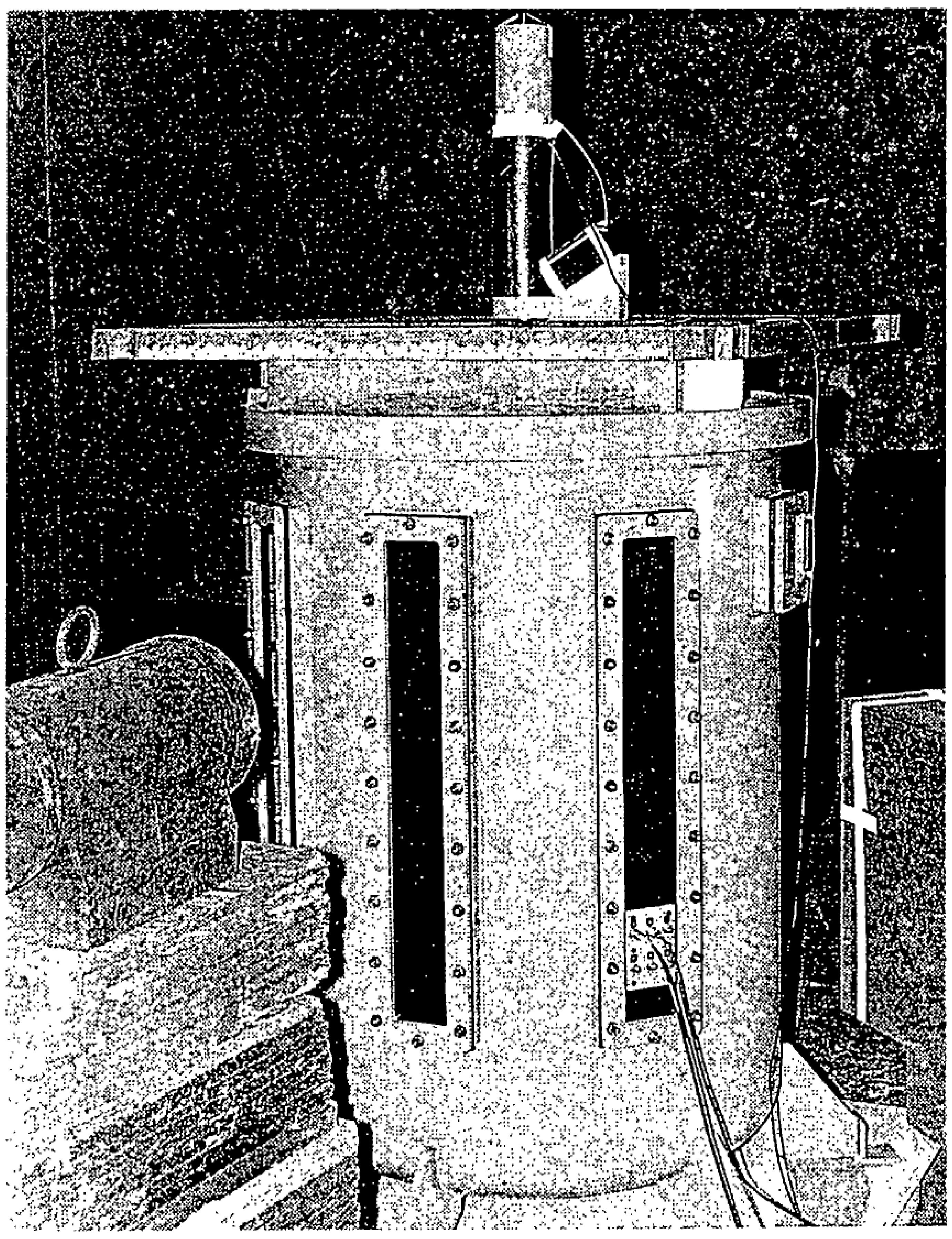


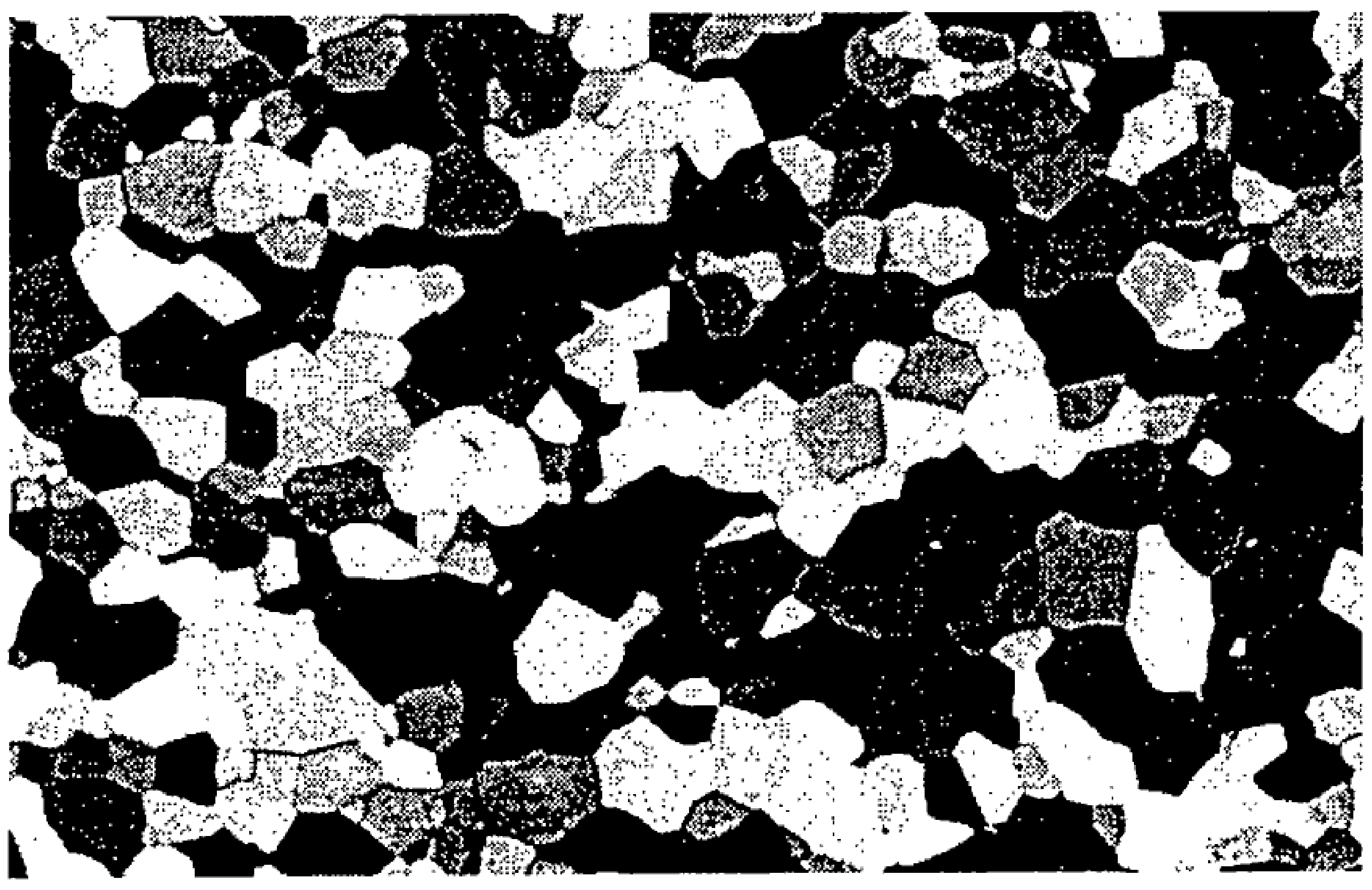
Figure 4. Photograph of test vessel with projectile launcher.

In a primary study (Refs. 1, 2) the feasibility of the test facility was demonstrated by laboratory tests on typical targets consisting of thin bumper plates spaced before a thicker back wall.

4. ASSESSMENT OF REPRODUCIBILITY

4.1 Manufacture of the projectile launcher

The aluminium for the liner has to fulfil high standards with respect to purity, fine grain size, and homogeneity. The R&D Division of VAW (Vereinigte Aluminium Werke) in Bonn produced according to mutually discussed specifications several rods of high quality aluminium Al 99.9% + 0.5% Mg. Figure 5 shows a microphotograph of the grain structure of the middle section of one of the rods together with the analytical grain size data.



Minimum grain ø	22 µm
Maximum grain ø	156 µm
Mean grain ø	64 µm
Elongation	1

Figure 5. Grain structure of Al 99.9% + 0.5% Mg.

The liner was manufactured by first processing a rod segment on a CNC machine. The inner liner contour was finished by spark erosion to the required high surface quality.

The high explosive charge consisting of Composition B (CompB) was casted as a cylinder around the liner, and then crafted to the desired conical form on a special lathe.

The final design of the shaped charge is outlined in Figure 1. The charge is 200 mm high to get a detonation front at the liner apex that is flat and has a good axial symmetry. The amount of high explosive CompB is merely 1.27 kg due to its base diameter of only 90 mm and due to its conical shape.

The experimental set-up of the projectile launcher on top of the vacuum vessel is depicted in Figure 3. The shaped charge assembly with the particle catcher at its base is borne by a PE-tube which stands on an adjustable support that is mounted on a blast shield. The slug catcher is fixed to this PE-tube. The shortening device fits into the entrance flange of the vacuum vessel and serves also as a vacuum tight seal. Its casing consisting of massive PVC contains a body of PVC-foam Airex with density 90 kg/m^3.

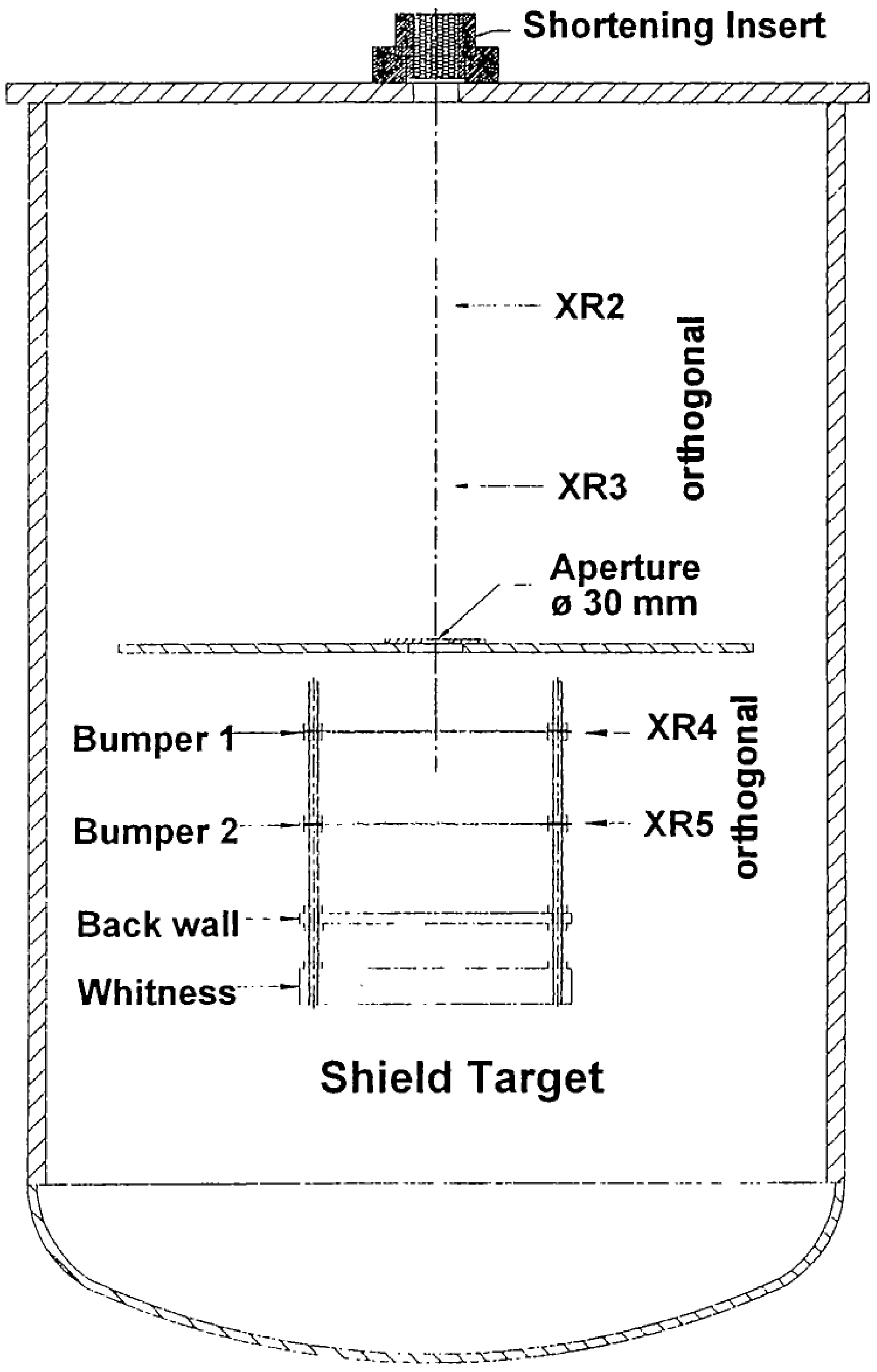


Figure 6. Test set-up inside vacuum vessel.

Fig. 6 shows the test set-up inside the vacuum vessel. A blast shield with an aperture of 30 mm is positioned half way down the vessel in order to keep away from the target the blast and the debris ejected off the shortening device. Up to four flash X-ray pictures can be taken inside the vessel. Two orthogonal pictures at different levels above the inner blast shield serve to determine the properties of the final projectile (shape, length, axial symmetry, compactness, velocity). The remaining two pictures are taken at the levels of the bumper plates of the target and allow to observe the penetration behaviour of the projectile (ejecta cloud, residual projectile).

4.2 Testing of the reproducibility

To conclude the assessment of the reproducibility of the projectile generation three hypervelocity impact tests have been carried out with full instrumentation. All parameters have been kept constant at the three tests with exception of the shortening device whose thickness was varied in order to arrive at a particle with L/D = 3.

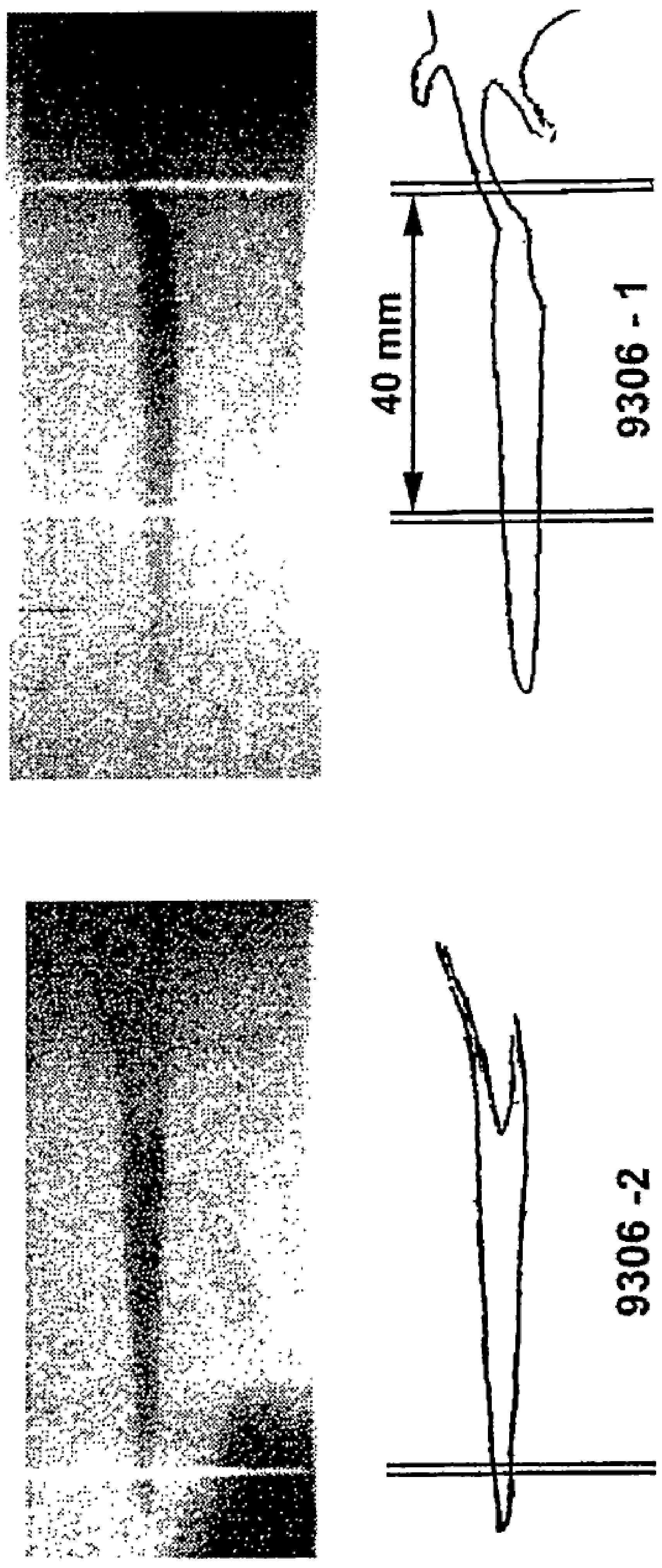


Figure 7. Orthogonal X-ray pictures of the primal particle of experiment 9306.

Target # Experiment #		1 9475	2 9476	3 9477	4 9478	5 9479	6 9480	7 9481	8 9482
Tilt angle		⊥	⊥	45°	⊥	⊥	45°	⊥	⊥
Bumper 1 Al 6061 T4	mm	2.5	4	2.5	2.5	2.5	2.5	2.5	2.5
Spacing	mm	200	200	200	100	100	60	60	60
Bumper 2 Al 6061 T4	mm	—	—	—	2.5	2.5	2.5	2	2
Spacing	mm	—	—	—	100	100	60	60	60
Back wall Al 2219 T851	mm	12	12	12	8	5	5	5	4 ★
Back wall perforated?		yes	yes	yes	no	no	no	no	yes ✚
★ Al 6061 T4					✚ excessively long projectile				

Table 1. Target parameters of the eight tests on shields.

As an example the X-ray pictures of the experiment 9306 are presented. Figure 7 shows orthogonal views of the isolated primal particle taken at different levels above the shortening device. Figure 8 shows the final projectile after shortening to L/D = 3.7 (L = 18.8 mm; D = 5.1 mm; mass = 1.1 g).

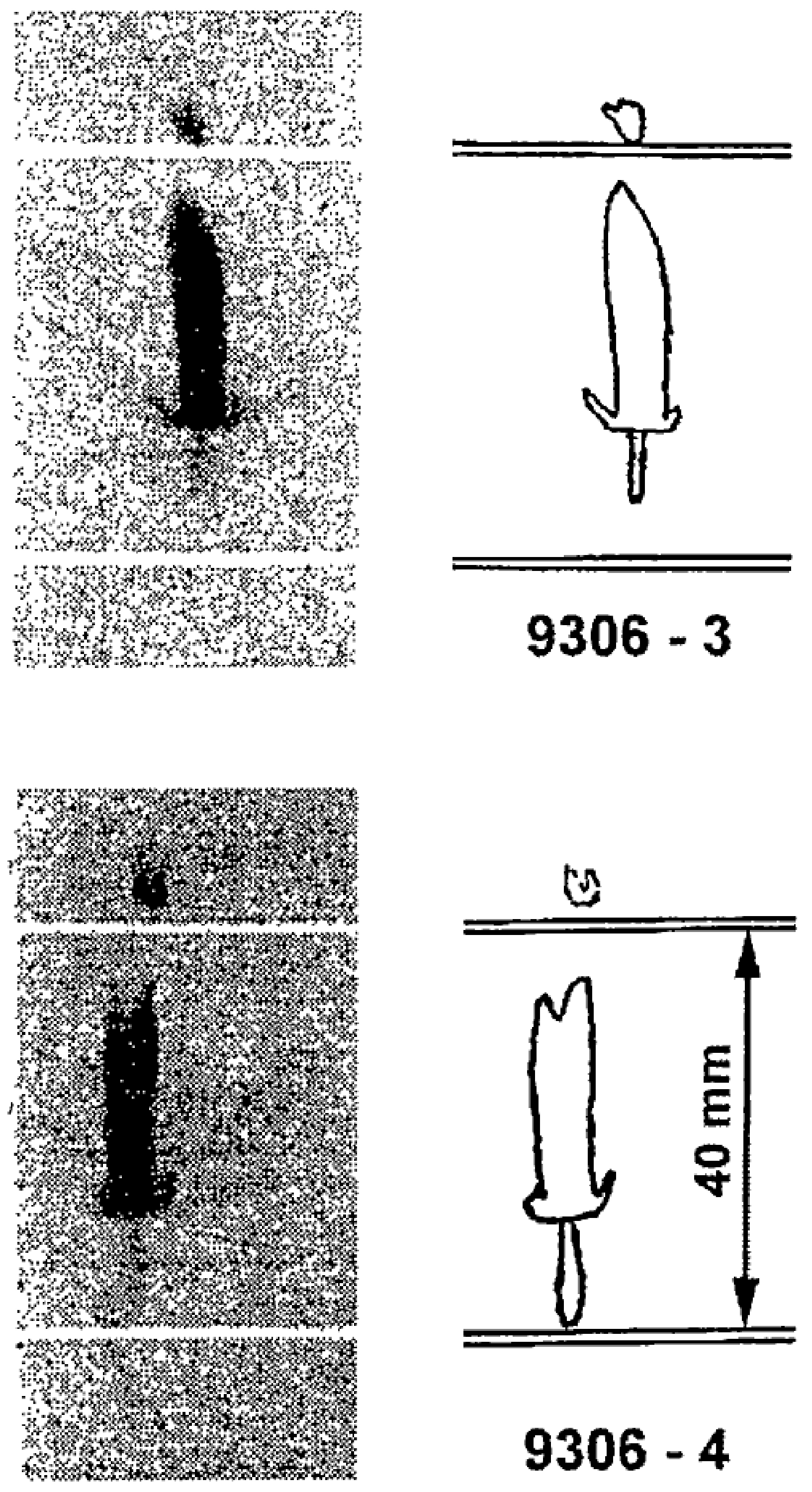


Figure 8. Orthogonal X-ray pictures of the final projectile of experiment 9306.

The velocity of the projectile was 11.2 km/s for all three experiments. The length of the primal particle was 47 mm, 48 mm, and 45 mm respectively. That is a variation of less than 6% regarding the primal length itself, but has a large effect on the aspect ratio L/D of the final projectile. In order to avoid, in case of short primal particles, shortening to aspect ratios below 2 which may be detrimental to the compactness, coherence, and stability of the projectile it has been decided to perform the tests on space debris shields reproducing the conditions of the test 9306.

5. HYPERVELOCITY IMPACT TESTS ON SPACE DEBRIS SHIELDS

Eight hypervelocity impact tests on different target configurations have been performed. The debris protection shields consisting of the back wall and of one or two bumpers varied in thickness and spacing of the target plates. Two tests have been executed at oblique impact of 45°. In Table 1 the target parameters of the experiments 9475 (target 1) to 9482 (target 8) are compiled. The tests yield the reproducibility of the impact condi-

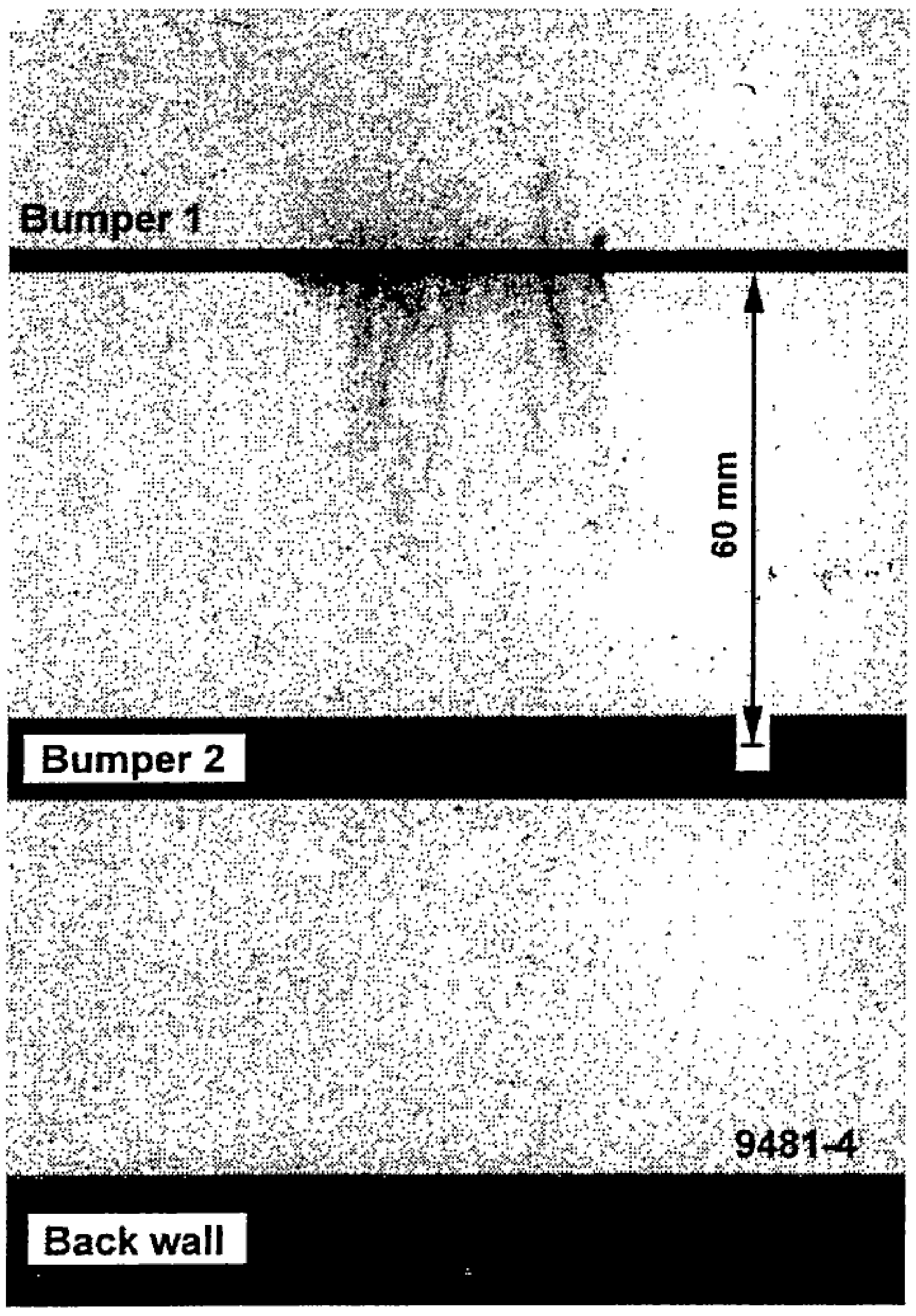


Figure 9. Experiment 9481: Situation after perforation of bumper 1 of target 7.

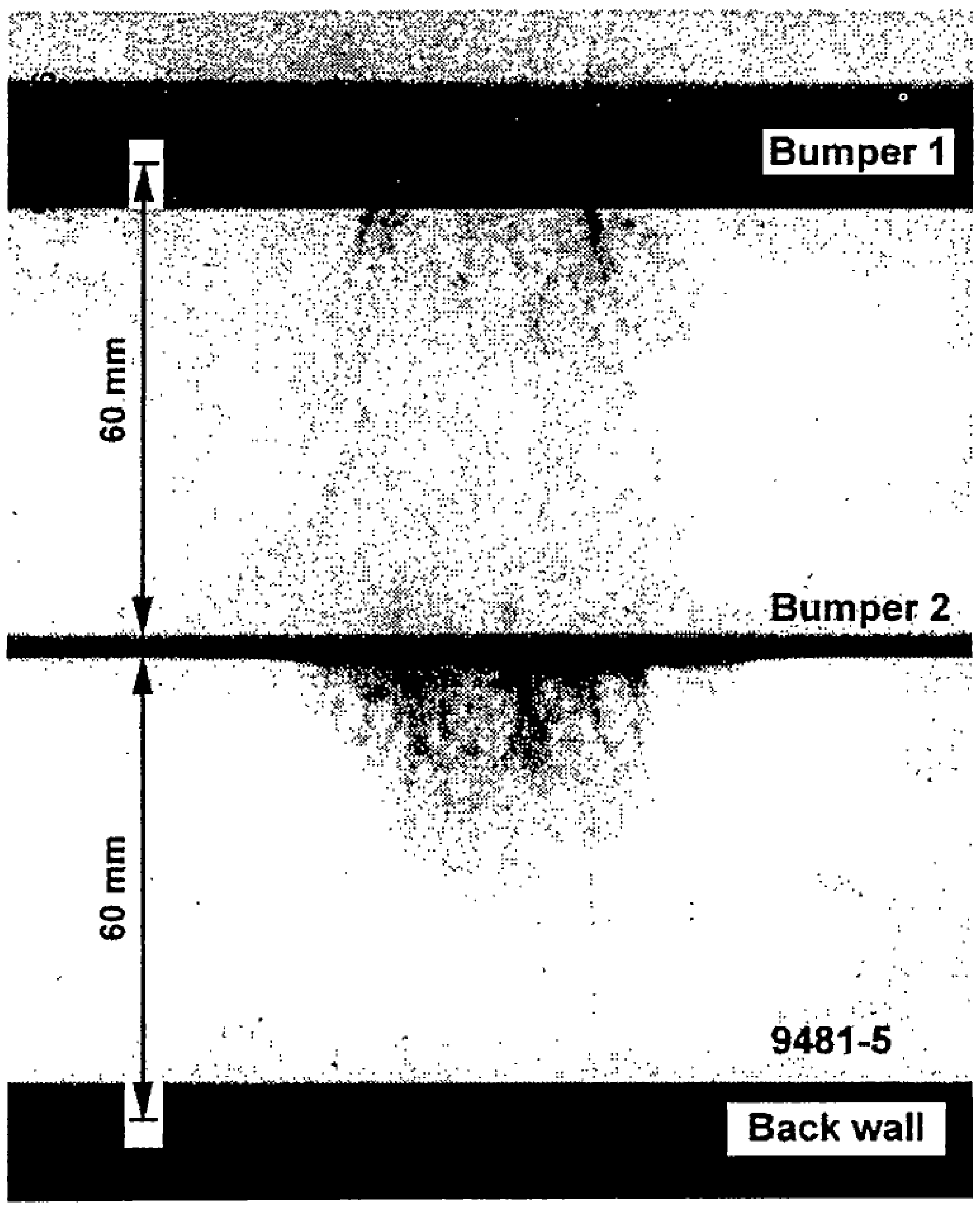


Figure 10. Experiment 9481: Situation after perforation of bumper 2 of target 7.

tions as well as the protection capability of the shields. The scope of the target damage together with the X-ray pictures of the target penetration are used by ESA/ESTEC to verify computer simulations of the impact and penetration behaviour of cylindric projectiles in the velocity range above 10 km/s.

Shot #	Velocity km/s	Length L mm	Diameter D mm	L/D	Volume cm³	Mass g
9475	11.2	46	6.0	7.7	0.60	1.6
9476	11.1	48	6.0	8.0	0.65	1.8
9477	11.2	45	6.0	7.5	0.61	1.7
9478	11.2	48	6.0	8.0	0.65	1.8
9479	11.2	47	6.2	7.6	0.65	1.8
9480	11.2	47	6.6	7.1	0.83	2.3
9481	11.1	46	6.0	7.7	0.69	1.9
9482	11.2	52	6.2	8.4	0.79	2.1

Table 2. Properties of the primal particle of the eight tests on shields.

Shot #	Length L mm	Diameter D mm	L/D	Volume cm³	Mass g	Velocity km/s
9475	19	5.0	3.8	0.36	1.0	11.2
9476	22	5.0	4.4	0.39	1.1	11.1
9477	20	5.2	3.8	0.38	1.0	11.2
9478	19	5.5	3.5	0.46	1.2	11.2
9479	21	6.6	3.2	0.43	1.2	11.2
9480	22	5.2	4.2	0.44	1.2	11.2
9481	19	6.2	3.1	0.43	1.2	11.1
9482	29	5.5	5.3	0.54	1.5	11.2

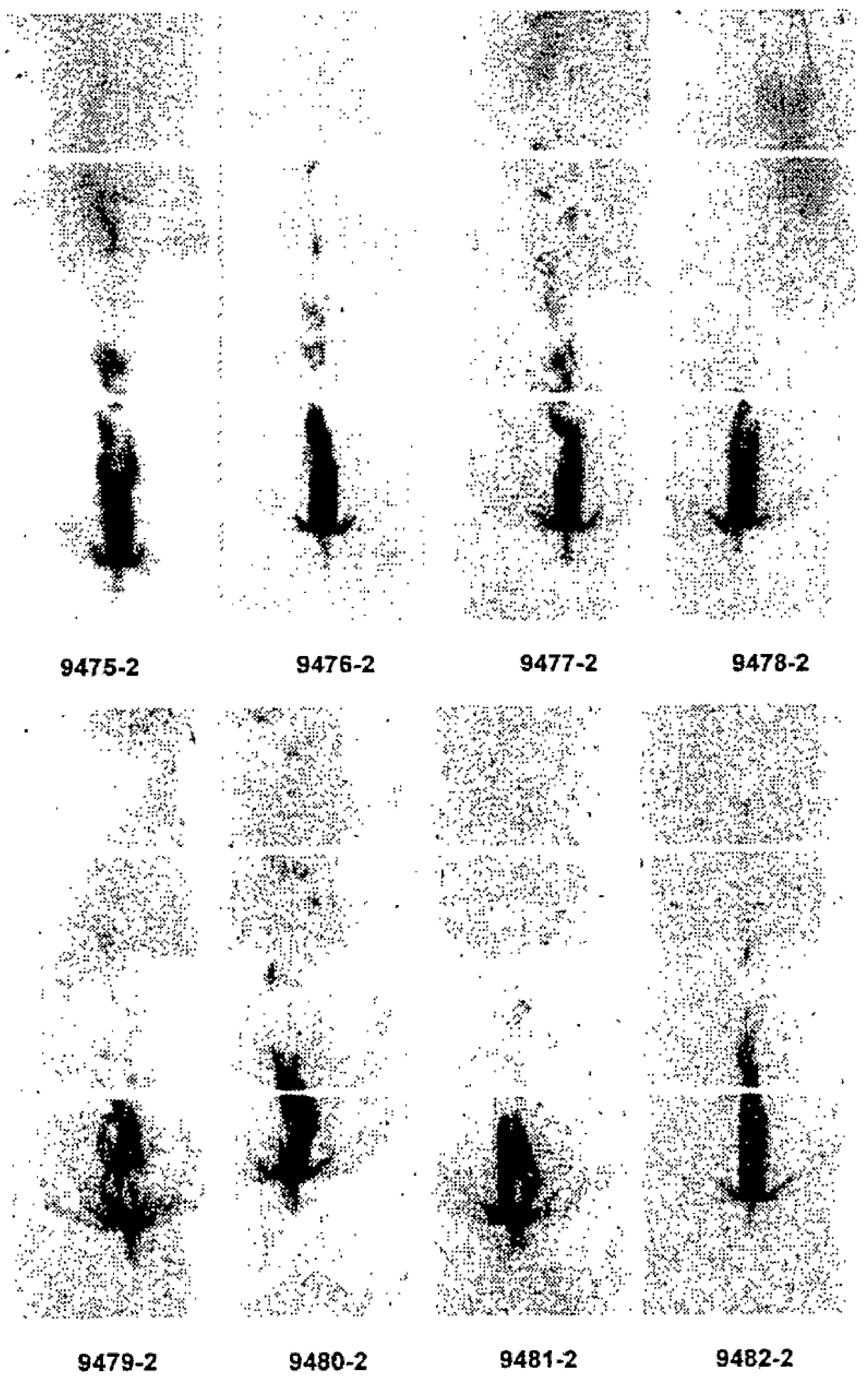
Table 3. Properties of the final projectile of the eight tests on shields.

As an example, the X-ray pictures of the penetration of target 7 at experiment 9481 are depicted. After perforation of bumper 1 no residual projectile is left (Figure 9). Figure 10 demonstrates the situation after perforation of bumper 2 by the impinging cloud of pulverized and vaporized aluminium.

In this paper, only the reproducibility of the impact conditions is discussed.

Table 2 comprises the essential properties of the primal particle for the eight tests on shields. Note the exceptionally large length of the primal particle in experiment 9482.

Figure 11 shows for each of the eight experiments the shortened projectile as it appears on the X-ray picture that was taken after perforation of the shortening device.



9475-2 9476-2 9477-2 9478-2

9479-2 9480-2 9481-2 9482-2

Figure 11. X-ray pictures of the final projectiles of the eight tests on shields.

The data for the assessment of the reproducibility of the projectile are listed in Table 3. The properties of the projectiles vary within acceptable limits with exception of the already mentioned experiment 9482.

6. CONCLUSIONS

6.1. General

As the main result of the study it can be stated that

- the shaped charge technique for launching hypervelocity projectiles
- the hypervelocity impact test facility
- the test procedure

are now established with well characterized and reproducible standards. The shaped charge hypervelocity impact test technique is ready for use as a standard procedure.

6.2. Specifications

In tests to come, the parameters of the projectile will be reproduced within the following limits:

Velocity	11.2 km/s ± 0.1 km/s
Mass of aluminium	1.1 g ± 0.15 g
Shape	cylindrical
Length L	21 mm ± 2 mm
Diameter D	5.6 mm ± 0.6 mm
Aspect ratio L/D	3.7 ± 0.7
Pitch (flight attitude)	< 10°
Deviation of impact point	< 7 mm (< 10 mrad)

7. PROSPECTS

7.1. Improvements

The shaped charge technique for hypervelocity impact testing has still a potential for perfection. In the first place, the reproducibility of the primal particle can be further improved by:

- Finer grain size of the aluminium for the liner
- Swaging or flow turning of the liner
- Pressing of the charge using the high explosives RDX or HMX which are superior to Composition B

7.2. Adaptation

The established standard test conditions may be readily adapted to different requirements for dimensions and mass of the projectile without additional principal investigations.

8. REFERENCES

1. J. Bol, V. Friehmelt; Hypervelocity Impact Test Facility to Simulate Orbital Debris by Shaped Charge Single Projectiles; *Proceedings of the First European Conference on Space Debris*, Darmstadt, Germany, 5-7 April 1993; 389-393.

2. J. Bol, H.-G. Baumgardt, V. Friehmelt; Shaped Charge Technique of Producing Ultra Fast, Heavy, Single Projectiles for Hypervelocity Impact Tests on Space Debris Protection Shields; *14th International Symposium on Ballistics, Québec, Canada, 26-29 September 1993; Proceedings Volume 2, 173-181.*