HYPERVELOCITY IMPACT RESEARCH

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ABSTRACT

Hypervelocity impact research is an important area of modern physics touching topics of geoscience, high pressure physics, planetary physics, space research, material science and defence research and technology. This contribution is focused on three current aspects of experimental simulation of hypervelocity impacts at velocities higher than 8 km/s with two-stage light gas guns, the impact on shields with layers of different shock impedance, and the impact at high angle of obliquity.

1. INTRODUCTION

Hypervelocity Impact Research is an important area of modern physics touching many other topics of research and technology.

Since the beginning of space flight, hypervelocity impact research has gained a steadily increasing importance because artificial man-made orbital debris are a potential danger to space stations, satellites and other functional space crafts. For the study of the physical processes in all areas of interest, one needs efficient accelerators to simulate the impact velocities and highly sophisticated instruments to get an insight into the processes. The limit of our experimental possibilities mark the boundaries of our understanding of the processes. Since the beginning of hypervelocity impact research, engineers, technicians and scientists have generated new types of accelerators or have improved their performances.

To produce projectiles in a wide range of velocities and masses, four large groups of accelerators exist:

- Electrostatic and electromagnetic propulsions
- Explosion propulsions
- Plasma accelerators
- Guns

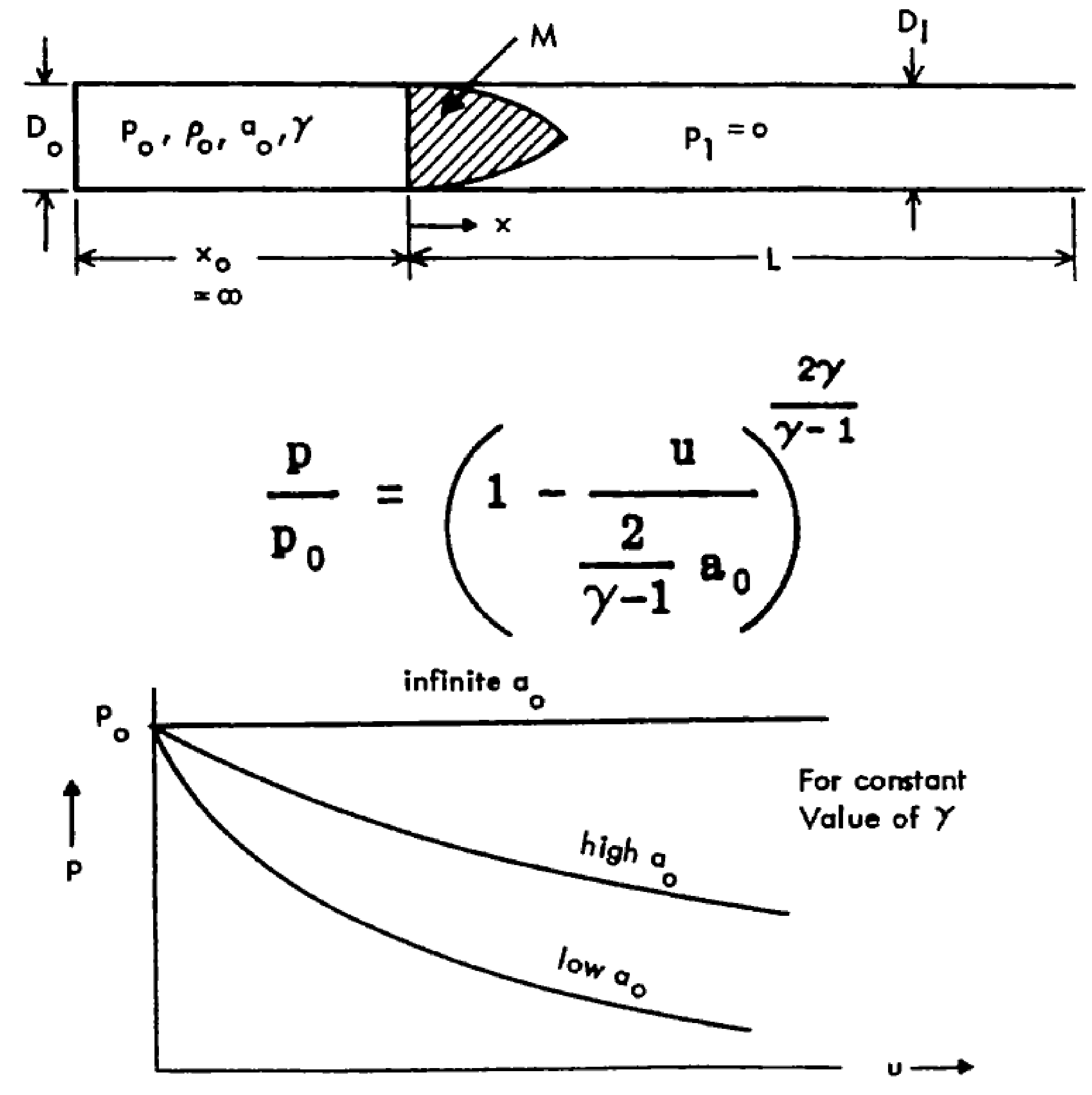
Each of these systems have limits and restrictions in mass, velocity, shape and material of the projectiles.

At present the best choice of high speed accelerators are light gas guns. These are now the only accelerators capable of firing projectiles with complex shapes, different materials and masses at velocities of up to 11 km/s. However, the 11 km/s are not a fundamental maximum limit in velocity for light gas guns.

The paper describes the fundamental and technological limits in light gas gun operations and some ideas and methods to exceed the present-day limits. Furthermore, a new shield concept with multilayers of different shock impedances will be discussed, some new results of impacts at high angle of obliquity will be presented which can also be used for shield arrangement.

2. FUNDAMENTAL LIMITS OF LIGHT GAS GUN OPERATIONS AND SOME TECHNOLOGICAL IDEAS TO MAKE THE GUNS FASTER

The maximum velocity attainable in a light gas gun is given by the maximum sound speed in the light driver gas . The higher the initial sound speed a_0 of the driver gas in the reservoir, the lower is the pressure drop behind the projectile during the acceleration in the barrel (Fig. 1). For an ideal gas the sound speed is proportional to the square root of the temperature



$$\frac{p}{p_0} = \left(1 - \frac{u}{\frac{2}{\gamma-1} a_0}\right)^{\frac{2\gamma}{\gamma-1}}$$

Figure 1. Interior ballistics of high velocity guns.

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divided by the molecular weight. In practice, there are many ways to heat and compress the light gas. The heating and compressing of the light gas by means of a piston compression is the most frequent and most flexible type of light gas gun operation. The interior ballistic cycle in a two-stage light gas gun is a complex event influenced by many parameters:

- guns geometry
- piston weight
- projectile/sabot weight
- loading conditions
- release pressures (piston, projectile, diaphragm)
- energy losses (friction, heat loss, etc.)
- chambrage failure

To find the best loading conditions for the highest velocity, computer codes or empirical methods can be applied.

For each gun construction, a maximum allowable pressure exists, which the construction of the gun and the sabot with the projectile can withstand. If the base pressure behind the projectile is kept equal to this maximum pressure during the entire travel in the launch tube, then the maximum attainable velocity for this gun-projectile system is reached. Such an ideal gun is called a constant base pressure gun.

Two fundamental method exist to realise a constant base pressure system: One method is to increase the pressure in the reservoir with time, as shown in Fig. 2. The other method pushes the highly compressed and heated gas behind the projectile. This type is therefore called an accelerated reservoir light gas gun. From our experience it seems that optimising the last method is the best way to make a light gas gun faster.

Requirements for this are a well-deformable compression piston and an optimal matching of the transition section with the entrance to the barrel (Fig. 3).

Other methods like preheating of the driver gas or adding a third stage to the gun are possible; however, they involve high risks and various technological problems, and do not considerably increase the performance.

The addition of energy along the barrel at successive locations is another possibility. The control of the energy release after the passage of the projectile is difficult and this schema has not yet been successful.

In summary one can state that the various methods proposed may prove to be useful in conjunction with two-stage guns, but none of them can increase the projectile velocity by more than 10 - 15 %.

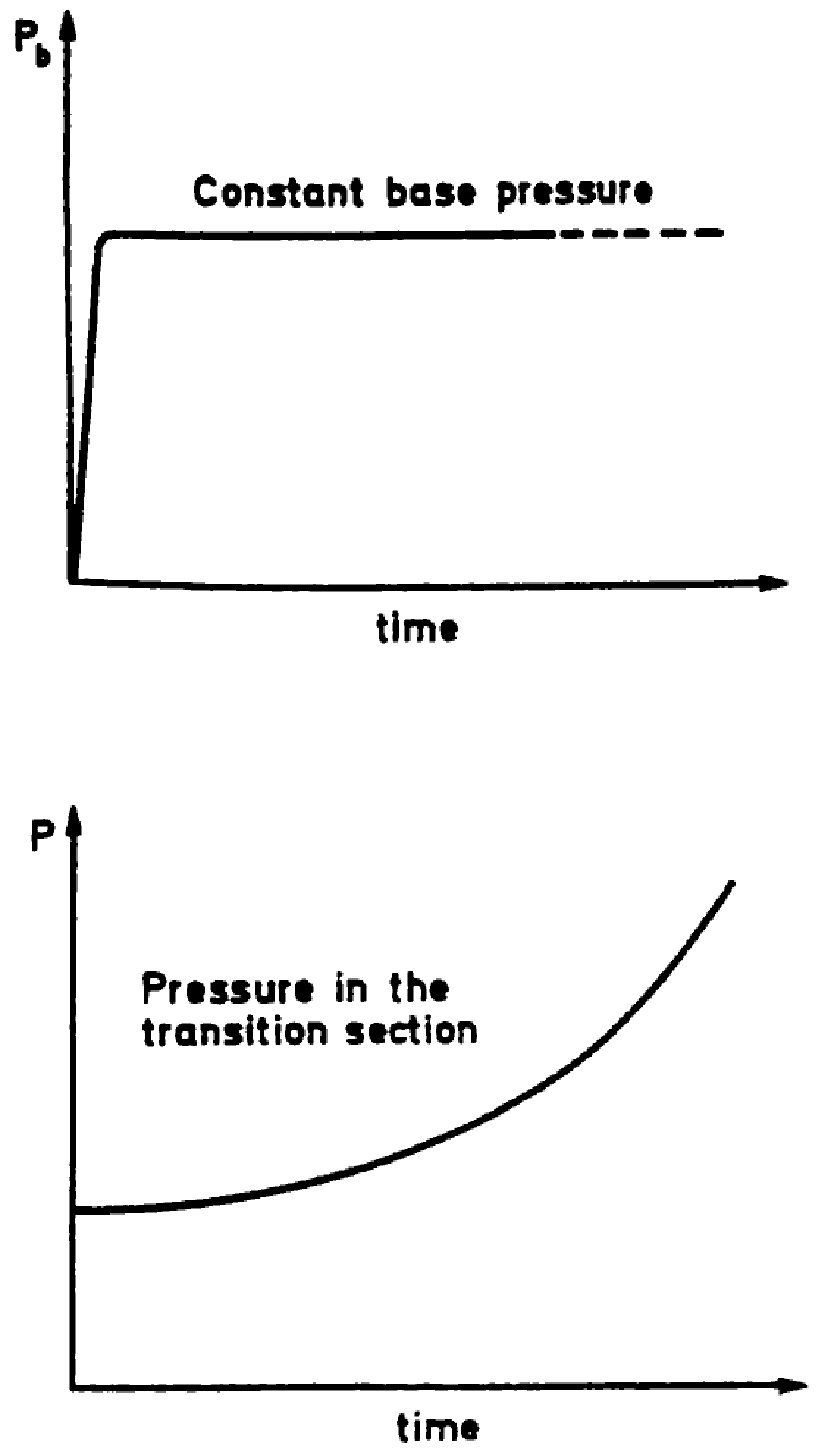


Figure 2. Constant base pressure gun requirements.

Lalit Chhabildas and co-workers at Sandia have demonstrated velocities up to 15.8 km/s by adding a third stage to a two-stage light gas gun with a graded density projectile (Ref. 1). A difficulty with this method is that the projectile thickness must be kept very thin to prevent spall fracture.

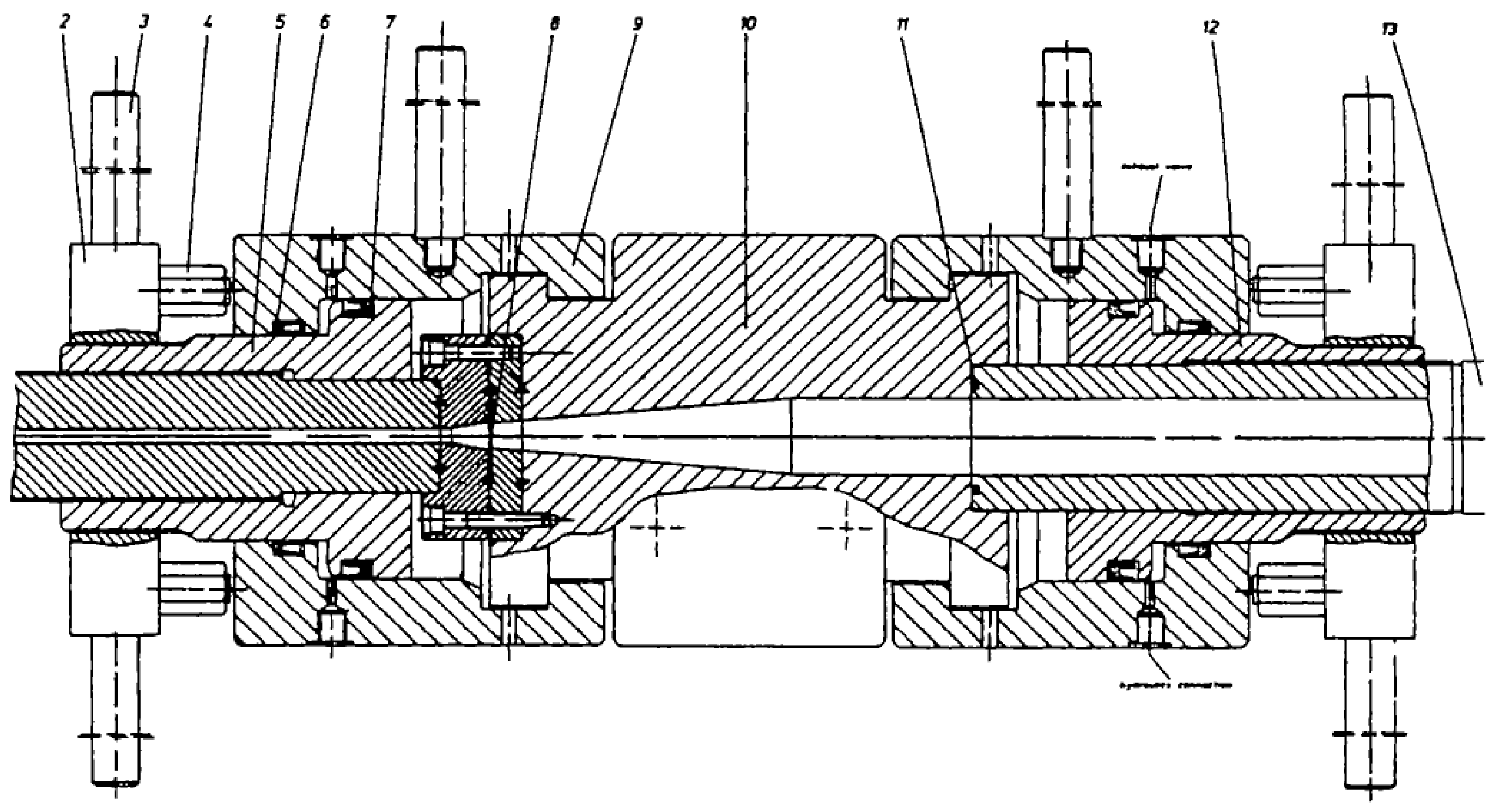
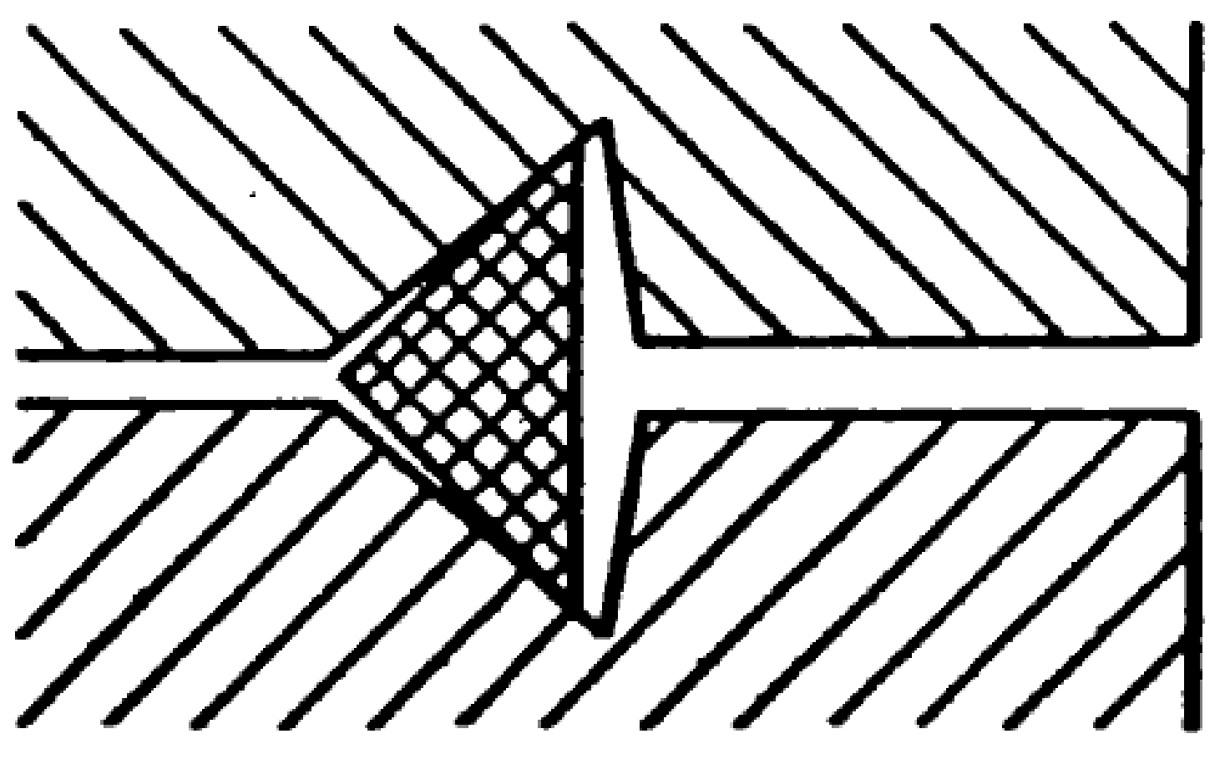


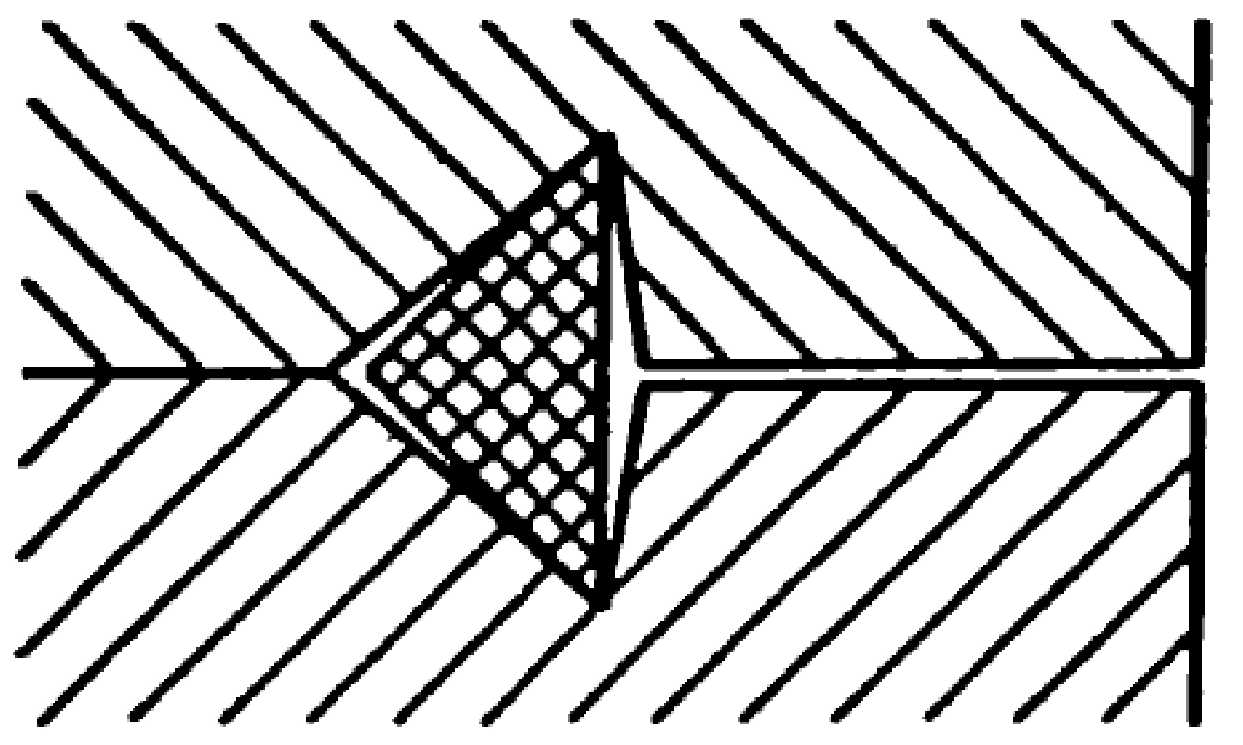
Figure 3. Transition section of a high performance LGG.

The design of the graded density projectile of the second stage is highly complicated and the kinetic energy efficiency of the third stage is less than 1 %. Modification of Chhabildas' methods proposed by Glenn (LLNL) (Ref. 2) predict much higher kinetic energy efficiency based on hydrocode calculations. Similar to the electromagnetic launchers, many of these concepts promise high efficiency and futuristic velocities in theory. When applied, however, many of these concepts fail by simple technical and mechanical problems.

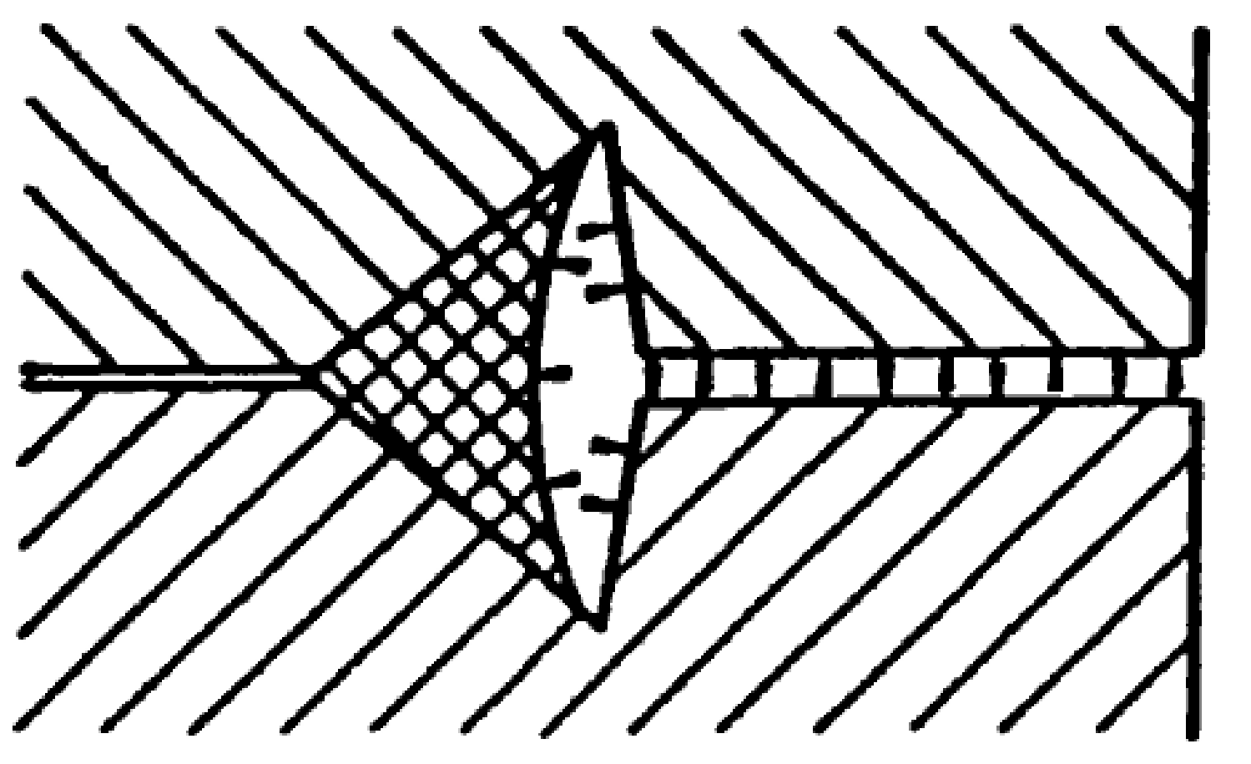
We have optimised a conventional medium-size, two-stage light gas gun by applying the simple empirical methods. We varied the gun geometry - the pump tube length and diameter, the transition angle in the high pressure section and a graded adaptation to the barrel diameter. High qualities surfaces in the pump tube and the barrel, good fits of the sabot in the barrel and of the piston in the pump tube to avoid blow-by and energy losses are standard requirements for the gun operations. With well-selected barrels and a high quality sealing technique shown in Fig. 4 standard velocities of 9.5 km/s with saboted projectiles can be reached easily; with unsaboted projectiles velocities up to 10.5 km/s can be reached without damaging the gun. We are sure that velocities higher than 11 km/s are possible by optimising all parameters and components, with new sabot techniques and materials, optimised clamping and sealing techniques.



no bolt load-no pressure load condition



maximum bolt preload-no pressure load condition



maximum bolt load-maximum pressure load condition

Figure 4. Dynamic sealing technique (Δ-ring seal).

We suggest now to use such an optimised system in a so-called counterfire concept to reach velocities higher than 10 km/s with different well-defined projectiles. This concept was first proposed by AEDC, USA. The scheme of a counterfire arrangement is shown in Fig. 5. In addition to an optimised small- or medium-size two-stage light gas gun, five other essential components and techniques are necessary to install and operate a successfully working counterfire facility:

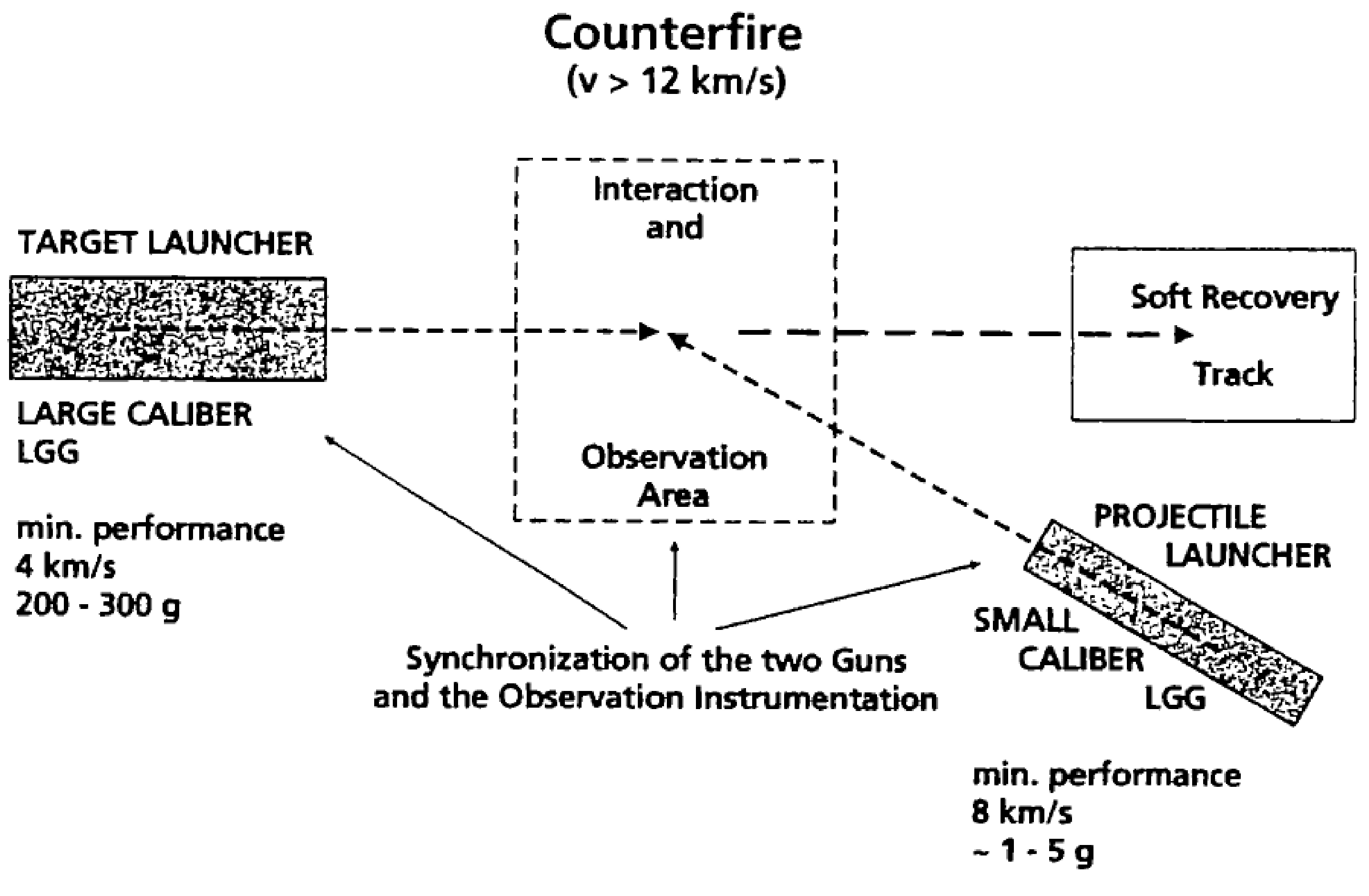


Figure 5. Conterfire principle.

- an impact range with a large caliber light gas gun (cal. ≥ 50 mm) to accelerate targets to velocities higher than 4 km/s
- a sophisticated sabot and sabot separation technique to launch the projectile and the target
- a soft recovery technique to catch the impacted target without secondary damages
- an advanced process control system steering the two guns and the measuring techniques
- a highly sophisticated observation technique with trigger and high speed photographic devices.

Impact velocities between 10 - 15 km/s appear possible as long as the targets are not too complex.

3. A NEW SHIELD CONCEPT

The conventional shielding system for satellites, space stations and other functional space crafts is the Whipple shield consisting of an outer bumper plate and a rear wall in a certain standoff distance to the bumper plate. In the last decades this concept has been improved by variations of material, spacing, thickness with the goal to achieve higher protection efficiency or saving weight in the structure.

T.D: Riney stated in his article "Numerical Evaluation of Hypervelocity Impact Phenomena" in the book *High-Velocity Impact Phenomena*, Academic Press (Ref. 3), that an impedance mismatch in layered bumpers has only secondary effects on the hypervelocity impact phenomena, and the predominant influence on the debris cloud formations and distribution is only the area density of the target. Based on experimental results we can demonstrate that the impedance mismatch causes an entirely different fragmentation behaviour of impactor and shield materials, and the material flux and distribution in the debris clouds behind and in front of the bumper shield are significantly different. These results are in strong contradiction to the numerical results of Riney. These effects can be a basis for the design of a new shield concept.

The first results about our studies were presented in the paper "Debris clouds behind Double-Layer Targets" at the Hypervelocity Impact Symposium in Freiburg last October (Ref. 4). In the following the most important results of the study are described.

We tested various layer combinations in different scales for a wide range of velocities. With double flash X-ray exposures the formation of the clouds was studied. Their expansion, downrange and uprange was observed. Witness plates in front and behind the double layer targets give additional information about the fragment distribution, fragment size, and material distributions.

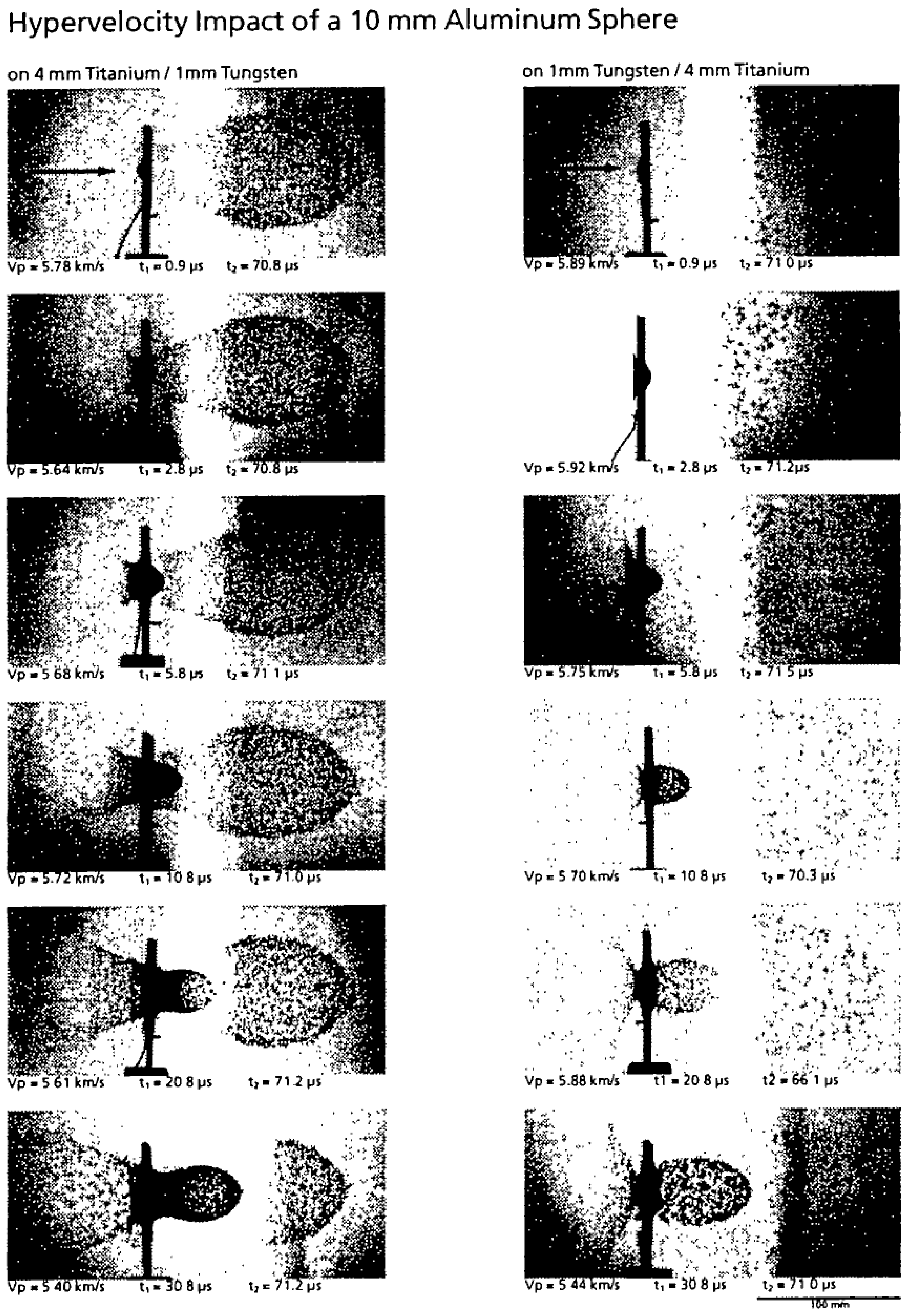


Figure 6. Series of X-ray pictures of the perforation of layered shields (Ti/W and W/Ti) at 6 km/s.

In addition, the results show that the shapes of the debris clouds down- and uprange are strongly dependent on the order of the two layers. For the layer combination Ti/W and W/Ti, respectively, the time-dependent formation process at an impact velocity of about 6 km/s is shown in the series of X-ray pictures in Fig. 6. The different shapes of the clouds are remarkable but, more important, the fragment size and distribution are very different. From the impact crater pattern on the witness plates it can be seen that the fragments are spread over different areas if the order of the plates is changed.

Based on these facts it is without doubt that material flux in the clouds can be influenced by impedance mismatch and by the order of the layers.

The quantitative analysis of the results show that the hole size in the targets and the velocity distribution are also influenced by the order of the layers as shown in Figs. 7 and 8.

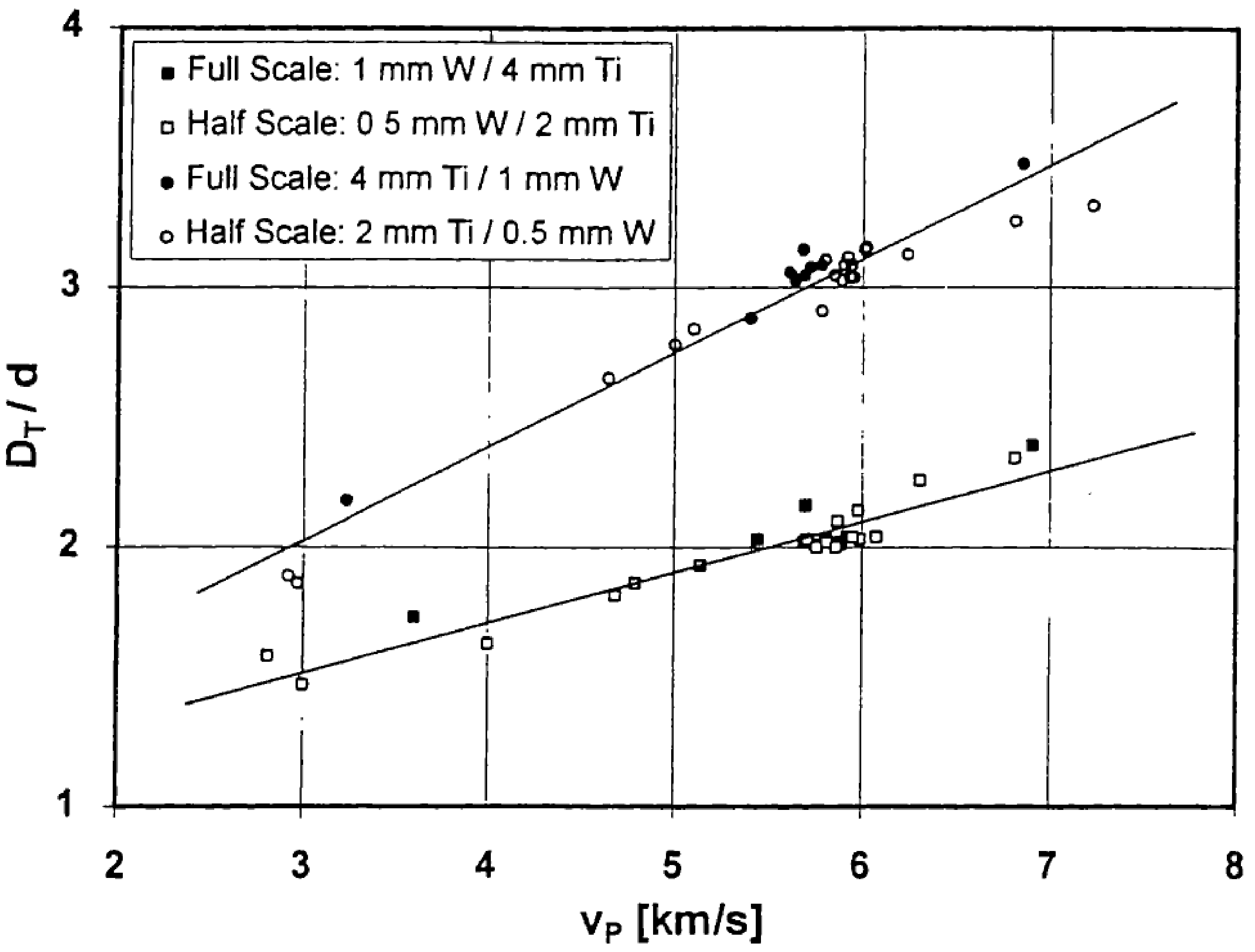


Figure 7. Normalized final crater in Titanium versus impact velocity.

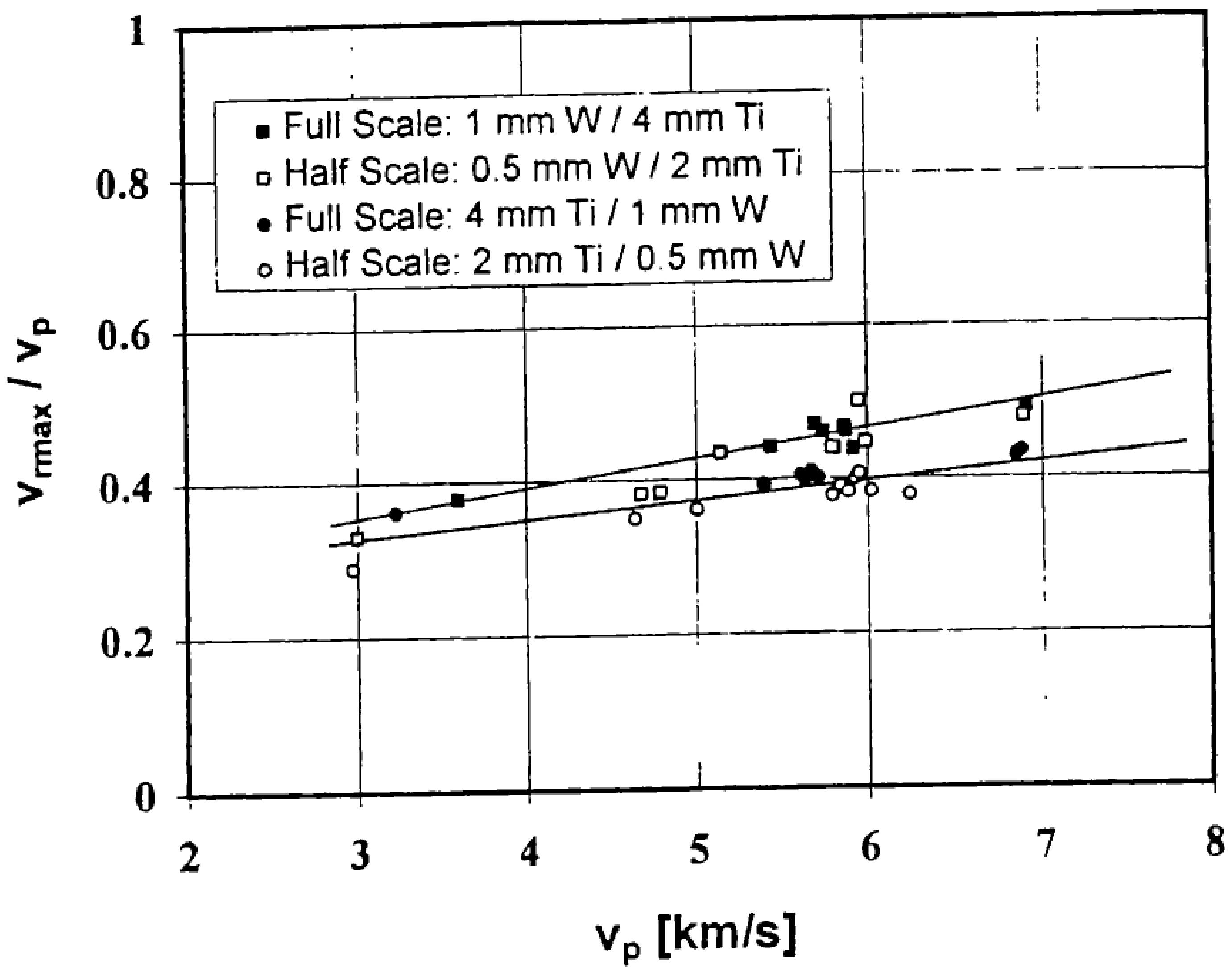


Figure 8a. Normalized maximum axial debris cloud velocity versus impact velocity.

In short, the shield concept with layers of different shock impedances offers the possibility to influence the energy and momentum distribution in such a way that the material flux against the impact direction increases with the impedance mismatch and the projectile fragmentation can also be increased at low impact velocities.

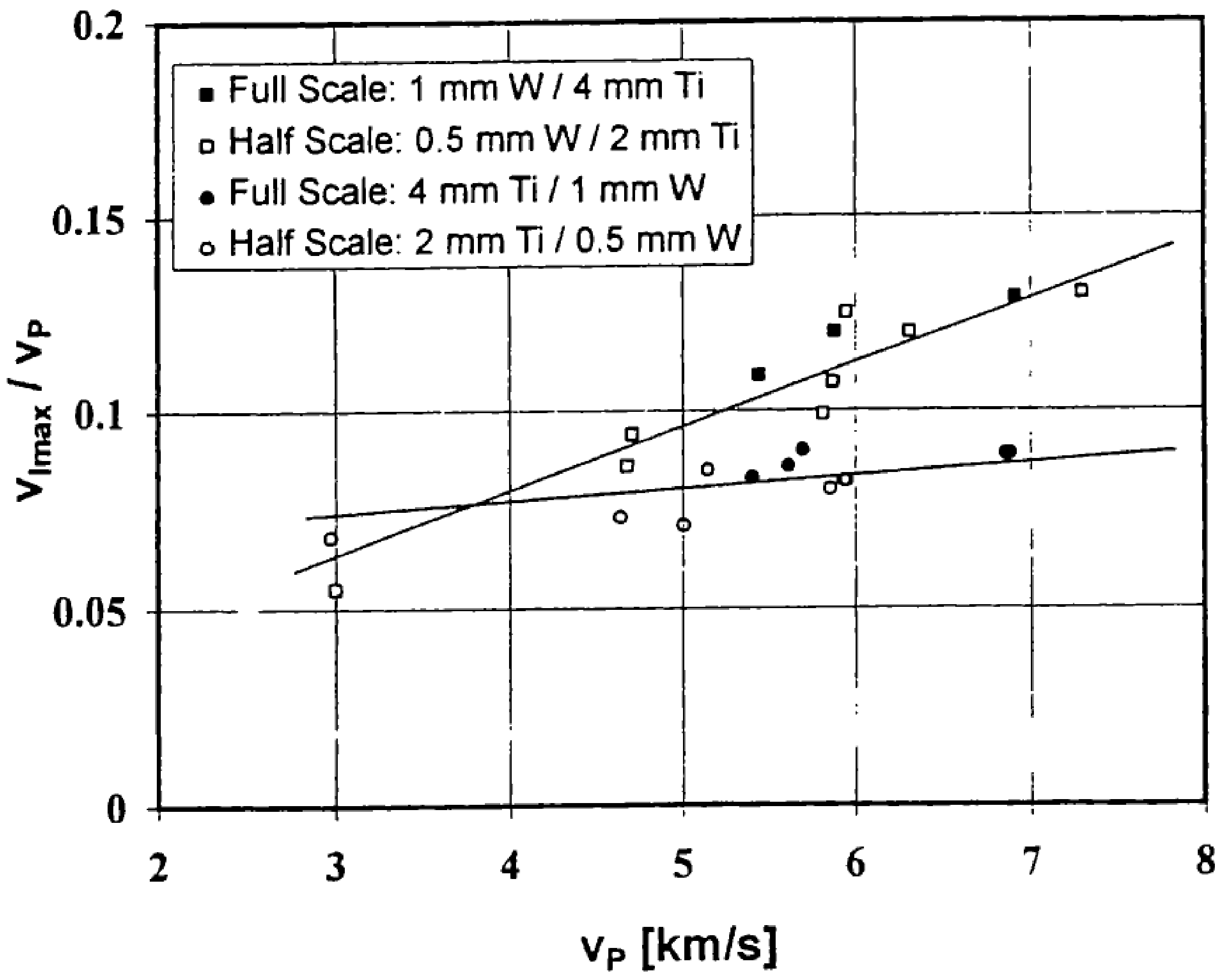


Figure 8b. Normalized maximum lateral debris cloud velocity versus impact velocity.

4. IMPACTS AT HIGH ANGLE OF OBLIQUITY

Complex structures and the operation constellation of spacecrafts, shuttles and satellites cause impacts at high angles of obliquity. Most shield concepts are tested at normal impact, less data is available for high angle of obliquity impact conditions. In the following, new results are presented which show that large damages can occur on the shields, but less energy is transferred behind the shields.

Impact angles for the study reported here were about 10°. The primary interest was to study the perforation phenomena and to know which part of the projectile ricochets on and which part perforates the shield of a spaced target. The fragments used in the experiments were cubes, the impact velocity was about 3 km/s. The low obliquity targets were 4 mm Alu-alloy plates. The ricochet and the perforating parts of the fragments were captured in a stack of plywood with Alu foils in between. The test set-up is shown in Fig. 9. The circle marks the observation area. The impact point is the centre of the dashed circle in Fig. 9.

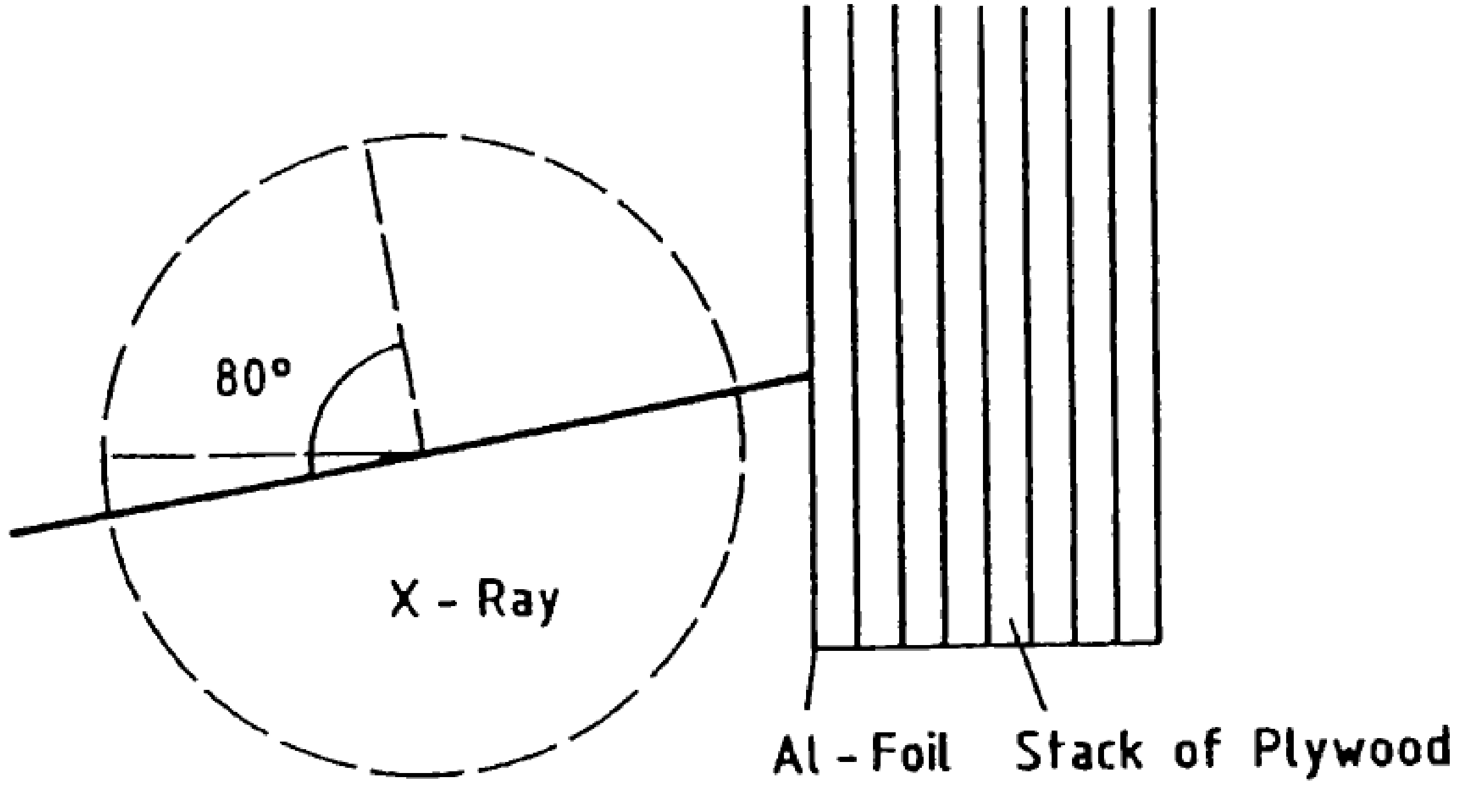


Figure 9. Test set-up.

The method of pseudo X-ray cinematography was applied to visualise the perforation event, i.e. all test parameters, such as impact velocity, impact point, projectile orientation, target obliquity, were kept constant for tests, only the delay time of the X-ray exposure was varied. In Fig. 10 a series of 8 X-ray pictures with delay times from 6 - 66 µsec are shown.

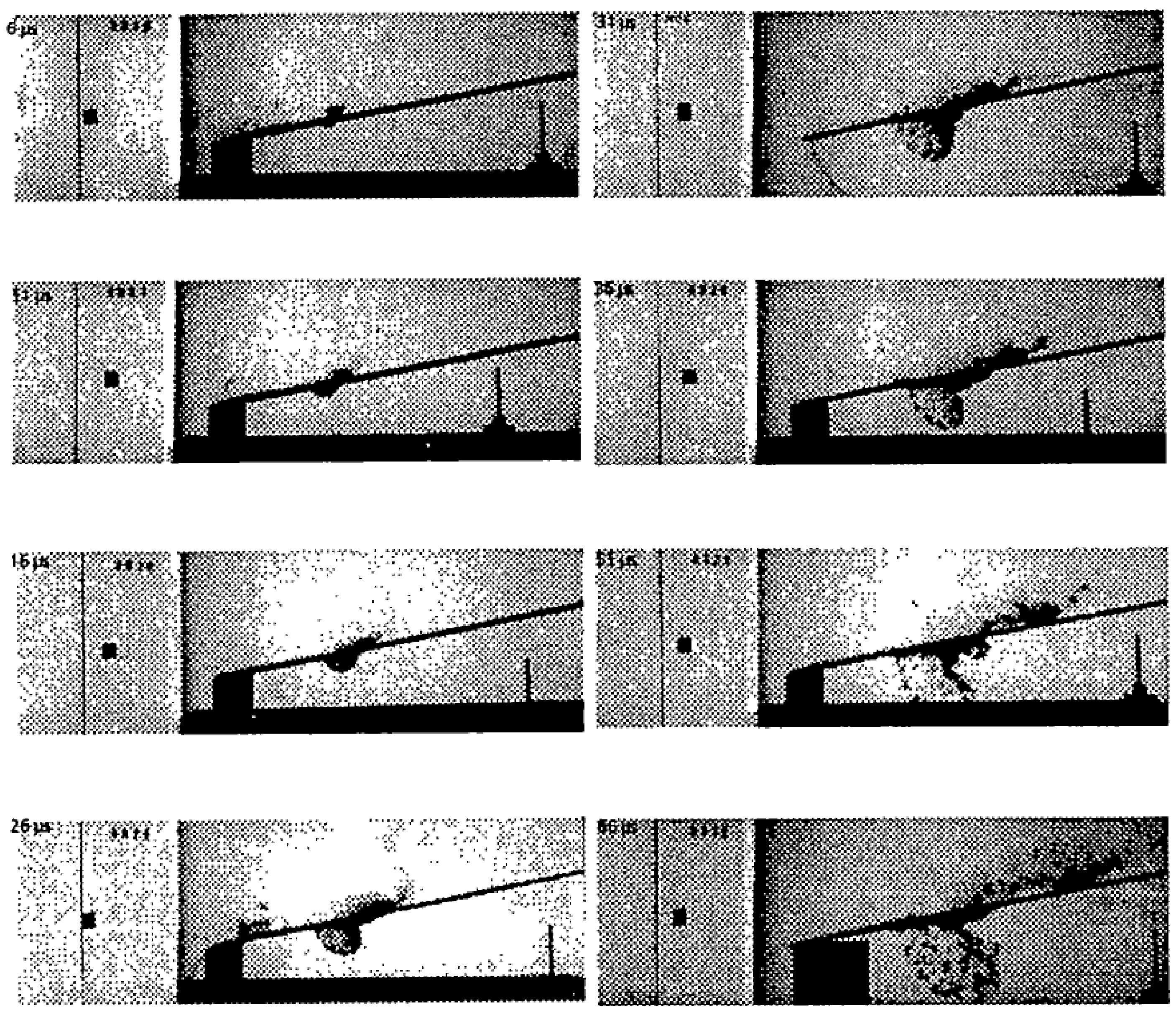


Figure 10. Series of X-ray pictures (6 - 66 µs) of the low angle impact event

The most interesting phenomena shown in this series are the ricochet process along the shield surface and the debris clouds formed at the rear side of the shield with the forming of several bulges, bursting step by step. The inspection and the analyses of the residual fragment collector behind the shield show that the penetrating part of the projectile is nearly zero (Fig. 11).

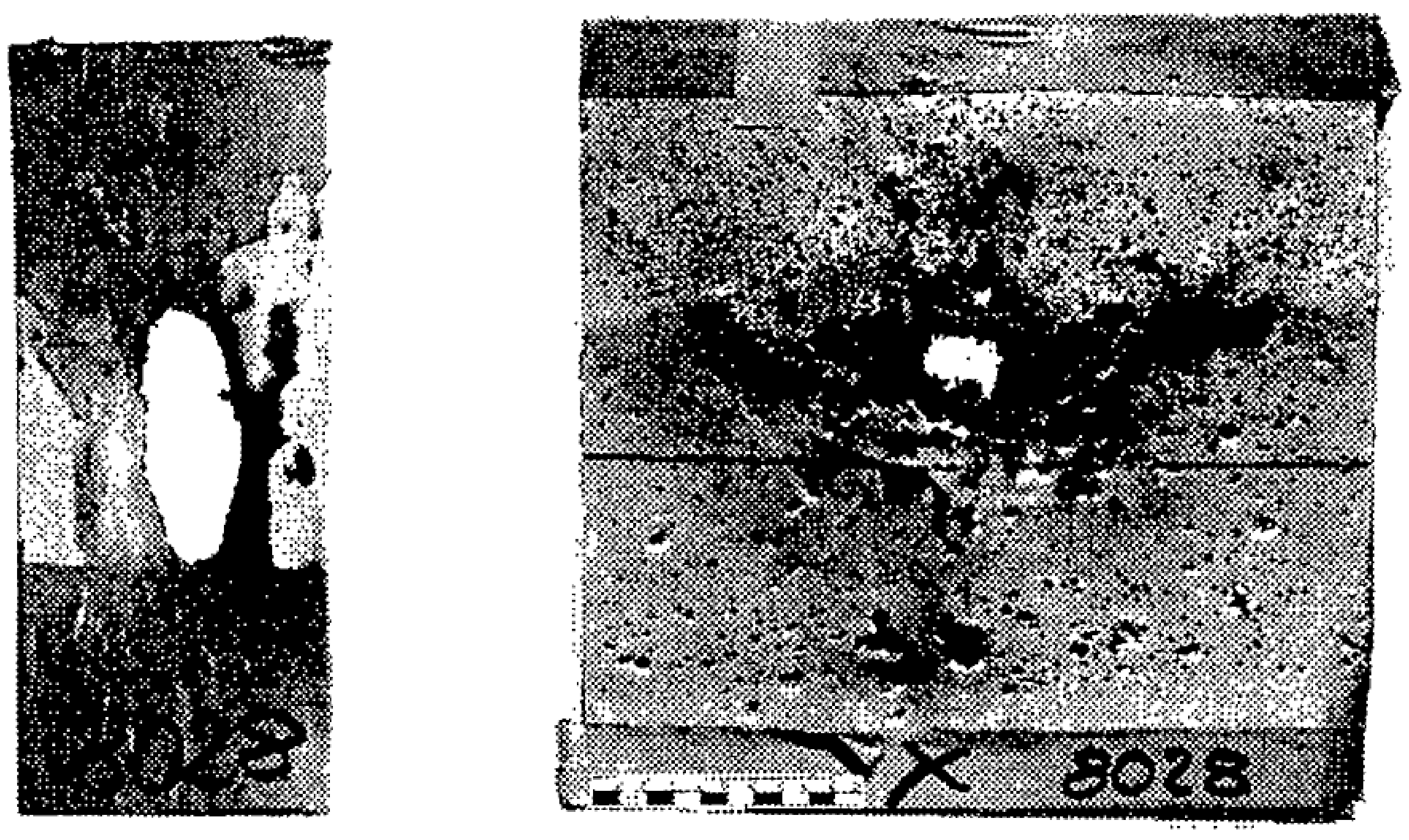


Figure 11. Perforated plate and recovery stack after impact.

The impacts below the conterline marked in Fig. 11 are mainly caused by fragments coming from the bulged shield areas. These fragments have much lower residual velocities in comparison to the fragments of the projectile which ricochet. The fact that more or less no projectile energy is transferred behind the target can also be used to design shield arrangements with a high angle of obliquity plates in front of sensitive areas of a spacecraft.

5. REFERENCES

1. Chhabildas, L. C. and Boslough, M. B., Experimental Techniques to Simulate Orbital Debris Impact on Space Shields at Impact Velocities over 10 km/s, *Proc. First European Conference on Space Debris*, Darmstadt, ESA SD-01, 1993.

2. Glenn, L. A., On How to Make the Fastest Gun in the West, *Int. Workshop on New Models and Numerical Codes for Shock Wave Processes in Condensed Media*, UCRL-JC-126057, Preprint.

3. Riney, T. D., Numerical Evaluation of Hypervelocity Impact Phenomena, *High Velocity Impact Phenomena*, Academic Press, New York, London, 1970.

4. Stilp, A. J. and Weber, K., Debris Clouds Behind Double-Layer Targets, Proc. 1996 Hypervelocity Impact Symposium, Int. Journal of Impact Engineering (in press).