

# Stopping Power of Explosive Reactive Armours Against Different Shaped Charge Diameters or at Different Angles

Manfred Held\*

TDW – Gesellschaft für verteidigungstechnische Wirksysteme mbH, 86523 Schrobenhausen (Germany)

## Summary

The experimental results of three different explosive reactive armour arrangements with single- and double-sandwiches are described against shaped charges of 64 mm, 96 mm, 144 mm and 200 mm base diameter under 60° NATO-angle and the 96 mm diameter shaped charge additional under the angles of 40° and 30°. Larger shaped charges give, as expected, more penetration capability. However, the 200 mm, not so precise shaped charge, only gives similar results compared to the 144 mm precision shaped charge. The stopping power depends extremely on the angle of the shaped charge axis to the reactive armour containing small layer thicknesses of high explosives.

## 1. Introduction

At the beginning of the explosive reactive armour area three different target types of explosive reactive armour (short ERA) were selected where two would be possible layouts for a frontal or glacis armour with one ERA-sandwich, respectively with two sandwiches. The third, which also consists of two sandwiches, would be a side armour. The sandwich plates were selected in their dimensions for the possibility to test also KE-rounds against these targets as first screening tests, not knowing any earlier results. At first, shaped charges of different diameters were fired against each type of these reactive armours and also the 96 mm shaped charge under different NATO-angles.

Nevertheless these first tests gave some indications of the stopping power of such explosive reactive armours to defeat shaped charge jets.

## 2. Used Shaped Charges

Four different shaped charge sizes, all with so-called wave shapers, were used in this investigation

- 64 mm base diameter
- 96 mm base diameter
- 144 mm base diameter
- 200 mm base diameter

The three smaller shaped charges consisted of so-called squeeze cast TNT/RDX high explosive charges with about 15% TNT and 85% RDX with charge densities of about 1.8 g/cm<sup>3</sup>. The 200 mm shaped charge had a normal cast TNT/RDX.

The 64 mm shaped charge had a 1 mm copper liner of 60° and with the help of the wave shaper it achieved a jet tip velocity of about 9 mm/μs. The 96 mm shaped charge had a 2 mm liner of 60° which gave about 8.5 mm/μs jet tip velocity. The 144 mm shaped charge had a 2.5 mm copper liner of 60° and again a wave shaper in a short distance to the tip of the liner, which gave also 8.5 mm/μs jet tip velocity. Finally the 200 mm shaped charge had a 3 mm copper liner of 60°. However, a normal cast high explosive charge with about 65% to 70% RDX and 35% to 30% TNT with a density of about 1.78 g/cm<sup>3</sup> was used for this shaped charge. The jet tip velocity was again about 8.5 mm/μs by means of wave shaping. All charges were fired at 2 caliber standoffs to the front face of the ERA-sandwiches.

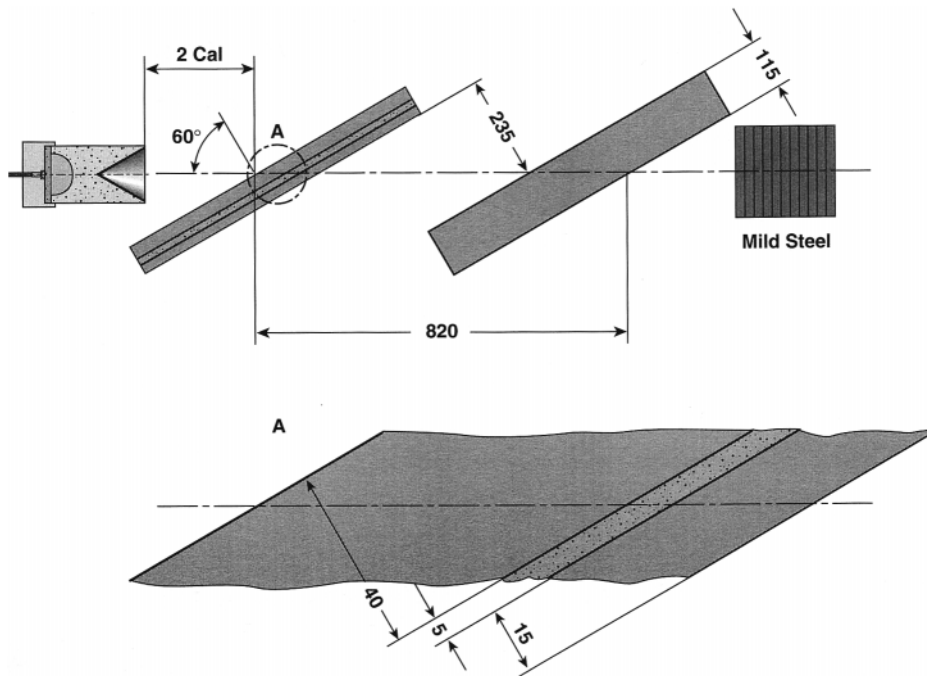
## 3. Test Results

### 3.1 Single ERA-Sandwich in Front of a Glacis Plate

The single reactive armour sandwich A1 (Figure 1) was designed with a 40 mm thick front plate of RHA, a 5 mm thick layer of a high explosive charge – some type of detasheet – and a 15 mm thick rear plate of RHA. The plate velocities are calculated by the asymmetric Gurney equation<sup>(1)</sup> to 160 m/s for the front plate and 440 m/s for the rear plate perpendicular to the surfaces. This sandwich is in front of a 115 mm thick armour plate with a perpendicular air distance of 235 mm. The total spacing from the front of the ERA-sandwich to the rear of the 115 mm RHA plate is 820 mm under 60°. The weight of the ERA A1 is about 1.35 t/m<sup>2</sup> in perpendicular direction or 2.7 t/m<sup>2</sup> in 60° direction or in line of sight (LOS). A witness block of mild steel was arranged behind this RHA plate along the charge axis to measure residual penetrations, if the target is perforated.

Shaped charges of 64 mm, 96 mm and 144 mm diameters were fired against this type of explosive reactive armour, arranged under 60° NATO-angle (Figure 2). The 64 mm shaped charge gave in the main target a residual penetration in line of sight of 10 mm. This gives a total crater length of 120 mm in RHA in LOS.

\* e-mail: manfred.held@tdw.lfk.dasa.de



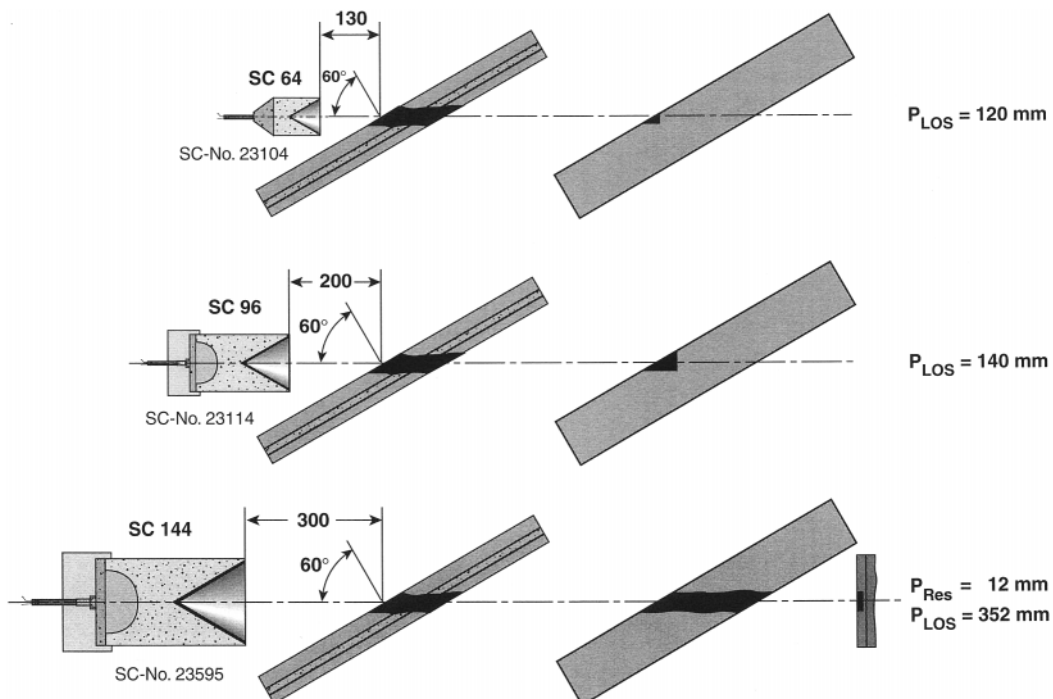
**Figure 1.** Glacis armour A1 with one reactive armour sandwich.

With the 96 mm shaped charge the residual penetration in the main armour was 30 mm which is also a drastically reduced penetration. The line of sight penetration in RHA was 140 mm.

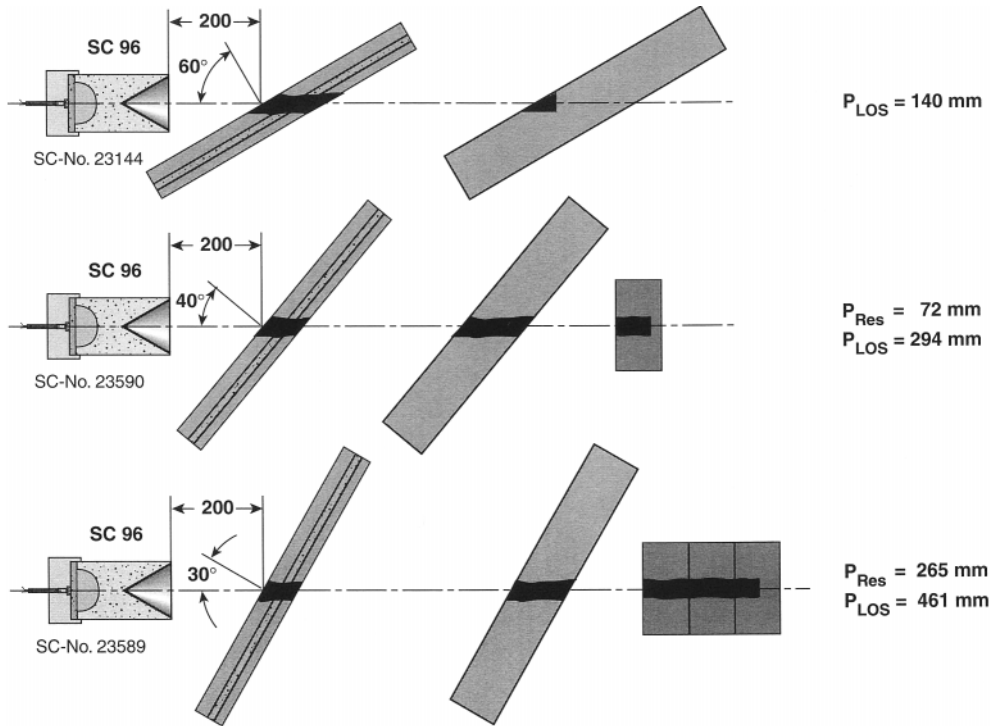
Only the 144 mm shaped charge perforated the armour arrangement A1 which consisted of the ERA-sandwich with 110 mm perforation length and of the main armour with additional 230 mm perforation length. The residual

penetration was 12 mm. This means that the total penetration path in RHA was 352 mm in LOS.

The 96 mm shaped charge was also fired against this type of ERA target A1 under 40° and 30° NATO-angle (Figure 3). The main target was perforated under 40° NATO-angle with a residual penetration of 72 mm in the mild steel witness blocks. This gives a total penetration length in RHA of 294 mm in LOS.



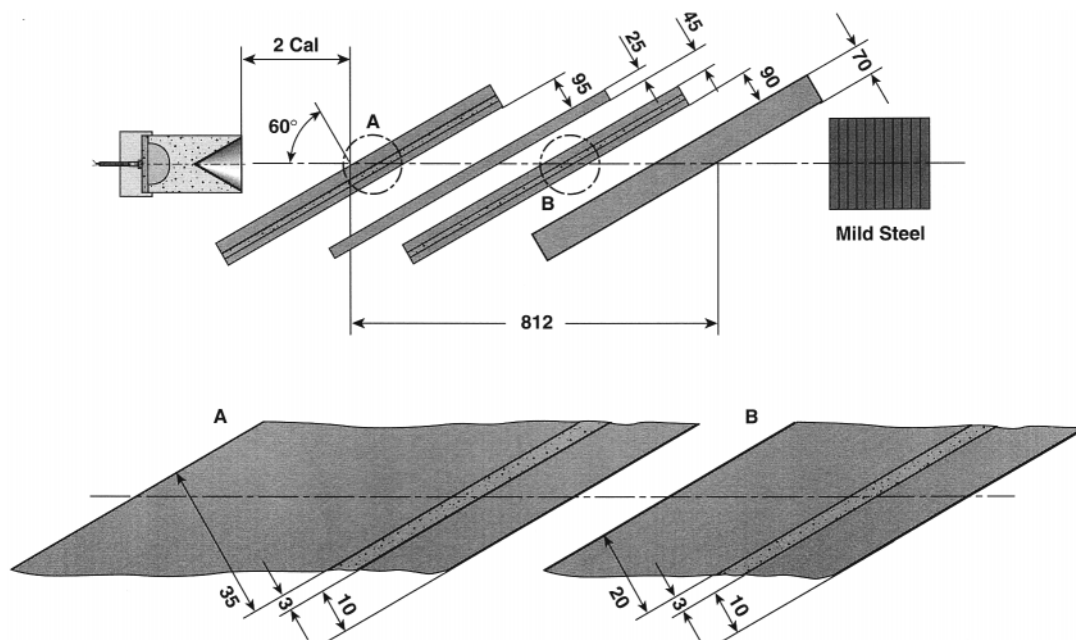
**Figure 2.** Test results with different shaped charge diameters fired at 2 caliber standoffs against the glacis plate explosive reactive armour A1 with one ERA-sandwich.



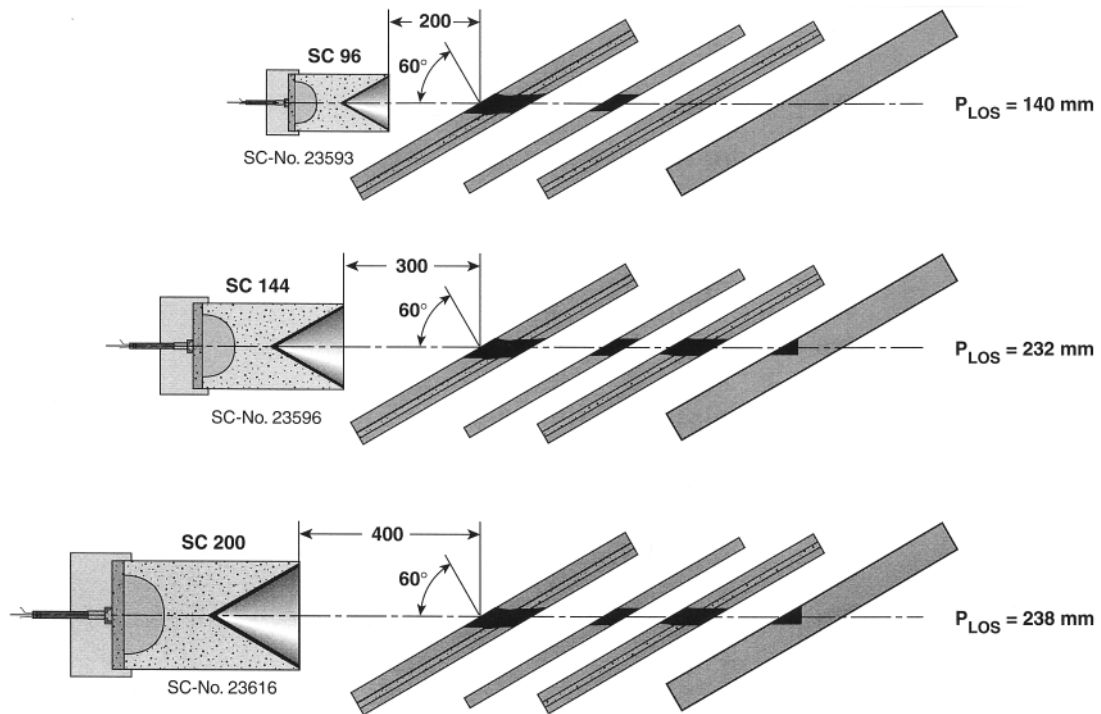
**Figure 3.** Test results of the 96 mm shaped charge at 2 caliber standoff against the glacis plate explosive reactive armour with one ERA-sandwich at three different attack angles.

With the decreasing NATO-angle to 30° the penetration increased remarkably again with a residual penetration in the mild steel witness blocks of 265 mm. The line of sight RHA perforation through the ERA-sandwich and main armour under 30° NATO-angle is 196 mm. This gives a total penetration length of 461 mm in LOS.

These tests under different angles clearly demonstrate that ERA-sandwiches of this configuration with a relatively small amount of high explosive have an extremely strong angle effect. As the 30° NATO-angle gave 461 mm penetration, the 40° NATO-angle 294 mm and the 60° NATO-angle gave only 140 mm LOS penetration in RHA.



**Figure 4.** Glacis armour ERA A2 with two explosive reactive armour sandwiches.

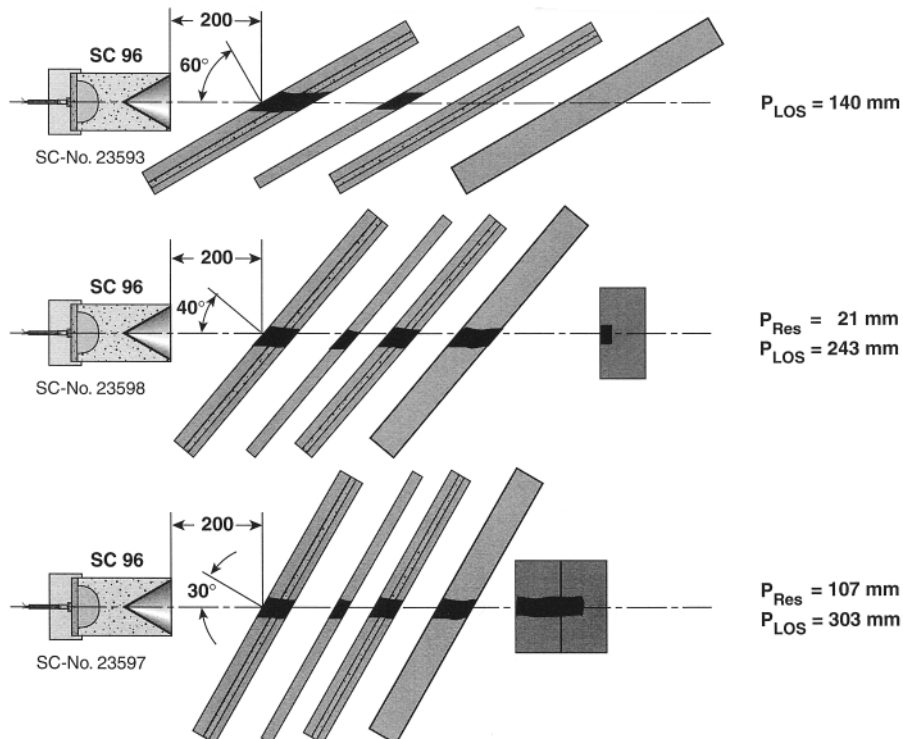


**Figure 5.** Test results of shaped charge firings with 96 mm, 144 mm and 200 mm diameters at two caliber standoffs against the glacis plate armour ERA A2 with two explosive reactive armour sandwiches.

3.2 Double ERA-Sandwiches in Front of a Glacis Plate

To see the influence of “two” ERA-sandwiches as first screening tests, the following target arrangement A2 was

laid out (Figure 4). The first ERA-sandwich with a 35 mm front plate, a 3 mm high explosive layer and a 10 mm rear plate was arranged in front of a 25 mm RHA-plate with 95 mm perpendicular air gap distance. This 25 mm RHA-



**Figure 6.** Test results of the 96 mm shaped charge at 2 caliber standoff against the glacis armour ERA A2 with two explosive reactive armour sandwiches at three attack angles.

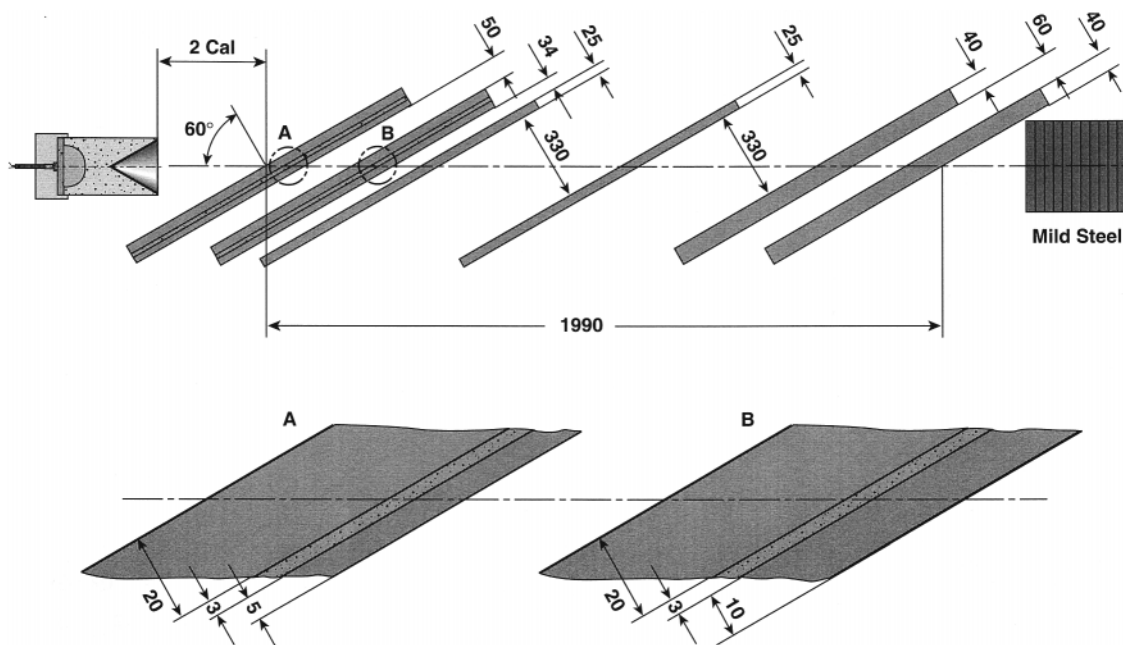


Figure 7. Side armour ERA A3 with two explosive reactive armour sandwiches.

plate had to separate both sandwiches. The second sandwich followed in a perpendicular air gap distance of 45 mm with a 20 mm front plate, a 3 mm high explosive layer and a 10 mm rear plate. The plate velocities were calculated for the first ERA-sandwich 35/3/10 to 125 m/s and 430 m/s and for the second ERA-sandwich 20/3/10 to 200 m/s and 400 m/s. The main armour of 70 mm thickness followed in an air gap distance of 90 mm. The total spacings from the front surface to the rear plate under 60° was 812 mm which is similar to the single ERA-sandwich with 820 mm spacings and the areal weight is exactly equal with 1.35 t/m<sup>2</sup> perpendicular or 2.7 t/m<sup>2</sup> in 60° direction.

Three shaped charge sizes with 96 mm, 144 mm and 200 mm base diameters were fired against this double ERA-sandwich arrangement (Figure 5). The 96 mm shaped charge perforated the first ERA-sandwich, the 25 mm spaced or separation plate and was stopped on the second sandwich. The total penetration achieved 140 mm in LOS.

The 144 mm shaped charge perforated and initiated the two ERA-sandwiches and was stopped by the main armour with 32 mm penetration in the firing direction or 232 mm LOS penetration in RHA.

It was also surprising, that the 200 mm shaped charge was stopped by this double ERA-sandwich under 60°. Only a little more residual penetration was achieved in the main armour with 38 mm or 238 mm LOS penetration in RHA in the firing direction.

None of the investigated shaped charges was able to perforate these double reactive armour system under 60° NATO-angle with 2.7 t/m<sup>2</sup> areal weight.

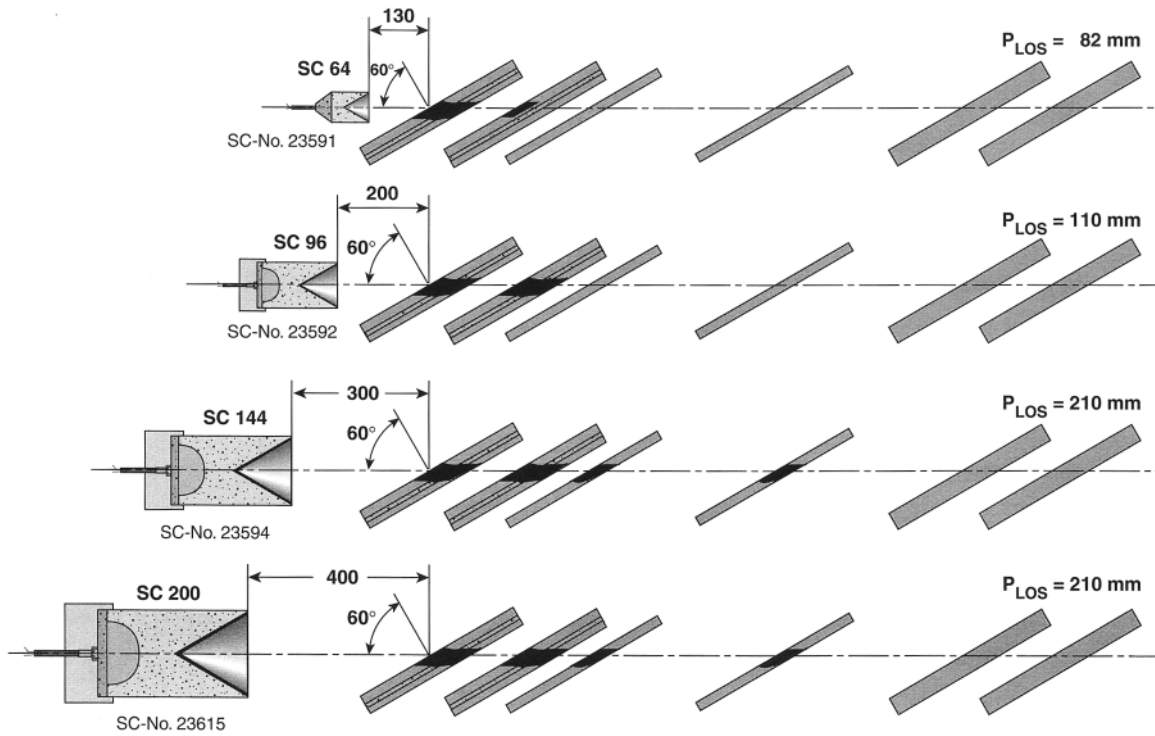
The 96 mm shaped charge was fired once against the A2 target under 40° and 30° NATO-angle. Under 40° this armour was just perforated with a small residual penetration of 21 mm or a total LOS perforation in RHA of 243 mm (Figure 6). The residual penetration in the mild

steel witness blocks increased again under 30° NATO-angle to 107 mm, which gave a LOS perforation in steel in total of 303 mm.

### 3.3 Double ERA-Sandwiches as Side Armour

In addition a double reactive test setup was designed as a heavy side armour with double reactive sandwich plates, defined as ERA A3 arrangement (Figure 7). A 20 mm front plate, a 3 mm thin high explosive layer and a 5 mm rear plate were used for the first ERA-sandwich. In a perpendicular air gap distance of 15 mm a second ERA-sandwich with 20 mm front plate, again 3 mm thin high explosive layer and a 10 mm rear plate were arranged. For the first relatively light ERA-sandwich 20/3/5 plate velocities were calculated to 150 m/s for the 20 mm front and to 600 m/s for the 5 mm rear plate. The second sandwich 20/3/10 is the same as in A2 with the calculated velocities of 200 m/s, respectively 400 m/s. A 25 mm thick RHA plate was installed in a 34 mm perpendicular air gap distance behind the second ERA-sandwich. In 330 mm air gap distance a 25 mm thick medium hard steel plate was used, as it is given in the NATO triple target, and as the main armour was used a spaced armour of two 40 mm thick RHA plates with a 60 mm air gap distance. The areal weight under 60° NATO-angle is about 3 t/m<sup>2</sup>. This target arrangement A3 was very largely spread over a distance of nearly 2000 mm. A witness block of mild steel was attached in the firing direction to measure residual penetrations.

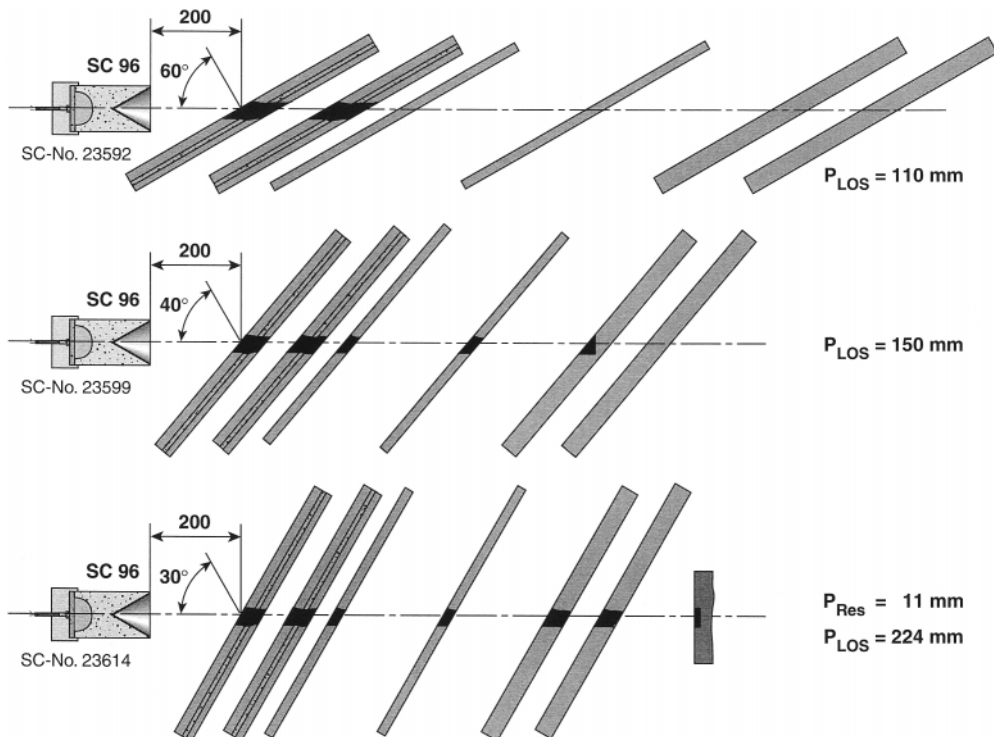
Against this target A3 all four shaped charge sizes were fired (Figure 8). The double sandwiches of this ERA side armour with the large distances to the main armour, are against all tested shaped charge sizes under 60° NATO-angle very effective. The 64 mm shaped charge did not perforate the front plate of the second ERA-sandwich and



**Figure 8.** Test results of four different shaped charge sizes against the side armour ERA A3 with double reactive armour sandwiches at two caliber standoffs.

was therefore not able to initiate the high explosive charge of the second reactive sandwich. The total measurable pass length in RHA was only 82 mm.

The 96 mm shaped charge perforated and initiated the two sandwiches, but no impacts were visible in the 25 mm spaced plate after the two ERA-sandwiches. This means that the jet



**Figure 9.** Test results of the 96 mm shaped charge against the side armour ERA A3 with double explosive reactive armour sandwiches at three attack angles.

was so strongly disturbed by the two ERA-sandwiches, that no holes were created in the 25 mm plate at only 68 mm distance. The perforation path in RHA was only 110 mm in LOS.

The 144 mm charge was able to perforate the 25 mm middle plate and has got a residual penetration of 50 mm in line of sight in the 40 mm first plate of the main armour. The total penetration path was 260 mm in RHA in LOS.

In addition it was surprising that the 200 mm shaped charge did not make more penetration than the 144 mm shaped charge.

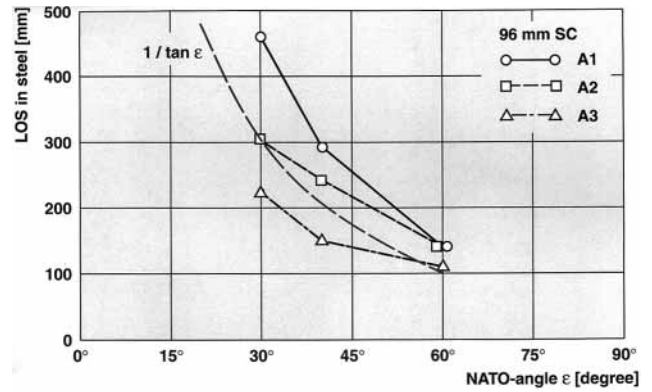
This double reactive side armour arrangement A3 was tested again with the NATO-angles of 40° and 30°, too (Figure 9). The 96 mm shaped charge was not able to perforate this ERA A3 under 40°. It achieved 150 mm in LOS in the strongly separated target plates and was just capable of perforating the target under 30° NATO-angle with a residual penetration of only 11 mm or with only 224 mm armour thickness in LOS or 1.8 t/m<sup>2</sup> total areal weight.

#### 4. Discussion of the Results

The Figures 10 and 11 give the penetrations in line of sight in steel for all 16 firings as a function of shaped charge diameters with the ERAs under 60° and as a function of the NATO-angles for the 96 mm shaped charge with the three ERA-layouts as parameter. As expected, with larger shaped charge diameters, the LOS-penetration values increased up to the 144 mm precision shaped charge. However, in two tests the 200 mm less precise shaped charge only achieved the same penetrations.

This was a surprising result as at this time a lot of people had believed that a more robust shaped charge compared to a high precision shaped charge will be less disturbed or influenced by reactive armour sandwiches.

Figure 11 demonstrates, that reactive armours with one sandwich and relatively small amount of high explosive per unit area have a very strong angle dependence on its protection level. In this diagram the single sandwich ERA arrange-

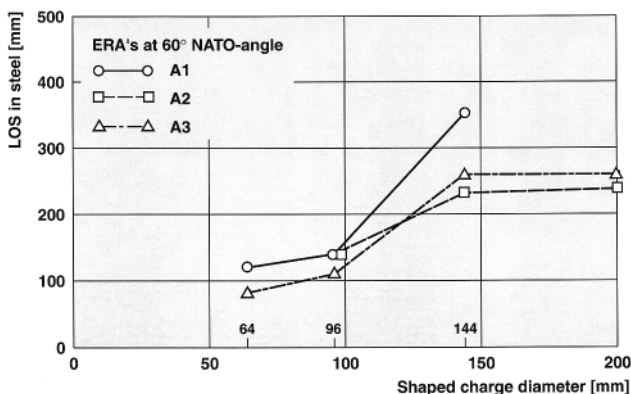


**Figure 11.** Line of sight penetrations in steel with the 96 mm shaped charge, fired at 2 caliber standoff at the investigated NATO-angles of 30°, 40° and 60° against the three types of explosive reactive armour systems.

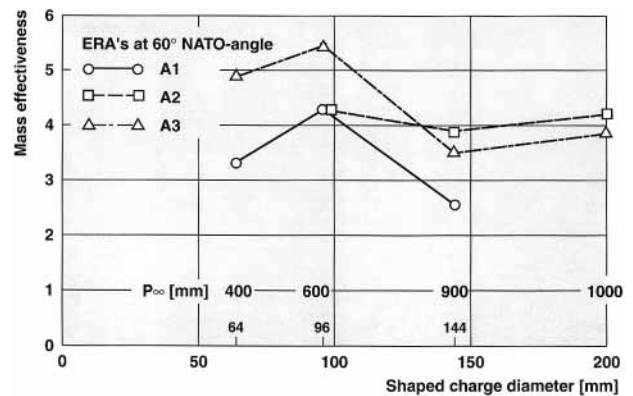
ment A1 disturbs less compared to the double sandwich ERAs A2 and A3. Surely, the wide spreading target A3 as the side armour gave the minimum residual penetrations in the long distances to the main armour. The decreasing penetration can be roughly described with an inverse tangent function ( $1/\tan \epsilon$ ) which is given as a rule of thumb by a simple momentum theory<sup>(2)</sup>. The dashed line in Figure 11 presents at least the trend.

The ERA A2 and ERA A3 with their double sandwiches seem to be more effective compared to ERA A1 with only one sandwich.

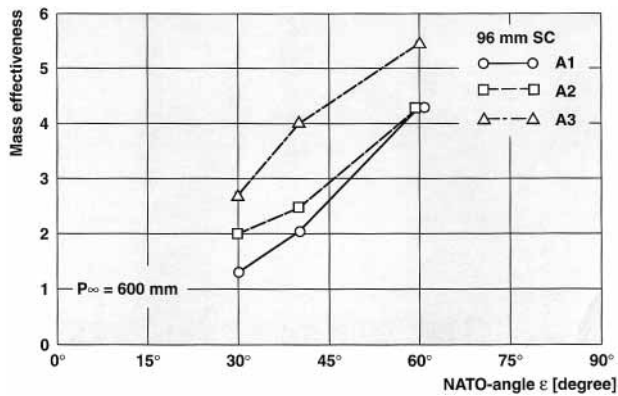
The gain in mass can also be expressed by the ratio of the penetration of the different shaped charge sizes in semi-infinite RHA targets and the achieved LOS penetrations in the ERA targets. These mass effectiveness factors  $E_M$ <sup>(3)</sup> are shown in the Figures 12 and 13. Surprisingly the 96 mm shaped charge seems to be better defeated than the 64 mm or 144 mm shaped charges. However, the level of  $E_M$  is around 3.5 with one exception of ERA A1 and the 144 mm shaped charge ( $E_M = 2.5$ ). The  $E_M$  values will nearly decrease linear from 4 to 1.3 for ERA A1 or from 5.4 to 2.7 for ERA A3, if the



**Figure 10.** Line of sight penetrations in steel as a function of shaped charge diameters in the three investigated ERA arrangement at 60° NATO-angle.



**Figure 12.** Mass effectiveness  $E_M$  as a function of shaped charge diameters, fired at 2 caliber standoff and under 60° NATO-angle, against the three types of explosive reactive armour systems. The reference penetration in RHA for the four investigated shaped charge diameters are given as  $P_\infty$  above the calibers.



**Figure 13.** Mass effectiveness of the 3 investigated ERA arrangements for the 96 mm shaped charge, fired at two caliber standoff as a function of the three investigated NATO-angles of 30°, 40° and 60°. The reference penetration is 600 mm in RHA at 2 caliber standoff.

NATO-angle is changed from 60° to 30°. Every point is only “one” test and no statistics is included in these values. Therefore, these diagrams only give the rough trend of such ERA-arrangements.

## 5. Conclusion

The 16 first screening tests of shaped charges with different diameters against three types of heavy reactive armour layouts demonstrated a high protection level, especially by double reactive sandwich arrangements. If the angles between the ERA-targets and the shaped charge axis decrease, their effectiveness will fast reduce.

## 6. References

- (1) M. Held, “Plate Velocities for Asymmetric Sandwiches”, *Propellants, Explosives, Pyrotechnics* 22, 218–220 (1997).
- (2) M. Held, “Momentum Theory of Explosive Reactive Armours”, *Propellants, Explosives, Pyrotechnics* 26, 91–96 (2001).
- (3) M. Held, “Effectiveness Factors for Explosive Reactive Armour Systems”, *Propellants, Explosives, Pyrotechnics* 24, 70–75 (1999).

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