Assessment of Explosives in Squibs

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Abstract: *Experiments in this study reveal that the initiating capability of commonly used squibs is not high enough to initiate PETN in all cases. The fulfilment of the 'new' essential safety requirement 4 as set out in the European directive 2013/29/EU and the categorization of squibs as theatrical pyrotechnic articles (T2) can therefore be justified, as the explosive investigated belongs to quite a sensitive type (initiation with low impulse energies possible). Underwater initiating capability tests according to EN 13763-15 led to meaningful results, showing that squibs are usually unable to initiate a secondary explosive. For a general assessment of the initiating capability of squibs and comparable (theatrical) pyrotechnic articles a threshold range of an equivalent initiation capability in grams of PETN on the basis of the performed underwater initiating capability tests was determined. It was found that squibs are generally not capable of initiating secondary explosives if the underwater initiating capability test showed an equivalent initiation capability below 0.25 g PETN. As a consequence of this result, the underwater initiating capability test gives an effective and safer alternative to the experimental confirmation of the 'new' ESR 4 by direct contact of the article with the secondary explosive and should then be preferred to it.*

Keywords: *Squibs, ESR 4, PETN, underwater initiating capability, EN 13763-15*

Introduction and background

The essential safety requirement (ESR) number 4 of the current European Directive 2007/23/EC[1] on the placing on the market of pyrotechnic articles requires the absence of all commercial blasting explosives (except for black powder or flash composition) and military explosives in pyrotechnic articles. However, some existing articles have contained commercial blasting explosives for many years now and where approved by the Member States on a national basis. Well known examples of these types are airbags and squibs to mimic bullet impacts for theatrical or television purposes. The recast of the above mentioned European Directive (2013/29/EU[2]) acknowledges this issue by changing the relevant ESR 4 to the following formulation:

'Pyrotechnic articles must not contain detonative explosives other than black powder and flash composition, except for pyrotechnic articles of categories P1, P2, T2 and fireworks of category F4 meeting the following conditions:

(a) the detonative explosive cannot be easily extracted from the pyrotechnic article;

(b) for category P1, the pyrotechnic article cannot function in a detonative manner, or cannot, as designed and manufactured, initiate secondary explosives;

(c) for categories F4, T2 and P2, the pyrotechnic article is designed and intended not to function in a detonative manner, or, if designed to detonate, it cannot as designed and manufactured initiate secondary explosives.'

Following this approach, an experimental proof of the non-initiation of secondary explosives is mandatory if the pyrotechnic article is designed and manufactured to detonate. An official harmonized

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test method for this investigation currently does not exist.

The main aim of this work was to investigate whether common squibs as theatrical pyrotechnic articles would generally fulfil the new 'ESR 4' for the European Directive (2013/29/EU[2]) as stated above.

For the investigations of this work common squibs available on the German market (under the national approval system valid until 2017) were used, as a comparable impact with regard to detonators for explosives was expected. Squibs were chosen as an appropriate representative of pyrotechnic articles where an initiation of secondary explosives cannot be excluded.

Reasons for the direct comparison of squibs with detonators were mainly twofold:

- Squibs contain comparable explosive substances to detonators, and
- Approved test methods for detonators exist for the determination of their performance characteristics.

The squibs of different intensities used in this study (manufacturer Josef Köhler Pyrotechnik; including the net explosive contents [NEC]) are listed in Table 1.

The reference detonators for explosives used for comparison (manufacturer Austin Detonator) are given in Table 2.

Table 1. *Squibs used in this study.*

Type of squib		NEC/g
Squib (Bullet hit)	'HE 1'	0.078
Squib (Bullet hit)	'HE 4'	0.302
Squib free of heavy metals	'Cl-1/4G'	0.008
Squib free of heavy metals	'Cl-1/2G'	0.018
Squib free of heavy metals	'Cl-1G'	0.028
Squib free of heavy metals	'Cl-2G'	0.060
Squib free of heavy metals	'Cl-6G'	0.205
Squib free of heavy metals	'FL-1/8G'	0.006
Squib free of heavy metals	'FL-1/4G'	0.010
Squib free of heavy metals	'FL-1/2G'	0.020
Squib free of heavy metals	'FL1G'	0.028
Squib free of heavy metals	'FL-2G'	0.060

Table 2. *Reference detonators used.*

Copper REF DET 1	0.25 g PETN
Copper REF DET 3	0.60 g PETN

Experiments – comparison of shock energies and maximum pressures of squibs and detonators for explosives

The underwater initiating capability test according to EN 13763-15[3] was applied for the determination of the shock energies and maximum pressures. For every type of squib 3 items and for every reference detonator 5 items were used for reproducibility. The pressure time dependencies were detected with the piezoelectric sensor PCB-W138A05.

This test is based on the principle that the detonation of an explosive charge under water generates a spherical shock-wave and a volume of gas, which expands and then collapses as the bubble rises through the water. The shock-wave and the volume of gas bear a finite relationship to the energy released. By measuring the shock-wave pressure and the time interval between the shock-wave pressure peak and the first collapse of the gas bubble, the equivalent shock and bubble energies can be calculated.[3] Both parameters were determined for the investigated squibs and reference detonators and compared against each other.

The experimental setup in accordance with EN 13763-15[3] is illustrated in Figure 1.

The water tank made of hard plastic had a volume of about 1.4 m^3 with the following dimensions: height 1.2 m, width 1 m, depth 1.16 m.

A typical pressure time dependency including the collapse of the gas bubble is given in Figure 2.

The area in grey is the integral of the shock-wave with the pressure maximum (P_{max}) and $t = t(P_{max}/e)$, where t_b is the time interval from P_{max} to the collapse of the gas bubble.

The following definitions for the equivalent shock and bubble apply (formulas 1 and 2):

Equivalent shock energy

$$E_s = k_s \int_{t=0}^{t=t(\frac{P_{max}}{e})} P^2 \mathrm{d}t \quad (1)$$

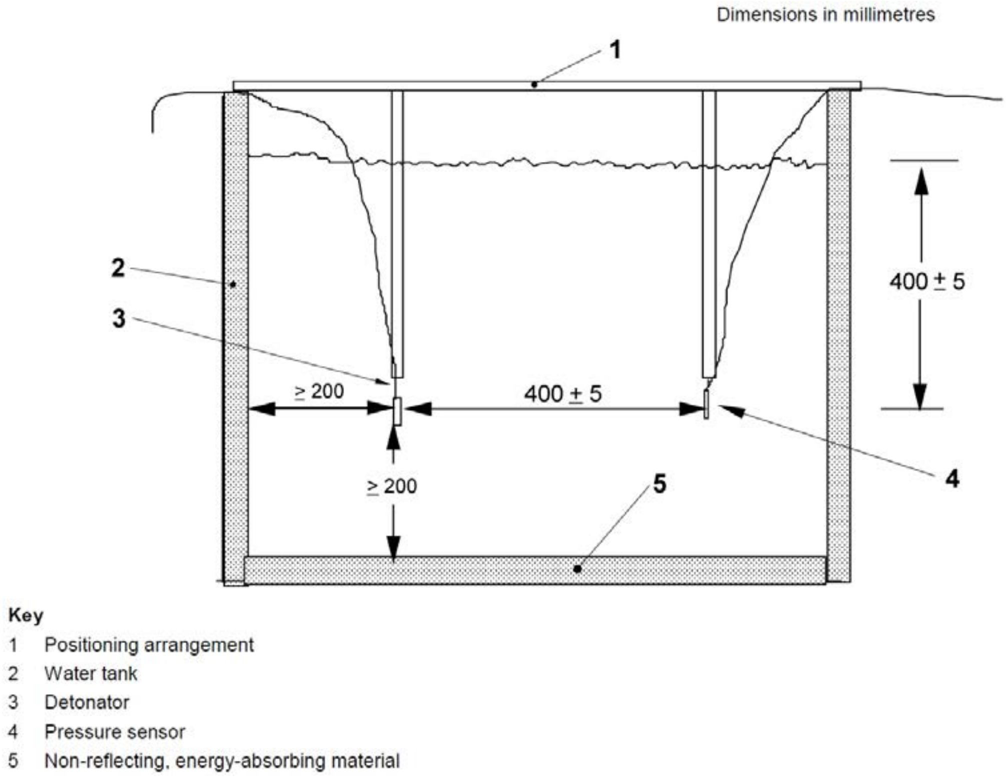


Figure 1. *Scheme of the water tank used with positioning system for sensor and detonator/squib (source: EN 13763-15[3]).*

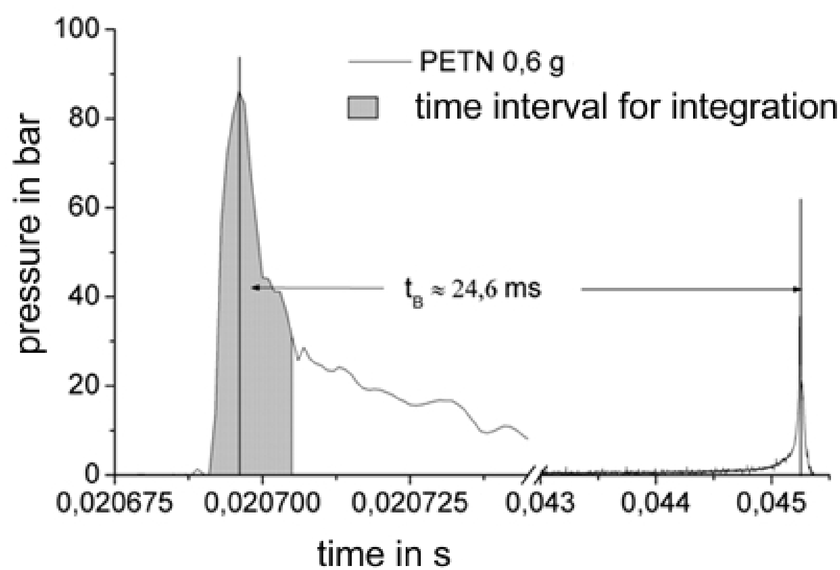


Figure 2. *Typical pressure–time dependence during the underwater initiating capability tests according*

where E_S = shock energy, P = pressure, t = time, e = Euler number, k_s = constant.

Equivalent bubble energy

$$E_B = k_B(t_B)^3 \quad (2)$$

where E_B = bubble energy, t_B = time interval from P_{max} to the collapse of the gas bubble, k_B = constant.

Results and discussion

The results of the calculated shock energies of the investigated squibs based on the performed pressure time tests are displayed in Figure 3.

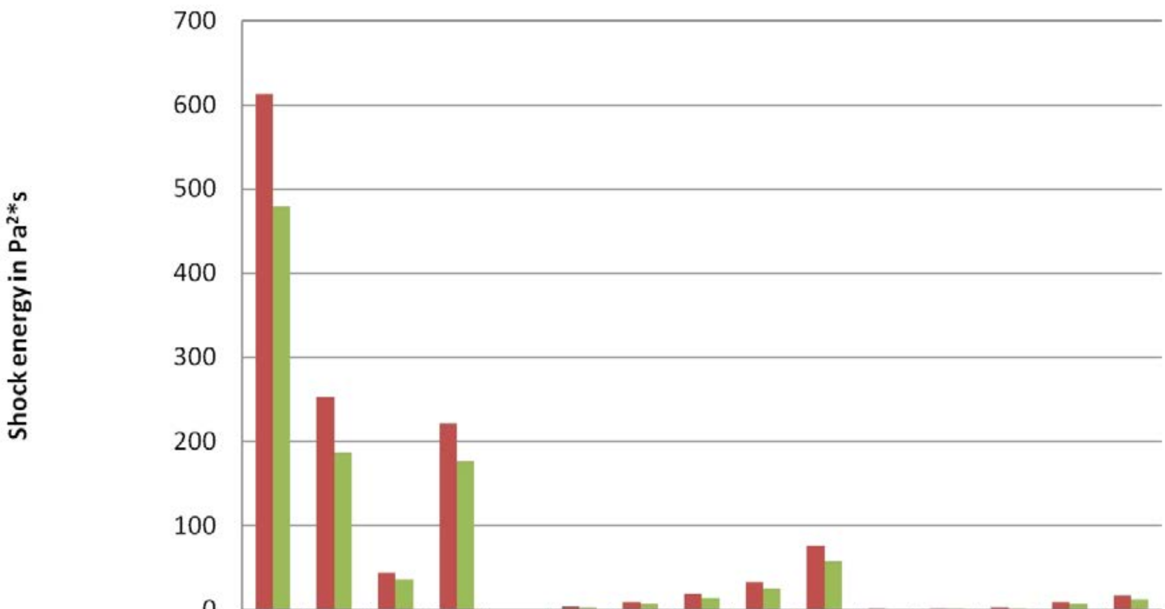
All displayed data are averaged values, based on 3 measurements per squib type. The maximum shock energy displayed in Figure 3 was calculated by integration below the pressure curve from the beginning until the culmination of zero over-pressure.

The results reveal that only the squib type 'HE 4' developed comparable shock energies to the reference detonator '0.25 PETN'. All other squibs showed significantly smaller shock energies. The levels of the shock energies thereby correlate with the NECs of the squibs.

The corresponding maximum pressure values are illustrated in Figure 4.

The averaged values of the maximum pressures observed for the squibs were in all cases smaller than the values for the detonators. As for the shock energies, the squib type 'HE 4' was found to have the highest maximum pressure, followed by 'Cl-6G' and 'HE 1'. The differences between the maximum pressures of the squibs and the reference detonators were not as distinct as with the observed shock energies.

The assessment of the bubble energies was abandoned, as the results revealed that no significant comparison between the squibs and the reference detonators with regard to the initiation



	PETN o,6	PETN 0,25	HE 1	HE 4	Cl-1/4 G	Cl-1/2 G	Cl-1 G	Cl-2 G	Cl-3 G	Cl-6 G	Fl-1/8 G	Fl-1/4 G	Fl-1/2 G	Fl-1 G	Fl-2 G
Shock energy max	613	253	44	222	1	3,8	10	18,8	33	76	1,8	2,2	3,4	10	17
Shock energy	479	187	36	176	0,8	2,9	7,6	14,3	25,5	58	1,4	1,6	2,4	7,5	13

Figure 3. *Shock energies of the investigated squibs and the two reference detonators.*

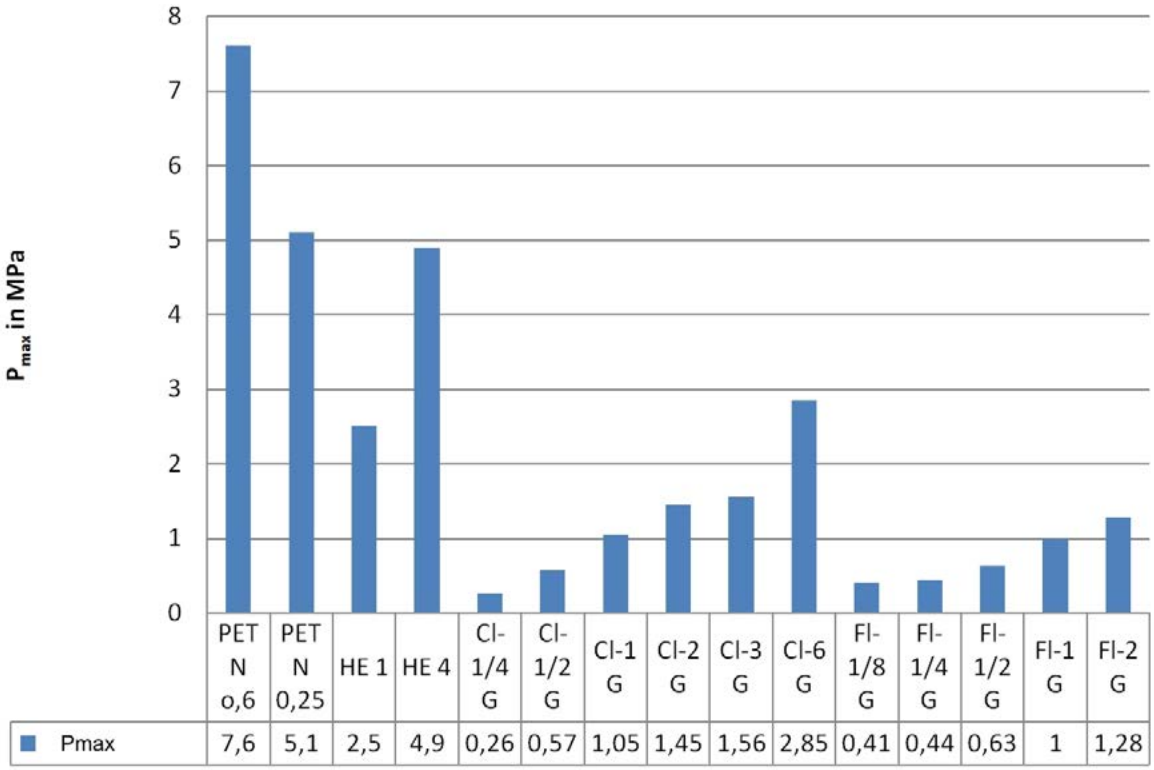


Figure 4. *Maximum pressures of the squibs investigated and the two reference detonators.*

capability was possible.

Figure 5 and Figure 6 illustrate exemplary time–pressure dependences for the reference detonators and some investigate squibs.

The influence of casing material on the detonation characteristics was not further investigated due to the insignificant impact during the underwater initiating capability tests based on the experiences of BAM.

In order to find a better comparison between the investigated squibs and the reference detonators a specific scaling was performed. This scaling reveals for different explosives the required equivalent initiation capability in grams PETN. The shock-wave parameters peak pressure and energy were taken as the basis for characterization, as the initiation is purely due to shock–detonation transition (SDT) in this case.

In direct comparison of the investigated squibs and the reference detonators only the squib 'HE 4' revealed a comparable outcome with the reference detonator 0.25 g PETN. All other investigated squibs showed a significantly lower energy level during the underwater test. Due to this finding, the detonator 0.25 g PETN was chosen for reference in this work. The combination of this reference detonator and the sensitive explosive corresponds to a worst-case-assessment with regard to the capability of initiating secondary explosives.

The calculation of the equivalent initiation capability of the squibs was performed with the following formulas 3 and 4:

$$\frac{p_{\mathrm{T}}}{p_{\mathrm{R}}} \approx \left(\frac{M_{\mathrm{T}}^{1/3}}{M_{\mathrm{R}}^{1/3}} \right)^{1,2} \quad (3)$$

$$\frac{E_{\mathrm{T}}}{E_{\mathrm{R}}} \approx \frac{M_{\mathrm{T}}}{M_{\mathrm{R}}} \quad (4)$$

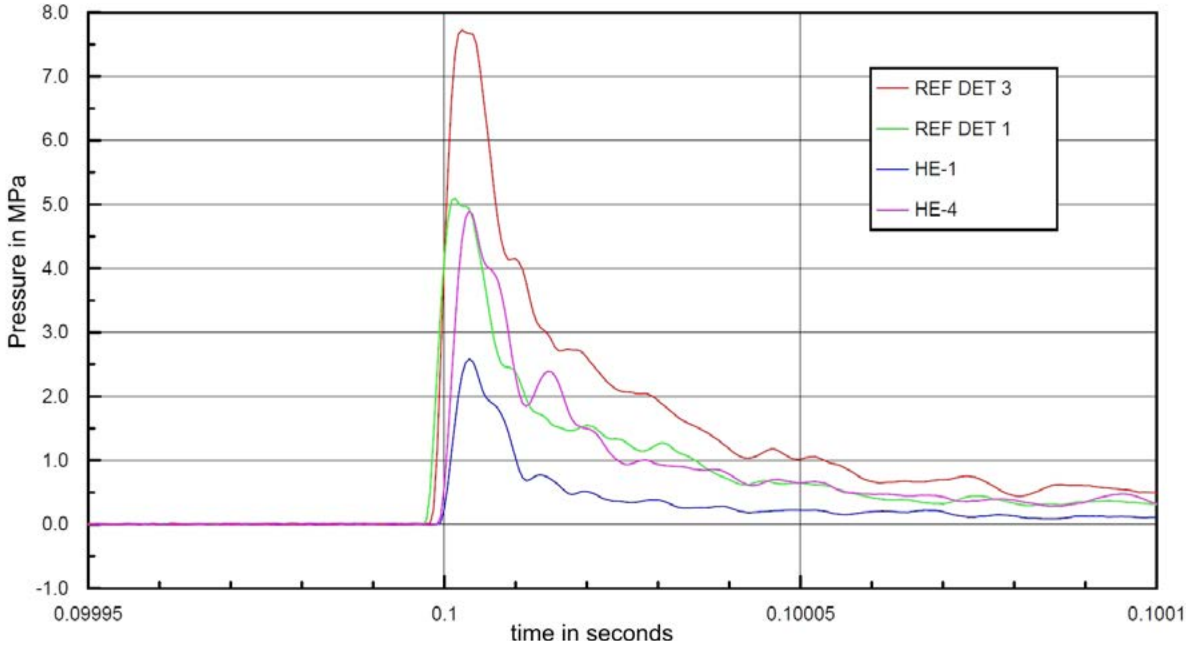


Figure 5. *Time–pressure curves of the investigated squibs 'HE 1' and 'HE 4'and the two reference detonators.*

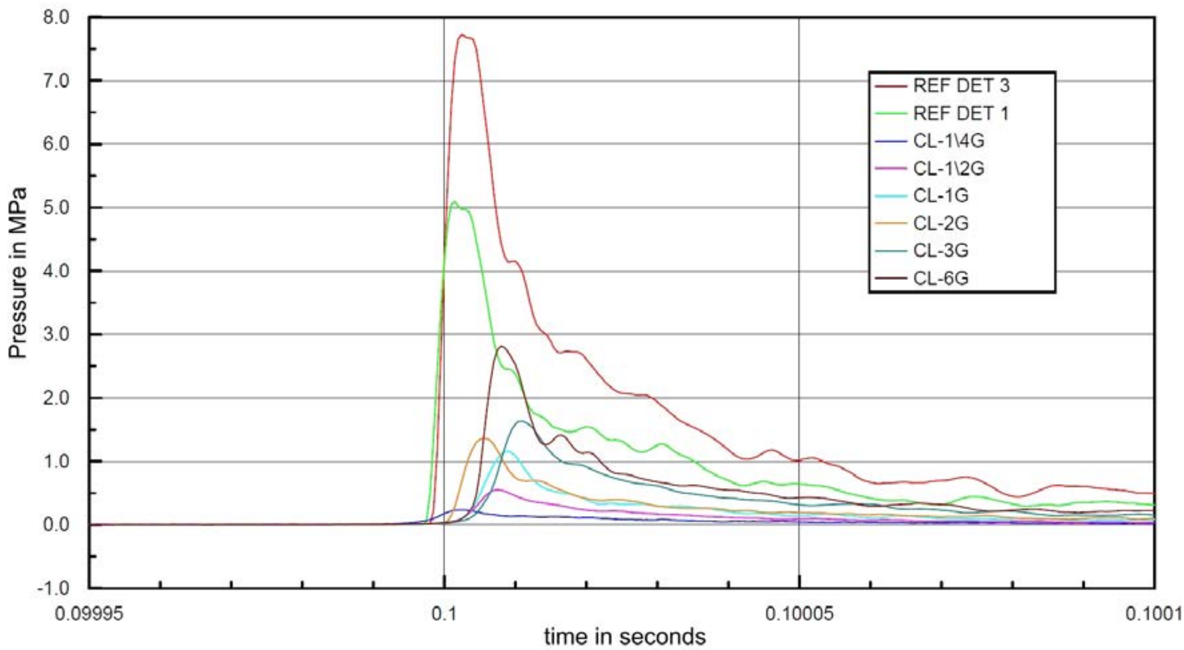


Figure 6. *Time pressure curves of the investigated squibs 'Cl series' and the two reference detonators.*

with the following definitions: p – pressure; M – mass of charge; E – energy of shock wave; T – subscript indicating test; R – subscript indicating reference.

For formula 3 the maximum pressure and for formula 4 the shock energy were taken as the basis for the calculation of the equivalent initiation capability. For the squib 'HE 4', the following values were achieved:

0.20 g PETN on the basis of the maximum pressure (see formula 3);

0.24 g PETN on the basis of the shock energy (see formula 4).

The squib 'Cl-6G' showed the second largest equivalent initiation capability:

0.14 g PETN on the basis of the maximum pressure (see formula 3);

0.08 g PETN on the basis of the shock energy (see formula 4).

The lower value of equivalent initiation capability on the basis of the shock energy in comparison with the reference detonator is due to the slower pressure rise and the lower maximum pressure, see Figure 6.

Since the other squibs showed much lower equivalent initiation capabilities, an initiation of the secondary explosive with direct contact was therefore not performed. Only the squib 'HE 4' with its high equivalent initiation capability led to the assumption that an initiation of sensitive explosives is likely. However, the results of the underwater test of the squib 'Cl-6G' were also taken into account for verification purposes.

Initiation of secondary explosives with squibs

For verification of the results of the underwater tests, initiation tests with direct contact of the squibs with the explosive NSP 711 (plastic) were carried out. This secondary explosive is made on the basis of PETN, is cap sensitive, water-resistant and has a density of 1.45 g cm^{-3} and a detonation velocity (VOD) of greater than 7.250 m s^{-1}.

Experiments with the squib 'HE 4'

An NSP 711 explosive charge of 260 g in total was formed, which was *ca*. 50 cm long, *ca*. 3 cm wide and *ca*. 2 cm high. A resistance sensor (500 ohm m^{-1}) with a length of 0.3 m coming from the side of the ignition point was placed in the centre of the cross-section of the explosive charge. The resistance sensor measures the VOD and was additionally taken to prove that initiation occurred. The run up distance between the bottom of the squib 'HE 4' and the starting point of the VOD measurement was more than 5 times the charge width. The squib 'HE 4' was treated as a strong detonator and was placed cross-sectionally centred into the end of the charge.

As a result of this setup, the squib 'HE 4' functioned properly based on aural observation. However, an initiation of the NSP 711 charge did not occur. After that the charred end of the charge was carefully removed and a detonator 0.25 g PETN was installed in a comparable way into the charge NSP 711. The detonator functioned properly, leading to an initiation of the NSP 711 charge. No further remnants of the explosives remained afterwards and the resistance sensor was completely destroyed.

Since the first experiment did not show an initiation of the NSP 711 charge with the squib 'HE 4', the setup was changed. A charge of 25 g NSP 711 was formed into a 'pear-like' shape and the 'HE 4' was primed into the longish end of this charge, see Figure 7.

For the sake of minimizing the experimental efforts (i.e. finding of explosives in case of non-initiation), the entire charge including the squib was placed in a thick-walled plastic tube. This tube was buried in the ground, see also Figure 7. The charge was placed at the bottom of the tube on the soil with no contact with the wall.

The first trial in this setup revealed also a complete functioning of the squib 'HE 4' without an initiation of the 'pear-shaped' NSP 711 charge. One third of the explosive charge was dispersed, whereas the other two thirds were found flattened at the bottom of the tube. However, the repetition trial of this setup showed with all likelihood an initiation of the 'pear-shaped' NSP 711 charge. The significantly different aural observation revealed a corresponding reaction. The observed damage also showed signs of at least an initiation of NSP 711. The plastic tube extensively ruptured from the bottom to the top and was found displaced at one side of the soil ground, see Figure 8. The

Figure 7. *Setup of the 'pear-shaped' charge NSP 711.*

Figure 8. *Ruptured plastic tube as a result of the second trial with the combination of squib 'HE 4' and the 'pear-shaped' NSP 711 charge.*

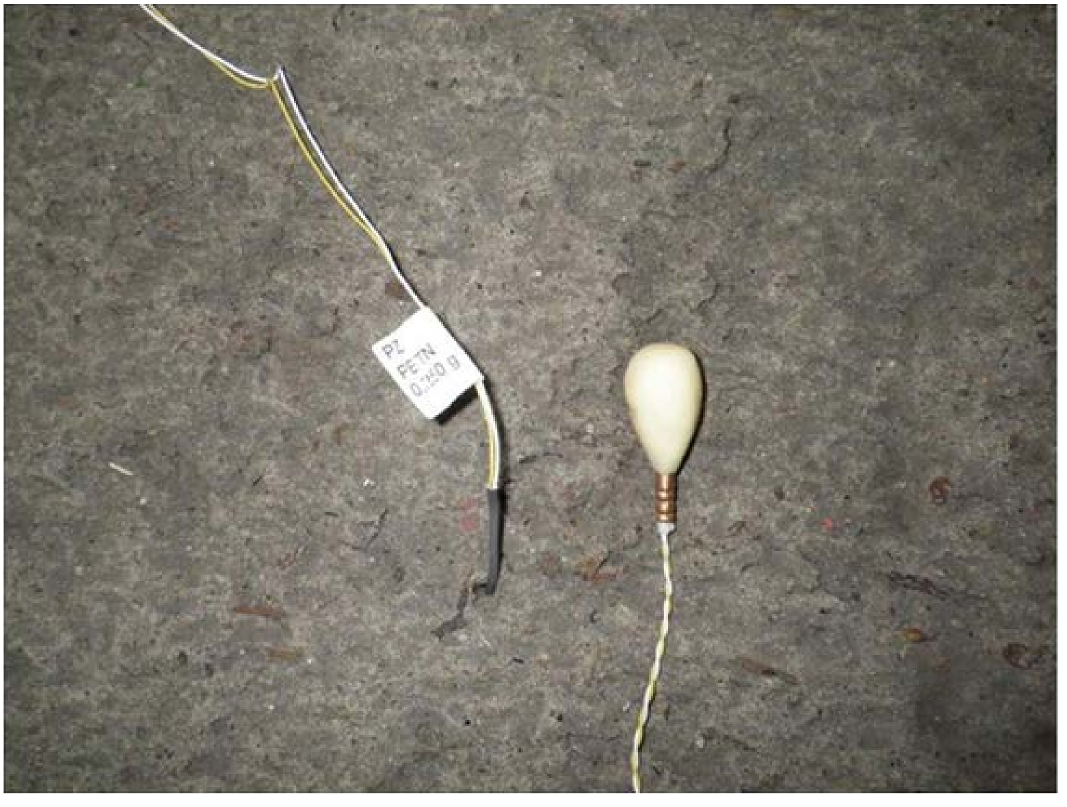


Figure 9. *Proof of the cap sensitivity of the NSP 711 charge with the detonator 0.25 g PETN.*

fragments of the plastic tube and the observations imply that the reaction occurred as a deflagration.

Experiments with the squib 'Cl-6G'

The setup with the squib 'Cl-6G' was identical to the ones with the combination 'HE 4' and 'pear-shaped' NSP 711 charge, as described above. The only difference in the setup occurred in the first out of four trials, where the reference detonator 0.25 g PETN and the explosive charge were not introduced into the plastic tube, as an initiation of the charge was likely to occur. The NSP 711 charge including the detonator was directly placed on the soil ground, see Figure 9. The charge was initiated by the detonator in the first trial as expected.

The other three trials with the squib 'Cl-6G' showed no initiation of the NSP 711 charges in any of the cases. The squibs functioned properly, which was acoustically observed. Almost the entire masses of the NSP 711 charges were always found on the bottom of the plastic tube, in some cases partly dispersed. The thick-walled plastic tube was found completely intact and it remained in its initial position.

Summary and conclusions

The results of this study reveal that the squibs investigated were not able to reliably initiate a plastic explosive on the basis of PETN. The combination of this reference detonator and the sensitive explosives corresponds to a worst-case assessment with regard to the capability of initiating secondary explosives.

The categorization of the squibs as theatrical pyrotechnic articles of the category T2 under the European Directive 2007/23/EC can be justified based on the results of this study. The new requirements according to the recast of this Directive (2013/29/EU; essential safety requirements no. 4) can be seen as fulfilled for the tested articles.

It was furthermore proved that the underwater test according to EN 13763-15 reveals meaningful results in order to demonstrate that squibs and comparable pyrotechnics are generally not able to initiate secondary explosives. The performance parameters of these pyrotechnics achieved from these tests allow a direct comparison with common detonators for explosives.

For a general assessment of the initiation capability of squibs an equivalent initiation capability in grams of PETN in connection with the underwater tests was determined. The results of the experiments with direct contact of the squibs on the secondary explosives confirm the assessments of the results of the underwater tests in the context of the definition of a threshold range for the equivalent initiation capability of squibs. As a conclusion it appears to be possible to substitute the initiation test by the underwater tests in combination with the calculation of an equivalent initiation capability.

It appears to be sensible that these findings and conclusions can also be applied to other comparable pyrotechnic articles.

Therefore, squibs and other comparable pyrotechnic articles are not able to initiate secondary explosives, if the equivalent initiation capability determined from the underwater test is less than 0.25 g PETN.

For the assessment of the capability of initiating a secondary explosive, the equivalent initiation capabilities of both the maximum pressure based and the shock energy based values should be taken into account. This appears to be particularly important in those cases where the equivalent initiation capability is greater than 0.2 g PETN. For those cases where the equivalent initiation capability is smaller than 0.2 g PETN (based on shock energy values), an initiation of secondary explosives by the pyrotechnic article is not expected.

The results achieved reveal that in most cases a setup with direct contact of the article with the secondary explosive can be avoided. In consequence, the problems associated with the performance of such experiments (e.g. finding of unexploded substances) do not occur.

Finally, it should be noted that the chosen configuration and setup of the underwater test in this study are only applicable for pyrotechnic articles with small net explosive contents. In cases where large net explosive contents are investigated, appropriately bigger water tanks should be used.

References

1 Directive 2007/23/EC of the European Parliament and of the Council of 23 May 2007 on the placing on the market of pyrotechnic articles, *Official Journal of the European Union*, 14.6.2007.

2 Directive 2013/29/EU of the European Parliament and of the Council of 12 June 2013 on the harmonisation of the laws of the Member States relating to the making available on the market of pyrotechnic articles (recast), *Official Journal of the European Union*, 28.6.2013.

3 EN 13763-15:2004 Explosives for civil uses - Detonators and relays - Part 15: Determination of equivalent initiating capability, European Committee for Standardization CEN, 2004.