# Validation of the New Ignition Source "Exploding Wire" for Dust Explosion Testing in the 20-L-Sphere

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The safety characteristics Maximum Explosion Pressure $p_{max}$, Maximum Explosion Pressure Rise $(dp/dt)_{max}$ and Lower Explosion Limit LEL are determined in closed vessels such as the 20-L-sphere according to international standards. Dust ignition is carried out using pyrotechnical igniters which are defined in the standards. Due to various disadvantages of pyrotechnical igniters the need for alternative ignition sources arises again and again. Studies at the Federal Institute for Material Research and Testing (BAM) with ignition units which were able to generate ignition energies up to 2000 J showed that the so-called "exploding wire" or "fuse wire" is suitable as an alternative ignition source. The paper presents further test results for the validation of the exploding wire for the determination of $p_{max}$ and $(dp/dt)_{max}$ in the 20-L-sphere. The tests were performed with a new ignition unit and improved electrodes which allowed ignition energies up to 10000 J. The paper also analyses propagation of flame and electrical arc on basis of high speed camera recordings. Turbulence measurements with a LDA system in the 20-L-sphere allowed investigation whether the activation of the ignition sources has an influence on the turbulence field generated during dust dispersion and whether the influence differs depending on the ignition source.

Keywords: dust explosion testing, exploding wire, explosion characteristics, ignition source

## Introduction

Safety characteristics are essential for the determination of explosion hazards during handling of combustible dusts and for the design of safety measures. The safety characteristics Maximum Explosion Pressure $p_{max}$, Maximum Rate of Explosion Pressure Rise $(dp/dt)_{max}$ and Lower Explosion Limit LEL are determined in closed vessels such as the 20-L-sphere. Tests are preformed according to international standards, for example EN 14034 part 1 and part 2 [1], [2] or ASTM E1226 [3]. In order to determine the safety characteristics the dust samples are dispersed in air and ignited using two pyrotechnical igniters with energy contents of 1000 J (LEL in 20-L-sphere) or 5000 J ($p_{max}$, $(dp/dt)_{max}$). Since the igniters could have an influence on the test results e.g. due to different flame volume, burning time, generated pressure, ignition delay time or generated turbulence they are defined in the test standards.

Because of various disadvantages of pyrotechnical igniters such as high costs, legal requirements concerning its storage and use as well as high energy input in comparison to most ignition sources in practice, the need for alternative ignition sources arises, see also Krietsch [4]. A suitable ignition source should be less expensive, readily available and the operator should be able to use it without a certificate of competence. In addition to that it is not unusual that ignition sources are requested which allow adjusting ignition energy over a wide range e.g. from the order of magnitude of typical ignition sources found in practice, such as electrostatic discharges, mechanical sparks or hot surfaces up to the values described in the test standards.

Studies at the Federal Institute for Material Research and Testing (BAM) showed that the so-called "exploding wire" or "fuse wire" is in principle suitable as an alternative ignition source for the determination of $p_{max}$ and $(dp/dt)_{max}$ [5], [6], [7], [8]. This type of ignition source is used for the determination of explosion limits of gases and is described in the standard EN 1839 [9]. For these studies $p_{max}$ and $dp/dt)_{max}$ of different dusts were determined using ignition units which were able to generate ignition energies in the range of 100 J to 2000 J. Calorimetric and electric measurements obtained information on the ignition energy of the exploding wire delivered to the mixture.

During the studies some tests were performed in a windowed autoclave. With these tests it was possible to get information on the shape of the generated flame or electrical arc and its propagation. High speed recordings showed that the flame generated from the pyrotechnical igniter after ignition propagated faster than the electrical arc and the plasma field generated from the exploding wire and reached a larger volume. Recordings with a fast IR camera system confirmed these test results. Therefore the igniter should have a significant influence on the determined $p_{max}$ and $(dp/dt)_{max}$ values. However, such an effect was not determined during the measurements of $p_{max}$ and $(dp/dt)_{max}$. For all tested dusts and ignition energies of 100 J, 500 J, 1000 J and in first tests with 2000 J comparable values of $p_{max}$ and $(dp/dt)_{max}$ could be determined for both ignition sources. It was also found that the values for $p_{max}$ were less than 10 % lower than values determined according to the test standard with two pyrotechnical igniters of 5000 J. As a result the influence of the ignition energy of the igniter on $p_{max}$ seemed to be almost negligible.

However, $(dp/dt)_{max}$ values determined according to the test standard led to 30 % higher values, especially in comparison to tests with ignition energies of 100 J and 500 J. Only tests with two 1000 J ignition sources led to reasonable test results in comparison to tests performed according to the standard procedure. Based on this studies it follows that the effect of the ignition energy on the rate of explosion pressure rise seems to be much stronger than on the maximum explosion pressure. As a result improvements with the exploding wire are necessary so that tests with comparable ignition energies as described in the test standards are possible.

This paper presents results of new test series for the validation of the exploding wire for the determination of $p_{max}$ $(dp/dt)_{max}$ and in the 20-L-sphere. The tests were performed with a new ignition unit and new designed electrodes which allowed ignition energies up to 10000 J. The dusts were selected such that different combustion mechanisms were considered. The paper also analyses propagation of flame and electrical arc on basis of high speed camera recordings.

# Test assembly and test settings

## 20-L-sphere

Main component of the test assembly was the 20-L-sphere [1], [2], [10]. In order to reach almost homogeneous dust dispersion into the test chamber the so-called "rebound nozzle" was used.

Tests with pyrotechnical igniters as an ignition source were performed using the standard control unit of the 20-L-sphere. For tests with exploding wires an external ignition unit was necessary. An isolation amplifier allowed the determination of the ignition energy by measuring current and voltage. The principle of measuring the ignition energy delivered to the mixture is described in [5], [11].

## Ignition Sources

The main difference of the two ignition sources pyrotechnical igniter and exploding wire is the ignition mechanism. While for the exploding wire an electric arc and plasma is generated the pyrotechnical igniter emits flames and burning solids.

For the validation tests the ignition sources were placed in the middle of the vessel such as it is described in the test standards. According to the European standards for the determination of the explosion characteristics $p_{max}$ and $(dp/dt)_{max}$ two 5000 J pyrotechnical igniters were used, firing horizontally in opposite directions [1], [2], [10]. For tests with the exploding wire electrodes were developed which allowed propagation of electrical arc and plasma field in the same direction as the pyrotechnical igniter. In addition to tests with two ignition sources of 5000 J tests with two ignition sources of 1000 J were performed because in earlier studies only a few tests with this ignition source were performed.

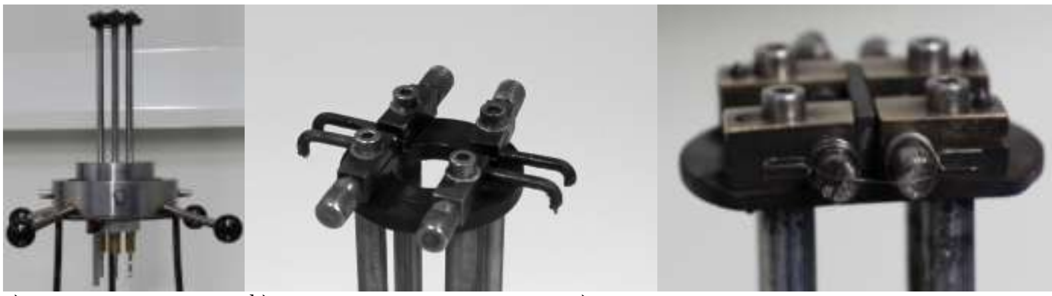
### *Pyrotechnical igniter*

All pyrotechnical igniters used for this work have the same composition as the standard igniters used for determination of explosion characteristics in the 20-L-sphere.

### *Exploding wire*

The principle of the exploding wire is the evaporation and ionization of metal particles from a wire due to a sufficient current flow within milliseconds. During that process a metal vapour is created in which an electric arc is generated between two electrodes because of the electrical conductivity of the plasma.

For earlier studies on the suitability of the exploding wire as well as for this validation study BAM developed different ignition units with isolating transformer, or capacitors which were able to deliver ignition energies up to 10000 J. In addition to that the bayonet lock of the 20-L-sphere was modified so that it was able to hold four electrodes, figure 1. This system allowed a simultaneous ignition of two exploding wires with a defined energy. A choke enabled elongation of the electrical arc during each test. More information on ignition units, electrodes and the principle of the ignition source exploding wire is found in [5], [11]. The material of the electrodes was tungsten. For the tests series shown in this paper the electrodes had to be modified in comparison to earlier versions to withstand the high ignitions energies up to 10000 J. All tests were performed with a nickeline wire with a diameter of 0.12 mm.



a) b) c)

**Figure 1.** Exploding wire with electrodes a) modified bayonet lock for two wires, b) electrodes for 2 x 1 kJ ignition energy, c) electrodes for 2 x 5 kJ ignition energy

## Recordings of Flame Front and Electrical Arc

In order to record the propagation of flame and electrical arc of both ignition sources a high speed camera system was used. It allowed recordings of 5000 frames per second. So it was possible to determine maximum flame (arc) volume and length as well as the time delay for activating the ignition source and its burning time.

## Measurements of Turbulence

A one-dimensional laser-Doppler system (LDA) was used for turbulence measurements in the 20-L-sphere. Since the optical accessibility in the 20-L-sphere could only be realized via a windowed flange with a diameter of 40 mm, it was only possible to measure the turbulence at one position next to the ignition source.

### Tested Dusts

Dust explosions generally show complex reaction mechanism, which depend e.g. on chemical composition of the dust, dust concentrations and flow conditions. Van der Wel [12] differs between different reaction mechanisms depending on whether the reaction takes place in the gas phase due to evaporation or at the solid surface in form of gaseous products, solid or liquid material. The dusts for the research project were chosen such that they represent different chemical classes and mechanisms as well as the dust explosion classes found in practice. This paper presents test results from lignite, maize starch, niacin and anthraquinone.

## Test Results

### Propagation of Flame and Electrical Arc (Plasma) after Activation of Ignition Source

Figure 2 shows the propagation of flame and electrical arc following the activation of the ignition source for two 1000 J pyrotechnical igniters in comparison to two exploding wires with the same energy. The propagation of flame and arc/plasma as well as their volumes are comparable. Comparing the measurement with earlier measurements described in [5]; [6], [7], [8] the propagation was somewhat unexpected because those measurements showed that the pyrotechnical igniter always propagated much faster and reached a greater volume than the plasma/arc of the exploding wire. The reason for the new test results could be improvements in the design of the electrodes as well as modifications in the duration of the spark. Another difference is that earlier tests were performed in an 11 L windowed autoclave, while these tests were not performed in an enclosure. This might affect the flame propagation of both ignition sources differently.

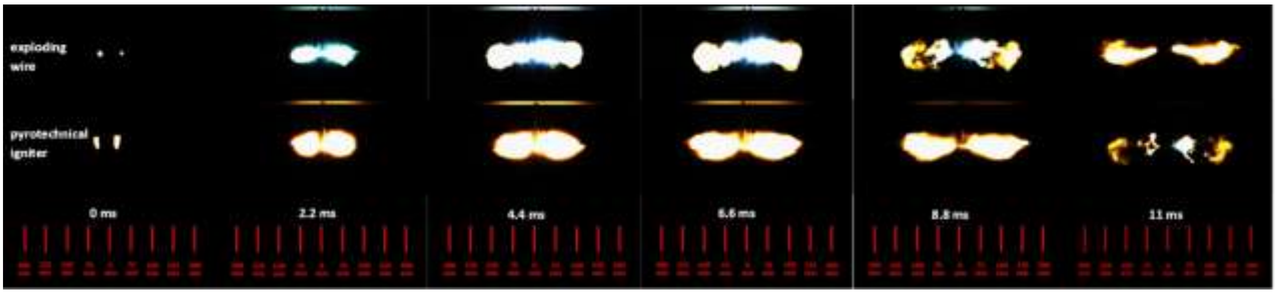



**Figure 2.** Propagation of flame and electrical arc following ignition of two 1000 J exploding wires and two 1000 J pyrotechnical igniters.

Figure 3 shows high speed recordings of measurements on the propagation of flame and electrical arc/plasma for two 5000 J ignition sources. From the sequence follows that the electrical arc/plasma of the exploding wire seems to propagate slightly faster than the flame of the pyrotechnical igniter for the first 2 ms after ignition. In the following the flame of the exploding wire seems to propagate faster and reaches a larger volume.

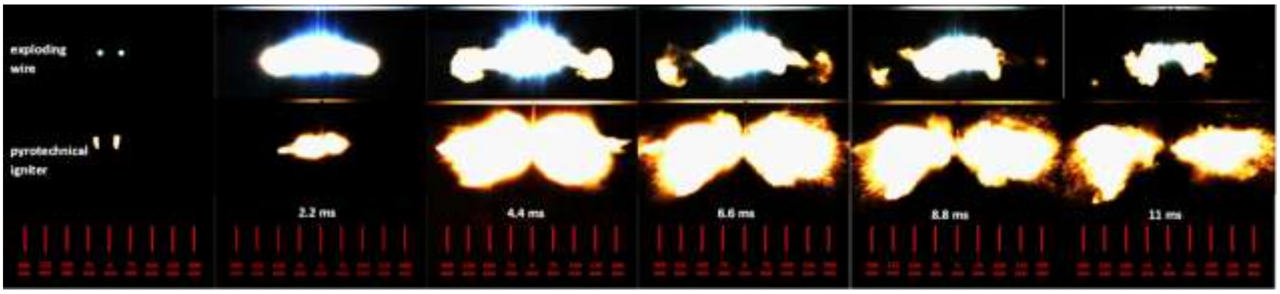



**Figure 3.** Propagation of flame and electrical arc following ignition of two 5000 J exploding wires and two 5000 J pyrotechnical igniters.

### Turbulence Measurements in 20-L-sphere

LDA measurements in the 20-L-sphere showed, that the dispersion of dust with the rebound nozzle generated a flow with a maximum flow velocity of more than 40 m/s. This flow velocity decreased rapidly with decreasing pressure in the dust storage chamber and with closing the inlet valve. However the turbulence generated due to the dispersion of dust was so strong that not additional turbulence for ignition energies up to 2000 J could be determined. In first tests with two 5000 J igniters only a negligible increase of the turbulence was found for both ignition sources. However, more detailed tests are planned, possibly under variation of the duration of the spark generated after activation of the exploding wire.

### Explosion Behaviour

Figure 4 presents the explosion (over)pressure of anthraquinone as a function of the dust cloud concentration for exploding wire and pyrotechnical igniter. In these tests two 5000 J ignition sources were used. Both curves show a comparable course and a comparable maximum of approximately 8.1 bar for the exploding wire and 8.6 bar for the pyrotechnical igniter.

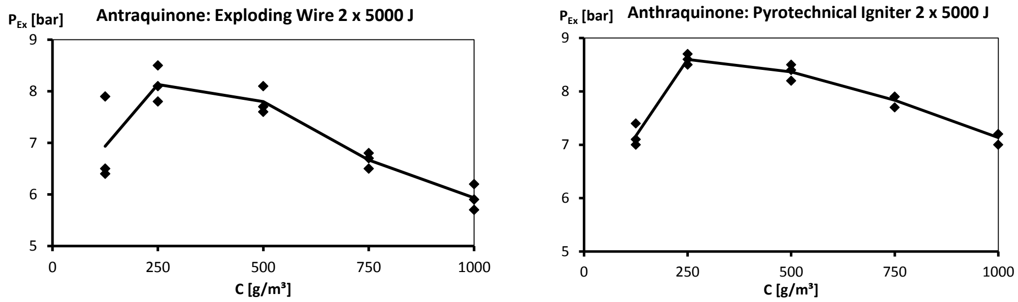



**Figure 4.** Explosion pressure of anthraquinone as function of dust cloud concentration determined with pyrotechnical igniters and exploding wires with ignition energies of 2 x 5000 J.

The determined values for the rate of explosion pressure rise as a function of the dust concentration for anthraquinone are found in Fig. 5. All test results show a good conformity concerning $(dp/dt)_{max}$ values which were almost identical. While $(dp/dt)_{max}$ for the pyrotechnical igniter was 1139 bar/s it was 1134 bar/s for the exploding wire.

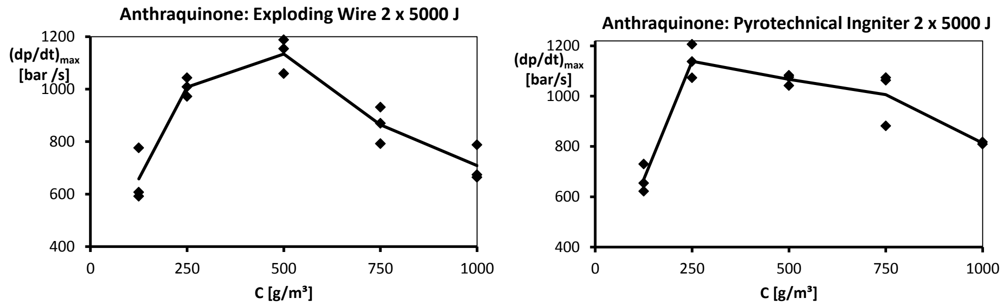
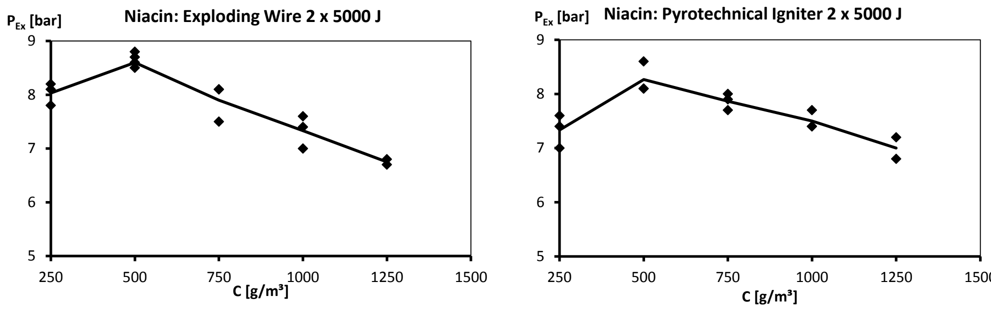



**Figure 5.** Rate of explosion pressure rise of anthraquinone as function of dust cloud concentration determined with pyrotechnical igniters and exploding wires with ignition energies of 2 x 5000 J.

Measurements with niacin with two 5000 J exploding wires resulted in larger deviations for $p_{max}$ and $(dp/dt)_{max}$ as shown in figure 6 and figure 7. As well the determined values for $p_{max}$ as for $(dp/dt)_{max}$ were markedly higher for tests with the exploding wire. The reason for that effect and also for an unusual scattering of the determined values for explosion pressures and rate of explosion pressure rise for higher concentrations is not clear so far but further tests are running on that subject.



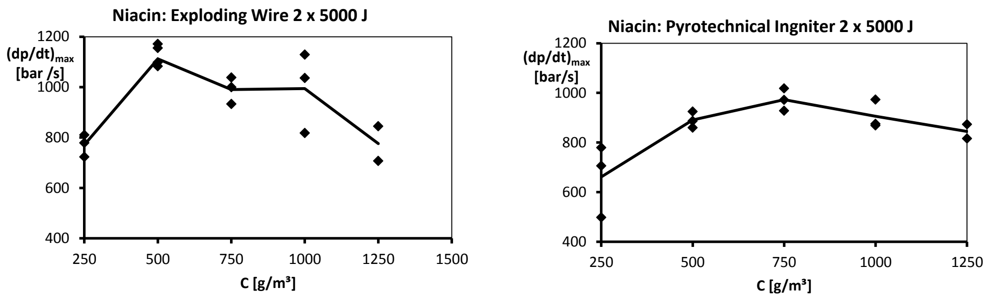




**Figure 7.** Rate of explosion pressure rise of niacin as function of dust cloud concentration determined with pyrotechnical igniters and exploding wires with ignition energies of 2 x 5000 J.

Figures 8 to 11 show the concentration dependent maximum overpressures and maximum values of rate of explosion pressure rise for lignite and maize starch. The deviations between the tests with pyrotechnical igniter and the exploding wire are marginal.

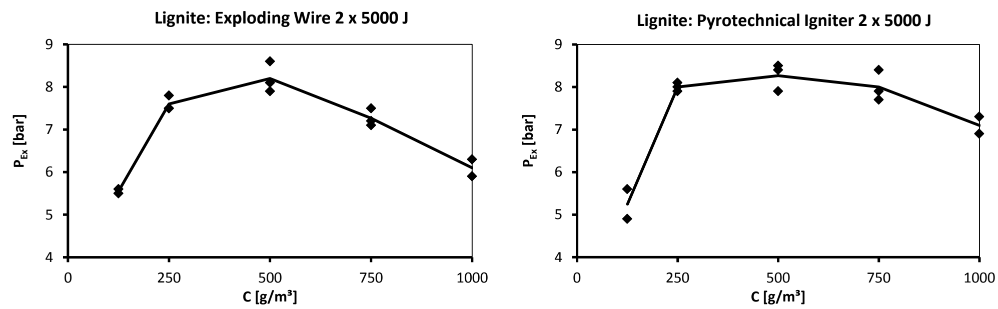



**Figure 8.** Explosion pressure of lignite as function of dust cloud concentration determined with pyrotechnical igniters and exploding wires with ignition energies of 2 x 5000 J.

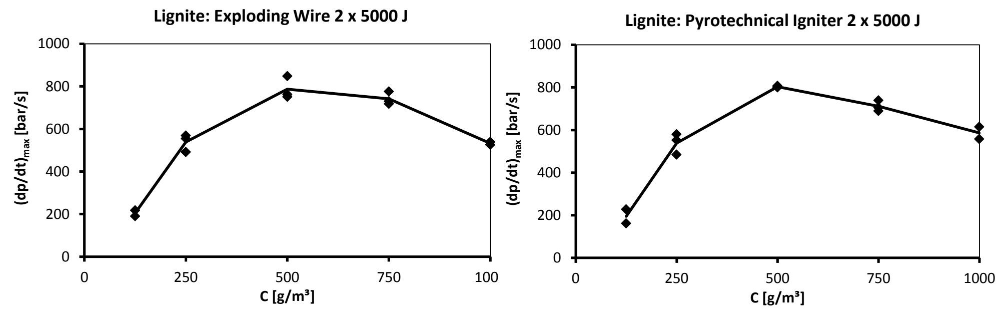



**Figure 9.** Rate of explosion pressure rise of lignite as function of dust cloud concentration determined with pyrotechnical igniters and exploding wires with ignition energies of 2 x 5000 J.

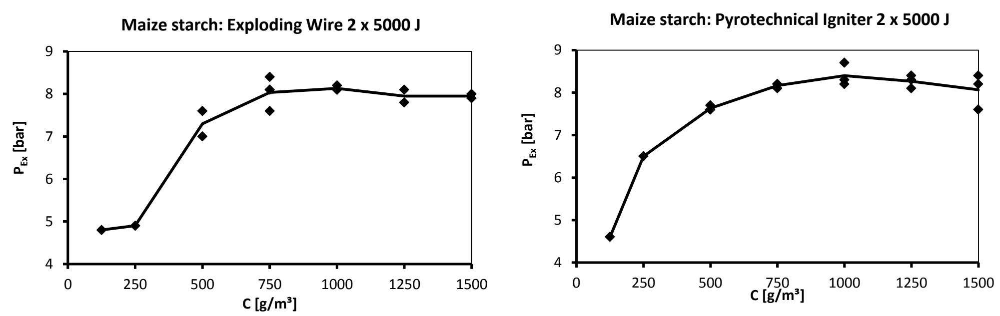



**Figure 10.** Explosion pressure of maize starch as function of dust cloud concentration determined with pyrotechnical igniters and exploding wires with ignition energies of 2 x 5000 J.

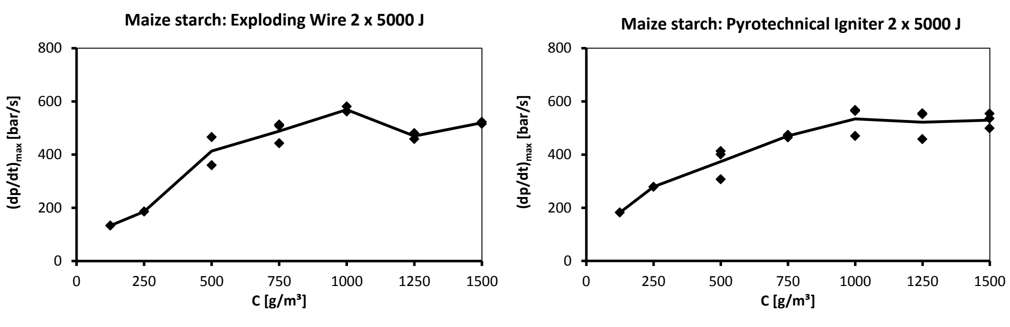



**Figure 11.** Rate of explosion pressure rise of maize starch as function of dust cloud concentration determined with pyrotechnical igniters and exploding wires with ignition energies of 2 x 5000 J.

Table 1 gives an overview of the determined values of $p_{max}$ and $(dp/dt)_{max}$ as well as for $K_{St}$ which were calculated from the $(dp/dt)_{max}$ values. A comparison of $p_{max}$ and $(dp/dt)_{max}$ determined using two 1000 J exploding wires with values determined according to the method described in the test standards with two 5000 J pyrotechnical igniters shows that the results are comparable while two 1000 J pyrotechnical igniters lead to lower values for lignite and anthraquinone. As a result it might be sufficient to test with two 1000 J exploding wires instead of two 5000 J pyrotechnical igniters.

However, only some of the dusts which have been selected for the study have been tested so far. Therefore further testing will be necessary to get more information whether this tendency can be generalized. Especially due to the fact that previous studies showed that $(dp/dt)_{max}$ values were up to 30 % lower in comparison to tests with two 5000 J pyrotechnical igniters [7]¸ [8]. The only difference between the new and the old study were more sophisticated electrodes and variations in the duration of the generated spark.

**Table 1.** $p_{max}$, $(dp/dt)_{max}$ and $K_{St}$ values for all tested dusts determined with exploding wires and pyrotechnical igniters with ignition energies of 2 x 1000 J and 2 x 5000 J.

| | | 2 x 1000 J | | 2 x 5000 J | |
|---|---|---|---|---|---|
| Dust | | exploding wire | pytotechn. igniter | exploding wire | pytotechn. igniter |
| Lignite median: 39 µm | $p_{max}$ | 7.5 | 7.9 | 8.2 | 8.4 |
| | $(dp/dt)_{max}$ | 708 | 626 | 787 | 803 |
| | $K_{St}$ | 192 | 170 | 214 | 218 |
| Maize starch median: 14 µm | $p_{max}$ | 8.1 | 8.3 | 8.2 | 8.4 |
| | $(dp/dt)_{max}$ | 554 | 539 | 569 | 562 |
| | $K_{St}$ | 150 | 146 | 154 | 153 |
| Niacin median: 15 µm | $p_{max}$ | 8.7 | 8.9 | 8.6 | 8.3 |
| | $(dp/dt)_{max}$ | 1059 | 1003 | 1112 | 973 |
| | $K_{St}$ | 287 | 272 | 302 | 264 |
| Anthraquinone median: 12 µm | $p_{max}$ | 8.0 | 8.1 | 8.1 | 8.6 |
| | $(dp/dt)_{max}$ | 1157 | 960 | 1134 | 1139 |
| | $K_{St}$ | 314 | 261 | 308 | 309 |

## Conclusion and outlook

High speed recordings with two 1000 J ignition sources showed that the flames generated from the pyrotechnical igniter and the electrical arc/plasma generated from the exploding wire propagated with a comparable velocity and reached a comparable volume. In tests with two 5000 J ignition sources the flame of the pyrotechnical igniter propagated faster than the arc/plasma of the exploding wire.

All determined values for $p_{max}$ and $(dp/dt)_{max}$ were almost similar for tests with exploding wire and pyrotechnical igniter with exception of niacin with 10000 J. Also the course of explosion pressure and rate of explosion pressure rise as a function of dust cloud concentration were comparable for most dusts.

On basis of the data determined so far the exploding wire seems to be an alternative ignition source for the determination of $p_{max}$ and $(dp/dt)_{max}$ in the 20-l-sphere.

Since the $p_{max}$ and $(dp/dt)_{max}$ values determined with the exploding wire with ignition energy 2000 J were comparable to those determined with pyrotechnical igniter with 10000 J it might be sufficient to test with lower ignition energies. However, only a few dusts have been tested so far so that the presented results are preliminary.

In the nearer future further tests with ignition energies of 2000 J and 10000 J with a larger number of dusts are planned. It is also planned to determine the lower explosion limit of these dusts under variation of the ignition energy and to perform tests in the 1-$m^3$-test vessel. Depending on these results the new ignition source may be included as an alternative ignitions source in upcoming new versions of the test standards.

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