

# Determining the incendivity of electrostatic discharges without explosive gas mixtures

ULRICH VON PIDOLL, EDWARD BRZOSTEK AND HANS-RUDOLF FROECHTENIGT  
Physikalisch-Technische Bundesanstalt  
38116 Braunschweig, Germany

**Abstract-** An analysis of the dependence of the minimum ignition energy *MIE* of a given explosive atmosphere on voltage and capacitance has shown that the charge *Q* transferred by a spark is a more suitable criterion than the *MIE* to describe its incendivity because it much less depends on voltage and gap width. Tables are presented which allow the determination of the minimum transferred charge  $Q_{min}$  necessary to achieve spark ignition for a number of different explosive atmospheres. It was found that the values for spark discharges are identical with the values for brush discharges determined up to now. In the case of single brush or spark discharges, *Q* can be easily obtained by charging a product as highly as possible in dry climate. Then a discharge to a ball electrode connected to the input of a coulombmeter is provoked. After removal of the electrode from the remaining electric field the displayed value is read and compared with the threshold value for *Q*. In the case of multiple discharges, e.g. from high voltage electrodes or textile materials, a high frequency shunt resistance connected to a rapid oscilloscope is placed in the earth line of the ball electrode and the value for  $Q = \int I dt$  is read. Oscilloscopic records of current curves of corona, brush and spark discharges are presented and discussed. Due to energy cumulation processes the proposed method needs further investigations to be suitable for determining the incendivity of permanent electric arc discharges.

**Keywords:** electrostatic hazards, spark discharges, brush discharges, current curve, ignitability, transferred charge, minimum ignition energy, spray gun.

## I. INTRODUCTION

The ever wider use of plastic materials and the increased application of high voltage for products intended for use in explosive atmospheres has led to the development of complex products whose ignition hazards are difficult to assess. Typical products of this kind are plastic parts with strongly structured surfaces, textiles for flexible intermediate bulk containers with small content of earthed metal filaments, surfaces self-discharging by corona, electric ionizers and electrostatic spraying equipment. The PTB as an accredited test laboratory for such equipment has, therefore, developed a rapid and reliable experimental method for assessing the incendivity of possible spark and brush discharges during the operation or malfunction of such products. This method is also suitable for the quality assurance purposes of the manufacturers. Theory, practice and limits will be presented in the following.

## II. BRUSH DISCHARGES

### A. General

Insulating plastic materials usually produce brush discharges when they are rubbed or when charged particles are brought on their surface. As brush discharges may lead to the ignition of gases and vapours, insulating plastic surfaces greater than a maximum allowed area must be experimentally tested under worst-case conditions.

Up to now such products were charged as highly as possible in dry climate and an earthed ball electrode surrounded by an explosive gas mixture was approached until a discharge with or without ignition of the test gas took place. Due to the increase in the ignition energy of the test gas as a consequence of its turbulence during flow and due to dilution caused by the surrounding air the test gas must be somewhat more incendive than the product is allowed to have for approval. Much experimental experience is necessary to balance these opposite effects to get safe results. However, in spite of this expenditure it cannot be ruled out that contradicting test results are obtained in the vicinity of the incendivity limit. For this reason this method is not suitable for Round Robin tests or quality assurance.

Gibson and Lloyd [1] found in 1965 that there is a correlation between the incendivity of a brush discharge and the charge *Q* transferred by it. Eisfeld [2] proposed in 1984 a test method based on this finding and applied for a patent for a coulombmeter he had developed [3]. Later, in 1988, Gibson and Harper [4] too stated "that the charge transferred in a discharge provides guidance on its incendivity".

It is evident that if the charge density on an insulating surface is as high as possible, the incendivity of the resulting brush discharge increases with increasing surface area exposed to charging. It is also well known from experiment that if the area of an insulating surface is surrounded by an earthed metal frame the insulated area may be increased by a factor of four to achieve the same incendivity as without the frame [5]. Fig. 1 shows that both known phenomena can be verified by the method of transferred charge [6].

For this reason an appendix to EN 13463-1:2001 [7] dealing with this method was initiated and the threshold limits of Table 1 were added. These limits were derived from Fig. 1 in combination with other literature data and the known safe surface area values for the three explosion groups for zone 0 (52 cm<sup>2</sup>, 29 cm<sup>2</sup>, 12 cm<sup>2</sup>) [8]. Meanwhile, this method has been included in new standards and rules concerning electrostatic hazards, e.g. [9-12], and suitable measuring instruments are commercially available, e.g. [13].

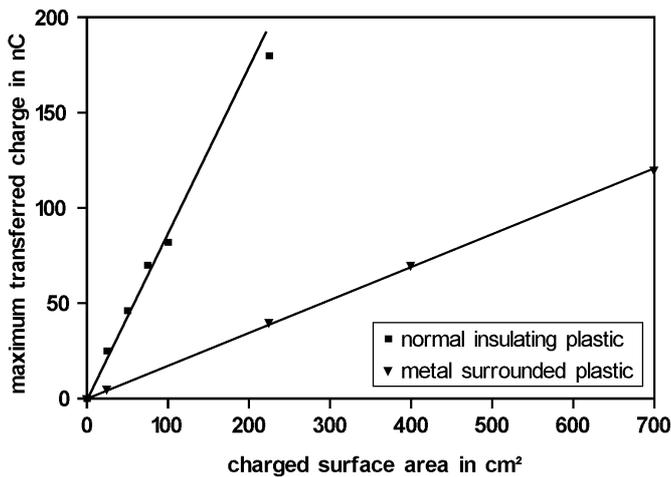


Fig. 1. Maximum transferred charge  $Q_{max}$  as a function of a polyethylene plastic surface area in dry climate

TABLE 1  
MAXIMUM ALLOWED VALUES FOR THE TRANSFERRED CHARGE  $Q_{max}$  OF A PROVOKED BRUSH DISCHARGE UNDER WORST CASE CONDITIONS [7,9-12]

Explosion groups according to [5]	I, IIA	IIB	IIC
$Q_{max}$	60 nC	30 nC	10 nC

### B. Experimental procedure

If the well-known limitation of areas for nonconductive solids [5,7,9-12] cannot be applied it can be proven by the test below that ignition hazards due to incendive brush discharges are unlikely to occur:



Fig. 2. Determining the maximum transferred charge  $Q_{max}$  of a provoked brush discharge for a test sample in dry climate.

- 1) The test sample is air-conditioned in dry climate (about 23°C at a relative humidity of 30% or less) for at least 24 h.
- 2) The air-conditioned test sample is then charged as highly as possible by rubbing with e.g. a felt cloth. Due to charge binding effects from table surfaces the test sample should be hung up in air or mounted on a plastic support to minimize these charge binding effects. It is, however,

also possible to carefully raise the charged test sample from charge binding tables before the measuring procedure.

- 3) The ball electrode (about 25 mm in diameter) of the coulombmeter is approached until a single discharge occurs (Fig. 2). It is very important that only one single discharge occurs. If discharge gaps of less than 2 mm (for explosion group I and IIA), 1 mm (for group IIB) and 0.5 mm (for group IIC) are observed, the resulting transferred charge may have a reduced incendivity due to electrode quenching effects.
- 4) After the discharge has taken place the ball electrode is immediately removed from the remaining electric field of the test sample and the display is read straight away (due to decay effects the displayed value decreases with time).
- 5) Steps (2) to (4) are repeated ten times provided the threshold limit is not exceeded (see e.g. Table 1).
- 6) Steps (2) to (5) are repeated by a second charging method (e.g. rubbing with nylon cloth, hitting with leather gloves).
- 7) Steps (2) to (5) are repeated but charging is achieved by spraying electrons from a metal tip on a potential greater than minus 35 kV. This step will be omitted if either the test sample is backed with metal or if there are great areas not accessible for rubbing or if the sample is dissipative or if the sample is a strongly concave shaped body.

The test is passed if the threshold level  $Q_{max}$  is not reached in any discharge. It is a good idea to verify this method from time to time with a reference plastic sample to make sure that no experimental errors occur. More details, especially of the technical data of the coulombmeter, can be found elsewhere [7].

## III. SPARK DISCHARGES

### A. General

Sparks occur if a discharge circuit of a capacitance  $C$  and a Voltage  $U$  is discharged. The incendivity of sparks is usually described by comparison of the energy  $W = 0.5 \cdot C \cdot U^2$  stored in the discharge circuit with the minimum ignition energy  $MIE$  of the explosive atmosphere present. However, the term  $MIE$  reflects already that the energy  $W$  necessary for igniting a certain explosive atmosphere is not a constant but depends on certain circumstances. It is well known from literature that - due to quenching effects -  $W$  of a constant explosive atmosphere decreases with increasing electrode gap  $d$ , reaches a minimum - the  $MIE$  value at the optimum voltage  $U_{opt}$  - and then again increases proportionally to  $d$  (Figs. 3-4).

This fact was explained by the minimum ignition volume theory of Lewis and von Elbe [14]. They stated that flame propagation in an explosive mixture takes place only if a certain minimum ignition volume has been completely ignited. As a consequence a spark gap  $n$  times greater than one single minimum ignition volume dissipates only the  $n^{th}$  part of its discharge energy in one minimum ignition volume. This

means that only about the  $n^{th}$  part of the spark energy is effective for ignition. This behaviour leads to the observed proportionality between spark gap  $d$  and energy  $W$  necessary to get ignition:

$$W = 0.5 \cdot C \cdot U \cdot U = const_1 \cdot d \quad (\text{for } U \geq U_{opt})$$

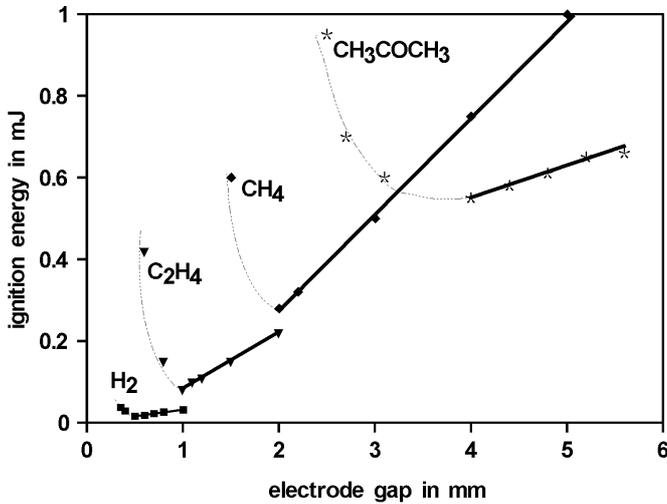


Fig. 3. Minimum spark energy  $W_{min}$  necessary to ignite fuel/air mixtures of optimum concentration as a function of the electrode gap  $d$ .

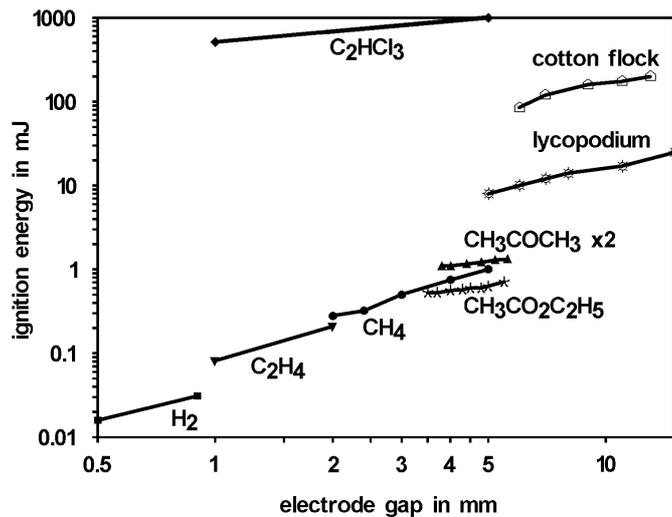


Fig. 4. Minimum spark energy  $W_{min}$  necessary to ignite the optimum ignitable fuel/air mixture as a function of the electrode gap  $d$  for  $U > U_{opt}$

On the other hand, Paschen's law [15,16] states that for ball electrodes of 25 mm in diameter there is a nearly linear correlation between voltage  $U$  and  $d$  for  $U$  up to 60 kV. Thus replacing  $d$  by  $0.5 \cdot const_2 \cdot U$  in the equation above and reducing one  $U$  leads to

$$C \cdot U = const \quad (\text{for } 60 \text{ kV} \geq U \geq U_{opt})$$

This equation predicts that the charge  $C \cdot U = Q$  transferred by a spark should be a suitable criterion for describing its

incendivity because it much less depends on voltage and electrode gap width than the spark energy. This behaviour is illustrated by comparison of Figs. 4 and 5:

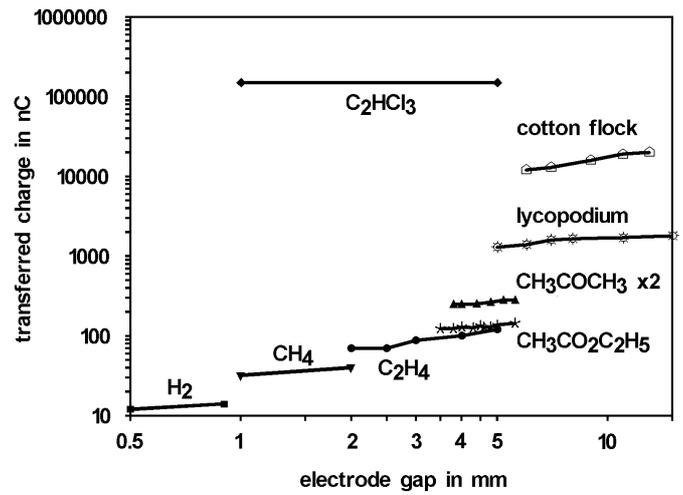


Fig. 5. Minimum transferred charge  $Q_{min}$  necessary to ignite the optimum ignitable fuel/air mixture as a function of the electrode gap  $d$  for  $U > U_{opt}$

It is obvious that  $Q_{min}$  is much less dependent on the electrode gap  $d$  than  $W_{min}$ . If  $Q_{min}$  for the smallest spark gap at  $U_{opt}$  is taken as the maximum allowed threshold limit  $Q_{max}$ , the deviations for greater and smaller electrode gaps are always on the safe side. If, as proposed, electrode diameters in the region of 25 mm are used for testing, the deviations become even smaller and the bends appearing in the decay are shifted towards higher gap values. These results show that it is indeed possible to use the maximum transferred charge  $Q_{max}$  by a spark to predict its incendivity.

TABLE 2  
NECESSARY ENERGY  $W_{MIN}$  AND CHARGE  $Q_{MIN}$  TO GET IGNITION OF QUIET FUEL/AIR MIXTURES FOR SPARKS OF DIFFERENT GAP WIDTH

Fuel	conc. Vol%	gap mm	diam. mm	$U$ kV	$C$ nF	$W_{min}$ mJ	$Q_{min}$ nC
Hydrogen	22	0.5	2	2.9	0.0038	0.016	12
	22	0.9	2	4.5	0.0031	0.031	14
Ethylene	8.0	1	2	5.4	0.0056	0.082	32
	8.0	2	2	10.5	0.0038	0.21	40
Methane	8.5	2	2	7.9	0.0090	0.28	70
	8.5	5	2	16.0	0.0078	1.0	125
Acetone	6.5	3.8	2	8.6	0.0148	0.55	127
	6.5	7	2	14.0	0.0097	0.95	136
Ethanol	6.5	7	5	14.5	0.013	1.38	190
	6.5	10	5	15.3	0.013	1.55	202
Lycopodium	opt.	5	2	12.5	0.102	8.0	1300
	opt.	15	2	27.5	0.053	20	1500
Trichloroethene	26	1	2	7.0	20.8	510	150000
	26	5	2	13.5	11.0	1000	149000
Dichloromethane	18	9	5	21.0	42.1	9300	880000
	18	16	5	35.0	26.1	16000	910000

Table 2 shows pairs of sparks at the ignition limit of the optimum fuel concentration for the optimum spark gap and another spark gap as great as possible with the apparatus used. All relevant parameters such as fuel concentration, electrode gap, electrode diameter, voltage and capacitance are given.

Lycopodium dust, trichloroethene and tichloromethane were measured with an inductance of 1.3 mH in the discharge circuit. All other substances were measured without inductance.

Table 3 lists some typical values for MIE,  $Q_{min}$  and  $U_{opt}$  for a number of fuel/air mixtures (gases, vapours, dusts and flock).

TABLE 3  
MINIMUM IGNITION ENERGY  $MIE$ , MINIMUM TRANSFERRED CHARGE  $Q_{MIN}$  AND OPTIMUM VOLTAGE FOR IGNITION  $U_{OPT}$  FOR SOME FUEL/AIR MIXTURES OF OPTIMUM CONCENTRATION

Fuel	$U_{opt}$ kV	$MIE$ mJ	$Q_{min}$ nC
Hydrogen	2.9	0.016	12
Ethylene	5.4	0.082	32
Diethyl ether	8.0	0.19	40
Benzene	8.0	0.20	45
Ethane	7.1	0.25	70
Propane	7.2	0.25	70
n-Hexane	7.5	0.24	63
Methane	7.9	0.28	70
Acetone	8.6	0.55	127
Epoxide dust, medium	8.1	3.3	830
Polyethylene dust, medium	8.5	5.2	1 200
EP/PE dust, medium	7.0	6.0	1 700
Lycopodium dust	8.1	9.9	2 400
Ammonia	14.8	14	1 500
Polyamide dust, medium	8.1	17	4 200
Cotton flock, fine ground	8.0	40	10 000
PA flock, coarse	13.0	254	39 000
Trichloroethene	7.0	510	150 000
1,1,1-Trichloroethane	14.7	4800	700 000
Dichloromethane	21.0	9300	880 000

If  $Q_{min}$  is unknown for a certain substance, it can be estimated if its  $MIE$  value is known:

$$0.5 \cdot Q_{min} \cdot U_{opt} = MIE$$

Note that the values for  $W$  and  $Q$  given in Tables 2 and 3 are those originally written in the documentation of the experiments. Due to rounding effects small deviations may occur in recalculation.

Table 3 shows that in the case of normal hydrocarbons,  $U_{opt}$  is in the region 7.0 kV to 8.0 kV. For substances of low incendivity,  $U_{opt}$  is usually higher. Very incendive substances normally have a lower  $U_{opt}$  value.

In Table 3 can be seen that hydrogen needs at least 12 nC, ethylene 32 nC and n-hexane 63 nC for ignition. These values are, however, the gross charge stored in the capacitance of the discharge circuit. As this capacitance is not completely emptied during sparking, these values must be reduced somewhat (normally about 5%) to get the net charge actually transferred by the spark.

If the mentioned values are rounded down the same values as in Table 1 measured for brush discharges of these substances are obtained. Table 1 is, therefore, valid also for spark discharges. It appears that the type of discharge has no influence on the transferred charge necessary for ignition, at least not in the case of gases and vapours. However, ignition

tests of quiet dust clouds with concurrent brush discharges with a sufficiently great charge transfer are difficult to realize [17].

### B. Experimental procedure

Many products contain small insulated conductors whose capacitance is difficult to measure. Other kinds of products may have insulated conductors which discharge themselves via corona discharge. In both cases it is difficult to decide whether or not incendive spark discharges are possible. However, the described measurement of the transferred charge  $Q$  of a single spark is a suitable method to answer this question.

The principle of this test is as follows: The insulated conductor is charged as highly as possible and the maximum possible transferred charge  $Q_{max}$  is measured as described for brush discharges and compared to the threshold values of  $Q_{min}$  derived from Tables 1 and 3.

- 1) The test sample is air-conditioned in a dry climate (min. 24 h at max. 30% relative humidity) and charged by spraying electrons from a metal tip on a potential of at least minus 35 kV.
- 2) A coulombmeter of the same type as used for brush discharges (see chapter II) is approached until a spark to its ball electrode occurs.
- 3) The transferred charge is then read from the display and compared with the threshold limits.
- 4) Steps (2) and (3) are repeated ten times.
- 5) It is recommended to regularly check the coulombmeter with an electrical pulse from a 1.5 V battery (battery voltage · input capacitance = displayed charge).

The test is passed if all results are below the maximum allowed threshold value. However, the following limitations must be taken into account:

- Multiple discharges must not occur.
- The pressure must be constant and about one bar.
- For best results the insulated conductor should be charged to a potential higher than  $U_{opt}$ , e.g. 8 kV.
- When results are to be compared, the same conditions should apply (e.g. ion concentration, humidity, electrode geometry, UV radiation).

## IV. MULTIPLE DISCHARGES

### A. General

In many cases the method described in chapters II and III is not applicable because multiple discharges occur. This is the case if e.g. discharges from high voltage electrodes or textile clothes containing metal filaments are to be evaluated. In this case it is, however, possible to measure

$$Q = \int I dt$$

with a suitable high frequency shunt resistance, connected to a rapid oscilloscope, in the earth line of a ball electrode

(25 mm in diameter). The coaxial shunt resistor must have a resistance of about  $0.2 \Omega$  to ensure, on the one hand, only little electrical influence on the occurring spark and, on the other hand, to deliver enough signal power for the connected oscilloscope. It is important that the resistance of the shunt is constant for frequencies up to 500 MHz, and that the oscilloscope has minimum 200 MHz band width, minimum 1 gigasamples/s, a  $50 \Omega$  input, a mathematical function for integration and is connected to the shunt via a double-shielded 50  $\Omega$  cable. Such equipment is commercially available, e.g. [13].

This method was first described by Brzostek and Krämer [18] and later improved by Smallwood [19]. It was, however, found that omitting the  $50 \Omega$  resistor in the shunt and minimizing its dimensions yields much clearer and sharper signals than those obtained in [18,19], see chapter V. It may be that the frequency behaviour of a normal  $50 \Omega$  resistor may contribute to the observed signal distortion.

Best results were obtained when the shunt did not exceed 20 mm in diameter. A construction of about 4 to 20 coaxially arranged high frequency SMD film resistors of  $1 \Omega$  to  $4.7 \Omega$  (e.g. [20]) is favored. Normal film resistors showed a small signal distortion but are also suitable. This type of shunt (Fig. 6) is even more suitable for rough handling than shunts built from SMD resistances. Shunts based on foils turned out to have an inductance and shunts based on coatings were found out to be not long-time stable.

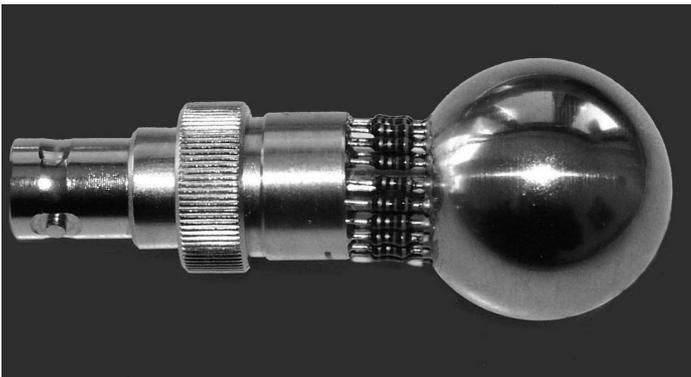


Fig. 6. High-frequency coaxially built shunt resistance with ball electrode, 25 mm in diameter, and connector to a rapid oscilloscope.

### B. Example of an experimental procedure

Electrostatic hand-held spraying devices produce electric discharges during their use in explosive paint atmosphere. This is why it has to be ensured by a type test that the strongest discharges produced during use are not capable of igniting the most incendive paint cloud present. Electrostatic spray guns are, therefore, a good example of how to provide an equivalent ignition test derived from a type test in explosive test gases and to compare the results of the two tests.

According to EN 50050 [21], spray guns for liquid paints have to be tested in a test vessel containing 5.25% by vol.  $\pm$  0.25% by vol. of propane in air. The MIE value of this test

gas is 0.24 mJ with an  $U_{opt}$  of 7.5 kV, corresponding to a  $Q_{min}$  of 64 nC.  $Q_{min}$  is rounded down to the maximum permitted charge  $Q_{max}$  of 60 nC.

The spray gun is operated in the test gas and approached to a ball electrode (25 mm in diameter) so that sparks as great as possible are produced. After 5 min of sparking, the test gas is changed and the test is repeated three times. The test is passed if no ignition of the test gas takes place during the total time of 20 min of sparking. More details of this test can be found in [21].

In the following section, an equivalent electrical discharge test is described as an example:

- 1) Spray gun, shunt and oscilloscope are set up in a dehumidified chamber of about  $23^{\circ}\text{C}$  and less than 30% relative humidity. This is necessary because the explosive test gas is dry and it was found that the occurrence of sparks strongly depends on humidity.
- 2) The shunt is connected via a double-shielded 50  $\Omega$  cable to the input channel of the oscilloscope. It was found out that the quality of this cable is important for clear signals. Special care must be taken to ensure that shunt and spray gun are properly earthed and that the shunt is direct connected to earth and not via the oscilloscope. In addition the earth cable shall be free from sharp bends e.g. knots. To avoid an earth loop in the system it may be necessary in rare cases to disconnect the protector ground of the oscilloscope from the mains.
- 3) The oscilloscope is set to 50  $\Omega$  for the input channel, 1 gigasample/s, trigger input channel, life triggered, mathematical function "integral input," and a range of medium sensitivity. Some oscilloscopes manufactured by Hewlett-Packard have a protector function which must be disabled.
- 4) It has to be verified that the oscilloscope does not detect any signal if the spray gun sprays at the earth line or at the connecting cable to the oscilloscope.
- 5) The spray gun is operated and the tip is approached to the ball electrode so that sparks as great as possible occur. The oscilloscope will now detect signals. Its sensitivity range may need to be adjusted.
- 6) After each detected spark, the trigger level is increased so that the next spark detected has a somewhat higher transferred charge than the spark before. This increase is stopped if new signals are detected only every 10 s to 30 s.
- 7) It is often desirable to influence the moving of the sparking test specimen in order to detect the maximum possible transferred charge. This can be easily realized by the proposed method. In the case of electrostatic hand spray guns, however, the displayed results must not influence the test engineer, otherwise, as a consequence of the systematical optimization of the speed and manner of how the test gun is moved, stronger discharges than in the "blind" test with explosive test gas would result. On the other hand, if optimized sparking conditions had been found by the proposed method, it was always possible to

verify their incendivity in explosive test gas if the same sparking conditions were applied. Consequently both methods are in agreement if the same discharges are evaluated.

- 8) After 20 min of sparking, the highest charge value displayed during the testing time is noted and compared with the threshold value of 60 nC.

Figure 7 shows a comparison of the ignition results in explosive atmosphere according to EN 50050 [21] and the proposed equivalent test method for paint spray guns via measuring maximum transferred charges. Except one gun, whose result lies, however, within the statistical scatter of 10% of this method, the two methods yield the same result.

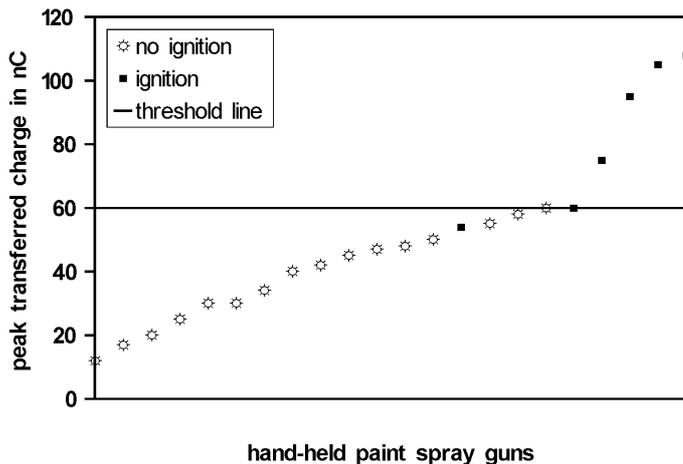


Fig. 7. Comparison of the test results for 22 hand-held paint spray guns devices sorted horizontally by their maximum transferred charge with the result of their ignition test in explosive gas mixture, shown by the symbol mark. The threshold line for  $Q_{max} = 60$  nC is also shown.

The comparison of the two methods was repeated with powder spray guns. In this case, the test gas is 12.0% in vol.  $\pm$  0.1% in vol % of methane in air [21]. In contrast to the test gas for liquid spray guns, two differences have to be taken into account: As gas leakage through the spray gun body cannot be avoided the concentration of the test gas decreases during the test and, due to the much smaller tolerance of the test gas concentration in comparison to the paint spray guns, the test gas concentration falls below the allowed gas concentration. Unfortunately,  $MIE$  and  $Q_{min}$  for this test gas concentration also depends strongly on the concentration.

For this reason  $MIE$  and  $Q_{min}$  were carefully measured for methane in the range of the test concentration, which was determined by two different calibrated pressure sensors. Our measurement yielded 1.0 mJ, or 125 nC, respectively, for 11.60% in vol.  $\pm$ 0.05% in vol. % ( $U_{opt} = 15.3$  kV) and 1.6 mJ or 203 nC, respectively, for 12.00% in vol.  $\pm$ 0.05% in vol. of methane in air ( $U_{opt} = 16.1$  kV). These energy values lie exactly on the fitting curve for the ignition energy of methane measured by Brzostek and Krämer [18].

The ignition tests of the powder spray guns in the test gas usually started at about 12.0% in vol. of methane and decrease

during the test to about 11.6% in vol. resulting in a threshold value for  $Q_{max}$  of 120 nC. Figure 8 shows a comparison of the test results for powder spray guns obtained in explosive atmosphere according to [21] and the equivalent test method via transferred charges. It is obvious that the tests in explosive atmosphere correspond with the expected threshold value of 120 nC. However, some spray guns with measured maximum transferred charge slightly exceeding the threshold value had to be repeatedly tested in explosive atmosphere until ignition occurs.

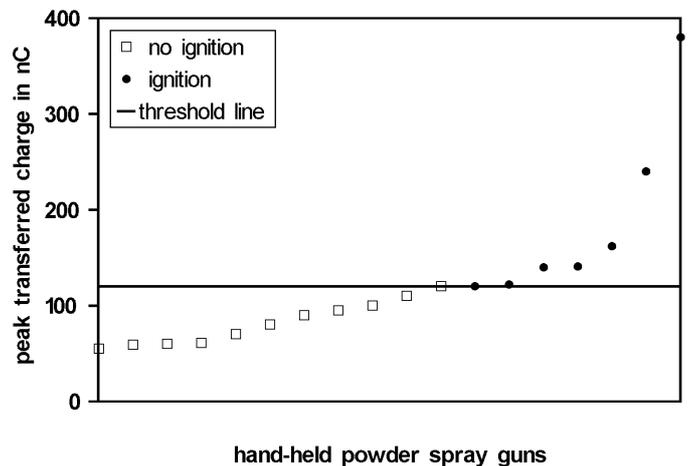


Fig. 8. Comparison of the test results for 18 hand-held powder spray guns sorted horizontally by their maximum transferred charge with the result of their ignition test in explosive gas mixture, shown by the symbol mark. The threshold line for  $Q_{max} = 120$  nC is also shown.

Figure 7 and Fig. 8 show that the threshold values  $Q_{max}$  derived from  $MIE$ -measurements are confirmed by the experimental ignition tests in explosive atmosphere. The threshold limits of 60 nC for paint spray guns and 120 nC for powder spray guns obtained are also in agreement with the charge threshold values of 120 nC for powder and 54 nC to 63 nC for paint spray guns, determined by Heidelberg by a different method [7]. The reproducibility of the proposed test method is limited by statistical scatter but clearly lies in an interval of  $\pm 10\%$  which is acceptable for safety purposes (Fig. 9).

It shall be noted that this scatter is not a consequence of the proposed method, but a result of the statistical scatter when reproducing electrical discharges.

Nine extra powder spray guns were additionally tested so that the methane concentration at the end of the ignition test was about 12.0% in volume. This concentration corresponds to a  $Q_{max}$  value for the test gas of 200 nC. As expected a correlation similar to Fig. 8 between the proposed method and the ignition test for that threshold value was observed. However, whether starting the ignition test for powder spray guns at 12% in volume of methane, yielding a threshold value of 120 nC, nor ending the ignition test at that concentration, yielding a threshold value of 200 nC, is the procedure described in the standard. It is, therefore, proposed to use a medium threshold value of 160 nC if paint spray guns are

evaluated by the oscilloscopic method of transferred charge. This value corresponds to a medium methane concentration of 12% in volume during the ignition tests.

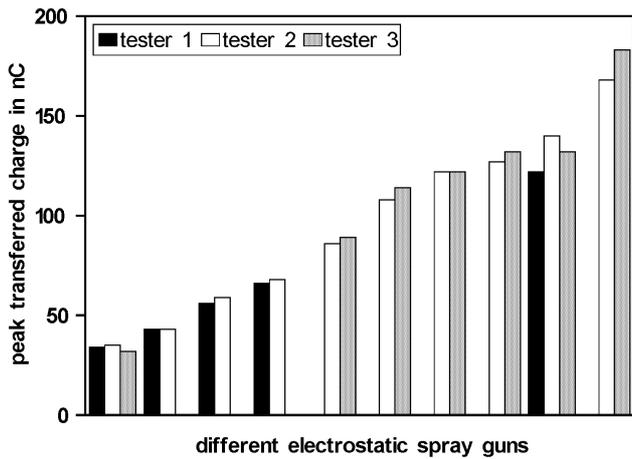


Fig. 9. Reproducibility of charge measurements

Another successful substitution of tests with flammable gases by the oscilloscopic method of transferred charges was demonstrated in the case of testing flexible intermediate bulk containers. More details can be found elsewhere [22,23].

### V. OSCILLOSCOPIC RECORDS

After numerous oscilloscopic records of electrostatic discharges it was observed that same types of electrostatic discharges show a similar current curve. In the case of spark discharges often a characteristic current curve is observed too. This behaviour not only allows to distinguish between the different types of electrostatic discharges but also gives hints about the dimensions and inductance of the discharged body. The following diagrams show records of some typical discharges. All Figs. 10-17 were recorded with the same shunt ( $R = 0.233 \Omega$ ). Fig. 11 has 25 nS/div, Fig. 17 has 400 nS/div, all other records 50 nS/div.

Fig. 10 shows a typical quiet corona discharge. Electrons are spraying with a current of  $30 \mu\text{A}$  from a needle lying on a potential of  $-35 \text{ kV}$  to the electrode of the shunt leading to a small continuous energy flow. This type of discharge is clearly not incendive.

If the voltage is increased, the corona discharge becomes noisy and small additional spark discharges from surfaces in the vicinity of the tip occur. Multiple spikes appear on the current curve which, however, are so short that only very little energy dissipation takes place. The incendivity of this type of discharge is still very low. The occurrence of corona discharges with a continuous current flow may be a reason why transferred charges from e.g. textile materials yield too high values if the method from section II is used.

Fig. 11 shows a spark discharge from a rod 2 cm in length and 2 mm in diameter without any sharp edge ( $C = 1 \text{ pF}$ ,  $U = 45 \text{ kV}$ ,  $Q_{\text{stored}} = 45 \text{ nC}$ ,  $Q_{\text{measured}} = 42 \text{ nC}$ ). Fig. 11 demonstrates that the current curve of small conductive items has the form of a peak.

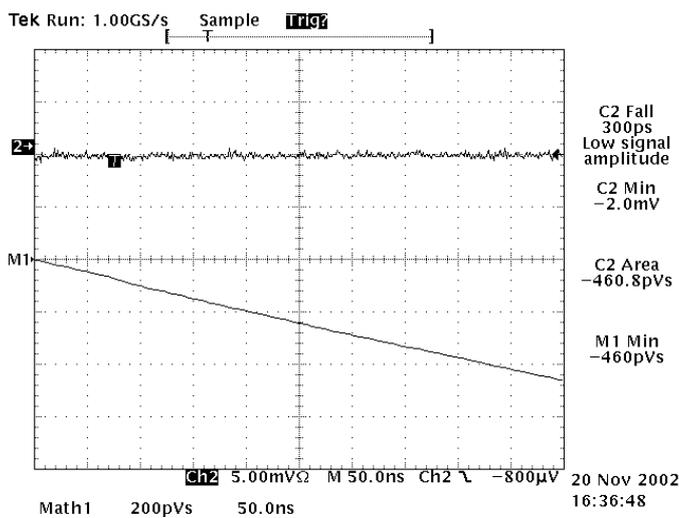


Fig. 10. Current record of a typical corona discharge

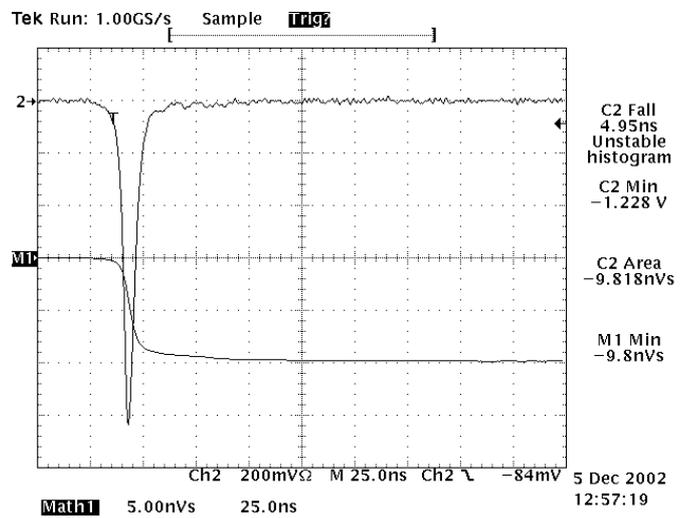


Fig. 11: Typical spark discharge from a small conductive item

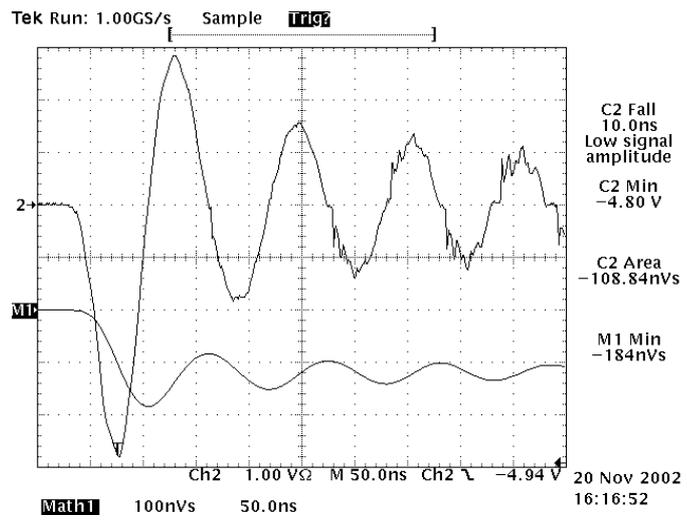


Fig. 12: Typical spark discharge from a normal rolled capacitor

If the dimensions of the conductive item is increased oscillations of the current occur at the end of the discharge. The amplitude of the oscillation is the higher the greater the inductance of the conductor. Fig. 12 shows the typical spark current produced by a normal rolled capacitor ( $C = 93.3 \text{ pF}$ ,  $U = 7.0 \text{ kV}$ ,  $Q_{\text{stored}} = 653 \text{ nC}$ ,  $Q_{\text{measured}} = 472 \text{ nC}$ ) with high inductance. Due to the inductance in the capacitor energy losses occur which are much smaller in the case of less inductive pulse-capacitors or air capacitors.

Great conductive items (e.g. containers, cars) show a complex but reproducible current curve as characteristic as a fingerprint. Fig. 13 shows the reproducible current curve from a 1000 l tin-wrapped plastic container ( $C = 480 \text{ pF}$ ,  $U = 3000 \text{ V}$ ,  $Q_{\text{stored}} = 1440 \text{ nC}$ ,  $Q_{\text{measured}} = 1228 \text{ nC}$ ).

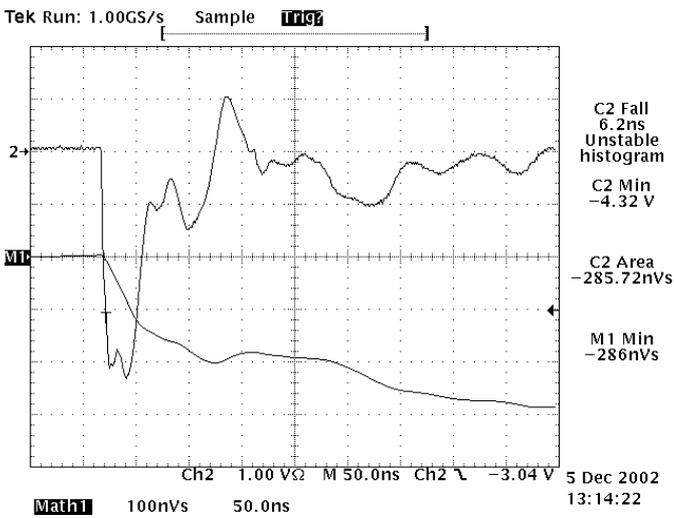


Fig. 13: Characteristic individual current curve of a great conductive item

Brush discharges from insulated plastic or textile surfaces show a current curve in form of a saw tooth (Figs. 14-15).

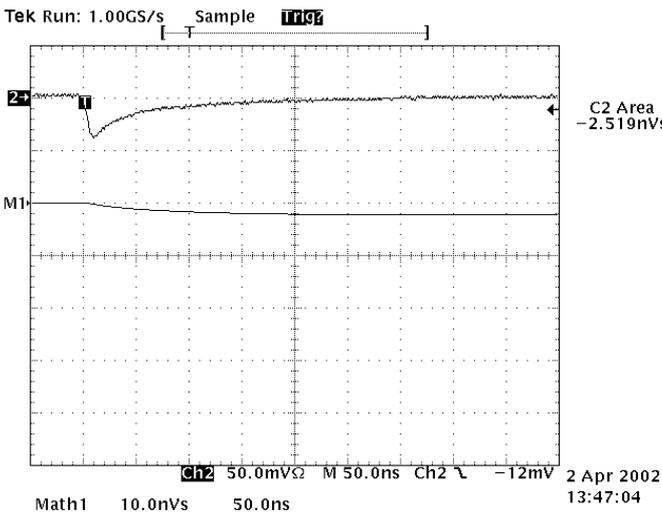


Fig. 14: Small brush discharge (11 nC)

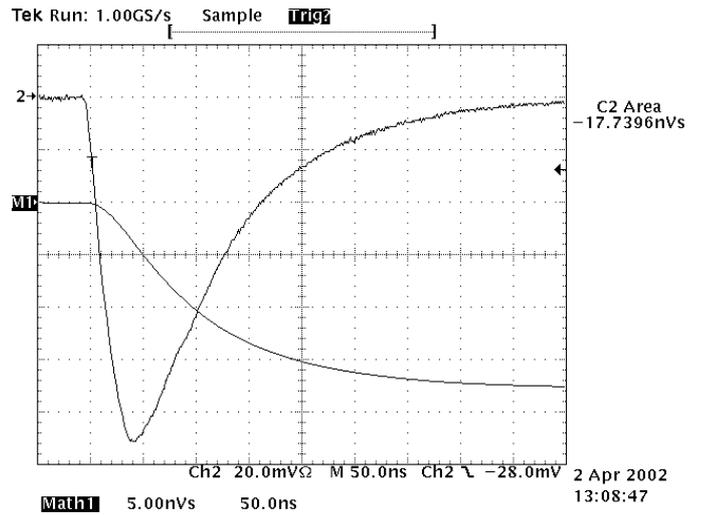


Fig. 15: Normal brush discharge (77 nC)

Very dissipative plastic surfaces (surface resistance about  $10^3 \Omega$ , measured according to [9-10]) show the same current curve as spark discharges (see Fig. 11). Discharges from materials with a higher surface resistance possess a shoulder in the current decay (see Fig. 16 for a material with a surface resistance of  $10^6 \Omega$ ). These shoulder becomes more and more apparent with increasing surface resistance until the current curve of a brush discharge is reached for substances with a surface resistance of about  $10^9 \Omega$  (see Figs. 14-15).

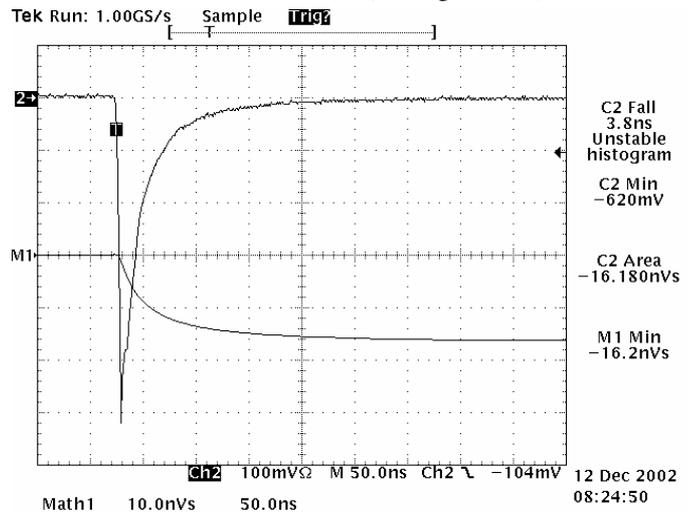


Fig. 16: Discharge from a dissipative cylinder 80 cm x 14 cm (69 nC)

Propagating brush discharges have current curves similar to strong brush discharges (e.g. Fig. 15), but their peak current is much higher and their discharge time much longer. They also usually appear in form of multiple discharges. Fig. 17 shows a typical small propagating brush discharge with a transferred charge of more than 28000 nC. As propagating brush discharges are highly incendive and can be easily identified visually, it is usually not necessary to measure their transferred charge.

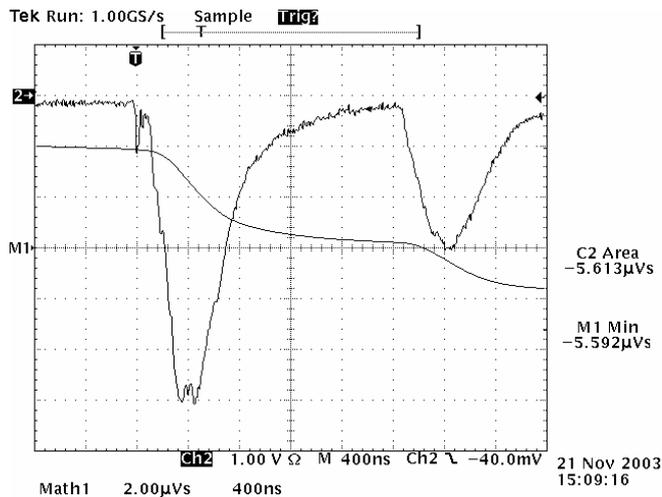


Fig. 17: Small propagating brush discharge ( $> 28000$  nC)

## VI. CONCLUSION

The experimental results obtained demonstrate that the charge  $Q$  transferred by an electric spark or brush discharge is a suitable parameter for predicting their incendivity for safety purposes. In practice the results obtained are the same as those obtained with explosive test gases.  $Q$  can be easily measured in the case of simple and multiple discharges. The reproducibility clearly lies in an interval of  $\pm 10\%$  which is acceptable for safety purposes.

It is possible to calculate the minimum transferred charge  $Q_{min}$  necessary to get ignition for any fuel/air mixture if its  $MIE$  and its optimum voltage for ignition  $U_{opt}$  are known.  $Q_{min}$  can be rounded down to a maximum permitted charge  $Q_{max}$  transferred by a discharge in an explosive atmosphere of that fuel. No experimental factors are needed. Deviations, if any, are always on the safe side.

As a numerical value of  $Q$  is displayed immediately after sparking, the method is suitable for quality assurance purposes and to systematically discover the best conditions for ignition. However, although this possibility is often useful, it interferes when substituting a test with unsystematically sparking in explosive test gases. In this case, the testing procedure must not be influenced by the displayed values. Otherwise, more incendive discharges would occur compared to the method using randomly sparking in explosive test gases. The two methods only furnish the same results if the same discharges are evaluated.

It was found that at least for gases and vapours the incendivity of normal electrostatic discharges is nearly independent of the type of discharge. This statement may not be true for discharges modified by resistance and inductance. Neither is the method suitable for permanent arc discharges because of energy cumulating. However, such an energy cumulating has never been observed in multiple electrostatic discharges.

It was observed that corona, brush, propagating brush and spark discharges show a different current curve which allows to distinguish between these types of discharges. Also the

inductance and resistance of materials discharged influence the current curve giving every discharge an individual fingerprint. The method of oscilloscopic charge transfer allows, therefore, to get even more information about the discharge occurring than just its incendivity.

## REFERENCES

- [1] N. Gibson and F. C. Lloyd, "Incendivity of discharges from electrostatically charged plastics," *British Journal of Applied Physics* 16 (1965), 1619-1631.
- [2] D. Eisfeld, "Elektrostatische Zündgefahr von Kunststoffteilen in explosionsfähiger Methan/Luft-Mischung," *Glückauf-Forschungshefte* 45 Vol. 3 (1984), 116-123.
- [3] Westfälische Berggewerkschaftskasse (applicant), D. Eisfeld (inventor), "Gerät zum Nachweis elektrostatischer Ladungen," German Patent application 3202702 (1982).
- [4] N. Gibson and D. J. Harper, "Parameters for assessing electrostatic risk from non-conductors - a discussion," *Journal of Electrostatics* 21 (1988), 27-36.
- [5] European Standard EN 50014:1997, "Electrical apparatus for potentially explosive atmospheres - General requirements."
- [6] U. von Pidoll, "Electrostatics requirements for intermediate bulk containers intended for use in explosive atmosphere," *Journal of Electrostatics* 51-52 (2001) 387-394.
- [7] European Standard EN 13463-1:2001, "Non-electrical equipment for potentially explosive atmospheres - Part 1: Basic methods and requirements."
- [8] E. Heidelberg, "Test and Judgement of ignition hazards caused by electrostatic spray guns and charged surfaces without the use of explosive mixtures," *Journal of Electrostatics* 21 (1988) 1-17.
- [9] CENELEC TR 50404:2003 "Code of practice for the avoidance of hazards due to static electricity" (new version of Cenelec Report R044-001:1999 "Guidance and recommendations for the avoidance of hazards due to static electricity").
- [10] European Standard EN 62013-1:2003 "Caplights for use in mines susceptible to firedamp. Part 1: General requirements - Construction and testing in relation to the risk of explosion".
- [11] Hauptverband der gewerblichen Berufsgenossenschaften e.V., Berufsgenossenschaftliche Regeln BGR 132 "Statische Elektrizität." St. Augustin (Germany), 2003.
- [12] Draft International Standard prIEC 60079-0:2004 "Electrical apparatus for explosive gas atmospheres - Part 0: General requirements".
- [13] Schnier Elektrostatik, Robert-Bosch Strasse 60, 72810 Gomaringen, Germany.
- [14] B. Lewis and G. von Elbe, *Combustion, Flames and Explosions of Gases*, 3<sup>rd</sup> Edition, Academic Press 1987.
- [15] F. Paschen, "Über die zum Funkenübergang in Luft, Wasserstoff und Kohlensäure erforderliche Potentialdifferenz," *Wiedemanns Annalen der Physik und Chemie*, Neue Folge 37 (1889), 69-96.
- [16] B. Gänger, "Der elektrische Durchschlag von Gasen," Springer Verlag, Berlin, 1953.
- [17] K. Schwenzfeuer and M. Glor, Aktuelle Zündversuche von Stäuben mit Büschelentladungen. Unpublished manuscript dated January 10<sup>th</sup>, 2002.
- [18] E. Brzostek and H. Krämer, Entzündungen explosionsfähiger Gemische durch elektrische Funken, 5. Kolloquium über Fragen der chemischen Sicherheitstechnik, Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin 1990, 65-82.
- [19] J. Smallwood, Simple passive transmission line probe for electrostatic discharge measurements. *Electrostatics 1999: Proceedings of the 10th*

International Conference Cambridge, Inst. Phys. Conf. ser. No. 163, 363-366.

- [20] Vishay Intertechnology Inc, Malvern PA, USA, 10 x 2 ohm, 1 watt, 5 GHz, type (H)CHP 2010 M 2R00 BE.
- [21] European Standard EN 50050:2001, "Electrical apparatus for potentially explosive atmospheres - Electrostatic hand-held spraying equipment."
- [22] U. von Pidoll, "Rapid determination of the incendivity of discharges from FIBC surfaces without explosive atmosphere," Conference record of the 3<sup>rd</sup> World Flexible Intermediate bulk Container 2002 6.-7. November, Antwerp.
- [23] Draft International Standard prIEC 61340-4-6:2003 "Electrostatics - Part 4-6: Standard test methods for specific applications - Test methods for the electrostatic safety of intermediate bulk containers (IBC)".



**Ulrich von Pidoll** was born in Cologne, Germany, and studied Physical Chemistry at the Technical University of Darmstadt. He there received the degree of a Dr.-Ing. in 1984. From 1985-1990 he was scientific referent at the Feldmuehle AG, Plochingen. Since 1990 he is expert in electrostatic ignition hazards, especially in electrostatic varnishing, gasoline stations and automotive fuel systems, at the Physikalisch-Technische Bundesanstalt, Braunschweig. In 1993, he won together with Dr. Helmut Kraemer the Helmholtz prize for his work about the safety of powder varnishing. Since 2001, Dr. von Pidoll is convenor of the Cenelec working group TC31 WG20 about electrostatic hazards. Up to now he has written two books, two patent applications and about fifty scientific publications.



**Edward Brzostek** was born in Warschau, Poland and studied electrical engineering at the University of Oppeln. He received the degree of a Dr.-Ing at the Polytechnic University of Gleiwitz in 1981. He then settled to Germany. Between 1985 and 2003 he worked in the Physikalisch-Technische-Bundesanstalt, Braunschweig in the fields of minimum ignition energies, computer-simulation of high-voltage fields and construction of an electrical pulse generator for pulse measuring technique. Since 2003 he is examiner of electrical devices for use in explosive atmosphere at Zelm-Ex, Braunschweig. All minimum ignition energies in this work have been determined by him.



**Hans-Rudolf Froechtenigt** was born in Braunschweig, Germany, and learned locksmith at the railway coach maintenance works Braunschweig of the Deutsche Bundesbahn. His final examination was in 1959. Later he visited the Technical School of Braunschweig and received the degree of an electrical engineer in 1970. Since 1969 he is examiner of electrostatic hand spraying devices at the Physikalisch-Technische-Bundesanstalt, Braunschweig. All ignition experiments in explosive gas atmosphere in this work have been carried out by him.