Vacuum insulator flashover, mechanisms, diagnostics and design implications

Vacuum Insulator Flashover
Mechanisms, Diagnostics and Design Implications

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ABSTRACT

This paper presents an approach for obtaining science-based answers to practical vacuum device problems. The question "How to translate scientific knowledge to design and operation practice" is rephrased to the more productive question "What research activities are required to provide science-based answers to practical problems?" Such activities involve the study of operational mechanisms in realistic geometries with the help of appropriate diagnostics. Within this framework, recent research developments on vacuum insulator flashover are reviewed, with emphasis on the implications for device performance and design. Secondly, an overview is given of recent research activities, performed at the Eindhoven University of Technology. By studying the relationship between flashover mechanisms and insulator performance, and the relationship between insulator performance and design, we aim at improved device performance, the formulation of guidelines, and the development of device diagnostics, for dc and ac vacuum devices.

1. BACKGROUND

1.1. THE "TRADITIONAL" QUESTION

THE scientific literature provides a wealth of information on fundamental processes and mechanisms important for breakdown or surface flashover in vacuum. Examples are primary or secondary electron emission processes, electron stimulated desorption processes, insulator charging, and so on. Usually this information is obtained for, and applicable to, relatively simple geometries such as a vacuum gap or an insulator between two electrodes.

On the other hand, industrial engineers deal with complex devices, and with practical questions such as how to design, condition and operate a vacuum device. The 'traditional' question raised by scientists and engineers is (Figure 1): "How can we translate scientific knowledge to design and operation practice?"

1.2. REPHRASING THE QUESTION

In many cases the gap between scientific knowledge and engineering practice is too large for a direct translation. On the basis of fundamental laboratory studies the performance of complex devices may be explained, but not predicted. The device complexity, on the other hand, does not allow to study fundamental processes in realistic designs. In order to bridge this gap we rephrase the above question to: "How can we aim research activities at providing science-based answers to practical problems?"

Three main requirements are formulated for such research activities (Figure 2). They have to involve operational mechanisms in simplified insulating structures and should use appropriate diagnostics.

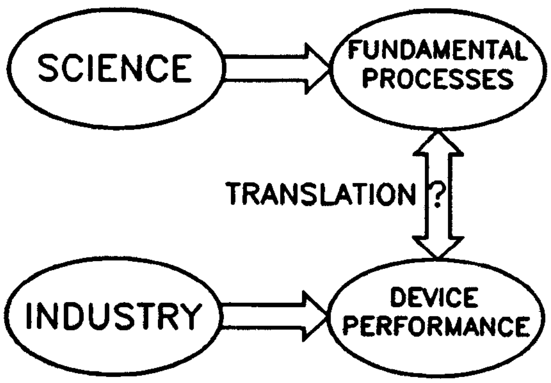

Figure 1. The traditional question.

1.2.1. OPERATIONAL MECHANISMS

We distinguish between fundamental processes and operational mechanisms. Fundamental processes describe a single type of event, often occurring on a microscopic scale. Operational mechanisms are the result of several fundamental processes, and are active on a macroscopic or device scale. In general, operational mechanisms modify device conditions or properties. As an example, insulator surface charging is an operational mechanism that is the result of fundamental processes (cathode electron emission, secondary electron emission from insulator surface), and has a direct impact on the device performance. Research can establish how operational mechanisms affect the device performance, and what design rules can be deduced. Operational mechanisms link fundamental processes to device performance.

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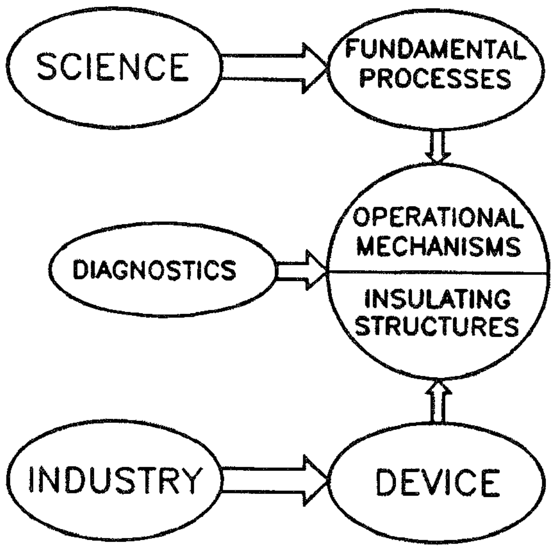

Figure 2. Linking fundamental processes and device performance.

1.2.2. INSULATING STRUCTURES

Often, devices are too complex to study the impact of different mechanisms on the device performance. However, in practical devices we can recognize distinct problem areas, such as vacuum gaps, insulating spacers and feedthroughs (each with different geometries, materials and treatment). With separate experimental geometries we can simulate problem areas and study the impact of operational mechanisms on device performance in a realistic environment. Insulating structures used for research on device performance have to represent realistic device problem areas.

1.2.3. DIAGNOSTICS

Appropriate diagnostics need to be developed and applied to the study of operational mechanisms in insulating structures. Such diagnostics should reveal how a mechanism takes place (*e.g.* how an insulator surface is charged), but also how this mechanism (*e.g.* surface charging) affects the overall performance. Diagnostics for research on device performance should reveal how mechanisms influence performance

1.3. SCIENCE AND INDUSTRY

So far, the approach discussed is a scientific one. Device applications of scientific results, such as design modifications and design rules, can only be achieved in an interaction between science and industry. An interaction model is shown in Figure 3.

In Section 2 some recent developments will be discussed, regarding surface flashover mechanisms, diagnostics and geometry studies. In Sections 3 and 4 we will discuss recent research activities at the Eindhoven University of Technology aiming at improved device performance and at formulation of design rules. Section 3 deals with dc insulating structures, Section 4 with ac insulating structures.

2. RECENT DEVELOPMENTS

In this Section recent developments are discussed. As a starting point, the 1993 review article by Miller is used [1]. For the original sources the reader should consult the references contained in that paper.

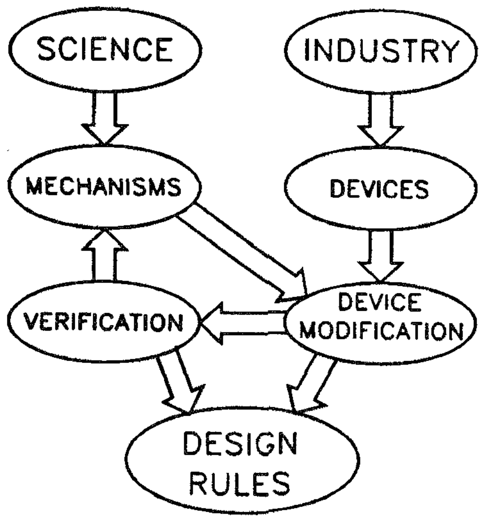

Figure 3. Interaction model science and industry.

2.1. MECHANISMS

2.1.1. FLASHOVER

Miller distinguishes three insulator flashover stages:

1. initiation,
2. flashover development and
3. final gas breakdown.

Cathode triple junction field emission is usually regarded the primary initiating mechanism. In the two leading theories the flashover developes either through a SEEA (secondary electron emission avalanche), or through an ETPR (electron triggered polarization relaxation). Other theories are reported as well, and it seems that no single theory is capable of explaining the surface flashover development under all circumstances. In the final phase, a gas breakdown takes place in desorbed surface gas or vaporized insulator material. In some materials (silicon) breakdown is reported to occur in a highly conductive surface layer.

In recent years many optical emission studies were reported by the University of South Carolina, Aston University, and Texas Tech University. Light emission is observed in order to study the (pre)flashover surface processes, the surface (micro)structure and possible defects, and their impact on the flashover characteristics [2–11]. Experiments with time-resolved detection of free electrons by a laser deflection technique indicate the presence of charge carrier amplification in a plasma above the surface. This is further substantiated by the response to magnetic fields [2, 3].

2.1.2. SURFACE CHARGING

Many investigators have recognized surface charging as an important mechanism in the surface flashover process, and report on the amount and distribution of charge, and the speed of the charging process [1]. Recent studies at the University of Strathclyde show how the cathode geometry affects the charging process for cylindrical Teflon™ insulators [12]. The temporal evolution of the charging process for cylindrical and conical insulators of different materials (PMMA, Al_2O_3, polyimide) was studied at Kyoto University with a 2D Monte Carlo simulation [13], a technique used earlier at the University of South Carolina [14]. Investigations at the Eindhoven University of Technology with many different insulator designs show how surface charging influences the insulator flashover voltage as well as the conditioning process. The effect of surface charging is determined from flashover and conditioning studies in combination with a non-invasive charge removal technique [15].

2.1.3. CONDITIONING

The mechanisms commonly considered relevant for conditioning are removal of emission sites, removal of surface gas, or removal of surface contaminants [1]. Recent studies also show that surface charging plays an important role [15]. The conditioning speed, the conditioning stability, and the conditioning effectiveness depend drastically on the presence or absence of surface charge, and may be optimized by the choice of a proper geometry [16]. With 'silent' conditioning, 'charge traps' are used to reduce the triple junction field and make conditioning unnecessary [16]. Here charge traps are (parts of) surfaces designed to collect electrons such that the local electric field makes it impossible for the electrons to leave the surface again.

2.2. DIAGNOSTICS

2.2.1. ELECTRICAL DIAGNOSTICS

Standard electrical diagnostics for flashover studies involve measurement of the dc current, the time-resolved current, the voltage waveform and the flashover voltage [2, 3, 6, 15, 17]. Recent studies also report PD (partial discharge) measurement. For dc studies, PD measurements provide additional information on charging processes [15], for ac studies the analysis of phase resolved PD patterns may provide information on the presence of defects [18].

2.2.2. OPTICAL DIAGNOSTICS

A wide variety of optical diagnostics is used in recent flashover studies: streak cameras [2, 3, 19], photomultiplier tubes, often in combination with monochromators or fixed filters for spectral resolution [6, 17, 20], CCD (charge-coupled device) cameras often in combination with image intensifiers [6, 20], laser deflection techniques [2, 3], X-ray detection [2, 3, 21], and scanning electron microscopes [6].

2.2.3. SURFACE CHARGE MEASUREMENT

Surface charge distributions may be measured with an electrostatic probe [12]. This measurement requires either the probe or the insulator to move, and is performed after voltage application, and with at least one of the electrodes removed. Another technique reported for determining surface charge distributions makes use of the deflection of an electron beam [22, 23]. Electron beams are not only used for charge measurement, but also to charge or discharge an insulator. With the SEM (scanning electron microscopy) mirror technique a surface is first charged with the SEM electron beam and subsequently observed with the same beam at lower energy [23, 24]. An electrical method which gives indicative information on the total amount of accumulated charge makes use of the dc current and the PD behavior of a stressed insulator upon stepwise voltage changes [15]. A helpful tool in surface charge studies is the possibility of removing surface charge, without modifying the insulating structure, by admitting low pressure N_2 gas [15, 16]. This allows a study of the impact of surface charge on the insulator performance.

2.2.4. OTHER DIAGNOSTIC TECHNIQUES

Apart from the diagnostics mentioned several studies make use of chemical analysis such as desorbed gas analysis [6].

2.3. INSULATING STRUCTURES

Experimental insulating structures may be chosen to facilitate observation. As an example recent work at Aston University involves a planar radial field system [4, 5], a three electrode system with transparent anode [6], and cylindrical and conical insulators between electrodes using a transparent anode [7].

In other cases experimental geometries are chosen to resemble a device problem area. In his review, Miller refers to a number of papers on the relation between insulator shape and flashover voltage [1]. The geometry influence is ascribed to the cathode triple junction field in combination with electron propagation processes along the interface. Methods reported for triple junction field control include the use of metal inserts in the insulator (see also more recently [12]) or insulators placed in recessed electrodes. Electron propagation is controlled by insulator shape and surface properties. Miller reviews the influence of area, material, surface properties and surface treatment. Recent work includes the work at the Technical University of Braunschweig on pulsed flashover of $Al(OH)_3$-filled epoxy insulators with different shape and length [25], and the work at the Eindhoven University of Technology on dc flashover of Al_2O_3 insulators of different shape [15, 16]. In the latter work the insulator studies were used to generate design rules which are applied to specific problems (*e.g.* a feedthrough). Design rules were derived by studying the relation between mechanisms and performance, and the relation between performance and design.

Occasionally, the literature reports on specific designs or design-oriented studies. An example is the work on spacecraft components by the University of South Carolina [26] and the Eindhoven University of Technology [16, 17, 27].

2.4. DISCUSSION

In recent years, considerable progress is made in applying new, in particular optical, diagnostic techniques to the study of fundamental processes and surface properties relevant to surface flashover. The lack of predictive models indicates that a satisfactory theoretical description is not available yet. As a result vacuum components are often designed on a 'trial and error' and an 'ad hoc' basis rather than on a scientific basis. Next to the further development of flashover theories, the application of scientific results to devices requires a systematic and scientific approach to design. In such an approach the results of specific design studies need to be generalized and verified, with the aim to find design guidelines.

3. dc INSULATING STRUCTURES

In this Section recent work is presented, performed at the Eindhoven University of Technology and aimed at HV design concepts for dc vacuum components. The experimental procedures will be described briefly, followed by a discussion of the approach used to relate mechanisms to performance, and performance to design. From this work design rules are derived.

3.1. EXPERIMENTAL PROCEDURES

We here give a brief outline of the experimental arrangements, a more detailed description is given elsewhere [17, 28]. The experiments are carried out in a stainless steel vessel, pumped down to a pressure around 10^{-4} Pa. Insulator test samples are placed between two OFHC (oxygen-free high conductivity) copper electrodes in a uniform field region. The cathode is connected to a 120 kV dc HV supply through a vacuum feedthrough and a 100 MΩ damping resistor. The anode is grounded directly or through a measuring impedance. The electrodes are regularly remachined to a roughness < 0.1 μm. Every test geometry is tested at least once with virgin electrodes.

The insulator test samples are made out of circular disks of 40 mm diameter and 5 mm thickness, made of Wesgo AL300 alumina (Al_2O_3), metalized at top and bottom with MoMn and Ni, and goldplated. The cylindrical surface is carefully machined under clean room conditions.

The diagnostics include dc emission-current measurements (sensitivity 0.05 pA), dc PD measurements (sensitivity 0.2 pC), and series of flashover voltage measurements, with limited energy. With photomultiplier tubes, the optical emission is studied. Further, samples can be inspected with an optical microscope and a SEM. A non-contacting technique is used to remove surface charge and thereby study its effect on the flashover behavior. This charge removal is achieved by admitting nitrogen at a pressure near the Paschen minimum, with no voltage applied.

The electrodes are conditioned prior to the measurements. Thereafter the insulator samples are mounted and a step-conditioning procedure is performed, which combines dc current conditioning (at voltages close to breakdown) and flashover conditioning [17, 28].

3.2. KEY MECHANISMS

Although many processes and mechanisms can be recognized in a surface flashover event, the following key processes are found to play a dominant role [15, 16]: cathode primary electron emission, insulator surface charging, and high-energy electron impact.

3.2.1. PRIMARY ELECTRON EMISSION

Many literature references show that the flashover voltage strongly depends on the insulator shape [1, 15]. To some extent this geometry effect can be ascribed to the cathode triple junction field and its effect on primary electron emission. Figure 4 shows the measured flashover voltage for a number of different geometries *vs.* the calculated triple junction field [16]. We observe a clear trend indicating the importance of the cathode triple junction field. We also observe a significant scatter, which shows that other mechanisms must be considered as well.

3.2.2. SURFACE CHARGING

Figure 5 shows some experiments which indicate the occurrence of insulator charging during dc voltage application [15]. The top graphs in Figure 5 shows a stepwise change in dc voltage level, and the corresponding current response. After compensation for the displacement current, an exponentially decaying current remains. The amount of charge involved is derived by integration. Equal voltage steps give about equal amounts of charge, and a voltage rise gives approximately the same amount of charge as does a voltage drop. The amount of charge

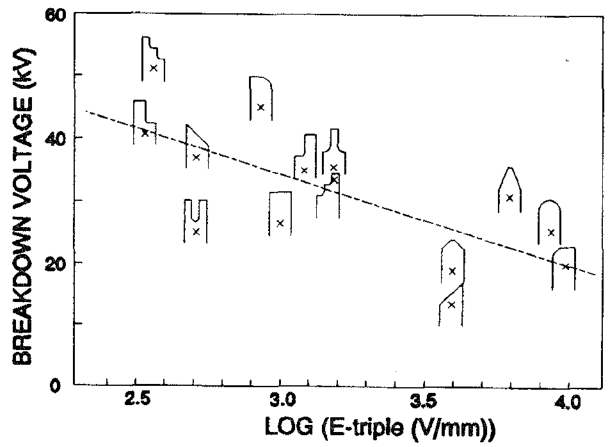

Figure 4. Unconditioned flashover voltage *vs.* the logarithm of the cathode triple junction field. The shapes involved are indicated (negative electrode on the left side).

depends on the insulator shape, showing that this behavior is not only a matter of polarization relaxation, but is at least partly related to the charging and discharging of the insulator surface.

The middle graphs in Figure 5 shows a rampwise change in dc voltage level, and the corresponding PD activity. PD is observed mainly during voltage changes which is again indicative of charging processes. Evidence of surface charging is found in experiments as shown in the bottom graph of Figure 5. A sample is subjected to a dc voltage or to a number of flashovers. Afterwards the power is switched off, the electrodes are grounded, and a small amount of dry nitrogen is admitted to the vessel. As the pressure approaches the Paschen mimimum a discharge is observed both optically and electrically. Without an external source present, the discharge is driven by the surface charge built up during the earlier voltage application. Also probe experiments performed after voltage application clearly have demonstrated the presence of surface charge [1, 12].

Surface charging appears to be a key mechanism in both the flashover and the conditioning process. This is clearly demonstrated by the series of flashover voltage measurements shown in Figure 6. When subjecting the insulator to a number of successive flashovers, the flashover voltage increases. When a flashover voltage of 60 kV is reached, charge is removed from the insulator surface by admitting low pressure nitrogen with no voltage applied. Subsequently the series of flashovers is repeated. These experiments show that the insulator surface collects charge during repeated flashovers; the flashover voltage gain of insulators obtained during conditioning is partly due to surface charging, but not exclusively: the faster rise in flashover voltage in the second series of flashovers shows that also a more permanent type of conditioning has taken place, ascribed to the removal of emission sites; and that the gain in flashover voltage may be lost when the surface charge is lost.

3.2.3. HIGH-ENERGY ELECTRON IMPACT

Electrons impinging on the insulator surface contribute to surface charging or gas desorption. Unless electrons are safely trapped (*i.e.* fixed to the insulator surface due to the local electric field), a field distribution which forces electrons to move towards the surface, either by

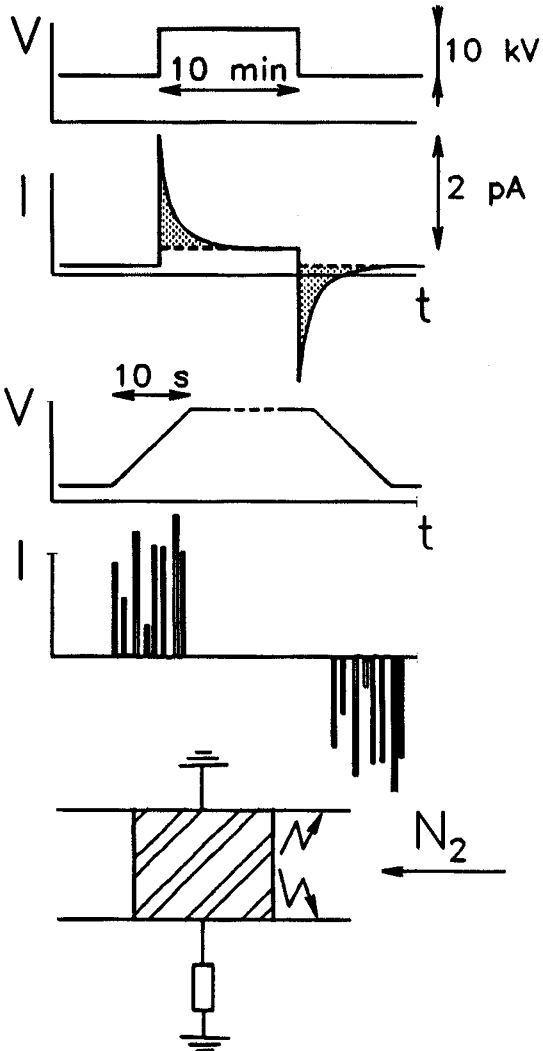

Figure 5. Experimental procedures which indicate the occurrence of surface (dis)charging processes.

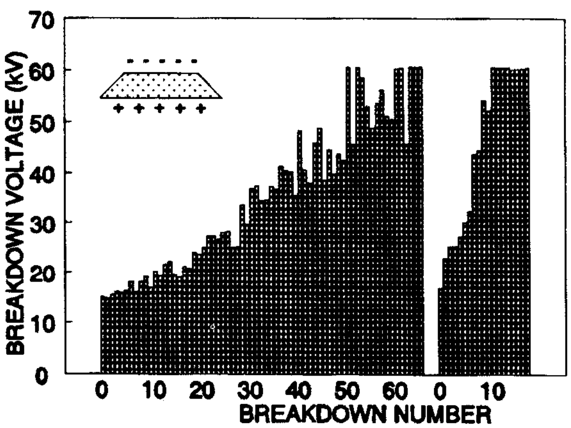

Figure 6. Measured flashover voltage evolution. After reaching a flashover voltage of 60 kV, the surface charge is removed with a low pressure nitrogen discharge (no voltage applied).

shape or by positive surface charge, causes a strong reduction of the flashover voltage, especially at high electron energy [29].

3.3. RELATING MECHANISMS TO PERFORMANCE

Experiments as shown in Figure 6 have been performed for a number of insulator geometries. The results are summarized in Table 1. The insulator performance is characterized by the performance parameters

1. the initial or unconditioned flashover voltage,
2. the conditioned flashover voltage,
3. the conditioning speed, and
4. the conditioning stability.

The number of flashovers required to reach a flashover field of 10 kV/mm is used as a measure for the conditioning speed, the drop in flashover voltage after removing the surface charge is a measure for the conditioning stability. In Figure 7 the insulators are divided in four groups based on their performance.

Sample	Averaged flashover field (kV/mm) MINIMUM	Averaged flashover field (kV/mm) CHARGE REMOVED	Number of flashovers to reach 10 kV/mm	Averaged flashover field (kV/mm) MAXIMUM
I	10.2	11.3	0	19.5
	9.0	12.0	1	16.0
	8.1	10.7	8	18.3
	7.4	12.0	5	20.0
II	7.1	9.3	36	16.1
	7.0	11.8	24	14.3
	6.7	11.3	45	11.4
	6.2	7.0	40	12.2
III	5.3	12.0	78	16.1
	5.1	9.3	61	13.4
	5.0	9.0	188	12.9
IV	4.0	5.4	25	14.1
	3.8	5.2	109	13.0
	2.7	3.5	71	15.4

Figure 7. Results of flashover evolution experiments. The average flashover field is defined as the flashover voltage over electrode distance (5 mm). All values are averaged over two samples. Before charge removal samples are conditioned up to 12 kV/mm. Maximum flashover field is an average over 5 consecutive flashovers.

3.4. RELATING PERFORMANCE TO DESIGN

In order to relate performance to design, design parameters are formulated which are correlated with the previously introduced performance parameters. From the key mechanisms for dc flashover, three design parameters are defined, each one characterized by a question:

1. is the cathode triple junction field high or low;
2. do electrons interact with the insulator surface; or
3. are electrons trapped upon hitting the surface?

Table 1 combines both design and performance parameters for all groups of Figure 7. The performance parameters are now simplified to a relative scaling. The following conclusions are drawn. An insulator with a low cathode triple junction field and without electron-surface interaction (group I) performs excellently; an insulator with electron-surface interaction where electrons are 'trapped' (group II) performs well, though inferior to group I; and an insulator with electron-surface interaction without charge traps (groups III and IV) performs badly in

Table 1. Comparison of performance parameters and design parameters for the groups of insulators in Figure 7. E_{ctj} is the cathode triple junction field, V_{ini}^{bd} and V_{con}^{bd} stand for the initial and conditioned flashover voltage. The terms 'impact' and 'traps' refer to the emitted electrons, the terms 'speed' and 'stability' refer to the conditioning process (as explained in the text).

	Design parameters			Conditioning performance			
group	E_{ctj}	Impact	Traps	V_{ini}^{bd}	V_{con}^{bd}	Speed	Stability
1	low	no	–	+	+	+	+
2	med-high	yes	yes	+/–	+/–	+/–	+/ –
3	low-high	yes	no	–	+/–	–	+/ –
4	high	yes	no	–	+/–	–	–

particular with respect to unconditioned flashover voltage and conditioning speed.

3.5. DESIGN RULES

The following design rules are derived for dc insulators:

DESIGN RULE 1: Minimize the cathode triple junction field.

DESIGN RULE 2: Keep electrons away from the insulator surface.

DESIGN RULE 3: If electrons hit the insulator surface, make sure they are "trapped".

DESIGN RULE 4: Tailor the design of an insulator shape to the way it is conditioned or operated.

DESIGN RULE 5: Avoid designs which are sensitive to small defects.

The first three rules are derived from the above discussion and Table 1. Design rule 4 is based on the observation that each geometry has its specific conditioning speed and stability. This implies that the optimum design of an insulator depends on the way it will be conditioned and operated. If flashovers are part of the conditioning process one should choose geometries with a high conditioning speed and stable performance. If no flashovers are used or allowed in the conditioning procedure (such as in many spacecraft applications), a high unconditioned flashover voltage is required. For components which may be switched off for long periods of time or which may be exposed to gases, stability is of major concern. Such designs should not rely on surface charging to attain a high flashover voltage. Figure 8 shows some designs optimized with the above rules, for an insulator between flat 8(a) or concentric 8(c) conductors, for cylindrical insulators 8(b) and for feedthroughs for space applications 8(d). More details are found in [16].

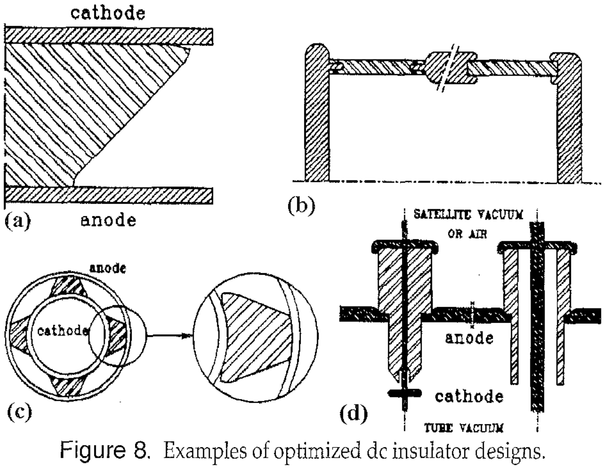

Figure 8. Examples of optimized dc insulator designs.

3.6. CONDITIONING

A step-conditioning procedure, which combines flashover conditioning with controlled energy and dc current conditioning close to the breakdown voltage, is an efficient way of removing emission sites [28]. The breakdown energy should be sufficiently high to be effective but low enough to avoid damage. Values of $\sim$ 10 to 30 mJ were found to be safe and effective.

For dc voltage 'silent' conditioning may be used [29]. During silent conditioning emission sites are, in fact, not removed but rendered harmless by incorporating carefully designed charge 'traps' or 'collectors' that collect electrons released near the cathode triple junction, and thereby reduce the triple junction field. The result is an increased initial breakdown voltage.

4. ac INSULATING STRUCTURES

4.1. KEY MECHANISMS

The fundamental processes important for ac vacuum insulators are basically the same as those for dc voltage. Their impact on the insulation performance however is different, for two reasons [18].

At dc voltage one of the electrodes serves as a cathode; triple junction field control is restricted to that electrode and can be achieved by concentrating the field at the anode. At ac voltage both electrodes serve as cathode and need to be controlled.

At dc voltage the insulator attains a stable surface charge distribution, which may either enhance or reduce the flashover withstand capability. This charge distribution may be used to achieve 'silent' conditioning by which emission sites are rendered harmless without being removed. At ac voltage no stable charge distribution is established. The charge deposited during one half cycle is discharged during the next, which results in an increased PD rate. This may result in damage and in an increased flashover probability by the release of adsorbed gases.

4.2. EXPERIMENTAL PROCEDURES

For ac insulation experiments we use the same vacuum system and insulator samples as for dc experiments, now with an ac power supply and an ac PD measurement system [18]. The ac power frequency is chosen 50.3 Hz in order to suppress PD patterns caused by 50 Hz related interference. PD is detected with an RLC impedance network. After amplification and pulse shaping the signal is fed to a MCA (multichannel analyzer) which records the magnitude and phase/time distributions. Phase resolved PD measurements are performed by repeatedly triggering the MCA, and accumulating PD during many sweeps. The PD detection level was $\sim$ 1 pC.

4.3. FLASHOVER PERFORMANCE

Figure 9 shows the conditioned flashover voltages for a number of different insulator shapes under ac and dc stress. For ac the influence of the shape on flashover voltage is not as pronounced as for dc For identical insulators the ac flashover voltage is always lower than the dc flashover voltage. Insulators with a poor dc performance have a relatively poor ac behavior as well. However, insulators with an excellent dc performance also tend to have a low ac flashover voltage: the typical dc strategy of reducing the cathode field and stabilizing the charge distribution does not work at ac voltages.

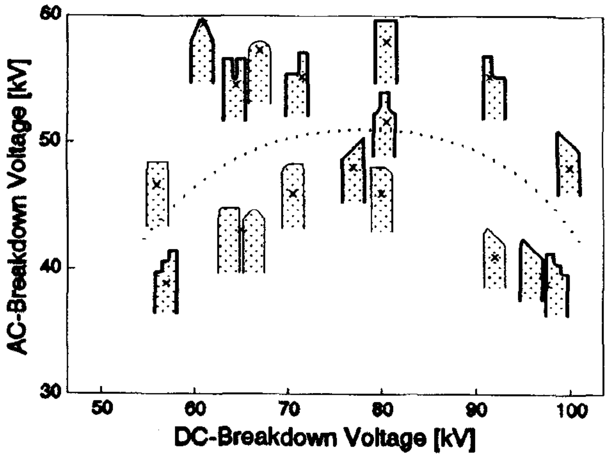

Figure 9. Conditioned ac flashover voltage (peak) *vs.* conditioned dc flashover voltage for different geometries. Left side is negative (in case of dc stress).

4.4. PD PATTERNS

ac PD measurement is a well developed diagnostic tool for quality monitoring of power engineering components. It also is a helpful diagnostic for research. Recently this technique was applied to the study of ac vacuum insulators. Some examples are shown as an illustration, for more details the reader is referred to [18]. The results of PD measurements may be represented in several ways. Figure 10 shows the measured PD rate *vs.* time for two different insulators at an ac voltage with an amplitude which is increased at regular intervals.

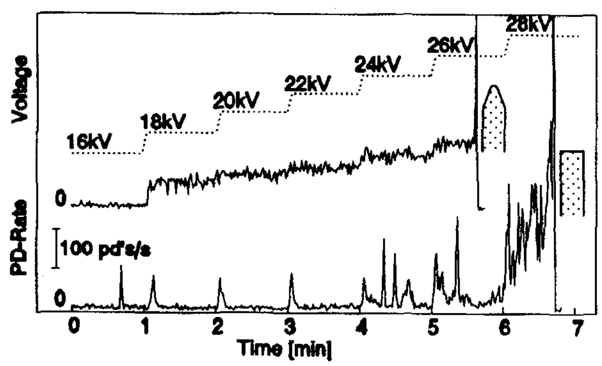

Figure 10. Evolution in time of the PD rate (1/s) for two different insulators, at an ac voltage which is increased by 2 kV(rms) every minute.

Figure 11 gives two alternative representations, a plot of the number of PD *vs.* discharge magnitude, and a polar plot of the PD rate. Two measurements, (a) and (b), are recorded for the same insulator at the same voltage, but in between the two recordings a flashover has occurred. This result shows that PD measurement may be helpful in studying discharge induced damage. This is further substantiated with the results in Figure 12, which gives the polar plots for a number of insulators shapes. In spite of the different shapes involved, all insulators show a similar PD behavior. Occasionally deviating polar plots, such as in Figure 11, were observed which are ascribed to insulator defects. Additional experiments with damaged insulators support this hypothesis. The observed PD patterns seem to be related to a continuous process of charge redistribution during the voltage cycles. Further work is needed in order to investigate the relation between PD patterns and insulator performance.

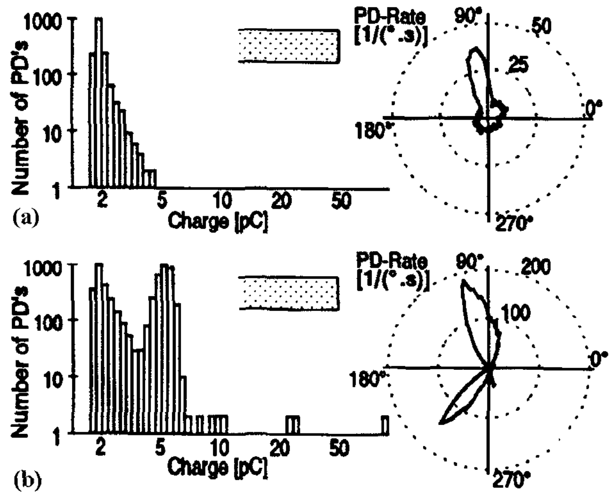

Figure 11. Different PD representations: number of counts versus magnitude (left) and polar plot (right) for a cylindrical insulator at 28 kV (rms). Dotted circles indicate the PD rate in 1/(s), which is plotted as a function of the phase angle. Between recordings (a) and (b) the voltage is increased until breakdown.

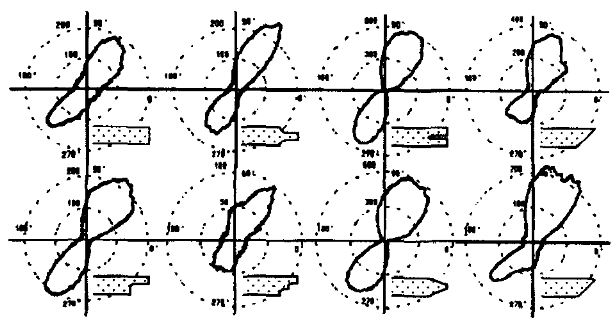

Figure 12. Standard pattern of discharge activity in the form of a polar plot.

5. CONCLUSIONS

In recent years considerable progress is made in the use of new, in particular optical, diagnostic techniques to the study of fundamental processes and surface properties relevant to surface flashover. The lack of predictive models indicates that a satisfactory theoretical description is not available yet. Next to further development of flashover theories, the application of scientific results to devices requires a systematic and scientific approach to design.

An approach is presented for obtaining science-based answers to practical problems related to vacuum devices. This approach makes use of appropriate diagnostics to study operational mechanisms in simplified insulating structures, with the aim to find design guidelines.

This approach is applied succesfully to insulators in dc vacuum devices. Key mechanisms are recognized from theoretical and experimental studies and their impact on device performance is studied. By relating performance to design, design rules are formulated.

Similar investigations are being carried out for ac vacuum devices. We have discussed the differences between dc and ac flashover mechanisms, and the impact on flashover behavior. PD measurement techniques seem to become a promising tool for ac device diagnostics.

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