

## HV design of vacuum components

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# HV Design of Vacuum Components

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## ABSTRACT

In this article we discuss a number of practical implications from recent studies on HVDC design concepts for vacuum components. These studies dealt with microwave tube technology. The conclusions, however, are valid for a wide range of components. The goal of this work is to provide a scientific basis for the design of HVDC vacuum components. From a study of breakdown and emission mechanisms, and from the measured insulating performance of many different geometries, we have derived guidelines for the design of for example insulators and cables. It is further shown how conditioning procedures and operating conditions (operating pressure, insulator charging) should be reflected in the design. We will discuss a number of practical implications regarding insulator design, conditioning, vacuum vs. air operation, HV cables in vacuum and potting.

## 1. INTRODUCTION

FOR many vacuum devices such as electron tubes, vacuum switches and particle accelerators the HV design is critical (see for example [1]). Apart from the inside of vacuum devices, vacuum insulation is important in spacecraft where equipment is being used in a space environment. In spacecraft an additional feature is the variation of the pressure under which the equipment is operated or tested: the satellite vacuum is deteriorated by outgassing, and atmospheric pressure is used during pre-launch tests.

We have previously reported on dc surface flashover mechanisms, and presented some implications of this work to the design and conditioning of HV insulators in vacuum [2-4]. The goal of the present work is to provide a scientific basis for the design of HVDC vacuum components. For this purpose we have studied breakdown and emission mechanisms, and determined the insulating performance of many different geometries. Above all we have attempted to derive and verify guidelines for the design of HV vacuum components. In this article we present the obtained insights and design rules. We will further discuss a number of practical implications regarding insulator design, conditioning, vacuum vs. air

operation, HV cables in vacuum and potting.

## 2. EXPERIMENTAL ARRANGEMENTS

We will give a brief outline of the experimental arrangements. A more detailed description is given elsewhere [3,5]. The experiments are carried out in a stainless steel vessel, pumped down to a pressure  $\sim 10^{-4}$  Pa. Insulator test samples are placed between two OFHC copper electrodes in a region of homogeneous field. The cathode is connected to a 120 kV negative HV supply (a Greinacher cascade circuit) through a vacuum feedthrough and a 100 M $\Omega$  damping resistor. The anode is directly grounded. The electrodes are regularly remachined.

The insulator test samples used in this study are machined out of circular disks of 40 mm diameter and 5 mm thickness, made of Wesgo AL300 alumina ( $\text{Al}_2\text{O}_3$ ), metallized bottom with MoMn and Ni, and gold plated. The outer surfaces are carefully machined under clean room conditions.

The diagnostics include dc emission current measurements (sensitivity 0.05 pA), dc partial discharge (PD) measurements (sensitivity 0.2 pC), and series of breakdown voltage measurements, with limited energy. Further samples can be inspected with an optical micro-

scope and a scanning electron microscope (SEM). A non-contacting technique is used to remove surface charge and thereby study its effect on the breakdown. This charge removal is performed by admitting nitrogen to a pressure beyond the Paschen minimum, with no voltage applied.

Prior to the measurements the electrodes are conditioned by slowly increasing the applied voltage at a constant gap distance of 5 mm, usually to 100 kV. After conditioning, the emission current amounts  $\sim 3 \mu\text{A}$ . With insulator samples mounted, a second conditioning process is performed. From earlier work [3,5] the 'step-conditioning' procedure was adopted as a most effective one. This procedure combines dc current conditioning (at voltages close to breakdown) and breakdown conditioning: "the voltage is ramped to breakdown; the voltage is then set at 90% of this first breakdown voltage for 5 min, and is increased by 5% every 5 min until a next breakdown occurs; the voltage is then set at 90% of this second breakdown value, and so on, until a preselected number of breakdowns has occurred (usually 6)".

### 3. VACUUM dc FLASHOVER MECHANISM

Key processes in the vacuum dc flashover mechanism are primary electron emission from cathode surfaces [2], surface charging of insulators [2], and high-energy electron impact [4]. These processes, and their impact on breakdown and conditioning, will be described below.

#### 3.1. PRIMARY ELECTRON EMISSION

It is well known from literature on insulators in vacuum that the breakdown voltage strongly depends on the insulator shape [2,6-8]. As an example, Figure 1 shows the breakdown voltage before conditioning for a number of different geometries. To some extent the geometry effect can be ascribed to the influence of the cathode triple junction field on the emission of primary electrons. As a check, Figure 2 shows the breakdown voltage for different geometries vs. the logarithm of the triple junction field as derived from electrostatic field calculations [2]. Because at the exact location of the triple junction the field may in theory be infinite, the field was calculated at a distance 0.1 mm away from the triple junction. We observe a clear trend indicating the vital importance of the cathode triple junction field. We also observe a significant scatter, which indicates that other mechanisms must be considered as well.

#### 3.2. SURFACE CHARGING

Next to primary electron emission, surface charging is a key mechanism in both the breakdown and in the conditioning process. This is clearly demonstrated by the

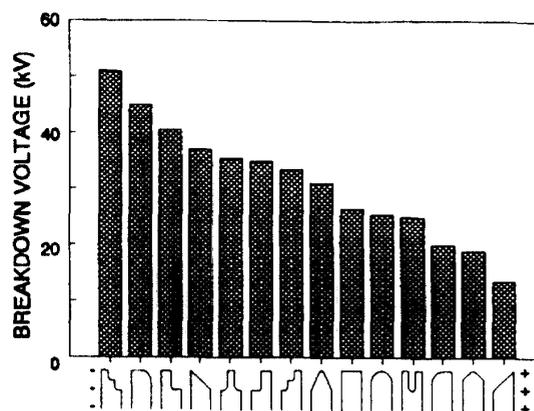


Figure 1.

Unconditioned breakdown voltage for a number of different geometries, in ranking order. Two samples of each geometry were tested. The bars represent the averaged value.

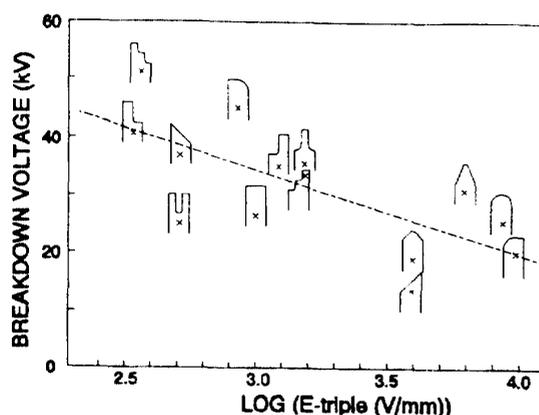


Figure 2.

Unconditioned breakdown voltage vs. the logarithm of the electric field amplitude close to the triple junction. The shapes involved are indicated (negative electrode on left hand side).

series of breakdown voltage measurements shown in Figure 3. When subjecting the insulator to a number of successive breakdowns, the breakdown voltage increases. When a breakdown voltage of 60 kV is reached, charge is removed from the insulator surface by admitting low pressure nitrogen with no voltage applied. With electrical and optical diagnostics it is observed that the surface indeed discharges. Subsequently the series of breakdowns is repeated. These experiments show that

1. the insulator surface collects charge due to the application of breakdowns;
2. the breakdown voltage gain of insulators obtained by conditioning with a number of breakdowns with lim-

ited energy, is partly due to surface charging, but not exclusively: the faster rise in breakdown voltage in the second series of breakdowns shows that also a more permanent type of conditioning has taken place, which is ascribed to the removal of emission sites;

3. the gain in breakdown voltage may be lost when the surface charge is lost.

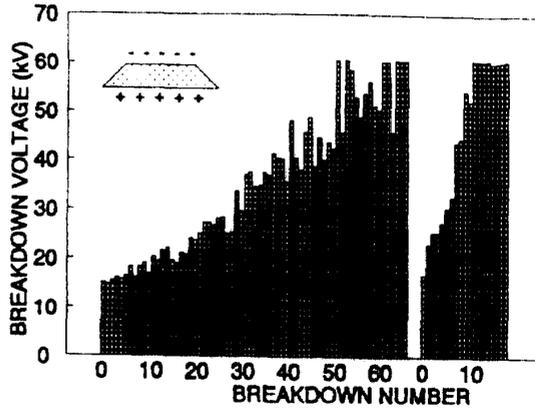


Figure 3.

Example of measured breakdown voltage evolution. After 67 breakdowns the surface charge is removed with a low pressure nitrogen discharge (no voltage applied).

### 3.3. HIGH ENERGY ELECTRON IMPACT

Electrons impinging on the insulator surface may contribute to surface charging or to desorption of gases, and have a detrimental effect on the breakdown voltage except when they are safely trapped [4]. A field distribution by which electrons are forced to move towards the surface, either by the chosen shape or by positive surface charge, causes a strong reduction of the breakdown voltage. This reduction is most significant if the electron trajectory is such that electrons hit the surface with high energy.

### 3.4. IMPLICATIONS FOR BREAKDOWN BEHAVIOR

The experiments such as shown in Figure 3 have been performed for a number of insulating geometries. The results are summarized in Table 1. The insulator performance can be characterized by what we call 'performance parameters' such as the initial and final breakdown voltage (or field), the conditioning speed and the stability of conditioning. The number of breakdowns required to reach a breakdown field of 10 kV/mm is used here as a measure for the conditioning speed, and the drop in breakdown voltage after removing the surface charge is a measure for the conditioning stability. In Table 1 the

insulators are divided in four groups based on their performance. The sample codes and groups are defined in Figure 4.

Table 1.

Results of breakdown evolution experiments. The sample codes refer to the shapes given in Figure 4.  $\langle E_{bd} \rangle$  is the breakdown field at 5 mm electrode distance, averaged over two samples. Indexes 'min' and 'max' refer to the unconditioned and conditioned values (average of 5 consecutive breakdowns).  $\langle E_{bd} \rangle_{dis}$  is the breakdown field when surface charge is removed after the sample is conditioned to 12 kV/mm.

Sample	$\langle E_{bd} \rangle_{min}$ kV/mm	$\langle E_{bd} \rangle_{dis}$ for 10 kV/mm	$N_{bd}$	$\langle E_{bd} \rangle_{max}$ kV/mm
a	10.2	11.3	0	19.5
b	9.0	12.0	1	16.0
c	8.1	10.7	8	18.3
d	7.4	12.0	5	20.0
e	7.1	9.3	36	16.1
f	7.0	11.8	24	14.3
g	6.7	11.3	45	11.4
h	6.2	7.0	40	12.2
i	5.3	12.0	78	16.1
j	5.1	9.3	61	13.4
k	5.0	9.0	188	12.9
l	4.0	5.4	25	14.1
m	3.8	5.2	109	13.0
n	2.7	3.5	71	15.4



Figure 4.

Insulator geometries used in the present work, with codes referred to in Table 1 (samples a to n) and Table 2 (groups I to IV). For all samples the left hand side is the cathode.

### 3.5. IMPLICATIONS FOR CONDITIONING

Different processes contribute to the conditioning of a HV vacuum component. The most important ones deal with the elimination of emission sites, which are considered the origin of each breakdown event [9-12]. Emission sites may be removed by conditioning, for example by breakdowns or by dc current conditioning at voltages close to breakdown. Emission sites can also be rendered harmless without being removed, in particular by charging processes. This process is here called 'silent' conditioning.

The observation that each geometry has its specific conditioning speed and stability implies that the optimum design of an insulator depends on the way it will be conditioned and operated. If breakdowns are applied in the conditioning process one should choose geometries with a high conditioning speed and stable performance (see also Table 1). If no breakdowns are applied in the conditioning procedure, a high unconditioned breakdown 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 breakdown voltage.

### 3.5.1. BREAKDOWN CONDITIONING

Breakdown conditioning with controlled energy is an efficient way of removing emission sites. The breakdown energy should be high enough to be effective but low enough to avoid damage. Values of  $\sim 10$  to  $30$  mJ were found to be safe and effective. The step-conditioning procedure described in Section 2 is an example of an effective conditioning routine. In fact, this procedure combines breakdown conditioning and dc current conditioning. Earlier, we have reported that such a combined procedure is most effective at voltages close to the breakdown voltage [3].

### 3.5.2. SILENT CONDITIONING

Silent conditioning may be achieved by incorporating charge traps that collect electrons released near the cathode triple junction. The result is an increased initial breakdown voltage. Charge traps should be designed carefully in order to avoid adverse effects. As an example, Figure 5 shows the influence of a cathode recess on the initial breakdown voltage. Two insulator designs, one of cylindrical and one of conical shape, are equipped with cathode recesses to trap charge. Two trap designs were tested, with collecting surfaces parallel to the cathode or making a small angle. The charge trap causes a significant improvement of the initial breakdown voltage for the conical insulator, but a slight reduction in performance for the cylindrical insulator. The latter is caused by the field modification introduced by the cathode recess. Figure 6 shows that for the cylindrical insulator with cathode recess the electrons are drawn towards the insulator surface, whereas they are repelled in case of the conical insulator.

## 4. DESIGN RULES

In Section 3.4 it was shown that the performance of an insulator can be characterized by what we have named the 'performance parameters': the initial or unconditioned breakdown voltage, the conditioned breakdown

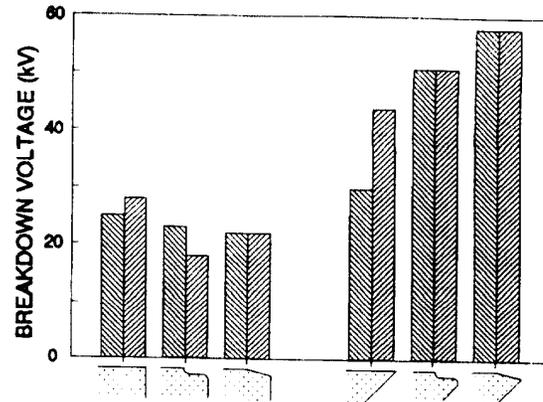


Figure 5.

Unconditioned breakdown voltages obtained for recessed insulators together with the reference shapes from which they are derived. Two samples of each geometry have been tested.

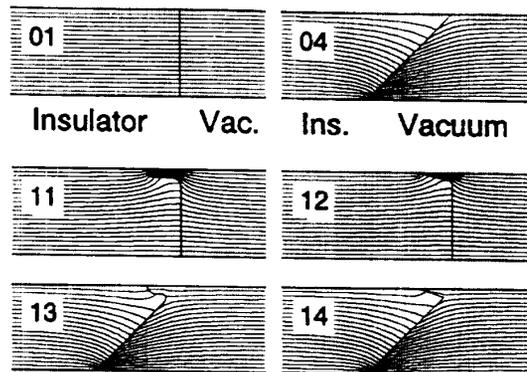


Figure 6.

Modification of electrostatic equipotential line plot caused by cathode recess (compare Figure 4). For the cylindrical insulator the cathode recess forces the electrons to move towards the insulator surface, whereas they are repelled in case of the conical insulator.

voltage, the conditioning speed, and the conditioning stability.

In this Section we will link these performance parameters to design parameters, and derive design rules. From the gained insight in the dc flashover mechanism we can formulate three key 'design parameters', each of them characterized by a question: Is the cathode triple junction field high or low? Can electrons interact with the insulator surface? Are the electrons trapped upon hitting the surface?

Table 2 combines both design and performance parameters for all groups of Figure 4. The performance parameters are now simplified to a relative scaling indicated by

symbols +, +/-, - or --. From Table 2 the following conclusions are drawn:

1. if the cathode triple junction field is low, and electrons do not interact with the insulator surface (group I), the insulator performance is excellent;
2. if electrons do interact with the insulator surface, but are trapped by the insulator geometry (group II), the insulator performs reasonably well, but is in all respects inferior to those of group I;
3. if electrons do interact with the insulator surface, and are not trapped by the insulator geometry (group III and IV), the insulator performance is bad in particular with respect to unconditioned breakdown voltage and conditioning speed.

From these observations and from our discussion on conditioning we can derive the following design rules:

#### 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 to the way it is conditioned or operated.

From field analysis [2] we have shown earlier that the cathode field is often efficiently reduced by enhancing the anode field (see for example Figure 2). For uncharged surfaces, field plots also give some information on whether and with what energy electrons will interact with the insulator surface, and whether they will be trapped or not. In the following we will discuss some implications for practical geometries.

## 5. SOME DESIGN CONSIDERATIONS

### 5.1. INSULATOR DESIGN

Figure 7 shows a number of different designs optimized with the design rules presented in the previous Section. Figure 7 A is an optimized insulator between parallel electrodes. The design is based on a conical insulator (low cathode triple junction field, no electron/insulator interaction). As discussed, a cathode recess causes an improved initial breakdown voltage, provided that the electron/insulator interaction is not enhanced (see also Figure 5). A cathode recess does not improve the conditioned breakdown voltage, but it tends to make conditioning unnecessary [4]. Furthermore, with a cathode recess, the design is less vulnerable with respect to small imperfections at the triple junction.

For most cylindrical insulators (Figure 7 B) the distance between electrodes is large, and the cathode field is not effectively reduced by enhancing the anode field. Because of the distance, however, the situation is not critical, and it is sufficient to shield triple junctions.

Example C in Figure 7, shows a recommended design for insulating concentric conductors. The arguments for the optimization are similar to those for the insulator between parallel electrodes (example A). The rod type spacers often used for easy alignment can only be applied safely at low voltages: breakdown voltage and conditioning speed are low, and the conditioning stability is poor.

Two examples of optimized vacuum tube feedthroughs for space applications are shown in Figure 7 D. The feedthroughs have one side in the tube vacuum, and the other side in vacuum (satellite) or in air (terrestrial). Inside the tube the cathode field is kept low by choosing a large conductor radius and conductor/insulator separation (right), or by shaping the insulator and shielding the triple junction (left). The inside of the insulator tube may be metalized but for dc the same effect is achieved by charging processes. A cathode recess could be used as in (A). Inside the tube the anode field is not harmful. Outside, different pressures may occur, and the field is controlled at both cathode and anode side.

### 5.2. VACUUM AND AIR OPERATION

Spacecraft components designed to operate in vacuum are sometimes exposed to air (prelaunch tests) or to deteriorated vacuum (outgassing). Equipment designed for terrestrial use, such as HV cables, may be incorporated in space hardware. Further, design rules for air operation (creepage distance) are sometimes applied to vacuum insulation and vice versa, although the breakdown mechanisms in vacuum and air are very different.

In air, charge carriers are produced in an avalanche of a certain macroscopic distance [13]. The avalanche is initiated by a first electron that originates from the insulating gas. Microscopic field enhancements are not very important, provided their scale length is short compared to the avalanche length. Long creepage distances are used to reduce the electric field parallel to (contaminated) insulators. The breakdown voltage obeys Paschen's law if the product of pressure and distance is above 0.01 Pa.m. The Paschen curve shows a minimum at  $\sim 1$  Pa.m. In atmospheric air we can formulate a critical field strength above which partial discharges occur (30 kV/cm). Depending on the field distribution this discharge may develop into a streamer, and initiate breakdown.

In vacuum, breakdown is initiated by electron emission from microscopic protrusions or imperfections at the

Table 2.

Comparison of performance and design parameters for the groups of insulators in Figure 4.  $E_{ctj}$  is the cathode triple junction field,  $V_{ini}^{bd}$  and  $V_{con}^{bd}$  stand for the initial and conditioned breakdown voltage. The terms 'impact' and 'traps' refer to emitted electrons, 'speed' and 'stability' to the conditioning process (see text).

Group	Design parameters			Conditioning Performance			
	$E_{ctj}$	Impact	Traps	$V_{ini}^{bd}$	$V_{con}^{bd}$	Speed	Stability
I	low	no	-	+	+	+	+
II	med high	yes	yes	+/-	+/-	+/-	+/-
III	low high	yes	no	-	+/-	-	+/-
IV	high	yes	no	--	+/-	-	-

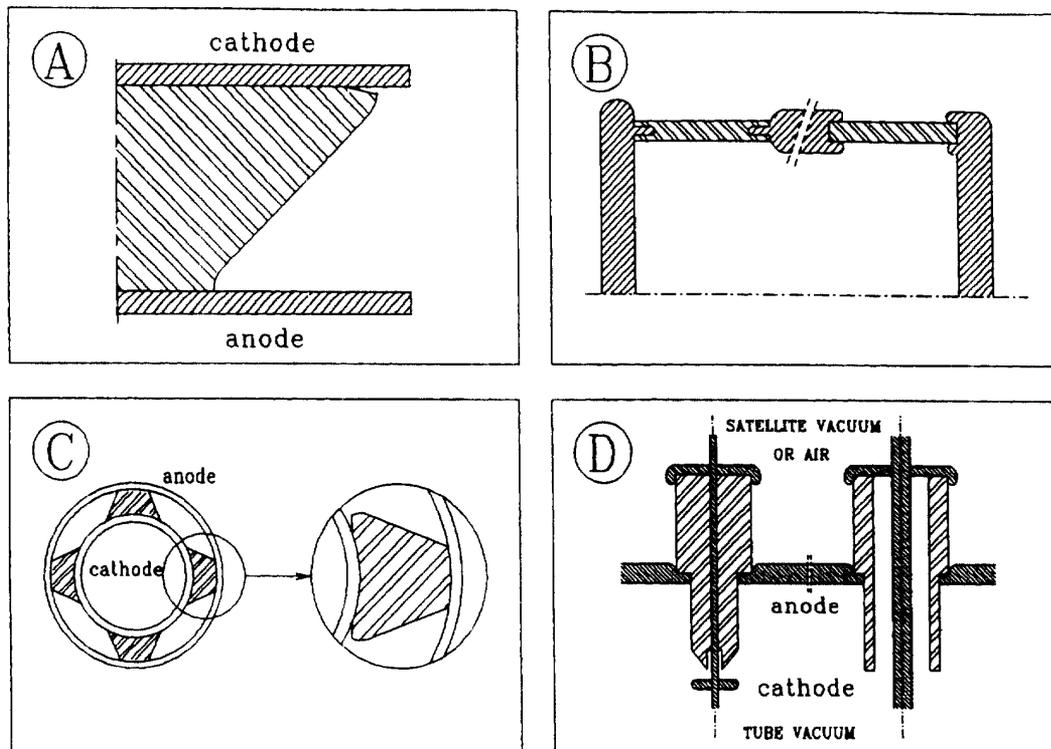


Figure 7. Examples of optimized insulator designs.

negative electrode, across the barrier of the work function [9]. This emission starts at microscopic protrusions or imperfections, either metallic, semiconducting or insulating [10-12]. Secondary emission is caused by energetic electrons impinging on the insulator surface. The field components perpendicular and parallel to the insulator surface both contribute to the collision energy. Secondary electrons are harmful if they hit the surface again with increased energy [14]. The creepage distance argument is not a valid design principle in vacuum.

The differences between vacuum and air breakdown are summarized in Table 3. Figure 8 shows the breakdown voltage vs. electrode distance for vacuum [9], and

the breakdown voltage vs. the product of electrode distance and pressure (the Paschen curve) for air [13]. Also, for a fixed electrode distance, the breakdown voltage is shown as a function of pressure. Figure 8 shows that equipment that operates safely in vacuum may fail in air (and vice versa). Tests in air are not representative for operation in vacuum (and vice versa), and may damage the equipment. Further, evaluation of the performance of vacuum equipment requires knowledge of the actual pressure. The most critical situation is a pressure cycle through the Paschen minimum with the voltage applied.

Table 3.  
Differences between vacuum and air breakdown.

	Air	Vacuum
1st electron	from the gas	from cathode
el. movement	as a 'hot gas'	as a beam
BD medium	gas	gas from surface
electrode role	less important	decisive
creepage path	important	unimportant
BD mech.	Townsend or or streamer	prim. emission + sec. processes

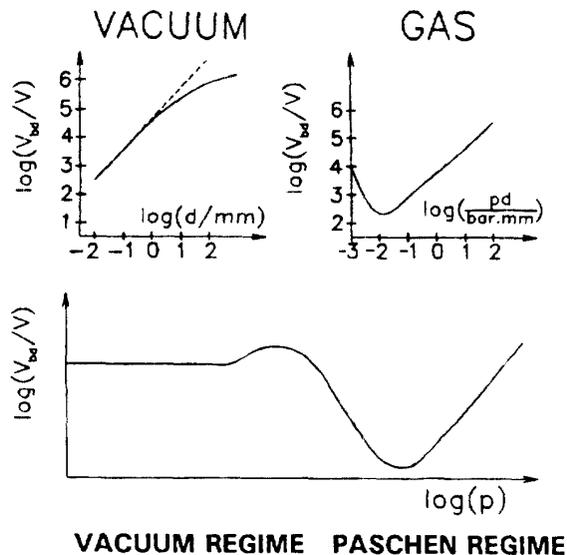


Figure 8.

Breakdown voltage vs. electrode distance for vacuum (top, left); Breakdown voltage vs. the product of electrode distance and pressure (the Paschen curve) for air (top, right); Breakdown voltage as a function of pressure for a fixed geometry (bottom).

### 5.3. HV CABLES IN VACUUM

Multi-wire HV cables, such as used in spacecraft, usually contain a number of wires made of tapewound and sintered dielectrics. The electric field in between insulated wires may be considerable. From a vacuum point of view a HV cable is a poorly vented component. This usually results in a parabolic pressure profile along the cable length. The maximum inside pressure depends on outgassing properties, flow resistance and cable length, and may reach values near the Paschen minimum at a cable length of a few meters [15]. The combination of high fields and uncontrolled pressure may result in partial discharge activity, and finally in cable damage. Partial discharge activity has indeed been observed in multi-wire HV cables, especially in air and after switching on or off

the power supplies [15]. The partial discharge activity may be eliminated by surrounding each insulated wire with a (semi-)conductive layer, and by using extruded, rather than tapewound and sintered, dielectrics. Such techniques are since long common practice in HV cables for power distribution.

### 5.4. POTTED DESIGNS

Potting is used often in vacuum applications for mechanical support or to improve the HV behavior. Properly applied pottings give reasonable results. This requires that the surfaces are clean before potting, and that the potting is applied under vacuum and is allowed to out-gas. Improper potting causes partial discharge activity in voids at the interfaces or in the bulk material. Potting of flexible components (cables) may cause voids and partial discharge activity. Potting may further prevent the out-gassing of the potted component which makes the inside pressure uncontrolled. In many cases a HV component can be designed such that it does not require potting for its HV withstand capability.

## 6. CONCLUSIONS

**K**ey processes in the vacuum dc flashover mechanism are primary electron emission from cathode surfaces, surface charging of insulators, and high energy electron impact. We have described how these processes effect the performance of insulators, and how insulator performance is linked to insulator design. Four so-called 'performance parameters' are defined: the initial or unconditioned breakdown voltage, the conditioned breakdown voltage, the conditioning speed, and the conditioning stability.

Further three 'design parameters' are introduced, which are related to the cathode triple junction field, electron/insulator interaction, and to charge traps for electrons hitting the surface.

From our evaluation we have derived the following 'design rules': minimize the cathode triple junction field, keep electrons away from the insulator surface, if electrons hit the insulator surface, make sure they are trapped, and tailor the design of an insulator to the way it is conditioned or operated.

We have discussed a number of implications for practical geometries, in particular with respect to insulator design, conditioning, vacuum versus air operation, HV cables and potting.

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