Partial discharge and corona theory and measurement

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THEORY AND MEASUREMENT

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PARTIAL DISCHARGE AND CORONA THEORY AND MEASUREMENT

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ABSTRACT

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A clear understanding of the processes of partial discharge and corona is an important tool in the design of high-voltage insulation systems. With a knowledge of the conditions under which different types of discharge activity are likely to occur, a designer can take measures to ensure against premature system failures due to partial discharge or corona activity. Also important to the design process is an understanding of the role and limitations of testing in diagnosing the condition of a development or production component. It is especially important that testing be conducted in a manner that provides legitimate indication of the condition of the component without causing damage that could affect future performance or life.
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CHAPTER I
INTRODUCTION

Partial discharge is an electrical breakdown that does not completely bridge a dielectric gap between two electrodes. The cause of partial discharge is the over-stressing of a region of dielectric due to an electric field gradient that exceeds the dielectric strength in that region. Common reasons for the local over-stressing of a dielectric include the existence of voids or impurities that have a lower dielectric constant or dielectric strength than the primary dielectric and electrodes with edges or corners that act as "stress risers" to the electric field.

Partial discharge is often confused with another discharge term, corona. In fact, the terms are sometimes used interchangeably, though they seek to describe two different types of discharge phenomena. Like partial discharge, corona is an electrical discharge that does not fully bridge a dielectric, but corona describes only a very specific type of discharge—the ionization of gas surrounding a surface of high electric potential. While it may be argued that corona is actually a type of partial discharge [1], corona and partial discharge by definition occur in different regions of an insulation system and are affected differently by environmental conditions such as pressure and humidity. In this study, the term partial discharge will be used to describe the electrical breakdown of a gaseous void within a solid dielectric or on a conductor-solid dielectric boundary. The term corona will be used to describe ionization that occurs in a gas volume surrounding a conductor or dielectric surface.

At the system level, partial discharge and corona are manifested as current transients--instantaneous movements of charge within the system to restore equilibrium--that result
from each discrete discharge event. In this sense, partial discharge and corona represent a source of electrical noise in the system. More severely, the ionization and avalanche breakdowns that make up corona and partial discharge produce a wide variety of electromagnetic radiation, ranging from audible and radio-frequency noise to local heating and visible light. This radiation, along with high-speed electrons produced in the process, can result in actual physical damage to the dielectric. When breakdown occurs within a gaseous void, for example, the discharge can alter the chemical composition of the gas in the void, as well as the material make-up of the walls of the void, sometimes leaving the void more prone to discharge than it was originally. As further discharges occur, causing additional damage, channels can form in the dielectric that eventually lead to a catastrophic arc failure mechanism known as "treeing."

Since all solid insulation has internal voids and impurities, how can partial discharge be prevented? In a practical high-voltage system, it usually cannot. However, partial discharge activity can be limited to a level low enough that it will not be the limiting factor on the life of the insulation, or, at worst, can be kept to a level low enough to ensure acceptable insulation life. The primary methods for limiting partial discharge activity are proper selection and processing of insulation materials, and proper selection of design parameters such as insulation thickness and electrode shape and size. While quality materials and careful processing can minimize the number and size of voids in the insulation, good design techniques can minimize the field stresses imposed on any voids that do exist. Other methods have been developed to discourage discharge activity in systems where the above practices are inadequate or are impractical to implement.

Throughout the design and production process, a high-voltage insulation system must be tested to verify that it will behave properly under actual operating conditions. Testing is especially important for components that are performance-critical, expensive, or difficult to replace, which is often the case in military or commercial aircraft applications, medical equipment, spacecraft, and high-power equipment. While testing must be
performed to ensure that a component will not fail prematurely, it must be conducted in a manner that does not damage or detract from the operational life of the component.

There are several classical methods of testing for partial discharge and corona activity, including acoustic noise detection, radio-frequency noise detection, electrical transient detection, and optical detection. Today, research, qualification, and acceptance tests are usually performed on very large, expensive test stands that utilize state-of-the-art electrical transient detection equipment. These systems often include the capability to test at reduced atmospheric pressures for simulating aircraft and spacecraft operating environments. However, despite the expense, complexity, and capability of this equipment, there is a lack of authoritative and theoretically-grounded test criteria to accurately reflect the condition of a test article. Proper theoretical and experiential determination of parameters such as test voltage, duration, and statistical limitations, as well as the use of historical comparison, are necessary for continued improvement in the accuracy of electrical testing. In cases where system-specific factors (e.g. geometry, electrical characteristics, unique application) make this impractical, other discharge-detection methods must be relied upon for providing information about the condition of a component.
CHAPTER II
IONIZATION AND BREAKDOWN THEORY

The transition of a gas from an almost perfect insulator to an almost perfect conductor, called electrical breakdown, is a phenomenon that can occur with extreme rapidity [2]. Indeed, the fastest high-power switches are gas gaps, some of which are able to provide a current path with delay times of only picoseconds. An additional remarkable property of gases is that they can usually recover to their previous near-perfect insulating state.

Despite the drama of these events, from the point of view of an insulation system, total electrical breakdown represents only the final, catastrophic event that marks the end of life for an afflicted component. One purpose of this study is to illustrate how smaller, partial, breakdown phenomena can work to greatly affect the life and usefulness of an insulation system. To accomplish this, it is necessary to first examine the fundamental theories of ionization and excitation of atoms and molecules in a gas, and then to examine under what conditions the phenomena are likely to occur in an insulation system.

Excitation and Ionization in a Gas

By definition, an electron is the fundamental particle of unit negative charge, while an ion is an atom or molecule that possesses a specific positive or negative charge due to the loss or gain of one or more electrons. An electron that is not constrained by the orbits of an atom, and has been set into motion by external forces, may be referred to as a "freed" electron. Although a freed electron is sometimes described as "the simplest form of
negative ion," strictly speaking, it is not an ion because it does not have the ability to bond with other electrons.

Normally, in an insulating gas, electrons are strongly bound to an atom by their coulomb attraction to the nucleus. The electrons are in constant motion--each has a specific energy state defined by its position, velocity, and rotation, with respect to the nucleus. However, when an atom "collides" with an energized particle (excited atom or molecule, freed electron, photon, etc.), one or more of its electrons may gain additional energy, elevating it to a higher-energy state with respect to the nucleus; the atom is "excited." If left alone, an excited electron will typically (on the order of 10-100 nanoseconds [3, 4]) revert to a more stable state, releasing surplus energy as electromagnetic radiation in the process. However, if an electron acquires enough surplus energy, it may be dislodged from the atom and become a "freed" electron; the atom is "ionized."

The liberation of electrons from atoms is a normal occurrence in dense gases, due to the incidence of high-energy particles associated with cosmic rays and ground-based radioactive decay (see Figure 1).
Once liberated, electrons participate in a vast number of collisions with other constituents in a gas, and generally become attached in a short period of time to neutral atoms or molecules to form negative ions, or with positive ions, sometimes thereby neutralizing them. However, when a gas is subjected to a strong electric field, freed electrons can be accelerated by the field and thus acquire additional energy. If a freed electron gains sufficient energy, one of its many collisions may have the effect of raising an electron of the impacted atom or molecule to an excited state. If the energy imparted by the collision (or added by immediately subsequent collisions) is sufficient, an excited electron may be set free from the impacted atom or molecule, creating a new freed electron/positive ion pair. Figure 2 illustrates this process.

![Diagram of ionization process](image)

Figure 2. Ionization caused by electrons accelerated by an electric field

Through this process, it is possible for a chain reaction to develop in which many neutral atoms and molecules of an insulating gas are broken into freed electrons and ions that each in turn move along the field gradient and represent a conducted current in the gas. Under certain circumstances, such an ionization current can build into an "avalanche" flow of charge—an electrical breakdown.
Static, Uniform-field Breakdown Theory

The classical treatment of electrical breakdown of a gas in a static, uniform field is that of Townsend, who described the total charge flow in a gas-filled gap between two metal electrodes as a function of spacing, given different values of electric field strength versus electron density in the gap. Although the electric fields in real systems where discharges occur are typically not uniform, an examination of the uniform-field breakdown process is a good starting point for further understanding of real-world breakdown phenomenon. It is also worthwhile to point out some background and limitations of the breakdown theories discussed in this section.

First, it must be remembered that breakdown theories are models that are developed to explain experimental observations. The accuracy of such models is inextricably linked with the accuracy of the sets of measurements they are developed to describe. For example, Townsend's experiments were conducted mainly with air, O₂, and H₂ at pressures of less than 150 mm Hg [5]. Therefore, Townsend's first theory was not able to explain the behavior of gases with certain other physical characteristics, or the behavior of gases at extended (higher or lower) pressures. Although more encompassing generalizations of Townsend's theory have been successfully developed, they are bounded by the accuracy and range of the data sets from which they were induced, as well as by the contemporary understanding of the physical processes in question.

Townsend's theory of exponential breakdown, and later generalizations of it, are based on the assumption that the number of electron and ion collisions in the gas is sufficient that a "steady-state electron and ion swarm" condition exists [6]. This swarm requirement can be explained by examining the exponential breakdown model from a mathematical point of view [7]. While electrons and ions represent discrete quantities of charge, the exponential breakdown model seeks to describe their accumulated motion with respect to time as a continuous function (this makes simple differentiation and
integration possible). In order to justify such a representation, the number of electrons and ions involved in ionization must be large enough to satisfy the statistical "Law of Large Numbers" [7]. If this condition is not met, the continuous function representation is mathematically invalid. Thus, the exponential breakdown theory is inherently unable to describe the total charge flow at pre-avalanche ionization levels or at very low gas densities, when the number of participating electrons is small.

Experience has shown that the exponential breakdown theory also runs into difficulty as pressure is increased above a region ranging from one to several atmospheres [6], depending on the specific gas in question. It seems that for pressures above one atmosphere, effects due to the composition and surface characteristics of the electrodes become increasingly significant. These effects also seem to contribute to behavior at very low gas pressures. Generalized theories that incorporate electrode effects have not yet been successfully developed [6].

Finally, it must be noted that the processes described in Townsend's theory are statistical in nature: the emergence of a freed electron in a gas to initiate ionization is a statistical event (this will be discussed in Chapter 3), and the numbers of collisions that occur in the gas during the breakdown are represented by statistical variables [6, 7, 8].

**Townsend Exponential Breakdown**

Townsend performed a series of experiments to produce plots of current flow ($I$) vs. electrode spacing ($d$), for specific values of electric field stress ($E$) vs. gas concentration ($n$). The shape of these plots can be modeled by the equation [6]:

$$I = \frac{I_0 e^{\alpha d}}{1 - \frac{\beta}{\alpha} (e^{\alpha d} - 1)}$$

(1)
where \( I \) is the breakdown current, \( I_0 \) is some initial liberated current, \( \alpha \) is a primary coefficient that accounts for ionization of atoms or molecules due to electron collisions, and \( \beta/\alpha \) is a secondary coefficient that accounts for the ionization due to positive ion collisions. Note that there is a certain distance \( d = d_s \) at which the denominator equals zero. At this point, the current \( I \) mathematically goes to infinity.

By measuring the small leakage current \( I \) present at values of \( d > d_s \), the coefficients \( \alpha \) and \( \beta/\alpha \) may be determined from equation (1). Then, \( d_s \) may be obtained from:

\[
1 - \frac{\beta}{\alpha} (e^{\beta d_s} - 1) = 0.
\]  

(2)

The solution for the breakdown voltage \( V_s = d_s \cdot E \) when the denominator of equation (1) is set to zero is often referred to as the Townsend breakdown criterion.

Generalized Townsend Theory

Though equation (1) accounts for the breakdown behaviors observed by Townsend, it is not adequate for explaining the observed phenomena over an extended range of gas densities, and cannot account for the behavior of strongly electronegative gases, which are often used as insulators in high-voltage equipment. A generalized equation describing the relationship \( I \) as a function of \( d \) must account for all secondary contributors to ionization in a gas. These include [6]:

a) ionization due to collision with positive ions, photons, and excited atoms,

b) ejection of electrons from the cathode due to bombardment by positive ions, excited atoms, and photons,

c) formation of negative ions in electronegative gases by electron attachment,

d) detachment of electrons from negative ions, and

e) conversions of mobile negative ions into larger, less-mobile ions.
An equation incorporating all these effects can be written [6]:

\[
I_0 \frac{\alpha (\lambda_1 + c + \Delta) e^{\lambda_1 d} - \alpha (\lambda_2 + c + \Delta) e^{\lambda_2 d} + (\eta + \eta')c + \eta \Delta}{\lambda_1 (\lambda_1 - \lambda_2)} \left[ 1 - \frac{\omega}{\lambda_2 (\lambda_1 - \lambda_2)} \left( \frac{\lambda_1 + c + \Delta}{\lambda_1} (e^{\lambda_1 d} - 1) - \frac{\lambda_2 + c + \Delta}{\lambda_2} (e^{\lambda_2 d} - 1) \right) \right]
\]

where:  
\( \alpha \) is the coefficient of primary ionization,  
\( \omega \) is a coefficient representing non-electronegative secondary effects,  
\( \eta \) and \( \eta' \) are coefficients for the formation of \( A^- \) and \( B^- \) ions,  
\( \Delta \) is the coefficient for detachment of electrons from \( A^- \),  
\( c \) is the coefficient for conversion from \( A^- \) to \( B^- \),  

and \( \lambda_1 \) and \( \lambda_2 \) are the roots of the equation:

\[
\lambda^2 - (\alpha - \eta - \eta' - c - \Delta)\lambda - (\alpha - \eta - \eta')(c + \Delta) - \eta'\Delta = 0.
\]

A more prevalent representation of the generalized Townsend theory (electronegative effects omitted) is identical in form to equation (1):

\[
I = \frac{I_0 e^{\alpha d}}{1 - \frac{\omega}{\alpha} (e^{\alpha d} - 1)}
\]

where Townsend's positive ion coefficient \( \beta/\alpha \) has been replaced with the generalized coefficient \( \omega/\alpha \), which embodies all non-electronegative secondary ionization effects.

Specifically, \( \omega/\alpha \) is a first-order approximation of the effects listed in items (a) and (b) above [2]:

\[
\omega = \beta + \delta + \epsilon + \alpha \gamma + \tau + \xi
\]
where, per ionizing collision within the gas:

\[ \beta/\alpha \] is the rate of ion production due to collision of positive ions with neutral atoms or molecules,

\[ \xi/\alpha \] is the rate of ion production due to ionization of already excited atoms or molecules,

\[ \tau/\alpha \] is the rate of ion production due to photo-ionization of neutral atoms or molecules,

\[ \gamma \] is the rate of electron liberation from the cathode due to incidence of positive ions,

\[ \delta/\alpha \] is the rate of electron liberation from the cathode due to incidence of photons,

\[ \epsilon/\alpha \] is the rate of electron liberation from the cathode due to incidence of excited atoms or molecules.

Depending on the gas pressure, electrode characteristics, and a variety of other influences, any one of the secondary processes may dominate the others and thus effectively define \( \omega \).

The Paschen Law

In spite of the theoretical significance of the generalized Townsend theory, it is not an exceedingly practical tool for engineers to use in predicting the breakdown behaviors of a wide variety of gases. The primary difficulty is that extremely specialized, controlled experiments are required to determine the sets of pre-breakdown coefficients necessary to describe the behavior of each gas. As a result of the scarcity of these data, system designers and researchers typically rely on another description of breakdown potential, the Paschen curve.

The Paschen Law describes the minimum potential at which breakdown of a uniform field gas gap can occur (\( V_s \)) as a function of the product of the gas pressure in the gap (\( p \)) and the distance separating the electrodes (\( d \)). While a dependence between breakdown
voltage and the product $pd$ was first documented by de la Rue and Muller, Paschen proposed, after extensive work with air, CO$_2$, and H$_2$, that $V_s$ is a function of the product $pd$ only [2].

The Paschen Law follows analytically from the generalized Townsend theory, because the parameters $\alpha/p$ and $\omega/\alpha$ can be written as functions of $E/p$. Substituting:

$$\frac{\alpha}{p} = \phi(E/p) \quad (7)$$

and

$$\frac{\omega}{\alpha} = \chi(E/p) \quad (8)$$

into equation (2) (the breakdown criterion), produces [6]:

$$1 - \chi(E/p)(e^{\chi(E/p)pd} - 1) = 0. \quad (9)$$

Since $E/p = V_s/pd$, it follows that:

$$V_s = f(pd), \quad \left\{ \begin{array}{l} \text{for a representation not dependent on temperature} \\ V_s = f'(nd) \\ \text{where } n \text{ is the gas concentration [3]} \end{array} \right. \quad (10)$$

A Paschen curve for a gas can be generated by measuring the onset breakdown voltage at different values of $pd$. The onset breakdown voltage is defined as the minimum potential at which the gas can experience electrical breakdown for a given value of $pd$ (at a given temperature), and is measured while irradiating the cathode to produce an ion swarm condition in the gas, ensuring that an avalanche breakdown will occur as soon as the electric field reaches the critical strength [7].
Paschen curves are available for virtually all commonly-used insulating gases and are used as a prime engineering reference for examining whether a particular gas possesses the dielectric strength (ability to withstand potential gradient) required for a given set of operating conditions. Although Paschen curves can be reliable indicators of gas behavior, it should be remembered that the accuracy of each curve is a direct reflection of the limitations of the experiment that produced it. For example, curves for electronegative gases may not reflect true operating characteristics unless the data was produced under very close to uniform-field conditions (field non-uniformities due to electrode surface effects can greatly affect the behavior of an electronegative gas) [7]. Also, like the Townsend theories, the accuracy of Paschen curves is limited at extremely low gas pressures (where statistical effects become macroscopic components of the discharge) and at higher pressures (where electrode effects become increasingly significant).

Finally, since Paschen curve data (breakdown voltage vs. $pd$) reflect behavior only for a specific gas temperature, a correction must be applied in cases where the desired operating temperature is significantly different from the temperature at which measurement of the curve was accomplished.
CHAPTER III
PARTIAL DISCHARGE THEORY

**Regional Dielectric Overstress**

*Regional dielectric overvoltage* refers to the condition where an area of dielectric is subjected to an electric field stress (typically described in Volts per meter thickness) that is greater than the dielectric strength in that region. For a study of partial discharge, the region of interest is a gas-filled void located either within a solid dielectric, or on a solid dielectric-conductor boundary. Due to its lower dielectric strength, the gas in the void can be significantly overstressed while the solid dielectric is stressed only well within its design limits.

The electric field stress on the gas within a void is determined by the geometry of the void, the physical properties of the gas, and the electric field gradient in the solid dielectric surrounding the void. Geometric factors include the size and shape of the void, as well as orientation relative to the external electric field gradient. These factors, together with the relative permittivity of the gas in the void and the material around the void, define the boundary conditions that determine how the external electric field acts on the gas within the void. The electric field in the solid dielectric medium itself can be influenced by many factors, including the presence of a stress riser on a nearby high-potential electrode or the placement of a low-potential electrode in close proximity to one of high potential. The shape and size of a stress riser determines the increase in field stress applied to the dielectric material in its region, while the geometry of the space
between a high-potential and low-potential electrode, along with the shape of the electrodes, determines the level of field stress on the dielectric material in that region.

Determining the Electrical Stress in a Void within a Solid Dielectric Medium

The electric field gradient ($\nabla V_o$) for a void-free system in which all charge is confined to the electrodes is given by Laplace's equation:

$$\nabla \cdot \nabla V_o = 0.$$  \hspace{1cm} (11)

For a simple coaxial conductor in which a center conductor of potential ($U$) is separated from a grounded outer conductor by a uniform solid dielectric, the boundary conditions are given by $V_o = U$ at the outer radius ($r_1$) of the center conductor and $V_o = 0$ at the inner radius ($r_2$) of the outer conductor. The solution for $\nabla V_o$ is:

$$\nabla V_o = \frac{-\hat{r}}{r \ln(r_2/r_1)}$$ \hspace{1cm} (12)

where $r$ is the radial position for which $\nabla V_o$ is evaluated, and $\hat{r}$ is a unit vector directed normally from the inner conductor.

When a discharge-free void is introduced into the solid dielectric between the electrodes, the equation for the field gradient ($\nabla V$) in the region of the void becomes:

$$\nabla \cdot (\varepsilon \nabla V) = 0$$ \hspace{1cm} (13)

where $\varepsilon$ is the permittivity of the material in which $\nabla V$ is being described.

In addition to the boundary conditions applied in the void-free discussion, the following condition must be met at each dielectric interface:
\[ \varepsilon_+ \left( \frac{\delta V}{\delta n} \right)_+ = \varepsilon_- \left( \frac{\delta V}{\delta n} \right)_- \]  

(14)

where + and - refer to the conditions on each side of the boundary, and \( V \) is differentiated normal to the boundary.

Due to the complexity of these boundary conditions, a solution for equation (13) cannot normally be provided through direct evaluation. As a result, alternative methods have been developed to provide approximate solutions, including implementation of various simplifying assumptions and the use of numerical analysis techniques [9]. A prevalent example of the former is to assume that the void is so small that the field in the dielectric in the region of the void may be considered uniform.

Crichton, Karlsson, and Pedersen offer a simplification in which the void-present field gradient \( \nabla V \) is approximated by the void-free field gradient \( \nabla V_o \) multiplied by a scaling factor \( (h) \) [10]:

\[ \nabla V = h \nabla V_o \]  

(15)

where \( h \) accounts for both the difference in permittivity between the solid and gaseous dielectric media as well as for the shape and orientation of the void, and is bounded by \( 1 \leq h \leq \varepsilon_r \):

\[ h = \frac{K\varepsilon_r}{1 + (K-1)\varepsilon_r} \]  

(16)

where \( \varepsilon_r \) is the relative permittivity and \( K \) is a factor that depends on the geometry of the void alone. For example, \( K \) for a generalized smooth-walled (ellipsoidal) void is given by [10]:

\[ K = \frac{2}{abc} \int_0^\infty \frac{ds}{(a^2 + s)^{3/2} (b^2 + s)^{1/2} (c^2 + s)^{1/2}} \]  

(17)
where $a$, $b$, and $c$ are the semi-axes of the ellipsoid and $s$ is a dummy variable. Axis $a$ is assumed parallel to the field gradient $\nabla V_o$.

Void Topography in Real Insulation

In the case of real insulation, the topography of voids is not quite so simple as in the preceding example. For one, the locations of voids within a real system are unknown and somewhat unpredictable. For example, it is likely that in a large system an area of dielectric may contain several voids in close proximity to one another. In such a region, the electric field in the dielectric may be considerably perturbed by the presence of the several voids. Further, if one of the voids undergoes breakdown (causing a reduction of field stress at its location), an adjacent void may experience a sudden increase in field stress, leading to its breakdown.

Also, the void size and shape is not always predictable. A single irregularly-shaped void located at a strategic point in the system, such as at a stress riser on an electrode-dielectric boundary, may suffer from repeated and violent discharge activity, and thus severely limit the life of the whole system.

Due to the complexity and variation inherent in the problem of voids within solid insulation, theoretical models that seek to describe breakdown probabilities in terms of assumed void distributions may be of limited assistance in predicting real system behavior or life. Part of this problem is exemplified in the difficulty of analyzing the behavior of even basic local formations, such as a cluster of voids or a void located near a stress riser, which require complex numerical analysis, statistical techniques, and an involved computer program to simulate. However, with a knowledge of the topography of voids likely to be found in a specific type of insulation, a system designer can use insight gained from the theoretical analysis of common void topographies to design the insulation system so that only a reasonable stress level will be applied to a void, wherever it may be positioned.
Therefore, a thorough knowledge of the sizes, shapes, positions, and gas composition that voids are likely to take is crucial when selecting an insulation material for use in a high-voltage application. For example, molded epoxy may develop regularly-spaced, smooth-walled voids when it is insufficiently de-gassed during curing, whereas shrinkage of the compound under some conditions can result in closely-spaced, irregularly-shaped cavities [11]. Disk or cigar-shaped cavities may be developed in polymers during the extrusion process. Some insulating materials may be susceptible to tearing, cracking, or de-lamination when exposed to operational fatigue or severe environmental conditions [12]. It must also be noted that faulty processing of even the highest-quality materials can result in very unfavorable void characteristics, and is often a prime cause of premature insulation failure [13, 14]. Information regarding the void characteristics, proper processing, and failure modes of high-quality insulation materials is typically available from the product manufacturer, published materials research, or from an experienced materials specialist.

Effects of External Environment on Void Gas Composition

According to the Paschen Law, the dielectric strength of an insulating gas is a function of both gas type and density. As a result, the breakdown potential for a void may be affected by changing external conditions, depending on the degree to which the void is "linked" with the external environment. Smooth-walled voids that are wholly contained within solid insulation are essentially "sealed off" from the outside environment and are not immediately affected by changes in outside conditions. However, over extended periods of time gas diffusion will occur in the insulation and will alter the contents of the void. The amount of time required for diffusion to significantly alter the gas composition of a void depends on the severity of the outside environment, the physical characteristics and condition of the insulation material, and the location of the void within the insulation.
Voids located on a metal-dielectric boundary may, in general, respond more quickly to changes in outside environment, since the metal-dielectric interface presents a less formidable "seal" against the diffusion of gases. This may be especially true in the case a stranded-conductor wire, where an array of air passages and spaces may provide a direct leakage path between the void and the outside world.

In addition, through aging, mechanical fatigue, exposure to radiation, and contact with reactive agents, insulation develops micro-cracks and fissures, which represent "voids" that are often directly connected to the external environment.

Due to the situation-dependence of the relationship between voids and the outside environment, care should be taken when applying Paschen curve data to determine the breakdown potential of voids within solid dielectric. While the gas composition of vented cavities is clearly influenced by the outside environment, the gas content of "sealed" cavities depends on a wide variety of parameters, including the amount of time the system is exposed to changing environmental conditions. Thus, it may not always be necessary (or appropriate) to estimate the dielectric strength of the gas within a well-sealed void according to the Paschen curve data for the external environment.

**Partial Discharge of Voids within Solid Dielectric**

**Statistical Influences on Electrical Breakdown**

Once a void is in an electrically-overstressed condition, an internal discharge may still not occur until a freed electron becomes available to initiate ionization that can lead to an avalanche breakdown. The emergence of a freed electron is a statistical event that depends largely on the environment in which the system operates. For example, in one cubic meter of air at ground level, an average of $4 \times 10^6$ ion pairs (freed electron + positive ion) are created every second due to radiation released by the decay of ground-based material; $4.6 \times 10^6$ electrons are created due to the decay of air-based material; and
1.5 to 1.8 \times 10^6 \text{ are liberated due to bombardment by cosmic rays} [15]. Over the open ocean and at high altitude, the effect due to ground-based decay is not present, but at higher altitudes, the contribution due to cosmic rays is increased. Ionization can also be greatly affected by atmospheric disturbances and local geographic features [15].

Knowledge of the expected rate of emergence of freed electrons in the operating environment of a system, coupled with knowledge of the topography and gas content of a void within the insulation, permits calculation of an average rate of electron emergence within the void. Based on this rate, an average time to electron emergence \((t_e)\) may be determined beginning from time \(t = 0\), when the field stress first exceeds the dielectric strength of the gas in the void.

Another statistical factor is the position within the void from which a freed electron emerges. In order for a freed electron to cause ionization that results in a net increase in the number of ions in the gas, the chain reaction must attain sufficient energy by being accelerated along the field gradient in the void. If the field stress on the void is equal to the critical stress (dielectric strength) of the gas, a freed electron is not likely to initiate a breakdown reaction unless it emerges at the point in the void that is furthest from the source of positive potential. However, if the field stress on the void is significantly greater than the critical stress, an electron can emerge from many positions and be able to initiate a reaction that will attain the energy necessary to develop into breakdown [11]. The position dependence factor can be combined with the average time for electron emergence to produce an average time to breakdown \((t_b)\), which is a function of electron emergence rate, void size, and level of gas overstress.

Partial Discharge in a Static (DC) Field

When ionization occurs in a static field, positive ions will be accelerated along the potential gradient in the direction of negative potential (or away from that of positive potential), while negative ions and freed electrons will be accelerated in an opposite
direction. Under normal conditions, these ions and electrons collide with a large number of atoms and molecules in the gas, but their energies are not sufficient to cause a net increase in the number of ions and electrons in the gas. Positive ions, negative ions, and electrons re-combine much more quickly than they are created and, in the macroscopic sense, ionization activity is not significant.

As the stress in the void approaches the dielectric strength of the gas, freed electrons can attain sufficient energy to cause a number of ionizing collisions in the gas, but the speed with which recombination occurs will still be equal to or greater than the rate of new ion production. Ionization can be described as being localized and sporadic. A very low-level drift current (net charge motion in a common direction) may be detectable, but, on the whole, very little charge transfer across the void can take place. When the rate of recombination is just able to balance the ionization occurring in the gas, the gas can be described as being in a steady-state ion and electron swarm condition, one of the pre-requisites for the Townsend avalanche breakdown model.

Once the stress on the void exceeds the dielectric strength of the gas, and the statistical time to breakdown $t_s$ has elapsed, a freed electron will emerge in a region of the void such that it will initiate a series of ionizing collisions that will result in a net increase in the number of freed electrons and ions in the gas. This constitutes the beginning of an avalanche condition, which is characterized by an exponential increase in the current flow within the void. Now a net charge transfer actually takes place through the void, with ions and electrons reaching and being deposited on the walls of the void.

Since negative charges are drawn to the positive side of the void, and positive charges are drawn to the negative side of the void, the deployed charges set up a local field with a gradient that is opposite in polarity to that of the driving field. As the breakdown continues, the magnitude of charge that is deployed on the walls of the void grows, increasing the magnitude of the counter-active field. Thus, the breakdown produces within the void a cancellation of its own driving energy source. For this reason, partial
discharge within a void surrounded by dielectric, under static-field conditions, is essentially a self-quenching process. Figure 3 illustrates the modified field distribution that results from the occurrence of a partial discharge within a void located in solid insulation between two parallel plates.

![Diagram of field distribution](image)

**Figure 3. Illustration of local field reduction as a result of partial discharge**

When the net field stress on the void reduces to a sufficiently low level, the current avalanche decays and ceases. Charges that remain in the gas drift along the remaining potential gradient and either reach a void wall or eventually re-combine with other charges to form neutral atoms or molecules. It is possible that some low level of sporadic ionization can continue in the void, but electrons that emerge in the region of reduced field stress will not attain enough energy to initiate another avalanche. If, however, a void has a size or shape such that the deployed charges do not reduce the field stress throughout the entire void, additional discharges may occur until no region of field overstress remains.
In a DC system, once a void has undergone "total discharge," it is highly unlikely that further discharge will occur at the same location unless the potential is altered (the system becomes time-variant) or if surface flash-over occurs due to the charge concentration on the void surface. If neither of these situations apply, further discharges will occur only after charge leakage reduces the counter-active field in the void \[5, 8\]. Mason sites the rate of such leakage to be approximately:

\[ t_{rep} = 10^{11} \sigma_v V/V_i \]  

(18)

where \( \sigma_v \) is the volume resistivity of the solid dielectric, \( V \) is the static potential difference of the system, and \( V_i \) is the minimum potential at which electron avalanche can occur.

**Partial Discharge in a Time-variant Field**

A time-variant field results from the application of a non-static potential to a system; a basic example of this occurs whenever a DC system is activated or de-activated. During those times, the potential either builds up to or decays from the operating level, and it is then that most partial discharge activity occurs. Thus, the greatest damage to DC insulation resulting from discharging of voids within the solid dielectric often occurs when the system is turned on or off.

Unlike a DC system, which turns on and off only once for every use, a system with AC potential turns "on" and "off" twice every cycle: once in the positive direction, and once in the negative. Thus, a given level of overstress will result in far more partial discharge activity within an AC system than it would in a DC system.

For a void that has not yet undergone any discharge, a discharge may occur only during those parts of the cycle where the field stress exceeds the dielectric strength of the gas in the void, and if a freed electron is available in the proper region of the void to
initiate the breakdown reaction. A statistical variable could be introduced to represent the total amount of time \( t_s' \) required for the coincidence of these events to occur. This variable would be a function of the average time required for electron emergence within the void \( t_e \), the size of the void, and the percentage of time during each cycle in which the void is overstressed.

Once \( t_s' \) elapses, and a discharge occurs, the void may be susceptible to multiple discharges during every subsequent cycle of the system [8]. For example, if the first discharge occurs during the positive half of a sinusoidal potential, charges will be distributed on the void walls in a manner that counteracts the field gradient set up by the positive potential. However, if the potential is still rising, the net field in the void will begin to build up again (the gradient caused by the raised potential will increase while the counter-active gradient due to the presence of surface charges deposited by the previous discharge remains constant). Whenever the net field in the void reaches the critical level and a freed electron is available in an appropriate position within the void, it is possible for an additional discharge event to occur.

Regardless of whether additional discharges occur during the positive half-cycle, when the potential begins to decrease and then swings into the negative half-cycle, the situation changes--the net field in the void suddenly grows very large in the opposite direction. The gradient caused by the system potential begins to increase in the negative direction, while the previously-counter-active gradient due to the surface charge distribution now adds to the field in the new direction. Therefore, it is highly probable that just after the potential swings negative, an "equalizing" discharge will occur in the void due to the unnaturally-high field strength in the region of the original discharge. After the "equalizing" discharge, it is possible for further discharge(s) to occur during the negative half cycle according to the same principles that govern the occurrence of additional discharges during the positive half-cycle. Figure 4 illustrates the initiation and
cyclic recurrence of partial discharge in an overstressed void within a system excited by AC potential.

![Diagram of discharge initiation and recurrence in a void within an AC system]

**Figure 4.** Discharge initiation and recurrence in a void within an AC system

Partial Discharge on a Conductor-Solid Dielectric Boundary

For a void located on the boundary between solid dielectric and an AC or a negative-potential DC conductor, discharge activity will almost always be more violent than partial discharge that occurs within voids that are completely surrounded by dielectric. Several factors contribute to this--interfacial voids are more likely to be irregular in shape, are often linked to the outside environment, and, perhaps most significantly, the adjacent conductor can serve as an additional source of electrons to discharges in the void.

Electron transport can occur from a conductor in significant quantity when the field stress is sufficiently high to allow energized electrons to make the "leap" from the conductor into the gas. The conditions under which this is likely to occur are discussed in more detail in Chapter 4. The most pronounced emission of electrons will typically occur near "stress risers" on a conductor--localities at which the radius of curvature is very small, and consequently, the field stress is very large.
Due to the potential severity of this problem, some high-voltage wires include a layer of semiconducting material extruded over the high-potential conductor before the main dielectric is applied. The semiconducting layer serves two purposes: it eliminates the possibility of discharge in voids that are directly adjacent to the conductor, and it increases the radius of curvature of the dielectric interface, reducing the field stress at any voids that may be located on the new dielectric boundary.

**Insulation Damage Resulting from Partial Discharge**

Both localized heating and electron bombardment of dielectric surfaces have been attributed as mechanisms of damage when partial discharge occurs. For example, Mason proposed that a discharge with energy exceeding $10^{-7}$ J could result in a temperature rise of several hundred Kelvins at the impact site, high enough to melt polymer insulation [5]. Other researchers cite molecular chain-scission due to electron bombardment as a probable mechanism of polymer damage. For example, with discharge energies below $10^{-6}$ J, some electrons may strike the insulation with energies greater than 10 eV—greater than both the 3.5 eV energy of the C-H bond and the 6.2 eV energy of the C=C bond [5, 8]. Atoms released from the insulation by this process may react with the gas within the void to form compounds that cause further insulation damage.

It has also been well-documented that ozone produced by discharges within voids containing air may initiate cracks and decay in a variety of insulation materials.

Experimental evidence suggests that discharges in a well-sealed void can produce by-products that inhibit the future occurrence of discharges of similar magnitude [5]. This seems to be particularly true of voids that do not contain oxygen or other reactive gases (for example, smooth-walled voids within epoxy will typically not contain oxygen, since it is likely to react with the compound during curing [11]). This contrasts with the case of a ventilated void, which not only responds to external pressure conditions, but also
receives a steady supply of "fresh" gas that may continue to react with degraded insulation and thus lead to further decay.

Prevention of Insulation Damage

A group of 1970s and 1980s surveys of manufacturers and users of miniature, high-voltage power supplies implicated gaseous voids as contributors in 59 percent of component failures [13]. Two explanations are possible: (1) poor workmanship or process control resulted in a distribution of voids or conductor stress risers less favorable than had been assumed in designing the component, and (2) poor design assumptions were based on materials having better characteristics than were reasonable to expect in a real-world application.

For a long-life or critical-function component, stress risers must be avoided at all costs on both conductor-dielectric and dielectric-dielectric interfaces unless the system geometry is so large as to warrant against failure. Only persons or processes that have a past record of producing high-yield, long-life materials and assemblies should be relied upon for component processing and assembly. Design rules must be grounded not only in the theory of operation under ideal conditions, but also according to conservative expectations of materials and process capabilities in the application arena.

Of the commonly-used insulation materials, mica appears to have the greatest ability to sustain long life in the presence of discharge activity, while silicone rubber also exhibits a long-life capability. All other insulation materials may suffer from a very reduced lifetime at power frequencies [16]. Other than over-designing systems to achieve long life (which is typically not a viable consideration), thorough understanding of materials and processes, use of well-conceived design parameters, familiarity with the operating environment, experience in application, and proper test techniques are the only reliable insurance against premature failure of components and systems due to partial discharge or corona activity.
Electrical Transients Resulting from Partial Discharge Activity

The electrical transients that appear on system conductors as a result of discharge activity can be explained in terms of the fundamental concept of electrical phenomena: charges at rest or in motion exert force on one another. A theoretical understanding of the transient-generation process is very important since many partial discharge and corona test procedures are based on the measurement and analysis of these transients.

When an ion or freed electron (i.e., space charge) exists in a gas-filled void within solid dielectric, it is subjected to forces exerted by the presence and motion of charges on nearby conductors. These forces are the driving energy source for ionization within the void. At the same time, the existence and motion of each space charge *itself* exerts a force on the charges of nearby conductors. For a static (or quasi-static) field, these forces can be described by the Lorentz force equation:

\[
\vec{F}_Q = Q(\vec{E}_R + \vec{v} \times \vec{B}_S)
\]  
\[\text{(19)}\]

where \(Q\) is the magnitude of the charge on which force is being exerted, \(v\) is the velocity of that charge, \(\vec{E}_R\) is the electric field produced by nearby charge or charge distribution \(R\), and \(\vec{B}_S\) is the magnetic flux density produced by nearby moving charge or charge distribution \(S\).

While the force that a conductor charge distribution exerts on a space charge in the void is very large, the force that a space charge exerts on the conductor charges is almost negligible—it could be compared to the force a person imparts on the earth when jumping. However, as ionization within the void builds into an avalanche breakdown, the number of ions and freed electrons in the void can become quite large (sometimes near to or greater than \(10^8\)) [8]. The cumulative effect of these space charges is to produce a measurable force on the charges of the conductor.
Further, in a partial discharge situation, the negative space charges collect on the void surface closest to the most positive conductor (or farthest from the most negative), while the positive space charges behave oppositely. In this way, the space charges are arranged in a manner that results in the maximum possible force being exerted on conductor charges. Since electrons are the mobile charge carriers on a conductor, on a positively-charged conductor, the force exerted by the space charges causes a motion of conducting electrons away from the area of the conductor that is closest to the void. On a negatively-charged conductor, the force causes a motion of electrons toward the area of the conductor closest to the void. The change in charge in those areas of the conductor (compared to the pre-ionization charge) is called the induced charge. Figure 5 illustrates this concept.

\[ V = \frac{Q}{C} \quad \text{pre-discharge equilibrium} \]

\[ V' = \frac{Q'}{C} \quad \text{post-discharge equilibrium} \]

\[ Q = Q' + q_i \quad C = C \quad V' < V \]

Figure 5. Cross-sectional view of pre and post-discharge equilibrium on parallel charged plates separated by solid dielectric, assuming no charge is allowed to leave or join the electrodes.
Note that the re-distribution of electrons on the conductors in Figure 5 results, for the positive conductor, in a slightly higher concentration of electrons on areas of the conductor away from the void. Likewise, the negative conductor attains a slightly lower concentration of electrons on areas of the conductor away from the void. Thus, the potential difference between the positive and negative conductors is lowered by a small amount.

To compensate for the decrease in potential, the system power supply, which essentially acts as an electron pump, forces an additional amount of negative charge to move from the positive lead onto the negative lead, in order to return the system to its proper potential. This process, which is observed as a current transient in the supply lead, occurs over a finite period of time based on the resistance, capacitance, and inductance characteristics of the complete system. Figure 6 illustrates the charging and transient generation resulting from a partial discharge in an ideal (purely capacitive) component. A hypothetical circuit configuration is used in Figure 6 to illustrate that the voltage transient is caused by induced charging in the sample, while the current transient results from the subsequent reaction of the system power supply. In a real system, the relationship between the voltage and current transients will be much more complex than in the idealized circuit.

The change in charge (as a function of time) that is observed at the measurement terminal of a system is called the apparent charge. It is interesting to note that in a practical system, the apparent charge is not equivalent to the induced charge, and may not be a reliable indicator of the discharge magnitude. This can be illustrated by examining the situation from a mathematical point of view.
Figure 6. Timing sequence of induced charging and electrical transient generation for an idealized discharge system
Mathematical Description of Observed Electrical Transients

The field theory provides a convenient, self-contained mathematical method for describing the effects of the fundamental force interactions discussed in the previous section. Although the direct solution for a system undergoing partial discharge would involve the solution of a Poissonian field (due to the presence of space charge within the field), a valid mathematical description of the current transients may be attained by applying the principle of superposition [17].

Since the electric field in most high-voltage systems is much stronger than the magnetic field, the electromagnetic effects—the forces due to the motion of charges on the conductor (current flow) and charges within the void (drift or avalanche current)—are usually neglected. The discussion of induced charge in this study will consider the effects of the electric field only. This approximation may not be valid for systems in which the magnetic field effects are within an order of magnitude of the electric field effects. In such cases the existence of the relatively strong magnetic field not only alters the mean path of the discharge and final distribution of charge on the void walls, but also affects the statistics of the discharge-initiation process and the discharge magnitude.

Induced Charge

The total charge on an electrode can be expressed as the sum of two quantities [17]: (1) the charge \( Q \) that would be present due to the potential difference between the electrode and all other nearby electrodes in the absence of any space charges, and (2) the charge \( q \) that would be induced on the electrode by the presence of space charges, in the absence of any potential difference among the various electrodes. The first quantity can be described as [17]:

\[
Q = \sum_{j=i}^{n} C_j(U - U_j)
\]  

(20)
where $U - U_j$ represents the potential difference, and $C_j$ the partial capacitance, between the electrode of interest and each other electrode, with the condition that the total sum of charge on all electrodes is equal to zero.

For the case of a gaseous void within solid dielectric, the second quantity can be expressed as[17]:

$$q = -\iiint \lambda \rho d\Omega - \iint \lambda \sigma dS$$  \hspace{1cm} (21)

where $\rho$ is the volume charge density in the void volume element $d\Omega$, $\sigma$ is the surface charge density on the void surface element $dS$, and $\lambda$ is a scalar function, the value of which depends on the position of $d\Omega$ or $dS$ and the permittivity $\varepsilon$ of the dielectric material in that position.

The function $\lambda$ can be obtained from Laplace's equation [10]:

$$\nabla \cdot (\varepsilon \nabla \lambda) = 0$$  \hspace{1cm} (22)

with the boundary conditions $\lambda = 1$ at the electrode of interest and $\lambda = 0$ at all other electrodes. Additionally, wherever a dielectric interface occurs, the following condition must be met:

$$\varepsilon_+ \left( \frac{\delta \lambda}{\delta n} \right)_+ = \varepsilon_- \left( \frac{\delta \lambda}{\delta n} \right)_-$$  \hspace{1cm} (23)

where $+$ and $-$ refer to the conditions on each side of the boundary, and $\lambda$ is differentiated normal to the boundary.

Since equation (22) and its boundary conditions (23) have the same analytic form as equations (13) and (14), the same methods used to solve for $V$ in that discussion can be applied to obtain an approximate solution for $\lambda$. However, this does not provide a complete insight into the induced charge—the integral nature of equation (21) indicates
that the induced charge \( q \) is not the result of a unique space and surface charge distribution; there are many possible distributions that could result in the same induced charge. Knowledge of the induced charge does not guarantee the ability to profile the ionization activity that produced it, particularly when the void geometry and position are unknown. Figure 7 illustrates the concept of how identical induced charge may result from dissimilar void charge distributions.

The induced charge changes with time, according to the quantity and position of moving charge and surface charge in the void at each given instant. Eventually, after the discharge extinguishes, virtually all charges remaining in the void will be located on the walls. The relationship between this "final" charge and the total charge involved at the height of the discharge is not defined (not all charges moving within the ionized gas reach a void wall intact).

![Diagram of oblate and prolate voids](image)

Figure 7. Concept of identical induced charge resulting from dissimilar charge distributions in dissimilar voids
Although dissimilar surface charges in dissimilar locations can produce identical induced charges, those identical induced charges may rightfully indicate that a similar amount of energy was involved in each process. For example, the smaller amount of charge in the prolate void in Figure 7 was displaced farther (and thus acquired more energy from the driving field on a per-unit basis) than the larger amount of charge in the oblate void. On average, the static level of induced charge that remains on the system electrodes after a discharge may be roughly proportional to the actual amount of energy that was involved in the discharge. Although numerous statistical and deterministic factors occurring within the ionization event can cause deviation from this proportionality, it is the idea that such a proportionality exists that leads to the desire to measure the induced charge. Unfortunately, the induced charge cannot be measured directly, but must be estimated by a new quantity, the apparent charge, as viewed from the measurement terminals of the system.

Apparent Charge

The apparent charge is the quantity most often measured during electrical detection of partial discharge. This is often accomplished by observing the magnitude of the voltage transient that appears at the terminals of the system, then back-calculating the responsible change in charge \( \Delta Q \) using the relation:

\[
\Delta Q = C(V_o - V_t)
\]  \hspace{1cm} (24)

where \( C \) is the capacitance of the system, \( V_o \) is the nominal operating voltage of the system, and \( V_t \) is the decreased, transient voltage observed as a result of the induced charging.

Unfortunately, the answer provided by this approach may not provide a true indication of the induced charge. The voltage transient is a function of time; it is a
function of the induced charge acting through the impedance of the complete system. In a system that is other than purely capacitive, the relationship between terminal voltage \( V \) and the total charge \( Q \) on the system is given by:

\[
Q(t) = \int \frac{V(t)}{Z} dt
\]  

(25)

where the impedance \( Z \) is a differential and/or integral function that acts on \( V(t)dt \), according to the resistance, inductance, and capacitance characteristics of the system.

The primary difficulty with measuring electrical transients is that the impedance seen by the induced charge depends on the location of the void relative to the measurement terminal. Thus, identical discharges in identical-sized voids located in different positions along a coaxial cable, for example, will result in two different computed apparent charges at the measurement terminal. The significance of the difference is determined by the impedance characteristics of the test component, power supply, and measurement device.

If a current transient could be measured entirely and then integrated with respect to time, the resulting quantity could be related to the induced charge on the electrode near the discharge sites [18]. However, there are problems in a real system that prevent such a measurement from being accomplished. For example, in a system where the induced charge acts through a large impedance to reach the measurement terminal, the magnitude of the current transient will be spread out considerably over time [18]. Thus, a large portion of the transient will have such a low level that it may not be distinguishable from ambient or detection noise. Further, a transient may not manifest itself as a single, contiguous pulse. For example, in a cable system, a portion of the current transient may propagate directly to the measurement terminal, while another portion may propagate down the line in the opposite direction, encounter an impedance mismatch (termination, disjunction, etc.), and then reflect back through the cable and arrive at the measurement terminal at a later time [19, 20].
It is virtually impossible in a real system to track a particular reflection with a particular pulse, account for energy losses, and thus accurately measure the apparent charge. Not to mention that in a system with multiple discharging voids, transients from separate discharges in different locations within the system may reach the measurement terminal at the same time and thus appear as a single transient resulting from a single, large discharge.

As a result of all these problems, measurement of the apparent charge cannot provide direct information about the energy of a particular discharge except in the simplest of cases [21] (e.g. a static system where there are very few voids, and the position and impedance to the measurement terminal of each is very well defined.) This does not refute the potential usefulness of electrical transient measurement in providing information about the relative fitness of a test article, but implies that the measured quantity cannot be correlated with an actual discharge event without resorting to techniques based on statistical analysis of a sufficient number of observations.
CHAPTER IV
CORONA THEORY

While classical theories of electrical discharge have been developed to explain electron and ion behavior under uniform field conditions, the occurrence of corona, or glow discharge, is a phenomenon associated with non-uniform field conditions. When a gas is subjected to a sufficiently strong uniform field, any appreciable ionization activity will quickly build into a concentrated avalanche of current that completely bridges the space between electrodes. But, in a non-uniform field, it is possible for the field stress in one region of the gas to be sufficient to promote ionization activity, while in another region, the field stress is so low that electrons cannot acquire enough energy to support ongoing ionization. Thus, ionization cannot completely bridge the space between electrodes.

A majority of corona experimentation has been devoted to the study of two cases—the area between concentric cylinders (see Figure 8), and the point-to-plane gap (favored as an extreme example of non-uniformity). Although such experiments have produced much insight into the behavior and occurrence of corona discharges, they have failed to result in a classical theory of corona [2].

**Discharge Characteristic in a Non-uniform Field**

One of the most fundamental observations from the study of corona is how the behavior of the discharge in a gap between two electrodes relates to a ratio of the distance between the electrodes relative to their radii of curvature. If the electrodes are spaced very close to each other relative to their radii of curvature, the field between them is close
enough to uniform that the first form of discharge activity to occur (upon raising the potential) is a spark breakdown of the gap. As the distance between the electrodes is increased slightly, the same behavior occurs, though a higher potential is required to initiate the discharge. The relationship between electrode separation and the sparking potential is non-linear.

![Cross-sectional view of non-uniform equi-potential lines between a 10 kV DC, 1 mm wire and a grounded cylindrical surface at 5 cm](image)

Figure 8. Cross-sectional view of non-uniform equi-potential lines between a 10 kV DC, 1 mm wire and a grounded cylindrical surface at 5 cm

When the electrode separation is increased to a critical distance, spark breakdown is no longer the first manifestation of discharge activity in the gap. At the critical distance, the field distribution within the gap becomes such that ionization activity can be supported in the direct vicinity of the electrodes (area of highest field strength) but cannot occur in the region in the center of the gap (area of lower field strength). Thus, as the
potential is raised, corona is the first form of discharge activity to appear in the gap. If the potential is raised still further, the field strength in the center of the gap will eventually surpass a value necessary to support avalanche ionization, and a spark breakdown may bridge the gap completely [4].

**Factors Influencing Corona Ionization**

From the preceding discussion, it is apparent that the occurrence and extent of corona discharge should be very situation-dependent. In addition to the obvious dependence on the shape of the electrodes and the distance between them, corona activity is also influenced by the type and density of the gas, the environment in which the gas resides (e.g. presence of impurities, extent of background radiation), and the polarity and surface characteristics of the coronating electrode(s). While the geometric parameters determine if field conditions are adequate to support corona, the latter group of factors combine to determine the availability of electrons and ions in the gas.

According to the generalized Townsend theory of electrical conduction in gases (see Chapter 2), the possible sources of charge carriers in a gas are ionization of atoms or molecules due to various types of interactions in the gas, and emission of electrons from a cathode due to a variety of internal and external interactions. In order for the first (ionization) processes to occur, initiating electrons must be available in the gas to begin the ionizing-collision-multiplication process. In order for the second (cathode) processes to function, a significant degree of energetic photons and ions must be present in the gas near a negatively-charged electrode (typically as a result of, or coincident with, the occurrence of ionization in the gas).

**Corona Initiation**

Since much interest in corona is associated with systems operating in atmospheric air, it is convenient to use air as an illustration of the general availability of electrons and ions
in a gas. As mentioned in Chapter 3, freed electron/positive ion pairs are regularly generated in gases due to bombardment by energetic particles associated with cosmic rays and other forms of radiation. Within nanoseconds of emergence in atmospheric air, freed electrons and positive ions provided by this process combine with other molecules to form primary, or "fast" ions that take the standard forms:

- negative ions: \( \text{O}_2^-(\text{H}_2\text{O})_n \) or \( \text{CO}_4^-(\text{H}_2\text{O})_n \)
- positive ions: \( (\text{H}_3\text{O})^+(\text{H}_2\text{O})_n \)

where \( n \) depends on temperature and water vapor pressure and can change many times over the life of an ion [15].

Electric conduction in atmospheric air is carried almost exclusively by these fast ions, since the number density of other ion groups is generally one order of magnitude lower. One other ion group is "slow" ions, which are aerosols often formed by impact from a fast ion. Incidentally, the average life of fast ions is greatly influenced by the density of aerosols in the air and can range from about 10 seconds in aerosol-rich air to 300 seconds in pure air. Although fewer ions are created over the open ocean compared to over land, the aerosol density in air over the ocean is typically lower, so the ions tend to last longer. The result is that the average ion density at ground level is fairly uniform over the surface, and varies primarily with altitude [15].

For the purposes of corona around a high-tension transmission line, for instance, it is apparent that there is an ample supply of freed electrons and positive and negative ions in bulk air at any given time (though the relative quantities of these can be greatly influenced by geographic features, humidity, storms, pollutants, etc.). All that is required to cause some degree of sustained ionization, then, is the application of an electric field (whether static or otherwise) strong enough to set the charge carriers into energetic motion.
Cathode Emission Processes

Just as the application of heat can cause a cathode to emit electrons in a "vacuum" tube, energy-transferring processes that occur during corona ionization can lead to electron emission from a non-insulated, negative electrode. Although the precise mechanisms involved in the emission of electrons from a conductor into a gas are as yet unknown, numerous studies have provided evidence of how some specific processes may contribute to the effect. These include: thermionic emission, photo-electric emission, incidence of positive ions, incidence of metastable and neutral atoms, and "field emission" [2, 3].

A typical way to view the electron emission problem is to consider that for an electron to make the "leap" from a conductor into a gas, it must attain enough energy to surmount the electrostatic barrier that exists at the conductor-gas boundary. The amount of energy a specific electron requires to overcome the barrier is described by the difference in potential across the barrier, and is referred to as the work function. While it is difficult (under non-vacuum conditions) for the thermionic, photo-electric, and collision processes to impart the energy necessary for electrons to leave the conductor, a strong electric field at the boundary has the effect of reducing the work function so that less energy transfer is required.

At moderate field strengths, this "field emission" has been mathematically described as the Schottky effect, which predicts an increase in the number of electrons emitted for a given amount of heating. However, at high field strengths (>10^6 V/cm), the Schottky effect alone cannot account for the increase in electron emission from the conductor. It is thought that under such conditions the work function is effectively reduced to a point where electrons can "tunnel through" the potential barrier by virtue of their wave properties, without acquiring additional energy [2, 3].
It has also been observed that the presence of particulate impurities on the electrode surface (e.g. layers of oxide, gas, and tarnish) often promotes the emission of electrons at lower field strengths than observed with newly-polished electrodes [2]. This is particularly relevant to the occurrence of corona in real world systems (e.g. a high-tension wire), since electrode contamination and oxidation is not only typical, but is often presumed.

Once liberated from a cathode, emitted electrons become immediate participants (and contributors) in the ionization processes occurring in the gas.

**Corona in a Static (DC) Field**

A classical method of describing the motion of freed electrons within a gas in the absence of an external field is to view the electrons as comprising a "gas" of their own, and to examine their behavior within the larger mixture based on the ideal gas laws. Thus, an uneven concentration of electrons within the mixture will result in diffusion of electrons away from areas of high concentration into areas of lower concentration. When an electric field is applied, an additional form of motion results—a net drift of electrons in the direction of the field. Finally, the number and distribution of electrons can change continually depending on the occurrence of ionization, recombination, attachment, and emission from conductors. The same properties of diffusion, drift, ionization, recombination, and charge transfer apply to ions, except that the velocities involved, and thus, the apparent effects, are orders of magnitude smaller [3].

Since corona is a macroscopic phenomenon, large differences can exist in the concentration of electrons and ions within the ionizing area. In the gas, there exists not only a non-uniform gradient of electric field, but also non-uniform gradients of ion and electron concentration. The behavior of the corona is influenced by all of these gradients and their interaction.
One conclusion resulting from the above discussion is that there must be clear differences in the behavior of corona around positive and negative conductors. For corona around a positive conductor, electrons are drawn in toward the conductor while positive ions are forced away from it. This arrangement typically results in a uniform, well-defined "sheath" of glow around the conductor. Contrastingly, negative corona may appear as tufts of light or an uneven glow around the conductor, sometimes with isolated striations distinguishable within the glow. This is understandable, since the negative conductor may serve as a source of electrons for a discharge, and the electron transfer is unlikely to occur uniformly over the surface of the conductor. For example, in a location where many electrons are being released from the conductor, increased ionization activity may result in the gas. Increase gas ionization results in additional photon and positive ion bombardment of the conductor, causing even further electron release from the conductor. This localized positive feedback mechanism provides an explanation for the existence of streamers and bright areas that may appear within negative corona.

Corona in a Time-variant Field

While drift, diffusion, ionization, recombination and electron emission also operate within corona in a time-variant field, the interaction among these processes becomes increasingly complicated. For example, in AC corona the field reverses periodically, alternating the directions of drift and diffusion and continuously rearranging the locations of electron and ion concentration. When the frequency is sufficiently high for a given system, a majority of available space charge may be confined to move within a limited region near the electrode. As ions and electrons repeatedly move past each other in the active region, sporadic and probabilistic increases in ionization and/or recombination activity can result, producing overall behavior that is difficult to predict [22]. Also, additional electrons may be added to the discharge through emission from the conductor during the negative half cycles.
Due to the higher availability of electrons compared with positive ions, and due to the unpredictable and random nature of local effects within the discharge, AC corona may appear more similar to negative DC corona than positive DC corona. In general, AC corona is more noticeable than DC corona and is much more likely to be observed in cases where the electrodes are not in direct contact with the gas. The actual physical size and intensity of the corona may vary greatly depending on the frequency of the driving field and a variety of environmental factors.

**Corona Power Loss**

The presence and movement of electron and ion space charge in the region around a coronating electrode incurs a power loss to a high-voltage system [22]. Since corona can be a steady-state phenomenon occurring in bulk volumes of gas, the total power loss can be quite significant. Therefore, despite the inherent difficulties of developing mathematical models for corona ionization, there is a great deal of interest in finding methods for predicting the power loss associated with corona, particularly around power transmission lines. This has important economic ramifications, since the maximum voltage at which transmission efficiency is limited is often determined by the extent of corona activity around the lines. Given the cost of implementing high-voltage power-transmission systems, design methods or models that allow meaningful prediction of corona behavior under different operating conditions could become indispensable tools.

The salient aspects of power loss calculation are solution of the space-charge-present field, and solution of the electron and ion transport equations. These quantities are interactive, and require at least a second-order non-linear differential equation to describe. Limiting assumptions and approximations are required to convert the equations to a solvable form. For example, in a DC system where the potential significantly exceeds the critical amount required for ionization, both the electric field and the transport of space charge might be considered to have steady, non-fluctuating values.
An extreme example of approximation for describing the field is to assume a coaxial geometry, i.e., the ground plane is so far away from the conductor that the distance to the ground plane is equal in all directions. This greatly simplifies the field geometry and permits discussion of space charge motion in the vicinity of the conductor in terms of charge distribution "shells."

A more involved approach is to examine the wire-to-plane geometry in a bipolar cylindrical coordinate system, a transformation that provides geometrical variables coinciding with the paths of Laplacian field lines within the asymmetrical wire-to-plane geometry. A prevalent approximation for the Poissonian (space-charge-present) field distribution, called the Deutsch approximation, relies on a perturbation of the potential along rigidly-adhered-to Laplacian field lines [23]. Thus, the field lines and equipotential lines no longer intersect normally. The magnitude of the perturbation is computed by a numerical evaluation technique. A side effect of this "Laplacian" orientation is that a discontinuity in potential exists at a distance that is infinity "above" the wire (in the direction directly away from the ground plane). This presents somewhat of an anomaly, since it is to be expected in a real-world situation that space charge be present in some form of "sheath" all around the coronating wire [23].

Wintle offers an alternative numerical approach that eliminates the discontinuity in potential and iteratively converges a solution for the field and transport equations [23]. Interestingly, the algorithm produces results that closely follow those of the Deutsch approximation in all areas around the wire excluding a wedge that subtends an angle of \(\pi/4\) radians away from the top side of the wire [23].

For an AC system, the mathematical difficulties are compounded by the fact that the space charge flow is not a unidirectional phenomenon. Also, due to the periodic reversal of potential, corona is not a time-continuous process--active ionization is likely to occur only during those parts of the cycle that lie above the corona initiation and extinction voltages. In one example of a treatment of this subject, researchers offer models for
determining "steady-state" values for initiation and extinction potentials, and discuss the interaction of "outgoing" and "incoming" shells of space charge in the active ionization region around the coronating electrode [22]. The approximations of critical-field and transport effects are then used to provide an estimate of steady-state power loss.
CHAPTER V
PARTIAL DISCHARGE AND CORONA TESTING

Electrical Detection of Partial Discharge/Corona as a Diagnostic Tool

An ideal test would both indicate the current condition of a component and provide a reliable estimate of remaining life. Much effort has been devoted toward the formulation of partial discharge/corona test criteria to produce results that correlate with actual insulation lifetime. Perhaps the most prevalent method for commercial testing has been electrical detection of the apparent charge. However, evidence indicates that this measurement alone may not provide good indication about the present or future condition of a test article [5]. It has been discussed from a theoretical perspective that measured apparent charge cannot be correlated with a responsible discharge event except under the most simple, controlled conditions (see Chapter 3). Research also indicates that there is not a recognizable relationship between the actual energy of the discharge and the amount of damage produced by it. For example, during the development of an electrical tree, the most rapid growth of channels has been observed in coincidence with only minimal discharge magnitudes [12, 18]. It is only later, after substantial channels are already established for arcs to track through, that maximum discharge energies are observed.

A necessary conclusion of these observations is that partial discharge/corona testing cannot easily serve as a reliable indicator of the future state of a test article. However, a connection may be drawn that detection of large-energy discharges can indicate the presence of existing problems in the insulation. In order to take advantage of this
connection, within the limitations inherent to measurement of apparent charge, observed behavior must be interpreted based on the statistical nature of the measured data.

For the purposes of diagnostic testing, advances in test equipment technology have made it more feasible to accurately determine the current status of a system. Pulse height analyzers have the ability to categorize observed voltage transients according to magnitude and keep a record of the total number of observations in each category. This allows compilation of a histogram, and provides the kind of information that is necessary to perform a statistical interpretation of the data.

Detection Sensitivity

The sensitivity of electrical detection of partial discharge/corona transients consists of several components:

**System Impedance-Limited.** The system impedance determines the magnitude of the observed voltage transient relative to the magnitude of the responsible discharge within a test article. For example, in an ideal, purely capacitive system, the magnitude of the induced charge ($\Delta Q$) acting in tandem with the total capacitance of the system ($C$) would produce a change in the potential of the electrode ($\Delta V$) according to the relationship:

$$\Delta V = \frac{\Delta Q}{C}.$$  \hspace{1cm} (26)

Although in a real system the above relationship does not hold true, the same idea of proportionality applies—the larger the system capacitance, the smaller the voltage transient that results from a discharge of specific magnitude.

In cases where a capacitively-coupled detection network is used, the measured voltage will be a filtered version of the electrode transient. A modified approximation for
the relationship between $\Delta Q$ and $\Delta V$ can be produced by evaluating the impedance transfer function of the system as viewed from the measurement terminal.

**Detector-Limited.** The minimum transient that can be detected may be limited by the theoretical minimum voltage resolvable by the transient-measurement equipment. Specifications for detection sensitivity are included with most high-quality measurement equipment. However, it must be assumed that less-than-optimal performance will be achieved if the device is used with a source impedance that is significantly different from the specified test impedance. Therefore, it is customary to assume a true detection sensitivity that is a de-rated factor of the sensitivity specified by the manufacturer.

**Noise-Limited.** Noise within the system determines the minimum discharge-induced transient voltage that is resolvable from background, unpredictable, or non-removable components of the measurement signal. Noise can take many forms, and is highly situation-dependent. The theoretical minimum noise is thermal noise in the source impedance of the measurement device.

![Diagram](image)

Figure 9. Transient detection using series resistor (this method is usually not favored due to safety considerations)
For a series resistor, measuring the power supply current transient (Figure 9), the noise voltage ($V_n$) is given by [18]:

$$V_n = \sqrt{4RkT\Delta f}$$  \hspace{1cm} (27)

where $R$ is the value of the source resistance, $k$ is Boltzman's constant, $T$ is the absolute temperature, and $\Delta f$ is the bandwidth to be detected.

For the more typical capacitively-coupled detection system (Figure 10), the source impedance is more complex, but may be approximated by a lumped capacitance in parallel with the detection resistance. The effective capacitance may typically be written:

$$C_{\text{eff}} = \frac{C_{\text{HVC}}(C_{\text{SMP}} + C_{\text{SUP}})}{C_{\text{HVC}} + C_{\text{SMP}} + C_{\text{SUP}}} + C_{\text{DET}}$$  \hspace{1cm} (28)

where $C_{\text{DET}}$ is the actual detection capacitance, $C_{\text{HVC}}$ is the high-voltage coupling capacitance, and $C_{\text{SMP}}$ is the capacitance of the test article. The power supply capacitance $C_{\text{SUP}}$ may be neglected if it is de-coupled from the rest of the circuit by a large series resistance.

Figure 10. Basic capacitively-coupled transient-detection network
For the capacitively-coupled detector, a reasonable approximation for the detection noise voltage $V_n$ relies upon the value of $C_{EFF}$ only [18]:

$$V_n = \sqrt{\frac{kT}{C_{EFF}}}.$$ (29)

Unfortunately, the thermal noise may be only a low-level quantity compared to other noise sources, especially in an industrial environment. External electromagnetic and radio-frequency interference (EMI/RFI), as well as direct coupling of noise through an AC line, may result from the operation of motors, lights, heaters, lasers, welders, and a variety of other equipment and machinery. If high-sensitivity detection is imperative, testing must be conducted in a shielded room with a sufficiently filtered supply line. In a noisy environment, in the absence of a shielded-room facility, testing should be conducted during an off-shift, or some other "quiet time," to prevent false information from being introduced into the test data.

Detection sensitivity can be increased by optimizing the bandwidth of the measurement system. The optimal detection bandwidth is determined by the relationship between the spectra of the observed electrical transients and the spectrum of noise in the system. For example, starting from a very narrow detection band, every incremental increase in detected bandwidth adds a certain amount of signal power to the detected quantity and a certain amount of noise power. If the electrical transient has a gaussian spectrum, and the noise spectrum is "flat" in the spectral vicinity of the transient, the added signal power decreases for each added increment of bandwidth while the added noise power remains constant. The optimal bandwidth is determined by the final bandwidth increment in which the added transient signal power exceeds the added noise power. The optimal detection bandwidth can be estimated for some systems, but usually the bandwidth must be optimized after obtaining actual measurements of the frequency characteristics of discharge-generated signals and the system noise.
Test Voltage

Over the course of the development of procedures for testing electrical components, increased test voltage has been a primary tool for achieving an "accelerated" test of insulation integrity. The premise of an over-voltage test is that a test article capable of passing a short duration test at increased voltage will be likely to survive an extended lifetime at reduced (operating) voltage. This idea has some basis in experimental observations, which indicate that, as a rule of thumb, a ten percent decrease in voltage results in a tenfold increase in the life of a test article. Unfortunately, the rule also implies that, under excessively high test voltage, a great deal of damage can be done to a component in a very short period of time. It is possible that an article that passes too severe an over-voltage test may later fail due to a loss in life incurred during testing.

Similar to using over-voltage as a means of "accelerating" a test, increasing the test voltage has also been used to "simulate" the operation of components at AC frequencies greater than that of the test supply. This practice stems from the observation that operation at higher frequency but identical voltage generally results in a decrease in component life (due to increased cycle count as well as polarization and relaxation effects) [13]. Therefore, testing an article designed for use at high-frequency at identical voltage, but at lower frequency, would not constitute a meaningful test. In the past, due to the general lack of test equipment for frequencies other than 60 or 400 Hz, it became prevalent to use empirical formulas to increase the low-frequency test voltage in an attempt to correlate with operation at higher frequencies.

At the time over-voltage test methods were introduced, the properties of available insulation materials limited the designed electrical stress in components to levels much lower than are now customary. As a result of the lower stress (i.e., the larger geometry of components), partial discharge activity was typically not prevalent in limiting the life of components, even during conditions of significant over-voltage.
Contrastingly, in many modern components, the quality of insulation materials permits, while pressure toward miniaturization forces, the designed stress to be much higher. Thus some low level of partial discharge/corona activity may occur during normal operation. In general, this activity will not result in a deficiency in the life of the component. However, if the component is subjected to a significant over-voltage, discharge activity can become much more intense, causing damage that may later develop into failure. Thus, the use of over-voltage testing for modern, high-stress insulation systems must be approached with extreme caution. The following test voltage guidelines are offered:

1) When over-voltage is specified as a requirement for a dielectric withstanding voltage test (such as ASTM D149), it should be conducted only on a one-time basis.

2) Every subsequent quality assurance or acceptance test should be conducted at a de-rating of 20 percent from the previous test over-voltage.

3) In general, components should be tested only at the designed operating frequency.

4) Generalized test requirements should not be applied to unique or highly-specialized systems without careful consideration of whether premature failure or deterioration of future performance may result.

5) Excessive testing of components should be avoided, especially when usable information regarding the condition of the test article will not be provided.

Test Duration

Test duration is a trade-off between accuracy and practicality. A prolonged test increases the likelihood of collecting a sufficient amount of data to provide a valid description of the condition of the test article. However, an excessively-long test may involve impractical cost and equipment/resource utilization as well as affect the future operational life of the test article.
Currently, many test specifications call for tests of such short duration that, in a well-designed DC system, for example, it may be virtually impossible for a partial discharge to occur even at a site where premature failure may be inevitable [11]. It is important that, in the future, specified test durations bear some relation to the statistical time lag over which a discharge is likely to occur. Statistical evaluation of discharge recurrence for a given system type could be used to determine the level of confidence with which data produced by a test of specific duration relate to the actual condition of a test article.

Interpretation of Results

Partial discharge and corona under near-inception-stress conditions are pulse phenomena, and appear as discrete transients of specific duration according to the impedance characteristics of the system. Corona under significant over stressing conditions (steady-state glow) may appear as a noisy offset applied to the nominal leakage current of the system, and may be best evaluated as a comparison of leakage between a "good," or "standard," system with test or suspected-problem systems.

The design of a component usually provides insight into the kind of activity to be expected from a defective or sub-standard sample. In high-voltage wires, for example, a shielded (coaxial) geometry is very unlikely to suffer from corona unless catastrophic, readily-observable defects exist in the continuity or ground connection of the shield. The failure mode of such shielded insulation is usually excessive partial discharge in voids resulting from defective materials or manufacturing processes. Conversely, an unshielded wire that is spaced some distance from a ground reference may be a prime candidate for corona, and is significantly less likely to fail as a result of discharges within the insulation. An unshielded wire excited by DC potential is likely to display erratic, pulse-corona behavior, whereas an unshielded wire excited by AC potential might easily sustain a steady-state corona.
Recently, methods of interpreting partial discharge data have been proposed that do not rely on the magnitude of apparent charge alone. Pattern recognition [24] and phase-correlation [8, 21] are two related techniques that seek to describe discharge phenomena based on the repetitiveness of pulse signatures in an AC system. In the future, for a more general, theoretical approach, correlation must be established between assumed ranges of void distribution and discharge energies, and the resultant possible apparent charges. Such studies could provide information regarding the confidence level that discharges of a specific energy are occurring within a system, given that a number of transients of specific magnitude are observed.

In many cases, data analysis based on averaging alone may not be sufficient for characterizing discharge phenomena [8]. For example, sporadic, low-level corona is likely to have little effect on the lifetime of a component built with high-quality insulation materials, although it may present a noise problem for the system. Sporadic partial discharge, on the other hand, may indicate the presence of a serious problem within a component. It may not be easy to distinguish between the electrical transients generated by these dissimilar conditions without resorting to spectral analysis or defect-localization techniques.

Finally, where constancy of test equipment and methods allow, and where the reliability of available data is good, evaluation of test results based on historical comparison may prove extremely valuable. Unfortunately, the rapid evolution of test equipment, component designs, and test parameters have made such historical comparisons difficult. But, in cases where quality assurance evaluation can compare the performance of test articles with the performance of previous test components that were observed to have favorable lifetimes, excellent test correlation might be attained.
Other Test Methods

While electrical detection of discharge transients is a widely-used and valuable technique, due to the inherent limitations discussed in previous sections, it is not practical for measuring partial discharge/corona activity in some situations. This is particularly evident when testing capacitors [25] or components with large geometry [26], or for testing in environments where direct or induced noise is a problem.

For example, a direct, electrical measurement of partial discharge or corona activity cannot practically be performed on operating power transmission equipment, so other test methods must be relied upon. A common alternative method is acoustical detection (which may be somewhat of a misnomer since it may involve detection of frequencies from audio to RF). Just as electrical detection suffers from situational limitations, acoustic detection has limitations, such as spatial propagation effects, absorption, reflection, refraction, compression, and sensor limitations [25]. A theoretical expression relating detected acoustic information to specific discharge events may be as difficult to write as the equation for a corresponding electrical signal. However, in many situations these same characteristics permit detection of an acoustic signal that is much less perturbed than the corresponding electrical signal.

Measurement of partial discharge or corona for high-voltage line insulators presents a difficult problem, since corona around the lines may dominate activity occurring in or around the insulator. Detecting excessive partial discharge within the insulators is an obvious concern, since a failing component presents an electric (and economic) burden on the transmission system, not to mention a safety hazard. In this case, an optical test based on the use of image intensifiers may be valuable for detecting external corona [26]. Optical detection of corona also offers the potential to distinguish between the amount of total power loss due to the corona activity as opposed to insulation leakage current.
A further application of non-electrical test techniques is in determining the location of discharge sites. Where the situation permits, coincident electrical and acoustic detection can provide information regarding the location of the responsible discharge [25]. For small or moderate-sized equipment, the use of an electrically-isolated wand with an acoustic detector may allow defect sites to be located by trial-and-error. In larger systems, the use of multiple acoustic sensors also allows the possibility of triangulation to the discharge site.
CHAPTER VI
CONCLUSION

From an engineering point of view, it is important to understand that theories of ionization and breakdown in gases are not capable of providing direct correlation to the real-system transients that can be observed in high-voltage systems. While research efforts have resulted in the ability to relate the characteristics of measured electrode current transients to discharges of specific magnitude in voids of specific geometry, this has been accomplished in only the simplest cases, and does not translate well into direct, real-system application.

The primary area of difficulty is that a variety of system factors combine to virtually ensure that a transient observed by a partial discharge measurement system will not be proportional (and thus, generally not traceable) to the actual discharge event that produced the transient. Among these factors are propagation effects (reflections, oscillations, damping, etc.); superposition of discharge transients with other transients and internal, external, and measurement noise; and the presence of crosstalk in multi-phase systems [21]. Two discharges of identical magnitude within voids located at different positions within a system may be manifested by two completely different transients on the measurement electrode.

In addition, the discharge events, whether partial discharge or corona, cannot be modeled by deterministic equations. For example, the time to onset of partial discharge and the discharge magnitude are governed by statistical events, such as the emergence of a free electron in an overstressed gas and the particular region of the gas in which the emergence occurs. For corona, directly-solvable equations that account for the non-
uniform field gradients, non-uniform charge-concentration gradients, electrode interactions, and statistical events within the ionization are not available.

As a result, the best course for a designer of high-voltage systems or components may be to use the available theories and experience to gain a fundamental understanding of the conditions under which discharge phenomena and corona are likely to occur, and how the phenomena might affect the life of an insulation system. By recognizing potential problem areas in system components, the designer can use in those areas design techniques that are formulated toward the prevention or limitation of discharge activity.

Partial discharge/corona testing is a necessary process for verifying component and system fitness, both during development and production phases. Currently, such testing is often performed according to specifications that were developed to address the problems of materials and applications that are no longer widely in use. Research must continue toward the development of improved test specifications and methods that:

1. Effectively determine the fitness of a component or system design for acceptable life in its particular operating environment,

2. Do not detract in any way from the integrity or life of the test article, and

3. Maintain flexibility toward advances in the understanding of discharge phenomena, the resulting effects on insulation life, and the most effective means of measuring those effects.
APPENDIX

DEMONSTRATION OF CORONA

A compact test system, such as illustrated in Figure 11, can be used to provide a striking demonstration of corona activity in air. I obtained good results when using a 28-gauge stranded, Teflon-insulated, high-voltage wire (insulation thickness approximately 0.012 inch) excited by a 15 kV AC potential, at a pressure of 10-to-20 torr.

![Diagram of test set-up for demonstration of corona]

Figure 11. Test set-up for demonstration of corona

To set up the experiment, I placed a semi-polished, aluminum ground plane (approximately 8 cm x 30 cm) inside a 6 inch-diameter cylindrical vacuum chamber fabricated from 1/2-inch wall polycarbonate tubing. I fed the high-voltage wire through the center of the vacuum chamber, bringing it out through a close-fitting hole in each endcap of the chamber. This arrangement placed the high voltage wire parallel to the surface of the ground plane, at a distance of about 5 cm above it.

I had placed a brass pipe-fitting in one of the chamber endcaps, to provide a hook-up for the vacuum pump. I attached a wire from the ground plane to the end of the brass
fitting on the chamber side of the endcap; this connection provides a means of making electrical connection to the ground plane from the outside of the chamber. NOTE: it was important that the vacuum-pump fitting, or any other metal fitting on the chamber endcaps, was located as far as possible from the high-voltage wire feed-through hole.

I terminated the high-voltage wire coming from one end of the vacuum chamber to the high-voltage power supply output probe. I placed a polished, steel sphere, with a hole drilled in it, over the end of the probe to minimize electron emission from the high-voltage connection. NOTE: for safety purposes, I isolated the high-voltage connection at least 5 cm from any nearby conducting surface, and physically shielded it so that no inadvertent contact with it could occur. Also, the end of the high-voltage wire coming from the other side of the vacuum chamber was isolated from contact with any conducting surface (for example, by molding the end of the wire in a glob of RTV silicone).

I attached the ground output from the high-voltage power supply to the brass fitting for the vacuum pump, on the outer side of the chamber endcap. NOTE: it was imperative that all metal surfaces that came into contact with, or fed through, the walls of the vacuum chamber were electrically connected to this ground. Otherwise, during a test, these conductors might have floated up to a high potential, and presented an extreme safety hazard.

To perform the experiment, I powered up the vacuum pump and regulated the chamber pressure to the desired level. After this was accomplished, I activated the high-voltage power supply and adjusted the output voltage. I turned off the room lights (the room must be almost pitch black to see the corona, so it was necessary to use electric tape to mask any pilot lights on power strips, the vacuum pump, or the high-voltage supply). With my eyes adjusted to the darkness, I could see the corona as a compact, violet-glowing sheath around the wire, through the entire length of the vacuum chamber.
REFERENCES


