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A STUDY OF INSULATOR BREAKDOWN UNDER NAVY ANTENNA HV RF CONDITIONS

C. N. Richards

Science Applications, Incorporated

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Conditions leading to initiation of corona streamers and breakdown in gases are reviewed. The effect of electric field strength at electrode surfaces and the pressure of the gas in the electrode gap on the accel_ration of free

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electrons with the ions and molecules in the gas are identified. The presence of water drops or contaminants can reduce corona onset field from about 30 KV/cm to about 6 KV/cm, can affect the voltage distribution, and can cause heating in strong VLF fields.

CONTENTS

I. INTRODUCTION

Conditions leading to initiation of corona streamers and electrical breakdown in gases are dependent upon several parameters. However, the most important parameters (and these which have received the most attention historically) are the electric field at the electrode surfaces and the pressure of the gas in the electrode gap. The reason for this importance can be seen by examining the basic physics involved in the initiation of an electrical discharge. The electric field must be large enough to accelerate free electrons to an energy sufficient to cause ionization of the gas molecules. The rate at which the electrons lose energy depends upon the collision frequency of electrons with the ions and molecules in the gas, thus the importance of the gas pressure on the initiation. Early research on electrical discharges (see for example Ref. 1) concentrated on just these two parameters, yielding empirical formulae which are valid for certain pressure regimes. Much of this work was performed with gas discharge tubes and as such was done at low pressures and with d.c. voltages. Later, as industry prompted it and technology made it possible, breakdown in air at pressures of one atmosphere with alternating voltages was studied (see for example Ref. 2). Even though much work has been done in the field of electrical breakdown, the number of parameters which can influence both the initiation and propagation of electrical discharges is almost endless. Unfortunately, the basic physical processes which are affected by the various parameters are not easy to describe mathematically, thus simple scaling laws cannot be written except for a few special cases. In the next section we shall examine the basic physical processes which occur in electrical breakdown and indicate when each is significant.

II. EFFECTS OF VARIOUS PARAMETERS

Let us first examine the parameters which are important for the initiation and propagation of electrical breakdown in the absence of any contaminants. They are as follows:

A. Electrode surface electric fields
B. Pressure and temperature of gas
C. Composition of gas
D. Field distribution throughout gap
E. Gap length
F. Waveshape of applied voltage

Now let us examine each of these parameters in turn.

2.1 ELECTRODE SURFACE ELECTRIC FIELDS

In any electrode configuration filled with gas the maximum electric field occurs at the surface of one of the electrodes. This is one of the reasons for the fact that electrical discharges initiate at electrode surfaces. The initiation process is dependent upon both the magnitude of the surface electric field and the polarity of the electrode. Let us consider each polarity separately.

1. Negative Polarity - When the electrode is negative and the surface electric field great enough (in excess of 30 kV/cm for an air pressure of one atmosphere) free electrons, which are usually present in concentrations of about $10^3/cm^3$, are accelerated away from the electrode by the electric field up to energies great enough to produce ionization of the gas molecules. This ionization not only produces an electron avalanche, but also leads to the production of ultraviolet radiation. This radiation produces emission of photoelectrons from the cathode

and photoionization of the gas. The negative streamer produced by this process in about 10^{-9} seconds is diffusive, i.e., the electrons tend to diffuse due to the negative space charge, and will rapidly attach to electronegative molecules such as oxygen. The propagation of this streamer into the gap depends upon the electric field configuration throughout the gap as we shall discuss shortly.

2. Positive Polarity - Electrical breakdown begins at positive electrodes when a free electron is accelerated toward the electrode to an energy sufficient for ionization and subsequent avalanche. However, in this case the resultant streamer is "conservative", i.e. the flow of electrons is from the gas into the streamer channel, thus giving it a filamentary appearance. Because of their conservative nature they tend to propagate faster and farther into the gap, depending upon the field distribution in the gap.

2.2 PRESSURE AND TEMPERATURE OF THE GAS

As we indicated in the introduction, as the pressure in the gas is increased, the rate of energy loss by the electrons to the gas constituents increases, thus opposing the effect of the electric field to initiate breakdown. It is for this reason that breakdown voltages are lower at higher elevations. This fact should be kept in mind when siting any high voltage equipment.

The effect of temperature on breakdown is negligible at room temperatures. It is only when the temperature of the gas is significant when compared with the ionization potential of the gas constituents. Such temperatures are of the order of several thousand degrees.

2.3 COMPOSITION OF GAS

The composition of the gas in the gap is important to breakdown phenomena in a way which is similar to the effect of pressure. Some gases will absorb the electron energy better than others, e.g. SF_6, and O_2 have electron affinities and will attach electrons where as H_2 and N_2 absorb very little electron energy. Thus air can be represented as a mixture of gases, one of which will attach electrons; the other will not.

2.4 FIELD DISTRIBUTION THROUGHOUT THE GAP

The field distribution in the gap affects the propagation of the electrical discharge. If the field is uniform throughout the gap, both negative and positive streamers will rapidly bridge the gap at speeds of the order of 10^7 cm/sec, producing electrical breakdown. If the fields are highly nonuniform, with large electrode surface fields and much smaller mid gap fields, the streamers will usually end in mid-gap. However, as we shall see below, the propagation of streamers in highly nonuniform fields can be affected by the waveshape of the voltage applied to the electrodes.

2.5 GAP LENGTH AND APPLIED VOLTAGE WAVEFORM

We choose to discuss the effects of gap length and voltage waveform in a single section since the two together determine the subsequent behavior of corona streamers. The initiation of the streamers are essentially independent of the voltage waveforms, pulsed or a.c., if the period of the waveform is longer than about 10^{-8} seconds. This is due to the fact that the initiation takes place in about 10^{-9} seconds. Thus it is safe to treat a.c. voltages as if they were d.c. for 60 Hz through VLF for the initiation process. Let us examine, however, the behavior of the corona streamers in d.c., 60 Hz and VLF fields for various gap lengths in nonuniform fields. In d.c. fields the corona streamers take the appearance of a short brush-like, bluish-pink glow. In effect the space charge produced by the streamer "chokes" it off until the space charge has time to diffuse via its self-field. The ions in the streamer have a mobility of about 1 or 2 cm/sec per volt/cm at a pressure of one atmosphere. The mobility of the free electrons have a mobility of about 10^3 that of the ions. Thus if the space charge field is of the order of 10 kV/cm, the diffusion speeds of the ions will be about 10^4 cm/sec and the speed of the electrons will be about 10^7 cm/sec. The rate at which the free electrons attach to molecules is between 10^{-3} and 10^{-5} attachments per collision (Ref. 3). Thus the electrons attach in about 10^{-6} seconds and the diffusion is limited in either positive or negative corona by the diffusion of ions. After the space charge has been removed by diffusion, the conditions are right for initiation of the streamer and the process is repeated.

The situation for corona at 60 Hz is similar, during each half cycle of the sinusoidal wave there is ample time for the ions to be drifted out of the gap after the corona streamers have occurred and before the applied field has reversed direction.

At higher frequencies and longer gaps, however, we approach a point at which there is not ample time for the space charge to be diffused out of the gap. As an example let us assume a nonuniform field atmospheric gap with a spacing of 1 meter between electrodes. Let us further assume that the peak (time-wise) mid gap field is approximately 1 kV/cm, that is oscillates with a frequency of 25 kHz, and that the surface electric field at one of the electrodes (say electrode A) is sufficient to initiate negative corona. Now let us use the results of the previous discussion to predict what will happen. Corona onset will occur near the peak of waveform at electrode A (see Fig. 1). Then there will be a time period of 10^{-5} seconds (1/4 of a period) during which the space charge will be drifted in the mid gap field. Free electrons will be drifted approximately

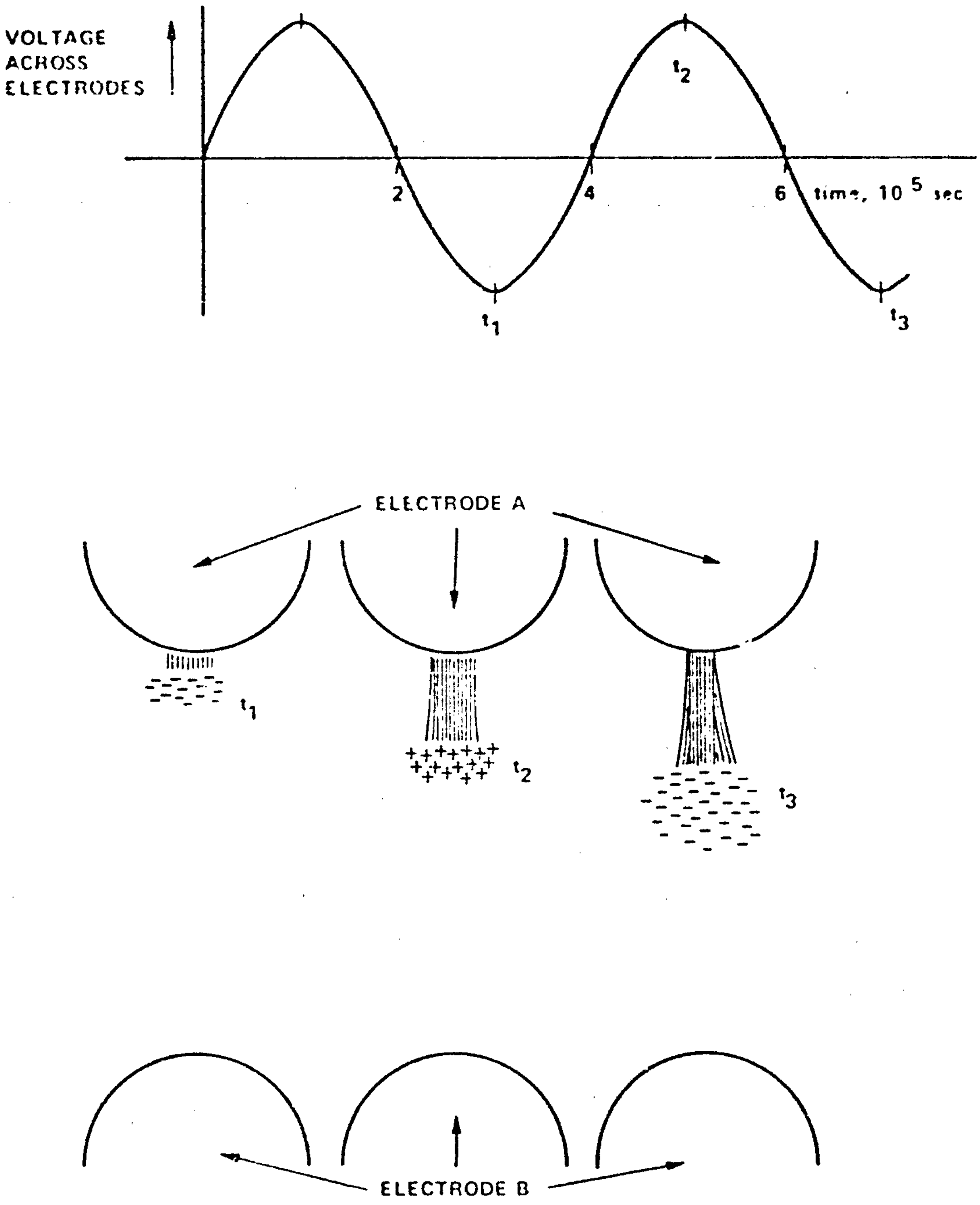


Fig. 1. Pictorial Description of Postulated Breakdown Process

10 cm during that period, failing to reach the opposite electrode. After the initial 10^{-5} seconds, the electric field goes to zero and the electrons attach to the gas molecules. As the electric field increases in the opposite direction, the presence of the negative ions creates a larger field at electrode A which is now positive, such that a positive discharge is launched to the region of the negative ions. This discharge leaves the mid-gap region with a positive space charge. Thus on the next half of the cycle the process will be repeated and the discharge will extend farther into the gap. Eventually, after several cycles, the discharge completely bridges the gap.

The difference in this case as opposed to the d.c. or 60 Hz is that during each half-cycle energy is pumped into the ionized channel left from the previous half-cycle.

III. EFFECT OF IMPURITIES

The effect of the presence of impurities such as water drops, salt particles, or ice particles in the gap is to cause electric field enhancement. For example if a conducting sphere is placed in a uniform electric field of magnitude E, the maximum field at the surface of the sphere is 3E.

The effect of the field enhancement is to initiate electric discharges which would not ordinarily occur. Thus the study of the effect of impurities on breakdown initiation is of great practical importance to the design of tower base insulators since these insulators are exposed to an open environment.

3.1 WATER

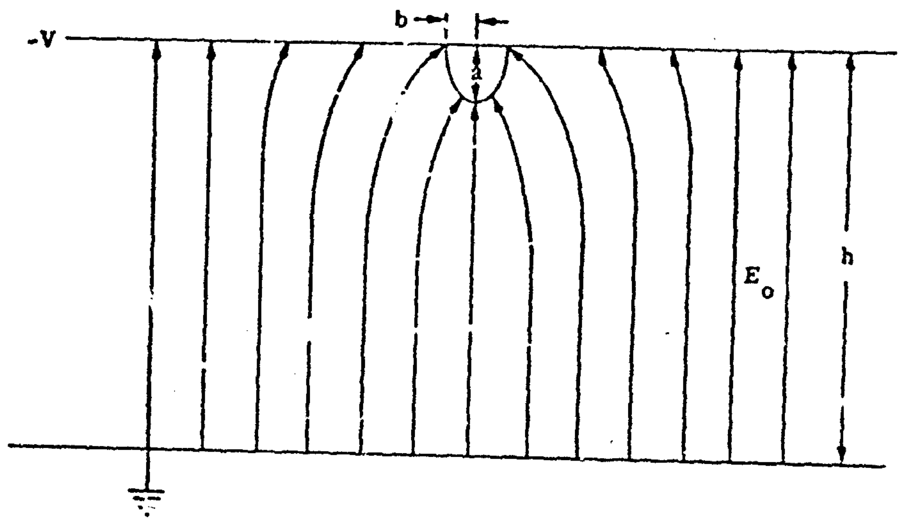
The impurity which appears to be the most likely to produce breakdown problems in liquid water since it represents a deformable conductor. As such it is susceptible to deformation by strong electric fields. The deformations thus produced cause even greater field enhancements. For sufficiently large fields, the electrical stress on the water surfaces is sufficient to completely overcome the counteracting stresses due to surface tension. When this occurs the water drop becomes unstable, begins to pull apart and produces such high fields that breakdown is initiated. Extensive research has been done in this field, especially for d.c. fields (see, e.g., Ref. 4).

3.1.1 Constant Electric Fields

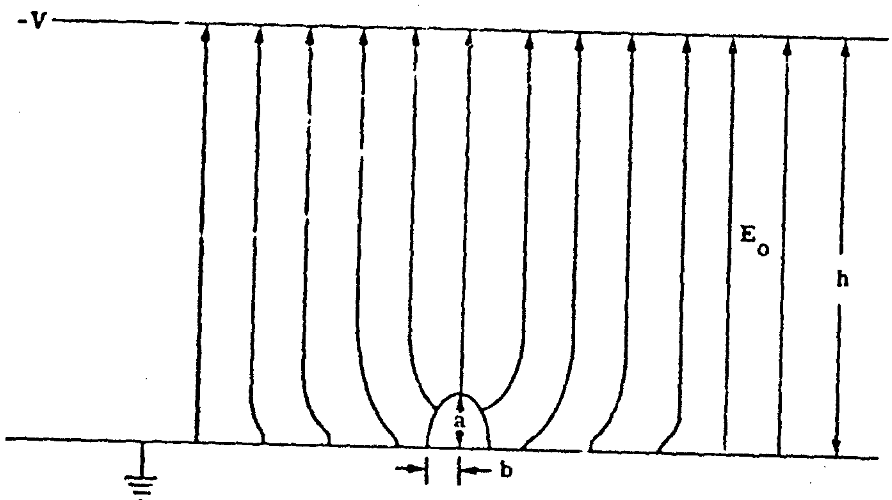
Considerable insight into the physics of the instability of water drops and subsequent corona initiation can be obtained by considering in detail the equilibrium (both stable and unstable) shapes of hanging and standing water drops as shown in Fig. 2. We shall assume the drops to be placed in an electric field which, prior to the insertion of the drops, is uniform and of magnitude E_o. It has been shown (Ref. 4) that the shape of conducting drops in electric fields can be very well approximated by a prolate spheriod, thus so are half prolate-spheroids attached to electrodes. The equation of motion of a prolate spheroid can be written in closed form. We shall omit the derivation (similar to those given in Ref. 4) and give the result:

$$\frac{d^2 a}{dt^2} = \frac{8a\,\xi_o^2}{\rho_w r^3(\xi_o^2-1)(3\xi_o^2-1)}\left[\sigma - \frac{\epsilon_o E_o^2 a}{4(\xi_o^2-1)]Q_1(\xi_o)]^2}\right] + \frac{3}{2a}\,\frac{(\xi_o^2-1)}{(3\xi_o^2-1)}\left(\frac{da}{dt}\right)^2 \pm \frac{g\cdot 2\xi_o^2}{(3\xi_o^2-1)} \quad . \tag{1}$$

In this equation a is the distance from the electrode to the tip of the drop, ρ_w is the mass density of the drop, r is the equivalent radius of the drop if it were a hemisphere, σ is the surface tension of the drop, g is the acceleration due to gravity, ϵ_o is the permittivity of free space, ξ_o is the prolate-spheroidal coordinate which defines the surface of the drop and $Q_1(\xi_o)$ is the first-order Legendre function of the second-kind. (Reference 4 gives a more detailed definition of ξ_o and $Q_1(\xi_o)$.) The sign of the last term in Eq. (1) is positive for a standing drop and negative for a hanging drop. All quantities are in MKS units. Equation (1) can be used to find the stationary equilibrium shapes and the criteria for instability of those shapes. This is done by setting the time derivatives to zero assuming a constant electric field, E_o, and rearranging to obtain:



a) Water Drop Hanging in an Electric Field E_o



b) Water Drop Standing in an Electric Field E_o

Fig. 2. Water Drops cn Electrodes

$$\frac{\epsilon_o E_o^2 r}{2\sigma} = \frac{2(\xi_o^2-1)^{4/3}[Q_1(\xi_o)]^2}{\xi_o^{2/3}} \left[1 \pm \frac{\rho_w g r^2}{4\sigma} \frac{(\xi_o^2-1)^{4/3}}{\xi_o^{2/3}}\right] . \quad (2)$$

We have written Eq. (2) in a form such that each of the terms are dimensionless, thereby showing the relative importance of each of the parameters. Figure 3 gives the family of curves obtained from Eq. (2) for several different-size drops. The unstable equilibrium shapes occur at the inflection points of those curves. These inflection points show the values of the electric field E_o which, if exceeded, produce instability and thus corona onset. Such a value of the electric field is known as the instability onset field. A plot of the instability onset field for various-sized drops is shown in Fig. 4. The curves in Fig. 4 show that the instability onset fields are smallest for large, hanging drops. However, a critical size of $r \cong 4.5$ mm occurs for which hanging drops become gravitationally unstable and fall off. This occurs when the gravitational force on the drop exceeds the integral over the surface of the surface-tension stress. Thus there is an upper limit of the size of drops which will become electrohydrodynamically unstable, namely $r \cong 4.5$ mm. The curves of Fig. 4 show that the smallest instability onset field is about 6.0 kV/cm for constant, uniform fields.

Even though the shape of the water drops are not exact prolate spheroids, it can be shown that the approximation is very good. We have tried to obtain better approximations by numerical techniques and failed. Figure 5 shows the detailed field configuration near a typical, large, hanging drop. This plot shows a field enhancement at tip of the drop to be about the same as a prolate spheroid with $a/b = 1.75$. The difficulty in using numerical techniques lies mainly in the inability to accurately calculate the gradients of the surface-tension stress and the electrical stress.

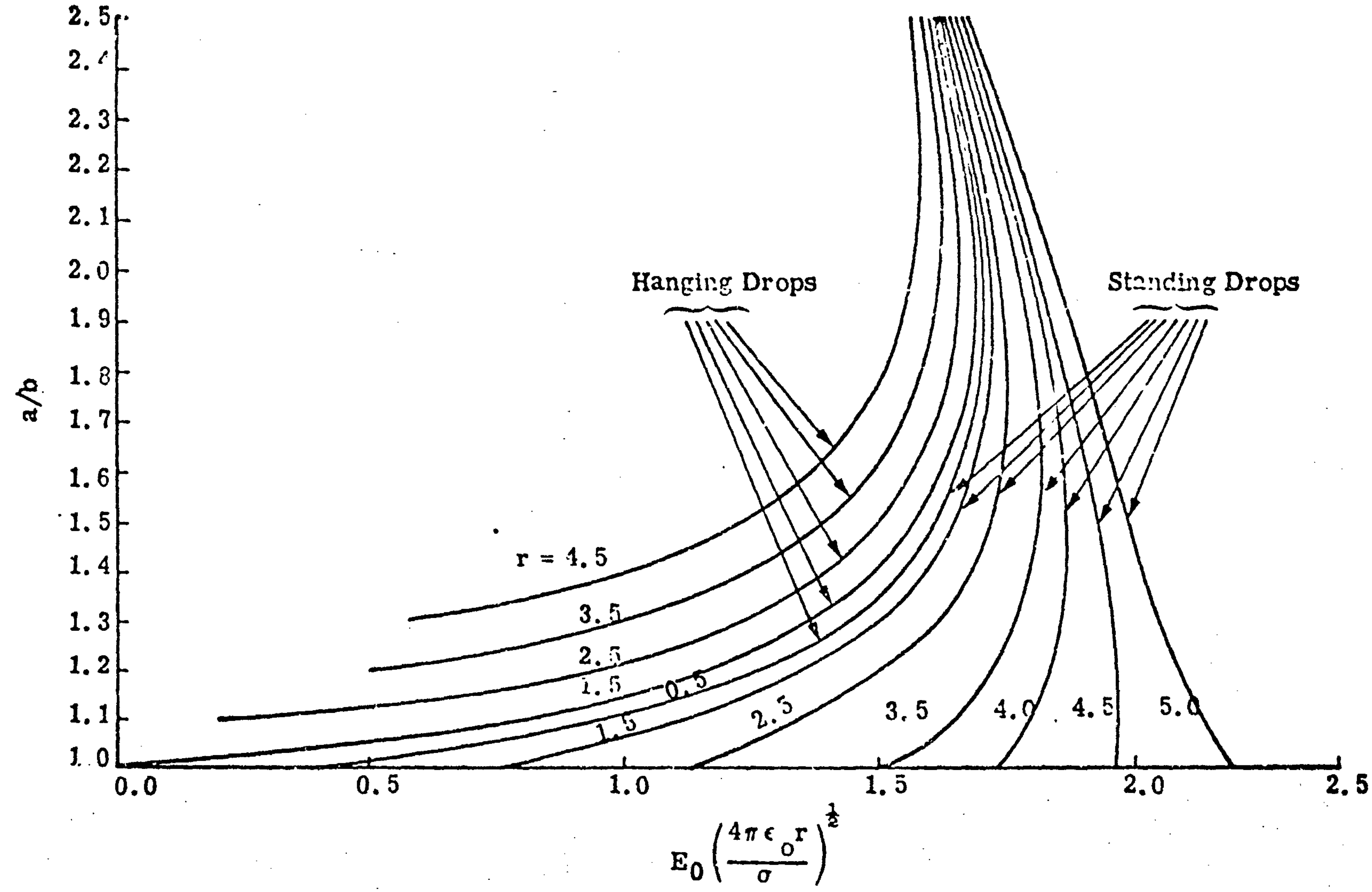


Fig. 3. Equilibrium Shapes for Hanging and Standing Water Drops

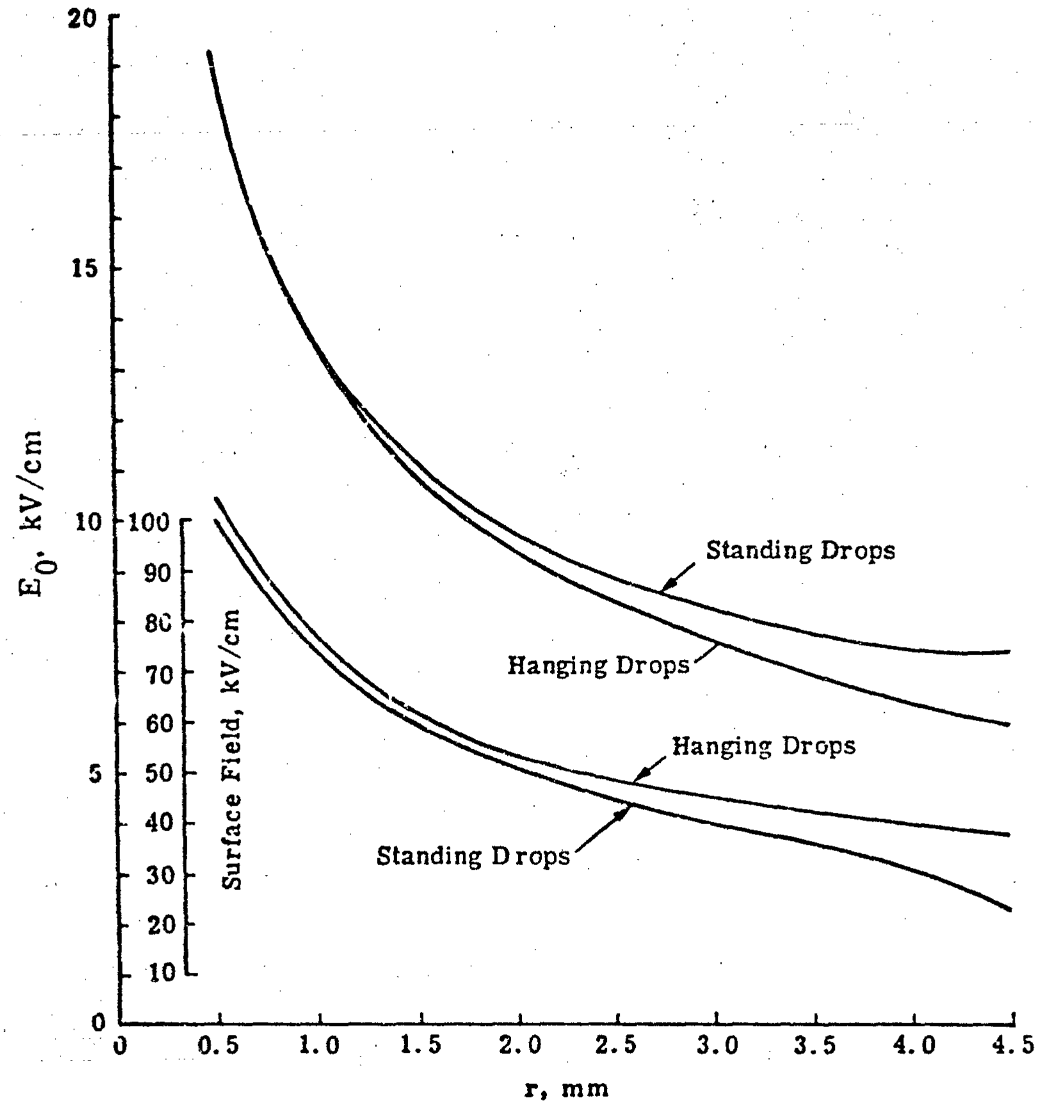


Fig. 4. Instability-onset Fields for Hanging and Standing Water Drops

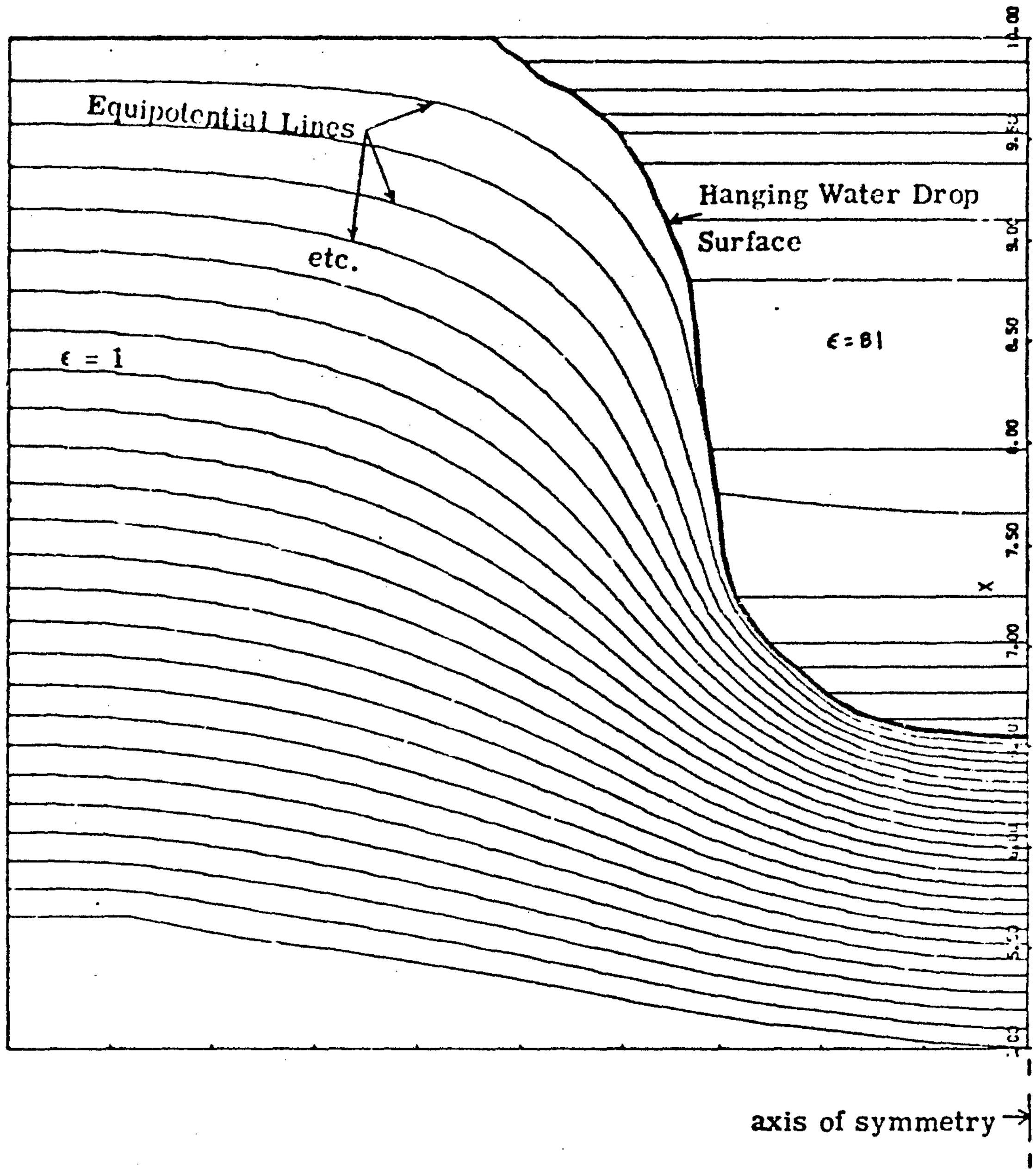


Fig. 5. Calculated Field Distribution about a Large Hanging Drop

3.1.2 Time-Varying Electric Fields

In order to obtain a complete picture of the effect of time dependent fields on water drops one would have to solve Eq. (1) with the correct time dependence given to E_o. We have not been able to find a closed-form solution for this equation when E_o is sinusoidal.

We can estimate the effect of the time-varying fields by looking first at the resonant oscillation frequency of various-sized drops. The resonant frequency of a drop in a field-free region drop is given by

$$f = \frac{1}{\pi}\left(\frac{2\sigma}{\rho_w r^3}\right)^{\frac{1}{2}} \quad . \qquad (3)$$

Equation (3) predicts resonant frequencies in the order of 100 Hz for drops of about 1 mm radius. Thus the drop sizes of interest have resonant frequencies much lower than VLF implying that the time dependence of the VLF fields probably do not enhance instability via a resonance effect.

The effect of an alternative electric field is to stress the drop electrically on each half cycle of the waveform. Thus the effective electric field--that which produces instability--will occur between the RMS and peak electric field, probably near the peak field.

3.2 OTHER IMPURITIES

Other impurities which can lower the onset fields at VLF and degrade the performance of insulator assemblies can be grouped into two categories: (a) those which strongly absorb electrical energy at VLF, and (b) those which are good conductors. The absorption and conductivity of many substances at VLF frequencies are not known and should be measured before use in any VLF application.

The presence of ice (or snow) can affect electrical breakdown at VLF if the conductivity of the ice exceeds about 10^{-7} mho/m. Typical values of the D.C. conductivity of ice are 10^{-8} mho/m. It would appear that solid ice particles will not enhance breakdown but large amounts of snow, because of the high dielectric constant of ice, can strongly affect field distributions.

The initiation of corona can be affected by the presence of conducting solid particles. The determination of the exact onset field for different materials cannot be made theoretically but an approximation can be found by a method similar to that of the water drops. Assume the particle to have a shape factor a/b where a is the length dimension of the particle in the direction of the field and b is the length dimension of the particle in the direction perpendicular to the field. Figure 6 shows the field enhancement which these particles would provide if they were prolate spheroids. Given the surface onset field of the material (~ 30 kV/cm for conducting crystals), Fig. 6 provides a method of estimating the ambient onset field.

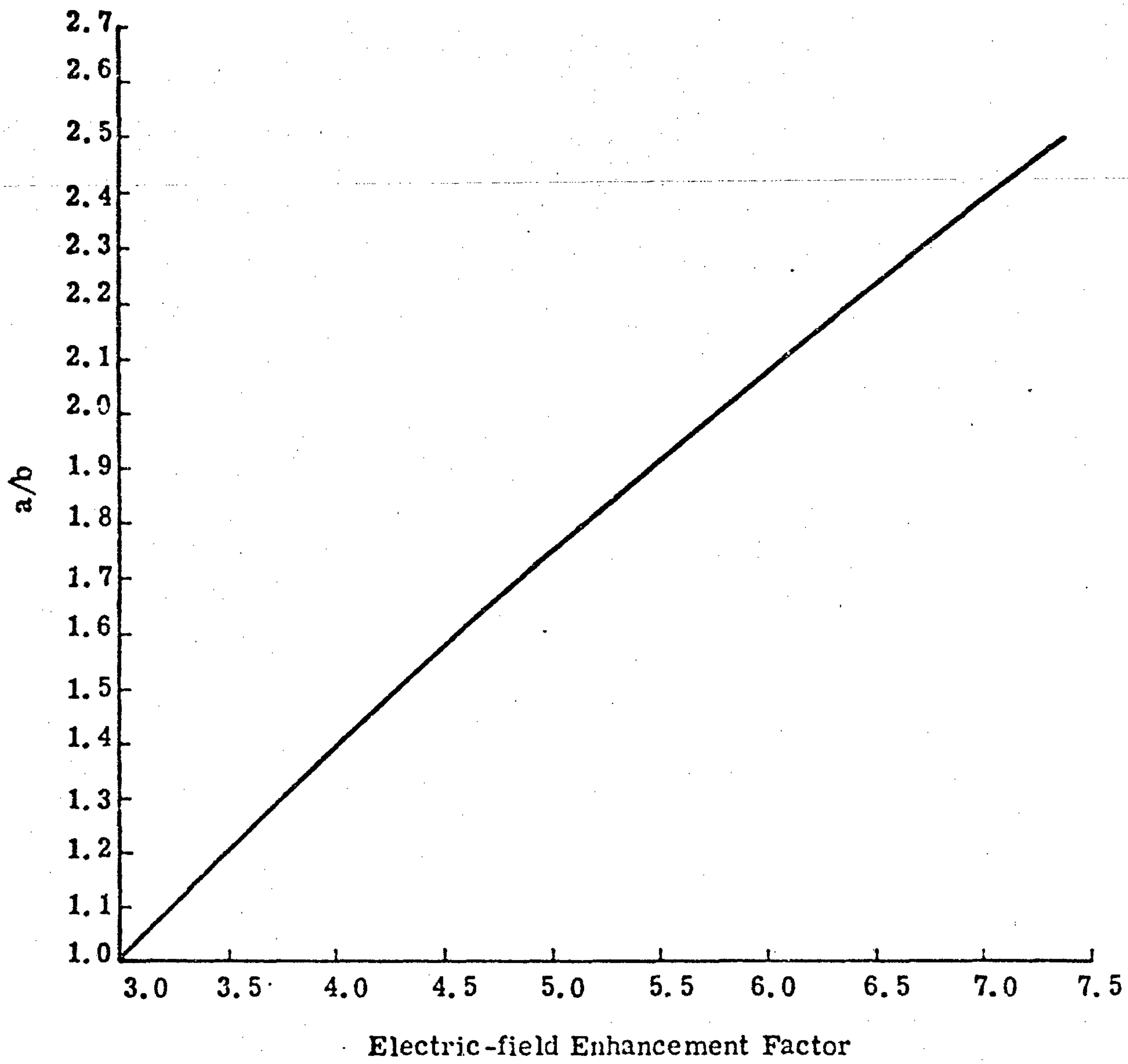


Fig. 6. Electric Field Enhancement at Surface of Prolate Spheroids

IV. CONCLUSIONS AND RECOMMENDATIONS

This effort has produced the following conclusions and recommendations.

4.1 CONCLUSIONS

1. The presence of contaminants in VLF gaps can affect the performance of insulator assemblies in three ways. Firstly, and most importantly, the corona onset field can be reduced from about 30 kV/cm to about 6 kV/cm by the presence of water drops or other similar, conducting liquids. Secondly, the presence of contaminants with a high dielectric constant can affect the overall voltage distribution across an insulator assembly, thereby overstressing regions within the assembly. Thirdly, dielectric heating can occur when certain contaminants are in high VLF fields.

2. A review of the literature shows a glaring lack of experimental data and theoretical effort in the following areas of VLF breakdown:

   a. There exist extremely little experimental data on the breakdown of long gaps (> 10 cm) with either uniform or non-uniform fields and with and without contaminants.

   b. Very little work has been performed modeling the basic physical phenomena which occur in long gaps (> 10 cm) in order to accurately predict breakdown under those conditions.

   c. The basic phenomena of the instability of water drops and corona onset in time-dependent fields has received almost no attention, either theoretically or experimentally.

4.2 RECOMMENDATIONS

4.2.1 Experimental

It is recommended that an experimental program be established to determine the effects of the following parameters on the breakdown criteria:

a. Effect of time dependent fields (VLF) on the basic phenomena of water drop instability and corona initiation (laboratory study using ~ 5 cm gaps).

b. Effect of gap length (in both uniform and non-uniform VLF fields (gap lengths up to 1 meter).

c. Effect of ice and salt crystals to initiate corona (laboratory study using ~ 5 cm gaps).

Additional experiments should be performed which will determine the susceptibility of various materials to dielectric heating. Some of the materials which should be tested are:

1. Portland cement
2. RTV compounds
3. Ice and water
4. Low-alumina porcelain

4.2.2 Theoretical

a. Extend theory described in this report to analyze the effect of time dependent fields on the instability of water drops.

b. Build a theoretical model which will analyze the initiation of corona, and the propagation of breakdown streamers in VLF fields. This model should include electron attachment and recombination, electron and ion diffusion and the electric fields due to space charge.

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