CHARACTERISTICS OF CORONA UNDER ALTERNATING CURRENT CONDITIONS

by

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INTRODUCTION

The investigation presented in this thesis is a furtherance study of the behavior or various corona mechanisms present in an alternately positive and negative electrically overstressed medium of air. An immediate consequence of the study was a need for some classifying terminology in order that one mechanism may be distinguished from another. This in turn demanded thorough consideration of such characteristics as polarity of the overstressed electrode, comparability of electrode curvature to average intermolecular dimensions, pulse repetition frequencies and relative pulse amplitudes.

The study was accomplished using the classical point-to-plane geometry in conjunction with oscilloscopic presentation.

THE 60 CYCLE CORONA GENERATOR

The power equipment used to energize and control the high voltage circuit is illustrated in figure 1-a. The equipment circuit is schematically shown in figure 2. The available waveforms are shown in figures 3-a and 3-b. Figure 3-a is the voltage waveform obtainable below about 50 kilovolts peak. Figure 3-b shows the distortion present for voltages above about 60 kilovolts peak.

The high voltage transformer was calibrated in conjunction with two voltmeters (for complete range coverage) and a 6.25 centimeter sphere gap. The gap was irradiated with ultraviolet light for spacings less than 1.0 centimeters. (This was to insure flashover stability.) The calibration was finally corrected to a relative air density of unity which corresponds to 760 millimeters of mercury and 25 degrees centigrade.

The plane electrode is cast aluminum 14 inches in diameter. The radius of the rounded edge is 0.875 inches. The plane axis is 22 inches above the ground sheet.

The dual electrodes (best shown in figure 1-b) are aluminum rods 0.25 inches in diameter and 1.375 inches apart. The left electrode has the facilities to hold a microdimensional point. The right electrode occasionally acts as a macrodimensional point. Both electrodes are continuously adjustable for gap spacings between zero and nine inches.

The two resistors seen in figure 1-b serve as terminating resistances for the corona generator. They are usually matched at about 1000 ohms each. Electrode connection is made by a contact screw (not shown.)

(a)

(b)

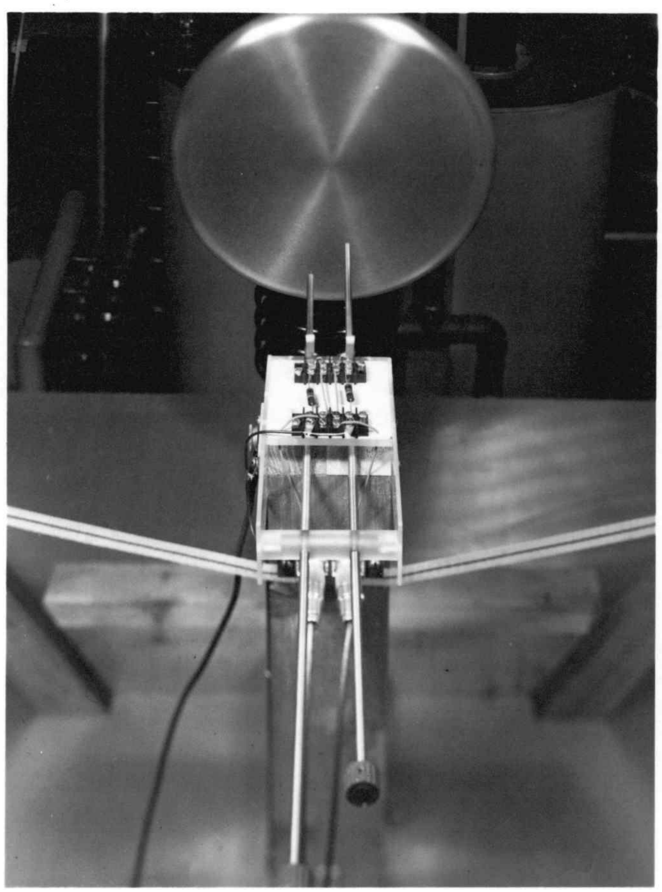


Figure 1. Upper picture (a) shows apparatus used in conjunction with corona research. Present are the isolation and high voltage transformers, resistor divider, plane electrode and supporting insulator, point electrodes, calibrated gap potential voltmeters, Tektronix Type 535 oscilloscope and DuMont oscillographic camera.

Lower picture (b) shows dual-electrode point-to-plane corona generator with termination resistors.

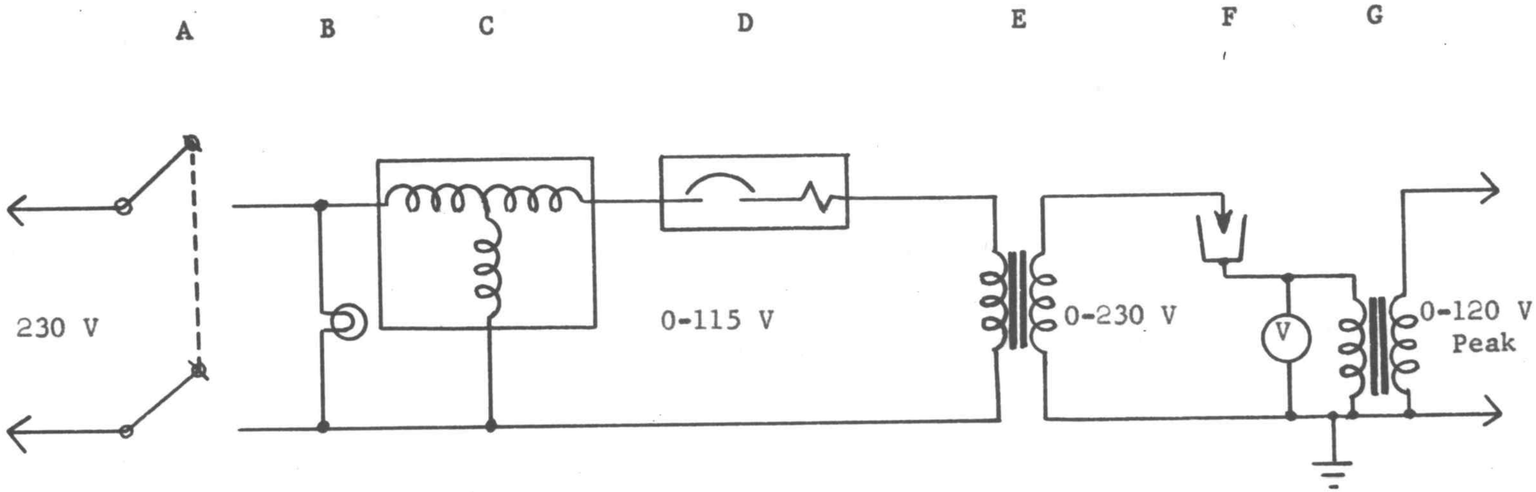


Figure 2. Schematic diagram of the power circuit used to derive the high voltage waveform. Knife switch "A" and magnetic circuit breaker "D" uphold the safety requirements of having two switches in a high voltage circuit. "B" is a red warning lamp. "C" is a manually controled induction regulator (± 50%). Transformer "E" provides isolation, thus eliminating common grounds. Variable series voltage dropping is provided by water box "F". This enables the induction regulator to operate on the high end of its scale over all voltage ranges, thus minimizing harmonic distortion. "G" is the high voltage transformer calibrated with voltmeter "V".

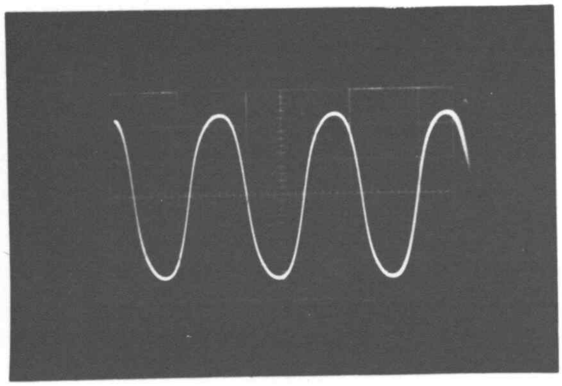


Figure 3-a. High voltage waveform when gap potential is less than 50 kilovolts peak. (Taken from a resistor divider.)

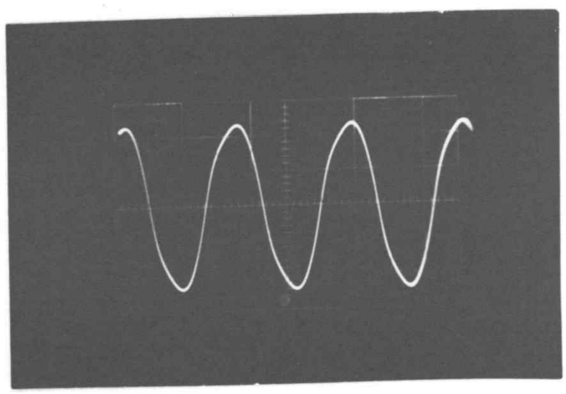


Figure 3-b. High voltage waveform when gap potential is greater than 60 kilovolts peak.

CLASSIFICATION OF VARIABLES CAUSING CORONA VARIATIONS

In general, corona is a result of an electrically overstressed medium caused by some field distorting electrode. The distortion is divergent so that complete breakdown of the gap does not occur. The medium is usually gaseous and exists at various temperatures and pressures. The electrode material is not restricted to conductors, only to materials having dielectric constants unlike that of the medium's. Also, the electrode does not need to be directly connected to one side of the voltage source since capacitive coupling is always present.

There are several well known forms or types of corona. They are commonly known as "positive, negative, spot, burst, streamer or plume." They are characterized as being repetitious impulses of current that may or may not be recursively stable. Another variable characteristic is relative pulse height, which is fundamentally related to the total charge transfer.

With all of the aforementioned variables it is immediately necessary to provide some form of classification. Since this present investigation is concerned with air at near-standard conditions and employs the metallic point-to-plane geometry, the forthcoming classifications will be limited accordingly. All that will be mentioned has been observed in the laboratory under research conditions.

Fundamentally there are two distinct types of coronas.

These are the positive and negative coronas where the adjectives "positive" and "negative" describe electrode polarity. The variations in characteristics that tend to distinguish between two or more mechanisms of like polarity are attributed to the following:

1. Minimum exposed electrode radius. If this radius is microdimensional (relative to about 0.1 inches) the corona produced will be quite different compared to any produced by a macrodimensional electrode. This is because molecular dimensions will not change with a scaling of electrode geometry. For this reason alone extrapolation of scale model results is prohibited.
2. Magnitude of overstressing relative to that at which corona first appears. If the overstressing voltage gradient is continuously increased, the initial corona mechanism may successively change to several different forms before the gap breaks down. Also of importance is any time rate of change of voltage. Corona characteristics recorded at some instantaneous value of a changing voltage will be different compared to the corona characteristics at the same value of d-c voltage.
3. "Condition" of the electrode. If the electrode accumulates deposits of foreign material such as dust, corona characteristics will change. Also,

long time use under super-stressed conditions will alter electrode characteristics (3).

4. Impedance and response of the circuitry between the corona generator and the observer. This factor is one of the most important contributions to observed variations in corona. The corona mechanism itself is apparently not affected by circuit impedance but the passive response of the connecting cables and the active response of the oscilloscope can and does mislead the observer.

Summarizing, corona classification should include electrode polarity, electrode type, electrode physical condition, relative magnitude of overstressing and some mention of measuring circuit constants.

THE IMPULSE MEASURING CIRCUIT

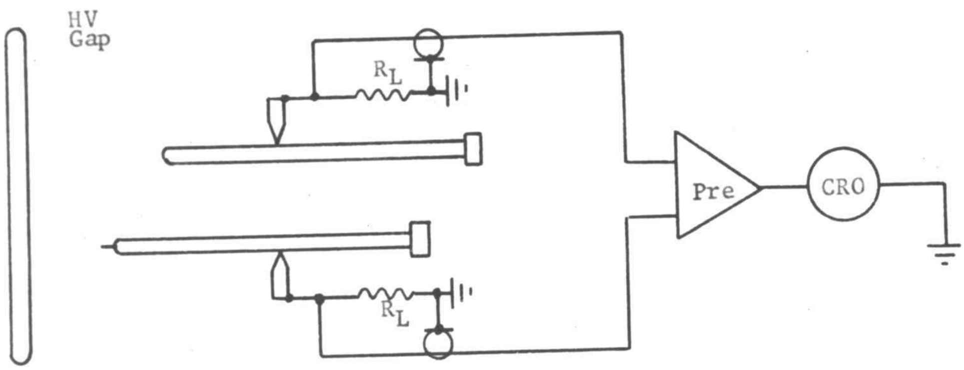
Referring to figure 4-a, the point and plane electrodes are shown constituting the high voltage gap, thus forming the corona generator. This generator, which provided impulses of current, is essentially terminated by the resistance R_L. At this point a 36 inch coaxial cable (RG 29/U) is connected to provide shielded coupling to the instruments. Since R_L needed to be on the order of 1000 ohms for adequate gain, it was not feasible to attempt impedance matching.

The displaying instrument primarily consisted of a Type 535 Tektronix oscilloscope with any one of the many Tektronix plug-in preamplifiers. Among those used were the differential, dual-trace, wide band and fast-rise units. The oscilloscope was equipped with a long persistence (Type p-11 phosphor) cathode ray tube.

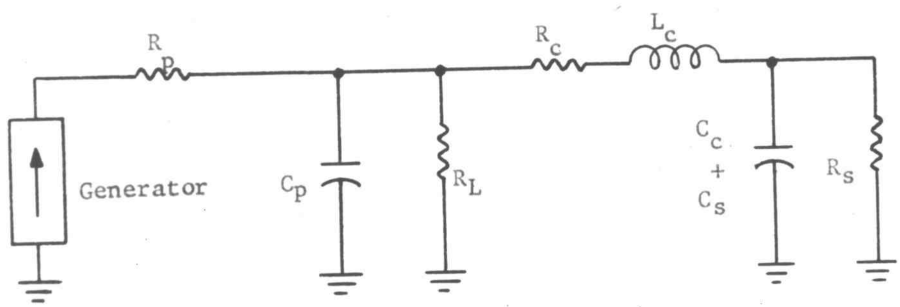
Two different cameras were employed for visual recording. One was a Polaroid Oscilloscopic Land Camera. The other was an Allen B. DuMont Oscilloscopic Camera utilizing $2\frac{1}{4}$ by $3\frac{1}{4}$ graphic film. Both cameras were equipped with f1.9 lenses.

At certain times it was also necessary to record radio influence voltage. This was done with a Stoddart Field Intensity meter (9).

Figure 4-b is the impulse equivalent of the entire



(a)



(b)

Figure 4. Upper drawing (a) shows the dual-electrode point-to-plane generator with its terminating resistances. (R_L). Connection to instruments is made with shielded cable (RG 29/U).

Lower drawing (b) is the impulse equivalent circuit of (a).

measuring circuit. The generator is that of any one of the corona mechanisms and includes its internal impedance. R_P and C_P represent the series resistance and shunt capacitance of the electrode and contact screw. R_c, L_c and C_c are the lumped constants of the coaxial cable. R_s and C_s represent the preamplifier input impedance.

The voltage waveform appearing at the input to the preamplifier is not a true picture of the corona current impulses. In fact, the waveform appearing across R_L is not even a true picture. Assume an impulse of current (either polarity) from the generator. This impulse has finite risetime. Being a current the tendency is to create a voltage drop across R_L in proportion to itself. However, the electrode stray capacitance to ground must accumulate charge fast enough so that its potential is exactly the same as R_L's. Fortunately, both R_p and C_p are very small and their time contribution to the voltage risetime across R_L is small.

The voltage falltime incorporates another story. The impedance seen looking back into the corona generator is practically infinite. Therefore C_p must discharge through R_L (R_s is very high). This causes a time contribution of approximately R_LC_p to that of the normal impulse falltime. This is approximately R_L divided by R_p times longer than the time contributed to the risetime.

Continuing, the voltage risetime that occurs across the preamplifier input is necessarily the time required to charge C_c plus C_s through R_c and L_c by whatever is available across R_L. Further, whatever charge manages to accumulate on C_c plus C_s must eventually discharge through either R_s or R_L. Since R_c and L_c are also very small the latter route will be favored.

In addition to the waveform modification by the passive network, there is also the very finite risetime of the preamplifier and the vertical amplifier of the oscilloscope. This completes the distortion of the very thing the viewer wishes to see.

Some examples of circuit response may be seen in figures 5-a,b,c,d and e. These are pictures of identical pulses (negative microdimensional corona) seen by the observer when R_L equals 5, 33, 50, 1000 and 10,000 ohms respectively. All resistors are deposited carbon. In figure 5-a ($R_L = 5$ ohms) there is some ringing. This indicates some natural circuit inductance that relies on R_L for damping.

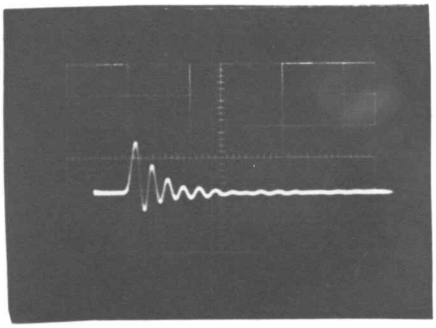


Figure 5-a. Single pulse (negative microdimensional) as seen by the observer when $R_L = 5$ ohms; $T = 0.1$ usec/div; $S = 0.005$V/div.

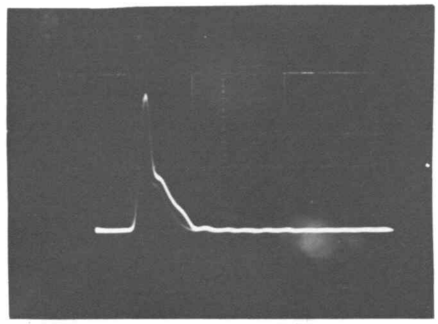


Figure 5-b. Same pulse type. $R_L = 33$ ohms; $T = 0.1$ usec/div; $S = 0.005$ V/div.

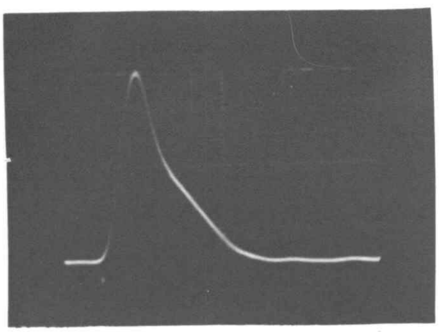


Figure 5-c. Same pulse type. $R_L = 50$ ohms; $T = 0.2$ usec/div; $S = 0.005$ V/div.

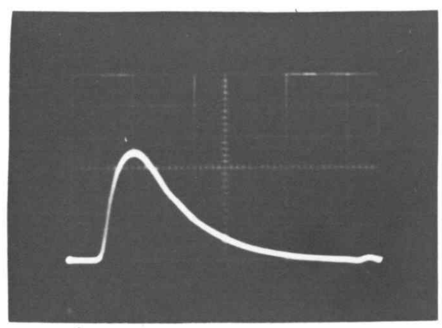


Figure 5-d. Same pulse type. $R_L = 1000$ ohms; $T = 0.5$ usec/div; $S = 0.05$ V/div.

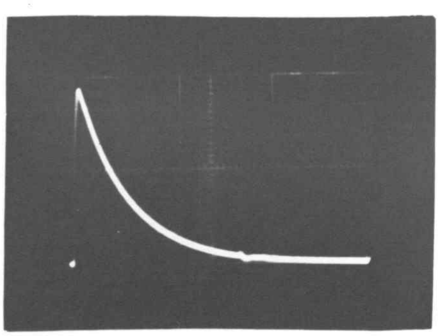


Figure 5-e. Same pulse type. $R_L = 10{,}000$ ohms; $T = 5.0$ usec/div; $S = 0.05$ V/div.

MECHANISTIC THEORY OF CORONA

As mentioned earlier (page 7) the one major difference between various coronas is dependent upon electrode polarity. The fundamentals of each mechanism will now be discussed.

Positive Mechanism

When the positive electrode causes a diverging field of sufficient intensity an electron appearing in the gap will gain enough energy during acceleration to cause excitation and ionization by collision. The resulting avalanche will continue until the anode is reached. Remaining will be a positive ion column which effectively extends the anode potential into the gap, thus causing an increase in field intensity. Meanwhile, a shower of photons from the original mechanism has caused new electrons to appear in the gap by photoionization. Some of these cause new avalanches which naturally proceed toward the point of highest potential, which is the head of the positive column. This causes lateral as well as axial extension, and the result is a conical shaped column with a spherical head. This process continues until the "head" gets large enough in diameter to weaken the field, thus denying new photoelectrons sufficient energy to cause more ionization. When this happens the mechanism stops.

Another discharge cannot occur until the positive ion space charge is removed from the gap and the original high fields restored. This requires what is known as clearing time. Since positive ions are relatively immobile it is characteristic for positive corona to have slow repetition rates.

In general positive corona pulse repetition frequency decreases and pulse height increases with an increase in gap voltage (7). Under ideal or controlled conditions it is possible to obtain recursion stability. However, in the case of an a-c gap voltage, stability is very hard to obtain.

Negative Mechanism

Due to some process (usually photoelectric emission) an electron leaves the cathode and forms an avalanche. The physical length and the time duration of this avalanche is very short. However, the photons created in the avalanche shower the cathode and knock off secondary electrons which in turn form avalanches. This is the progressive formation of a pulse. As with the positive mechanism, there is a column of positive ions left. Furthermore, the electrons from the avalanches have slowed down due to the decreasing field and joined with oxygen molecules in forming negative ions (O^-). This is a process known as "dissociative attachment" (6). The result is the formation of a positive ion space charge next to the cathode and a negative ion space charge just beyond that. Both space charges will continue to grow until their combined efforts reduce the field to the point where secondary electron ionization energy cannot be obtained, thus confining the pulse.

Later, when most of the positive ions have neutralized at the cathode (by picking up their image charges upon contact) and the negative ions have diffused more deeply into the gap, another pulse may start. This second pulse is initiated by one of two processes, either photoelectric emission or positive ion bombardment.

If the gap potential is raised, two factors will be increased, space charge clearing efficiency and electron ionization probability. The result is an increase in pulse repetition frequency. However, because of small cathode area, space charge limited current flow type of action is present. This results in a residual positive ion density increase (with voltage) which slightly reduces the total number of avalanches contributing to each pulse before smothering. The gradual build up of residual positive ions with voltage tends to effectively increase point radius. This effect will be mentioned again later.

If the point is microdimensional, the negative corona pulses will come at even intervals, much like the output of a relaxation oscillator. Pulses of this type are known as "Trichel" pulses after G. W. Trichel who first investigated them (10).

If the point is macrodimensional, exactly the same mechanism is present. The differences are characterized by a loss of recursion stability and a tremendous increase in pulse height. Repetition rate also drops, and onset becomes very high. The reasons are as follows: Assume that the initial avalanche has formed and the photons created have already knocked the secondary electrons from the cathode. Since the cathode radius is much greater than before, the fields will not be nearly so sharp, and as a result the avalanches will proceed much farther into the gap. This provides an even greater source of photons and the result is a larger cathode secondary electron emitting area. This process will tend to migrate over the entire cathode area, resulting in a tremendous charge transfer.

When the space charge finally smothers the pulse, the action of clearing begins. Since the cathode area is very large it is quite probable that the space charge is not of uniform thickness. In this event the next pulse may occur at the weak spot. This is why recursion stability is hard to obtain.

Comparing the microdimensional and macrodimensional negative coronas non-electrically, it was found that while the former situation produced no audible sound the latter case had a very noisy buzz. Actually, this is because the micro type had a repetition frequency far beyond the range of the human ear. In the other case the basic repetition rate was about 1 kc, which is certainly audible. However, the sound heard was not that of a 1 kc note. Instead, it was the result of a "gated" 1 kc note where the gating action is due to the alternating 60 cycle high voltage wave. The result is a definite buzz.

As A Constant Charge Generator

Corona is certainly a function that has been voltage forced. Employing this fact, R_L may be varied throughout a large range of values without altering the total charge transfer per pulse of a repetitive corona. This is true under the condition that R_L is very small compared to the impedance of the high voltage gap. This supplies a sufficient condition for constant point-to-plane voltage, thus yielding a constant corona current output.

Proof of the foregoing is illustrated by figure 6 which shows that total charge transfer per pulse is virtually independent of R_L. Negative point (microdimensional) corona was used to obtain the data. Gap potential was maintained slightly above onset for pulse stability. A single pulse waveform was displayed on the calibrated screen for a particular value of R_L. Each display was photographed with the Polaroid camera. A planimeter was used eight times on each picture to obtain an average area. (Planimeter calibration was obtained by intergrating the illuminated grid lines.) The area, when divided by the

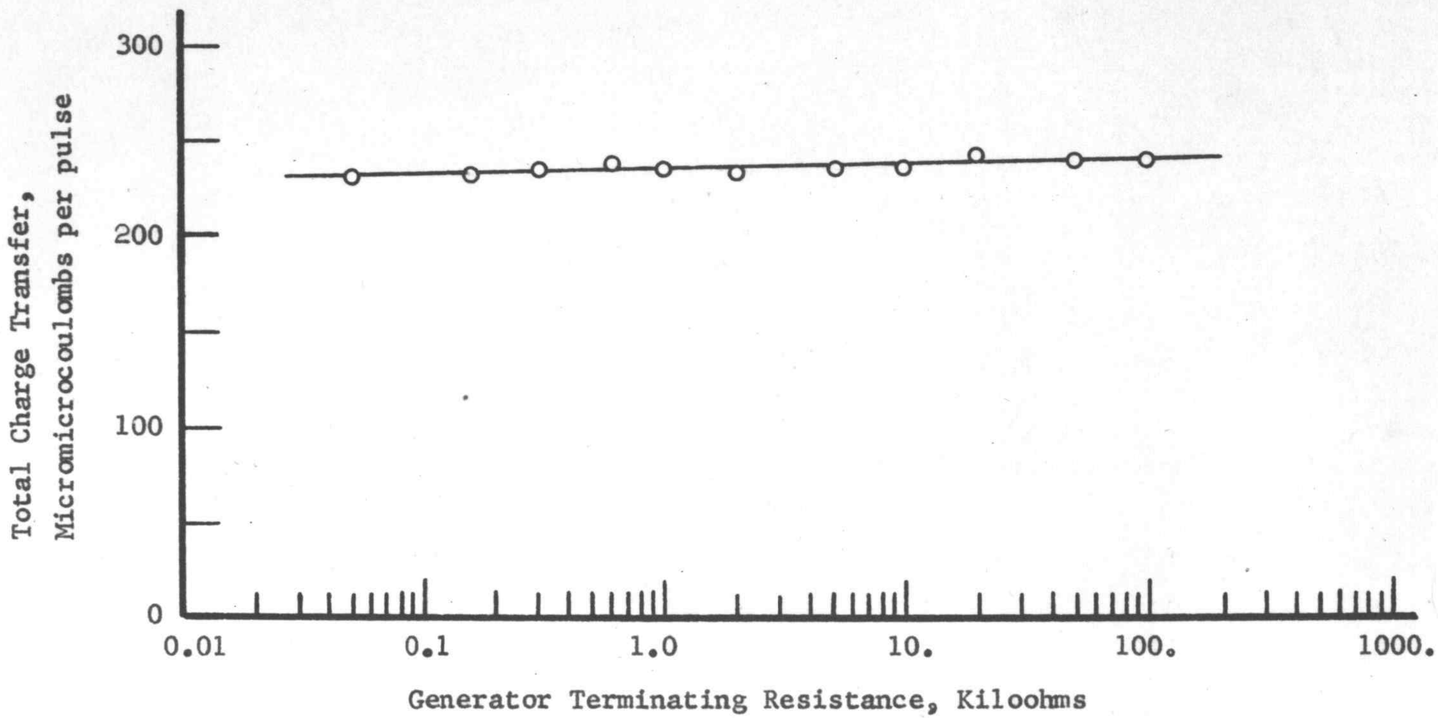


Figure 6. Showing negative corona charge transfer independency of the terminating resistance to ground. Gap was 7.5 inches and point radius was approximately 5 mils. Relative humidity = 58% and relative air density = 0.992.

measured value of R_L, provided total charge transfer by virtue of the equation $Q_T = R^{-1} \int_0^T e \, dt$.

The curve (figure 6) has a slight amount of positive slope. The reason for this and the limitation of 0.1 megohms imposed on R_L is attributed to the following: As R_L increases, the voltage drop due to the gap capacitance a-c charging current also increases. Since fundamental capacitive current leads voltage by about 90 degrees, the corona current pulses are usually superimposed on a changing slope. This was the case here, and as a result the pulse baselines were tilted. This tended to give a slight increase in area. Finally, when R_L passed 0.1 megohms, the oscilloscope could no longer be synchronized with the pulse.

The average total charge transfer per pulse of negative corona (figure 6) is $2.34 \times 10^{-10}/1.6 \times 10^{-19}$ or 1.47×10^{9} ions per pulse. This value agrees quite well with the 10^{9} ions per pulse referred to by M. R. Amin (3).

Even though the corona mechanism is a constant charge generator, it will not produce a peak voltage drop in direct proportion to R_L. This is adequately illustrated by figure 7-a. (The data was obtained by measuring the peak voltage on each picture used for figure 6.) This fact seems paradoxical at first, but in considering circuit time constants the explanation is quite simple.

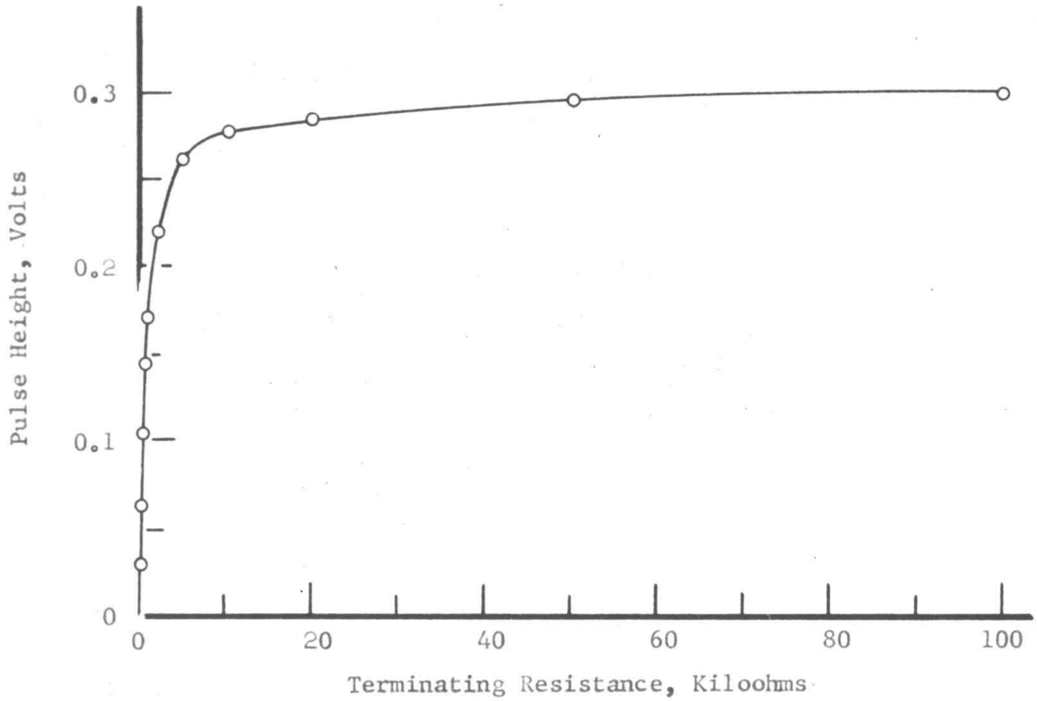


Figure 7-a. Negative corona pulse height as a function of R_L.

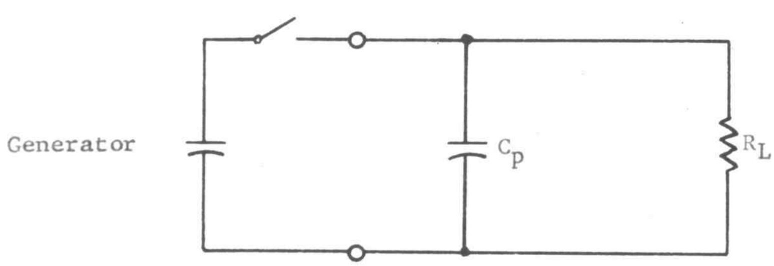


Figure 7-b. Corona mechanism analog feeding electrode circuit.

The very fact that the mechanism is a constant charge generator gives it most of the properties of an initially charged capacitor in series with an academic switch. This is the basis for figure 7-b. Here the corona generator analog is seen connected to an ultra-simplified version of figure 4-b. The capacitance C_p is the electrode shunt capacitance to ground and R_L is the variable terminating resistance. The generator analogy is as follows: At time zero (closing of the switch) there is a given amount of charge available that must flow through the electrode circuit in order for the entire circuit to attain electrical equilibrium. The amount of this charge is virtually independent of the electrode circuit impedance. If R_L is large, the discharge time will be large, and the peak voltage seen across C_p will approach an amount proportional to charge attained, which in turn is inversely proportional to its capacitance. One quantitative difficulty that arises is that the generator analog capacitor will change value as it decreases in charge.

Pulse Coincidence

Consider two or more corona generators operating in parallel, thus supplying the same load. In this situation, occasional partial pulse coincidence is inevitable. Since the pulses are current by nature the result should be that of direct addition.

Theoretically, two independent corona generators functioning identically with perfect recursion stability into the same load would yield an output of twice the magnitude of either one operating seperately. The absolute coincidence frequency is equal to the frequency of the generators. However, if the output of one generator is time delayed by some fraction of its period, there will never be any absolute coincidence. Further, if two unequal integer pulse frequencies are in phase at some point in time, there will be an absolute coincidence frequency equal to the highest common factor of each. For example, if f_1 = 1776 cycles per second and f_2 = 304 cycles per second, the ratio of f_1 to f_2 is 111:19. The highest common factor is 16, which is the absolute coincidence frequency. Again, if one generator is delayed, there will never be any absolute coincidence. The purpose of this discussion is to bring out the fact that perfect or absolute coincidence is very unlikely, even if the repetition rate of one or both generators is changing. (Such is the present situation where 60 cycle sinusoidal gap voltage is being used.)

Coincidence is not limited to pulses being perfectly in phase. Since corona pulses have finite width it should be true that partial coincidence will happen quite regularly, much more often than absolute coincidence. This was found to be true in the following situations.

Nearly Matched Two-Point Source. Two microdimensoinal points were selected having nearly the same radii. This was done with a 54X microscope. After being placed in the high voltage gap, the points were adjusted until negative corona occurred on each simultaneously. Point-to-plane voltage was then increased to about three times onset. Figure 8-a is a picture of the resultant corona envelope occurring each half-cycle. The two sources have nearly identical pulse heights. Therefore when partial coincidence occurs it is natural to expect the resulting addition to approach twice original pulse height. Also of interest are the regularity of partial coincidence in the center of the envelope, and the apparent absence of coincidence occurring on either end. It must be remembered, however, that the corona repetition frequencies are changing since a changing voltage is used across the gap.

Figure 8-b is a picture of the same envelope with the time scale increased. Now it is possible to observe the pyramiding effect as the pulses come into and go out of coincidence. Figure 8-c is a picture of one of the coincident periods. Here it is possible to see the two generators actually pass through synchronism.

Unmatched Two-point Source. Two points were picked at random and placed in the high voltage gap at slightly different point-to-plane spacings. Figure 9-a is a picture

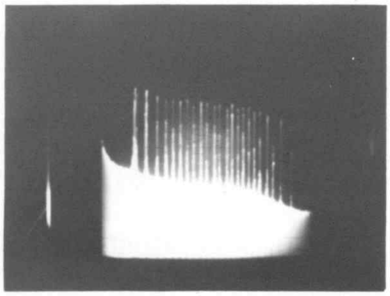


Figure 8-a. Envelope showing coincidence of pulses from two nearly matched points.

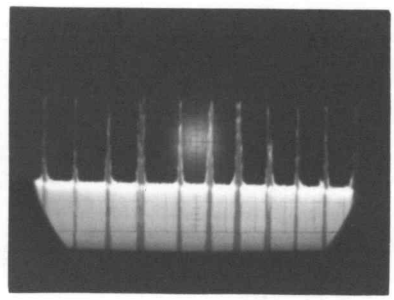


Figure 8-b. Increased time scale of above showing pyramid effect when the two generators come into and go out of synchronism.

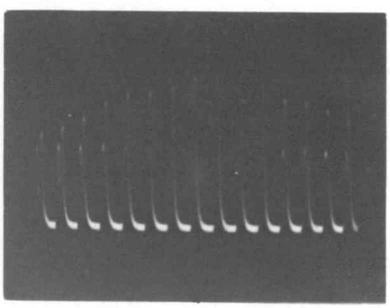
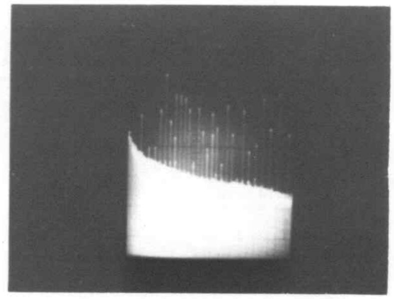


Figure 8-c. Microscopic view of one of the pyramids.

Figure 9-a. Envelope showing random coincidence of pulses from two unmatched points.



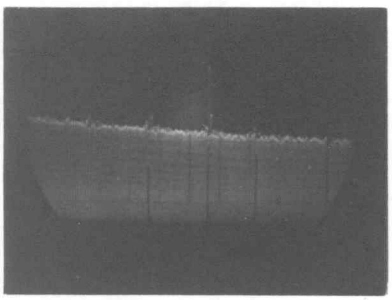
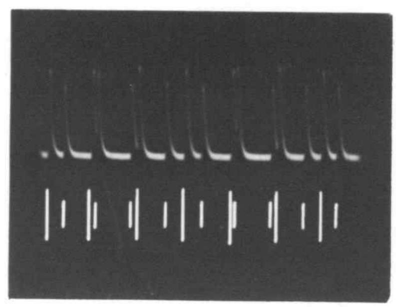


Figure 9-b. Expanded view of above showing occasional partial pulse coincidence.

Figure 9-c. Microscopic view of above.



of the resultant corona envelope. This time there is no regularity of coincidence. Figure 9-b is an expanded view of figure 9-a. An occasional occurrence of partial coincidence is all that is seen. Figure 9-c is a microscopic view of figure 9-b. This picture is an example of two different integer freqencies that are out of phase just enough to prevent coincidence. The long ink marks indicate the tall pulse positions and the short ink marks indicate the short pulses. The time between the first tall pulse and the first short pulse is exactly the same as between the fourth tall pulse and the fifth short pulse and the seventh tall pulse and the ninth short pulse. The ratio is 3:4. If any one of the pulses had been in phase, there would have been a coincidence frequency equal to one third the frequency of the tall pulses or one fourth the frequency of the short pulses.

Unmatched Nine-Point Source. Nine microdimensional points were picked at random and placed in the gap. All nine were terminated by the same R_L. Figure 10 is a selection of pictures taken at random of multiple coincidence.

The n-Point Source. If the number of the point sources in a given area is allowed to approach infinity as a limit, the over-all source will become macrodimensional. (Such is the case of a smooth round conductor in a radial field.) Likewise, the corona mechanism would become macrodimensional. If the gap voltage is raised to corona onset, there will be a certain average number of mechanisms occurring per unit of unshielded area. As the voltage increases, the mechanism "density" increases. This is quite noticeable to the observer in the dark. Also it is universally known in the technical field that radio influence voltage produced between a conductor in corona and ground increases with further increase in voltage. It may be of some help in understanding why if the principles of coincidence are considered.

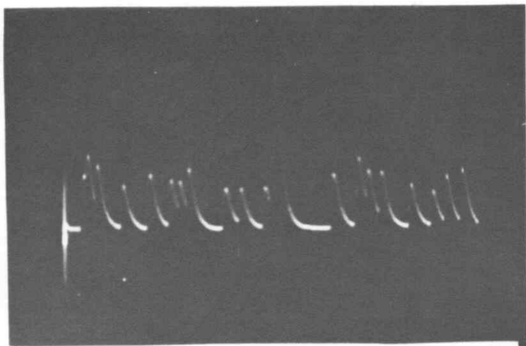


Figure 10. Random coincidence of pulses from a nine-point generator.

Figure 10. Second picture.

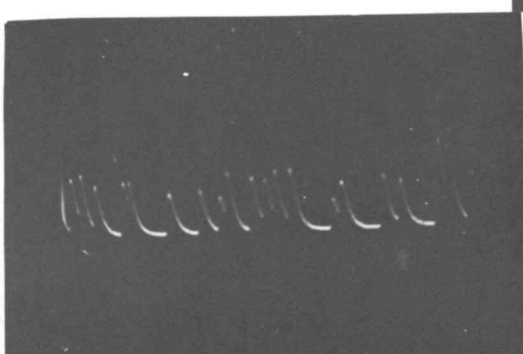


Figure 10. Third picture.

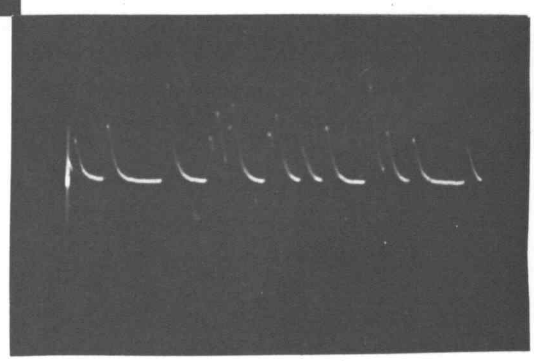


Figure 10. Fourth picture.

DYNAMICALLY GENERATED CORONA

It is now appropriate to illustrate the effects of changing gap voltage on corona characteristics. Negative microdimensional corona is the first appearing corona voltage wise and is the easiest to control stability wise. For these reasons it was used as the major argument of the investigation.

Onset and Extinction

Consider either an a-c or d-c system for producing corona. As the gap voltage is raised from zero, a critical value will be attained, at which time corona will appear. This is known as "onset." Conversely, if the system is producing corona and the gap voltage is then lowered, another critical value will be attained, at which time corona will disappear. This is known as "extinction." Generally, the voltage at onset will be greater than the voltage at extinction. This is true with a-c as well as d-c.

Next, consider just the a-c system for producing corona. In defining onset and extinction an over-all perspective was used. However, corona characteristics react to each cycle of the a-c voltage wave. This necessitates new terms for onset and extinction as applied to each individual cycle. They will be defined as follows. When corona appears during the ascending waveform, the term "initiation" will be used. Conversely, when the corona disappears during the descending waveform, the term "termination" will be used. Thus, the first and last corona pulses on each half-cycle will henceforth be called "initial" and "terminal" pulses.

As the a-c gap voltage is raised, corona onset will occur. This will consist of a single negative corona pulse on the peak of the negative half-cycle. Further increase in voltage causes more pulses to appear. The initial pulse occurs at exactly the same voltage as onset. The remainder of the pulses follow in an orderly sequence.

Figure 11-a illustrates a typical negative micro-dimensional corona pulse envelope. In this picture the majority of the charging current has been balanced out.* Figure 11-b is a picture of another corona pulse envelope shown with the corresponding a-c voltage waveform. This should give at least a rough idea of where negative corona occurs on the negative half-cycle. Figure 11-c illustrates the negative corona envelope of a highly stressed point and its relation to the negative half-cycle. The horizontal

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* Gap capacitive charging current may be partially balanced out by using the current from two electrodes (one active and the other a dummy) in conjunction with a differential amplifier. Theoretically, the remainder or unbalanced part is ion current. Unfortunately, this cannot be completely true. If corona should not appear, the two charging currents may be in balance over the entire voltage range. However, if corona does appear, the capacitive coupling to one or both electrodes is distorted by the ensuing space charge. The result is an immediate unbalance that may be <u>partially</u> ion current.

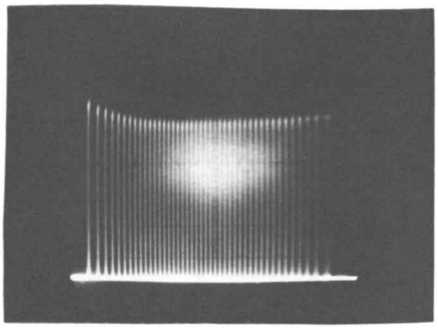


Figure 11-a. Corona (negative microdimensional) envelope. Trace is 2.0 milliseconds long. Initial pulse height is 0.1 volts across 1000 ohms.

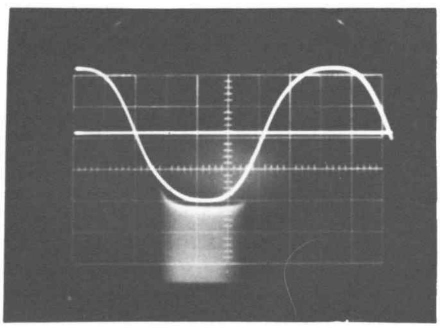


Figure 11-b. Showing a corona envelope and its time relation to the high voltage waveform.

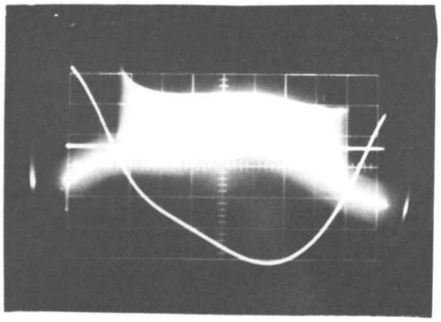


Figure 11-c. Showing a corona envelope when peak gap voltage is about ten times the value of onset. Horizontal line is a-c wave zero.

trace is the a-c zero line. In this picture, peak voltage is about 1000% of onset.

As was mentioned earlier, the initial negative corona pulse always occurs at a constant value of potential, regardless of peak magnitude. (The value is that of onset potential.) Proof of this is illustrated by figure 12, curves A and B. Curve B is the initial pulse electrical position locus as a function of peak potential (plotted sideways for depth). Curve A is the locus of a constant potential point equal to onset. The expected shape of curve A is that of a cosecant function, which follows from $e = E_{Max} \sin\theta$. Since "e" is constant, $E_{Max} = e(\csc\theta)$.

Curve C is the terminal pulse locus. It is interesting to note that this locus actually "leads" locus A. This contrasts with the fact that corona extinction is lower valued than corona onset. It is also interesting to note that the amount of the termination "lead" is constant except at low voltages. The phenomenon of "termination lead" is well shown in figure 11-c. The lead is the time distance between the terminal edge of the corona envelope and the second wave zero crossing, minus the small amount between the initial edge and the first wave zero crossing.

Curves D and E are the loci of the initial and terminal positive corona pulses (usually called positive streamers). An interesting characteristic of the positive streamer is the position of the first pulse (at onset). It actually

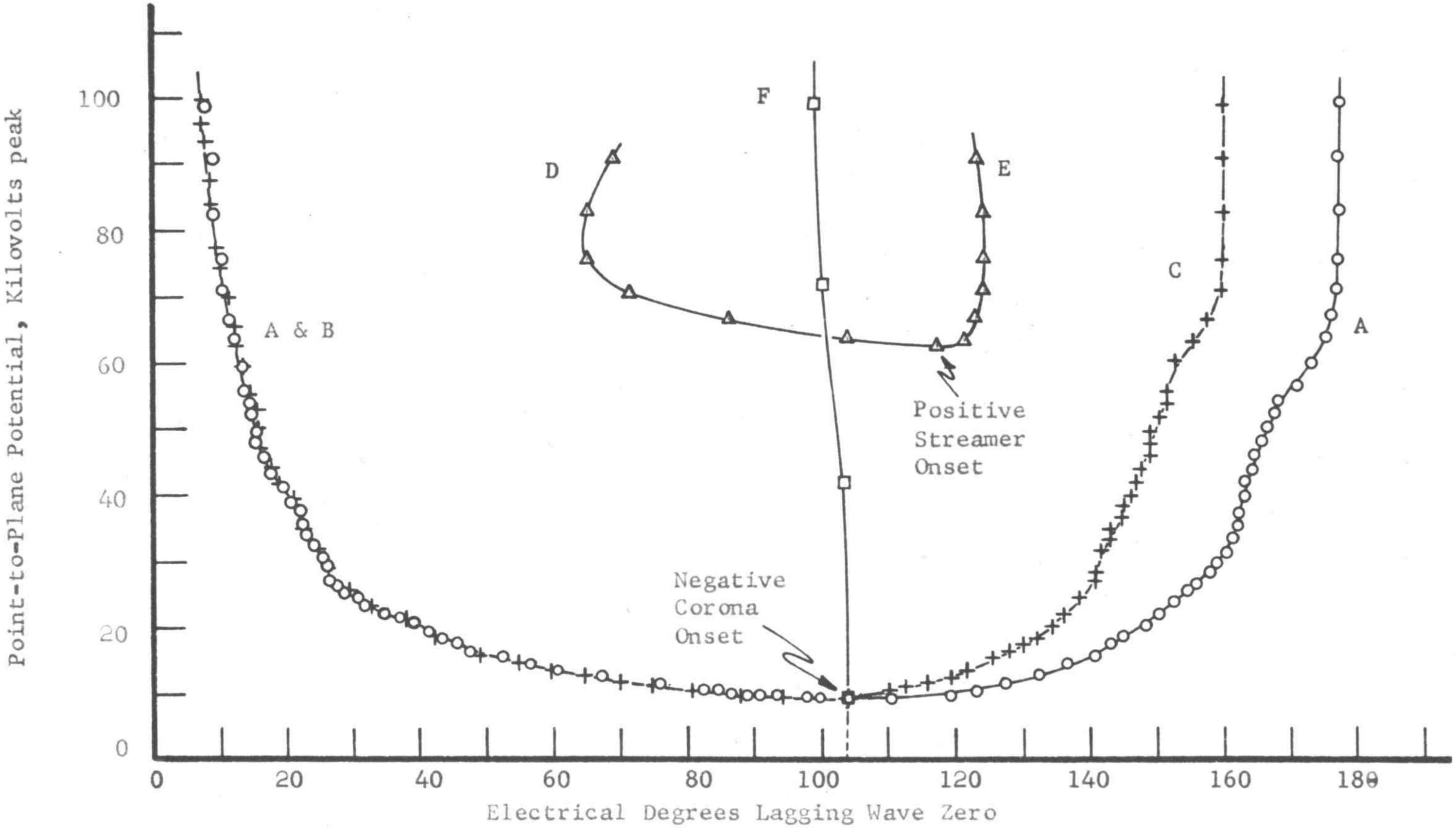


Figure 12. Electric position versus peak potential loci of constant 9.1 Kv potential (A), initial and terminal negative corona pulses (B & C), initial and terminal positive streamer pulse (D & E) and high voltage wave peak (F). Gap = 7.5 inches and point radius = approximately 5 mils. Relative humidity = 51% and relative air density = 0.996.

"lags" the peak of the high voltage wave.

Curve F is the locus of the peak of the high voltage wave (either half-cycle). The fact that it occurs over 100 electrical degrees (instead of 90) beyond wave zero is indicative of the distortion present in the power circuit.

Pulse Repetition Frequency

Investigation of d-c negative microdimensional point-to-plane corona has shown that a log-log coordinate plot of pulse repetition frequency versus gap voltage results in a straight line with positive slope (7). If the gap voltage is varying (i.e., at a sinusoidal 60 cycle rate), it is still possible to obtain a straight line in the log-log system. However, the slope of the line is much less when the voltage is increasing than when it is decreasing. This fact is experimentally shown in figure 13. The data was taken for a situation in which peak gap voltage was about ten times that of onset. Pulse periods were measured at various values of instantaneous voltage.

Interpretation of figure 13 indicates that pulse repetition frequency increases as the 1.44 power of increasing voltage and decreases as the 3.75 power of decreasing voltage. The qualitative reasons for the change are as follows: The theory of negative corona includes the fact that a residual positive ion space charge is present which increases with an increase in gap voltage. The effect is

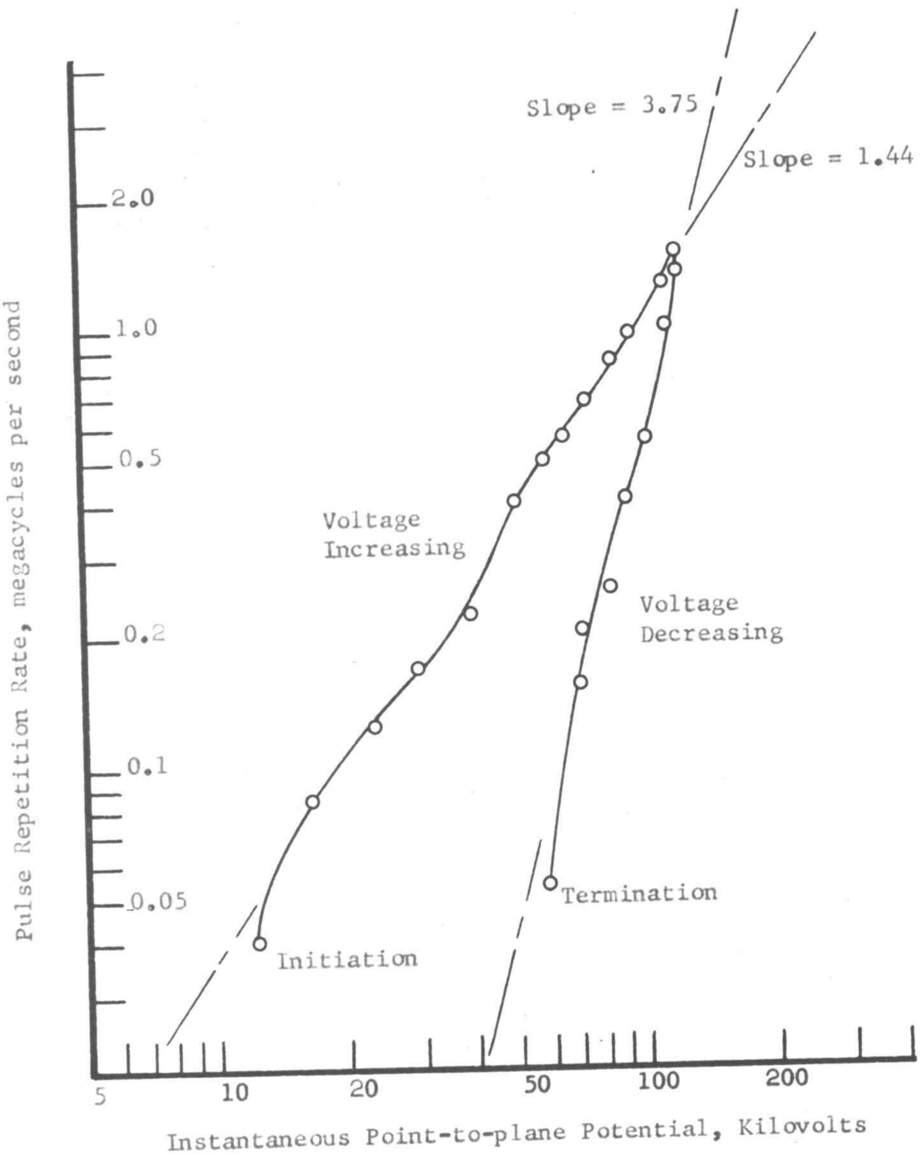


Figure 13. Showing negative corona repetition rate as a function of dynamic voltage as it varies over a single negative half-cycle. Onset = 11.6 Kv; Peak = 114.0 Kv; Gap = 9 inches; Point radius = approximately 5 mils; Relative humidity = 48% Relative air density = 0.999.

that of an increasing point radius. The same type of accumulative effect should be present with a dynamically increasing voltage. However, if the rate of voltage rise ($V'(t)$) is high, the accumulation may not be able to keep up with its steady state value. This would enhance a slight positive departure fron the normal pulse repetition frequency, implying a slightly greater slope to the log-log plot of frequency versus voltage curve. Referring to figure 13, there may be a correlation between the above-mentioned and the initiation vicinity of the curve. However, the points are too scattered to be able to tell with any certainty.

The important aspect of the positive ion accumulation occurs when $V'(t)$ becomes negative. The corona phenomenon suddenly finds itself in a rapidly weakening field with an effectively larger point radius. The result is a rapid decline in pulse repetition frequency and an early final smothering of the entire discharge. This accounts for "termination lead" which was mentioned in the previous section.

Further examination of figure 13 reveals negative microdimensional corona frequency ranging from about 40 kilocycles per second to about 1.4 megacycles per second. However, with peak voltages only slightly above onset, it was possible to obtain frequencies as low as 20 kilocycles per second. All measurements were made with points having a radius of approximately 0.125 inches. It is well to mention that negative macrodimensional corona pulses are occasionally identified as negative streamers in the technical literature. More often they are not identified at all.

Positive coronas (streamers) occurring on the microdimensional electrodes were found to have repetition frequencies on the order of 500 cycles per second. Also, there seemed to be no problem in obtaining recursion stability. However, there was a limited range of voltage above positive streamer onset in which investigation could be conducted. The upper limit was gap breakdown.

A second positive corona was occasionally present. On certain days the point would accumulate fine particles of dust by adhesion. These particles seemed to be affixed by electrostatic force. When the particles were present, apparently dozens of corona generators were operating simultaneously because the pulses could not be isolated for observation. It is believed that the many dust particles were simply acting as dielectric points, all producing corona at once. Whether or not there is any correlation between atmospheric conditions and the fact that the above phenomenon occurred only on certain days is not known.

Relative Pulse Height

Referring to figure 11-a (the picture of the negative microdimensional corona envelope), it is seen that pulse height decreases slightly as gap potential rises. Earlier investigation with d-c has shown that pulse height decreases exponentially with voltage rise (7). On that basis, semi-log paper was used to show the relationship between pulse height and dynamically changing voltage. The result is illustrated in figure 14. As with pulse repetition frequency, pulse height differences between increasing and decreasing dynamic voltage can be attributed to the effective increase of point radius while $V'(t)$ is positive.

It should be pointed out that there is not enough pulse height deviation (less than 20% of a logarithmic cycle) to warrant any conclusions from semi-log paper. In fact, there is little change in curve shape if the same data is plotted on rectangular coordinates.

A comparison was made between microdimensional and macrodimensional negative corona pulse heights. Oscilloscopic measurements indicate initial pulse heights of 0.15 to 0.20 volts and 1.0 to 5.0 volts, respectively. In this case, R_L was 1000 ohms, the microdimensional point radius was approximately five mils and the macrodimensional point radius was about 0.125 inches.

Further comparison was made by using a Stoddart radio noise meter (Type NM-20B), which is a narrow-band modulated amplitude receiver with vacuum tube voltmeter readout. The vacuum tube voltmeter can be position switched to provide either rectified average (detected) or integrated

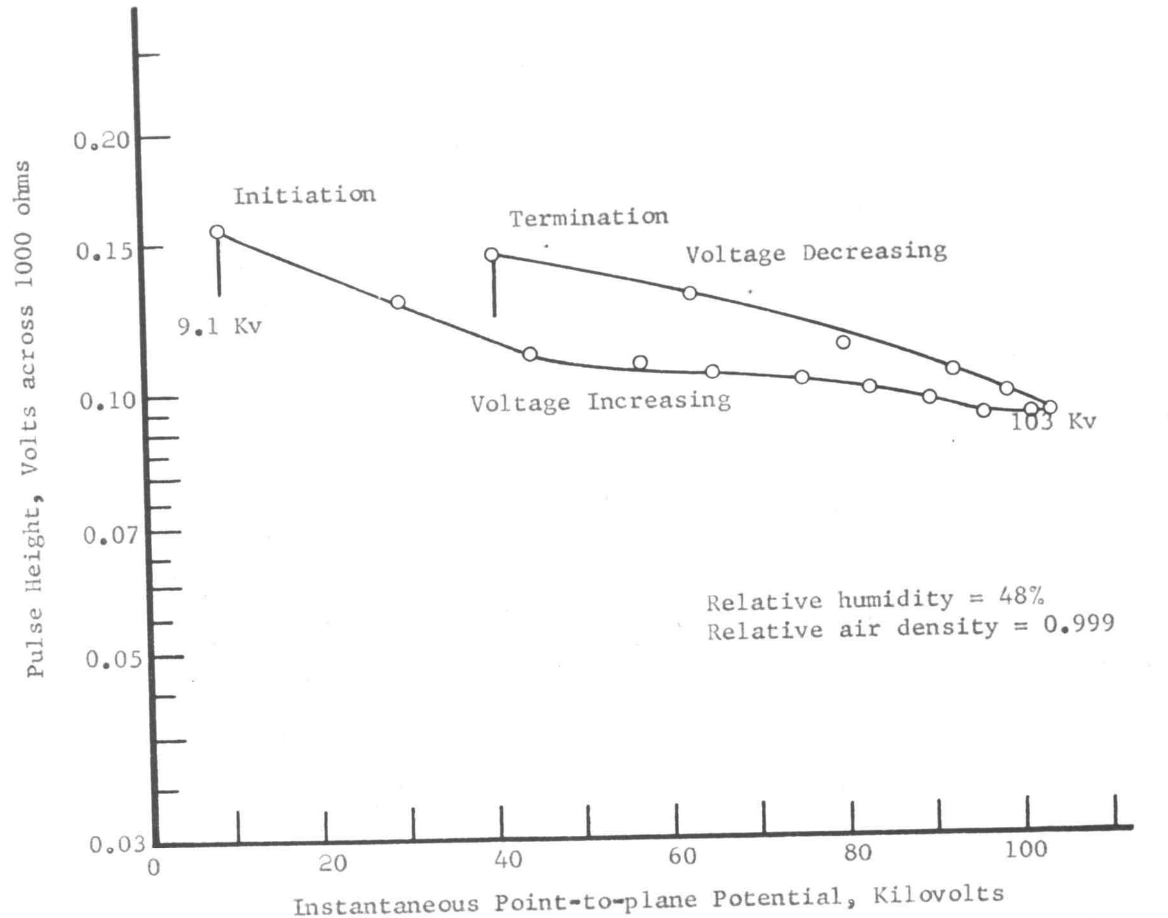


Figure 14. Showing negative corona pluse height as a function of dynamic voltage. Gap = 8.5 inches; point radius = approximately 5 mils.

(600 millisecond time constant) values. The rectified output is a measurement of field intensity (FI) and the integrated output is a measurement of quasi-peak (QP). The field intensity circuit was used to indicate radio influence voltage (RIV) existing between the electrode and ground ($R_L = 1000$ ohms).

Figure 15 illustrates the RIV differences between the two different points. The macrodimensional point has a much higher onset value than the microdimensional point, but when onset occurs, the macrodimensional point produces about five times as much radio influence voltage. Figure 16 shows the same comparison made with quasi-peak readings. It should be noted that both sets of curves are accompanied by a measurement of the background noise. In both cases there is an increase occurring at about 60 kilovolts peak. This is noise coming from the plane supporting insulator.

Measurement of positive microdimensional streamer pulse height was done only with the oscilloscope. Pulse heights were found to vary between two and eight volts across 1000 ohms.

Negative Microdimensional Pulse-free Corona

A type of corona yielding only a steady current (no pulse or radio noise characteristics) will occur on a negative microdimensional point that has been under high stress for a period of time. The normal negative pulse corona envelope is distorted and finally interrupted by

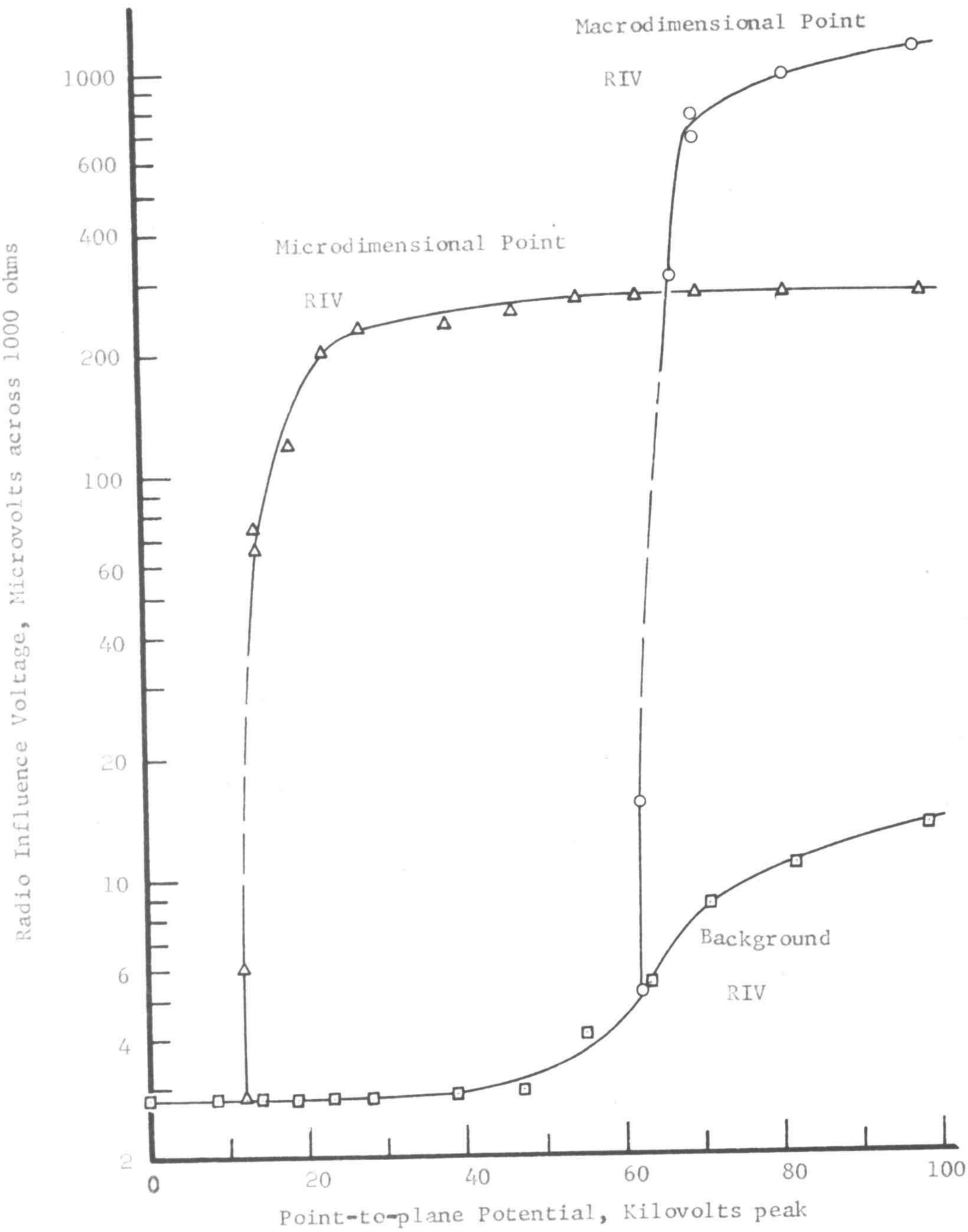


Figure 15. RIV comparison test. frequency = 830 KC; band-width = 4.5 KC; relative humidity = 46% ; relative air density = 1.004.

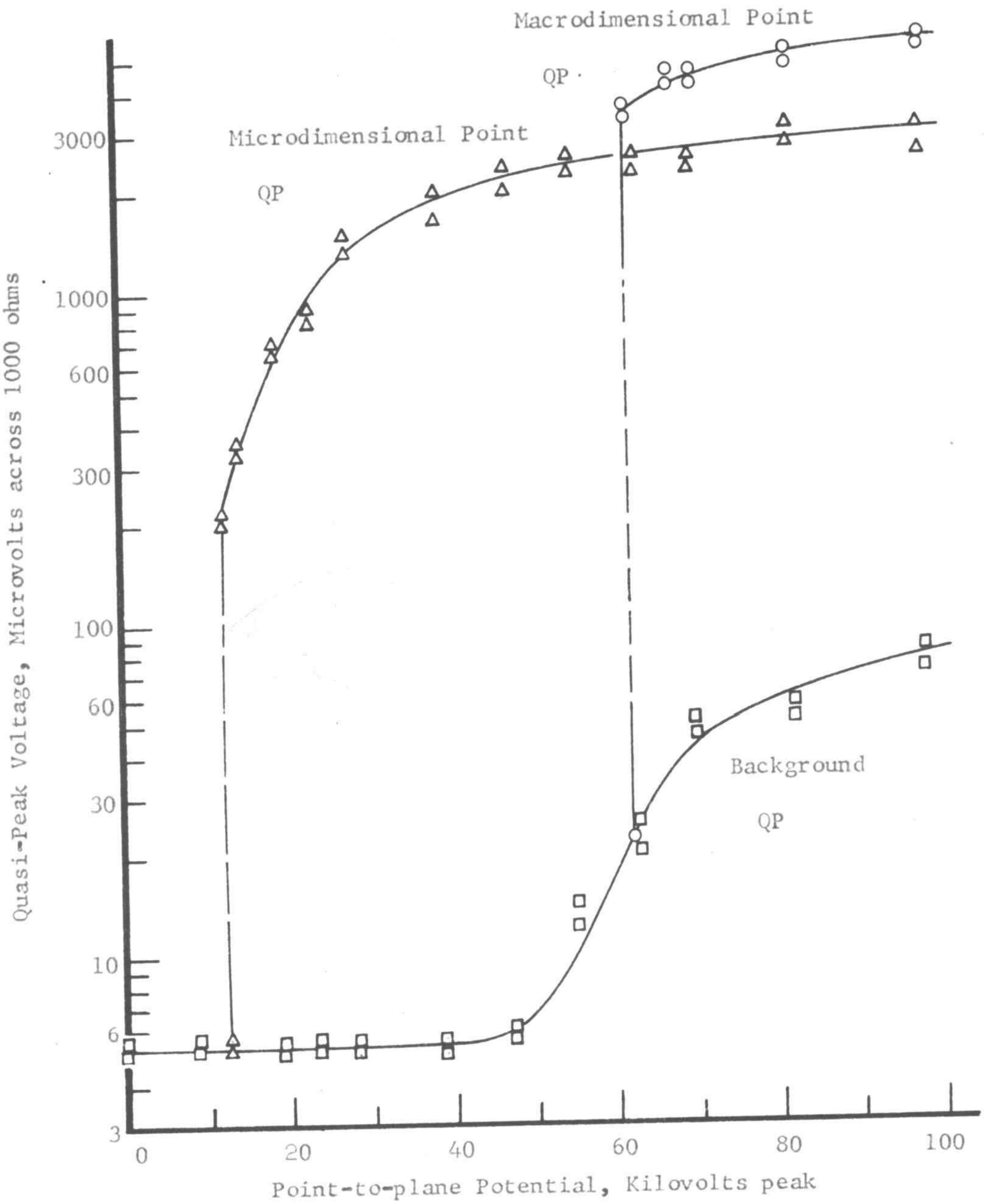


Figure 16. QP comparison test. Center frequency = 830 KC; bandwidth = 4.5 KC; relative humidity = 46% ; relative air density = 1.004.

the slow initiation processes of the pulse-free discharge. Figure 17 is a sequence of pictures showing the process in various stages of growth. Figure 18 is another sequence using a different point and a slower time base. Both sequences were taken at constant voltage (with the exception of figure 17-d).

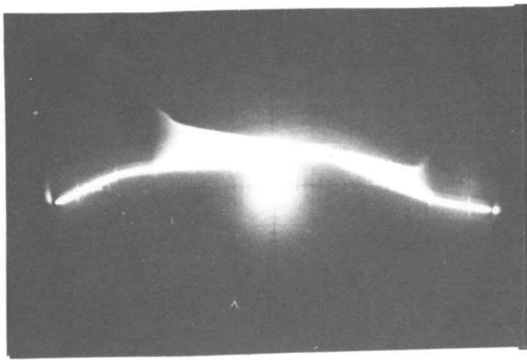
The mechanism analysis of pulse-free corona has never been explained, and no attempt will be made to do so here. It is characterized by a stable increase in current (about 15-20 microamperes) and a substantial increase in light. (Recent photomultiplier studies by G. A. Pearson in this same laboratory (8) have supported this fact.) A slight amount of work has been done with the d-c pulse-free corona by H. W. Bandel of the University of California (4). He has called the phenomenon "a Townsend-like discharge," which means it has the characteristics of a constant current density glow discharge.

Figure 17-d supports the aforementioned characteristic of constant current density (assuming the effective metal cathode area constant). Here the trace is seen to have reached a new level while it is within the pulse corona envelope discontinuity. The level is a constant value of current flow superimposed on the original charging current wave. Figure 17-b shows two "levels." Figure 17-e is a microscopic view of figure 17-b's dual level. It appears as though each pulse mechanism initiates the

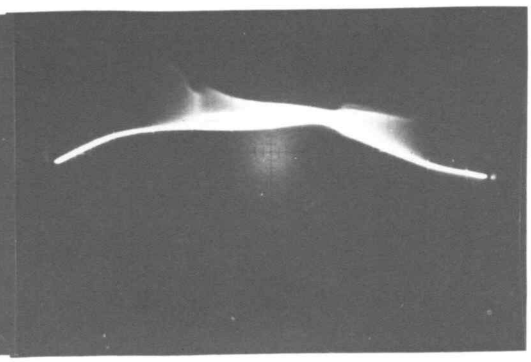
pulse-free mechanism, but for some reason the pulse-free mechanism fails to be self supporting. Figure 18-f shows another example of instability. Here the two mechanisms take turns being active. Figure 18-g is a similar picture, but the order of activity is erratic.

Figures 17-a,b,c & d. Sequence of pictures showing the initiation process of pulse-less corona. Point radius was about five mils and gap spacing was about six inches. Gap potential was about 65 kilovolts peak except for figure 17-d, which was 85 kilovolts peak.

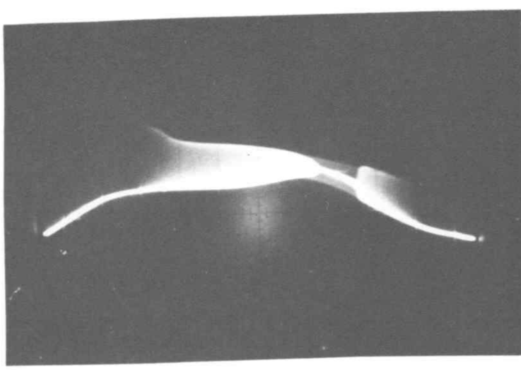
(a)



(b)



(c)



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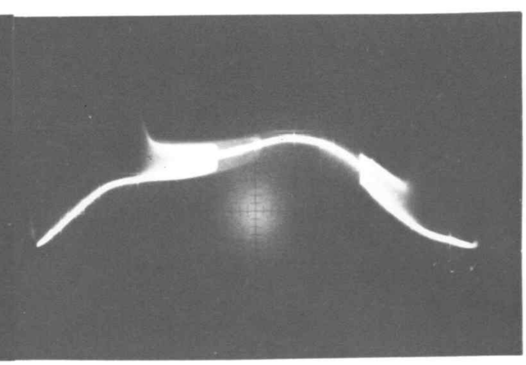

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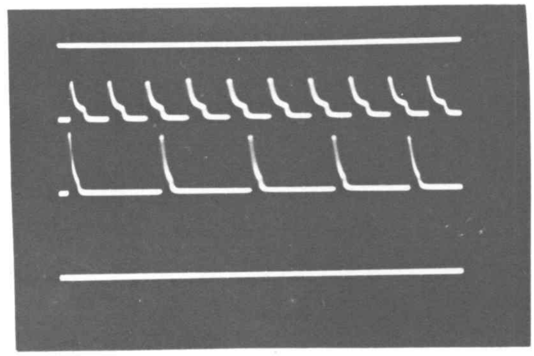
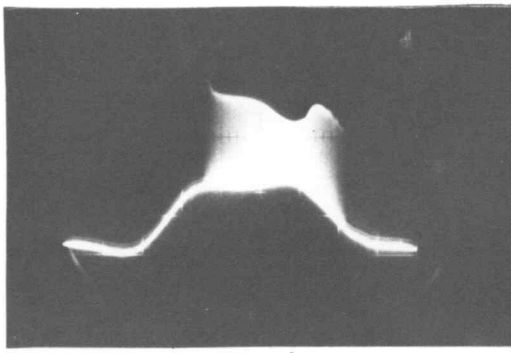
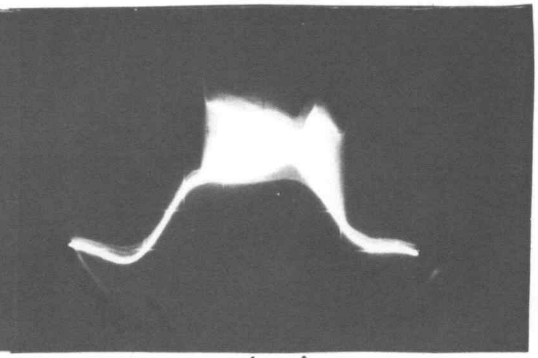


Figure 17-e. Microscopic view of the twin trace portion of figure 17-b.



(a)



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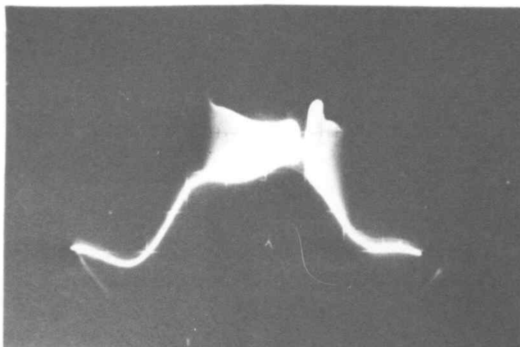

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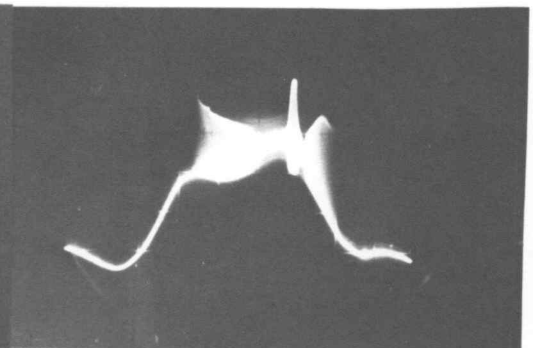
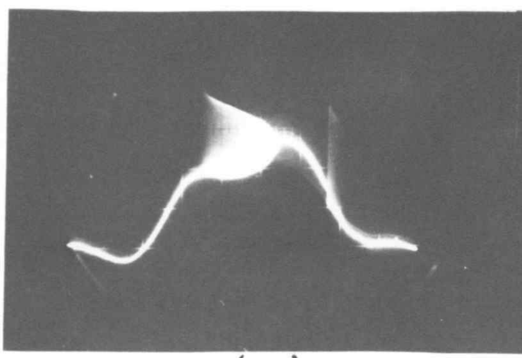


(d)



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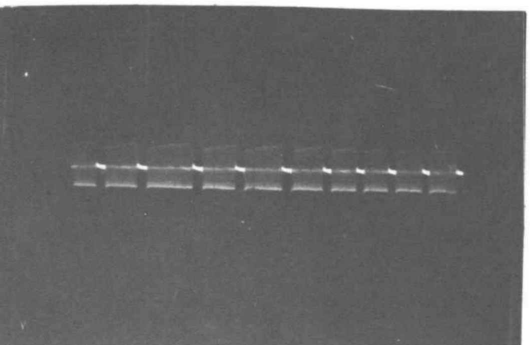
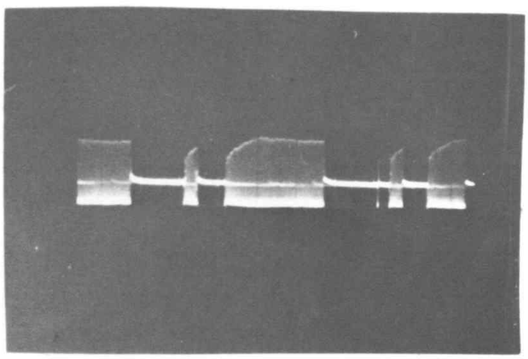


(f)



Figures 18-a,b,c,d, & e. Sequence of pictures showing the initiation process of pulse-less corona with a new point and slower time base.

Figures 18-f & g. Expanded view of the disrupted area showing intermittent pulse-less discharge.

CONCLUSIONS

1. There are basically two corona mechanisms possessing impulse characteristics, the positive and negative coronas.
2. The variations of each basic mechanism may be attributed to electrode relative size, electrode condition and relative overstressing.
3. The corona measuring circuit alters the true characteristics or details of the mechanism.
4. The corona generator has practically an infinite internal impedance, thus making it a constant charge generator.
5. Whenever two corona impulses at least partially coincide there will be addition of instantaneous values.
6. Corona initiation on voltage waveforms greater than onset will occur at an instantaneous voltage equal to onset.
7. Corona termination on voltage waveforms greater than onset will occur at some voltage higher than onset.
8. There will be less change in pulse repetition frequency on an increasing voltage wave than on a decreasing voltage wave.
9. Relative pulse height is less on an increasing voltage wave than on a decreasing voltage wave.

10. The mechanism of pulse-free corona has some of the electrical characteristics of direct current.

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