NBSIR 75-731

A Study of Air-Gap Breakdown at 28.5 Kilohertz

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Final Report
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Prepared for
U.S. Naval Electronic Systems Command
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U.S. DEPARTMENT OF COMMERCE, Rogers C.B. Morton, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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I. Introduction

Air plays an important role as an electrical insulating medium in any application involving use of high voltage at frequencies from DC to UHF. While the influences of such variables as the air composition, temperature, density, the humidity, the shape, size and spacing of the electrodes, as well as parameters associated with the applied voltage such as waveform, pulse polarity, and others, have been studied extensively at power frequencies during the past several decades, such studies still command a sizable share of the research efforts in the electrical power engineering field. The influence of frequency on gas breakdown has been studied to a more limited extent and then, with few exceptions, only at relatively low voltages. Most such studies have been academic in nature, motivated by a desire to understand the phenomena involved rather than directed toward the provision of data useful in engineering design.

The unexpected behavior of a protective gap in a VLF (15-30 kHz) radio antenna system prompted the study herein reported. It was initially directed toward the development of engineering criteria which could be used in the design of a satisfactory lightning and overvoltage protective gap system for the tower base insulator. The first effort was a literature search (summarized in Appendix A) to determine whether sufficient performance data already had been published to permit satisfactory engineering design. The literature search provided a useful insight into the problem and established a basis for a better understanding of the phenomena involved but it also revealed the need for additional experimental data. The VLF performance of several protective gap assemblies proposed by the contractor (Section III) provided further evidence of this need. The second major effort of this study was then directed toward the acquisition and analysis of data on the breakdown characteristics of air as a function of electrode geometry to provide a more solid basis than has heretofore been available for the engineering design of equipment planned for use at high voltages at VLF, as well as toward the more immediate objective--the development of a satisfactory lightning and overvoltage protective gap system for the existing VLF tower base insulator assemblies. In addition to a documentation and evaluation of these two efforts, this report discusses the performance of the protective gap system which was designed using the results of the study and explores briefly an alternative system.

The work herein reported was made possible by the existence of the excellent test facility constructed adjacent to the helix house of the VLF transmitter at the Naval Radio Transmitting Facility (NRTF), Lualualei, Hawaii. Designed by A. N. Smith of the Navy Electronics Laboratory Center (NELC), San Diego, California, and constructed and operated under his direction, this versatile facility utilizes the transmitter as a power source and the inductors and variometers in the helix house as the fine tuning elements of a resonant circuit which also includes the capacitor and inductor shown in Figure 1. A detailed description of this facility is to be given in a forthcoming NELC report.

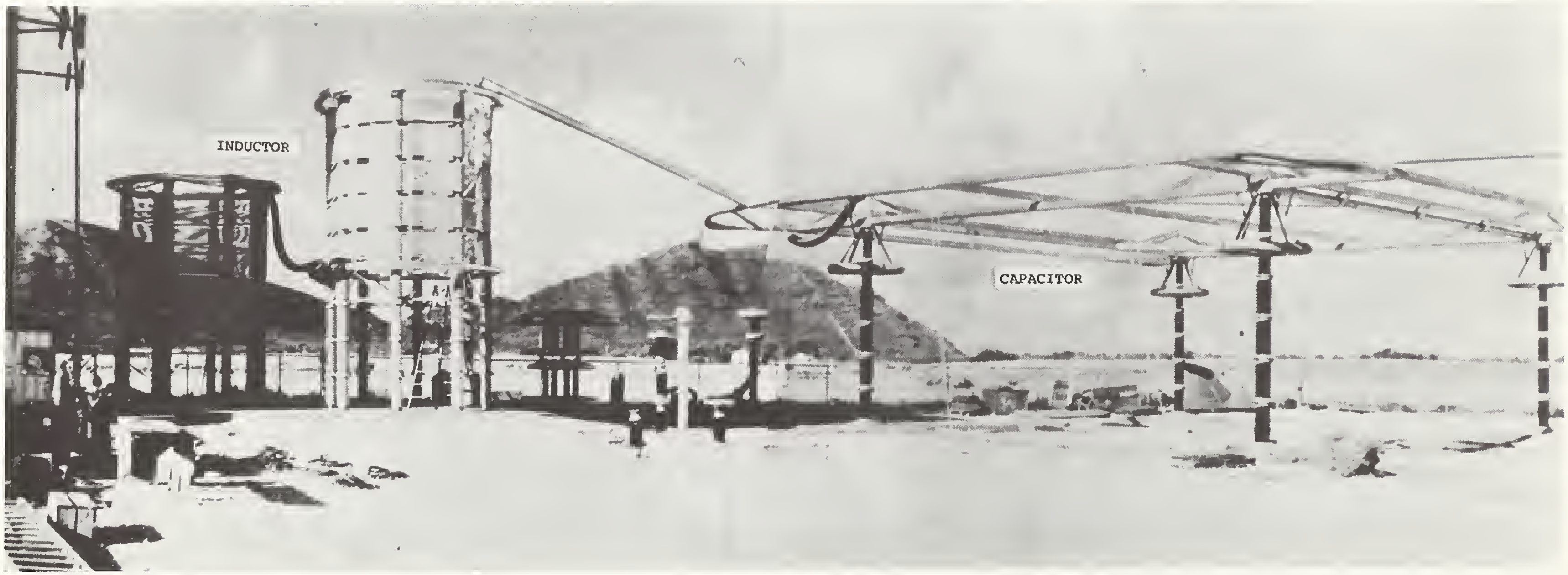


Figure 1 Outdoor Portion of VLF Test Facility at NRTF Lualualei, Oahu, Hawaii

II. Literature Search*

The effect of frequency on the dielectric strength of air and of other gases has been of interest to many investigators since the early part of this century. The earliest reference of significance found is contained in Dielectric Phenomena in High Voltage Engineering by F. W. Peek (1915) [1]. Figure 2 taken from that reference shows a reduction of the order of 10% in the breakdown voltage of a sphere gap over the range 0 to 1.3 cm spacing at 40 kHz relative to the 60 Hz value. Peek attributed the phenomena to the formation of needle-like streamers from rough places on the sphere as a result of the higher energy loss at the higher frequency and concluded that with highly polished spheres there would be no effect of frequency. This conclusion came into question as the results of other studies became available.

The technical literature prior to 1953 is well summarized in Meek and Craggs Electrical Breakdown of Gases (1953) [2]. The effect of frequency on the breakdown voltage of an air-gap had been shown to depend upon the electrode geometry and upon the gap separation. Figures 3 and 4 present representative results. It is to be noted that the frequency influence is much larger if the electrode geometry is such as to produce a highly non-uniform field--in which case a corona discharge precedes the breakdown.

The explanation for the frequency influence now generally accepted is as follows: At a low frequency, ions in the gap are swept to the electrodes during each half cycle of the applied voltage; however, as the frequency is increased a point is reached where there is insufficient time for an ion to cross the gap in half a cycle. Under these conditions a space charge may build up in the gap with a resulting field distortion and consequent lowering of the breakdown voltage.

The investigations summarized by Meeks and Craggs were intended, for the most part, to contribute to a better understanding of the phenomenon and were nearly all concerned with frequencies of the order of 100 kHz or higher and with air gaps from a few millimeters to a few centimeters in length. The fact that there appears to have been little interest in extending the studies to larger gaps and correspondingly lower frequencies may well be explained by the difficulty of meeting the requirement for a high-voltage power source at frequencies considerably above the power frequency range. However, there have been several studies which bear on the overall question, which in general tend to confirm the explanation offered above for the frequency influence and to justify extrapolation to the larger-gap, lower-frequency case.

Hepworth *et al.* (1972) [4] studied the effect of charged particles on impulse corona and breakdown. With non-uniform field gaps both short (1 cm) and long (1 1/2 meters), a significant influence of ionic space charge on corona formation and on breakdown voltage was observed. The effects were of relatively long duration--from a few seconds to several minutes.

By blowing air across a discharge gap into a charge detector, Fatehchand (1957) [5] demonstrated the existence of a positive space charge prior to breakdown when a high-frequency alternating voltage was applied across the gap. He also investigated the average space-charge density as a function of the frequency of the applied voltage. Zhukov (1965) [6] improved on Fatehchand's experimental techniques and was led by the result of his measurements in the vicinity of the "first critical frequency" to an empirical formula for

*See also Appendix A.

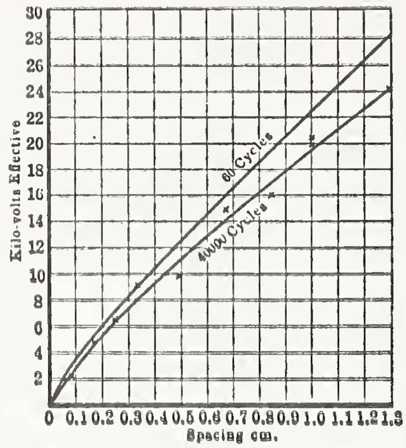


Figure 2—Sphere gap spark-over voltages at 60 cycles and 40,000 cycles. (From Peek[1])

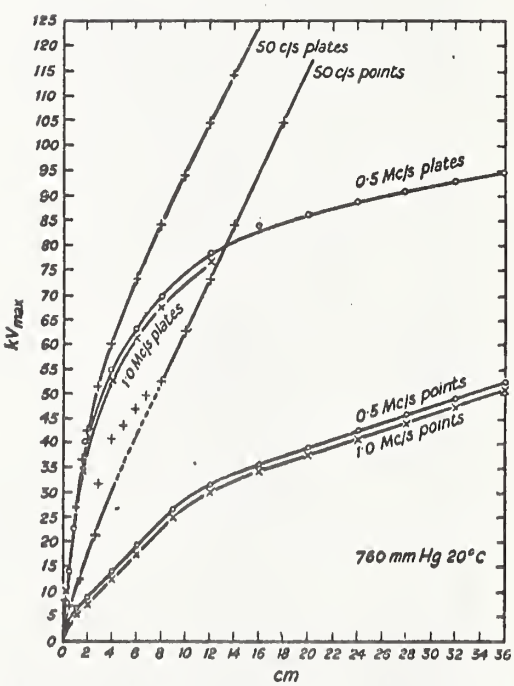


Figure 3. Breakdown voltage in air at atmospheric pressure as a function of gap length between plates and between points for frequencies of 50 c./s., 0·5 Mc./s. and 1·0 Mc./s. (From Meek and Craggs[2])

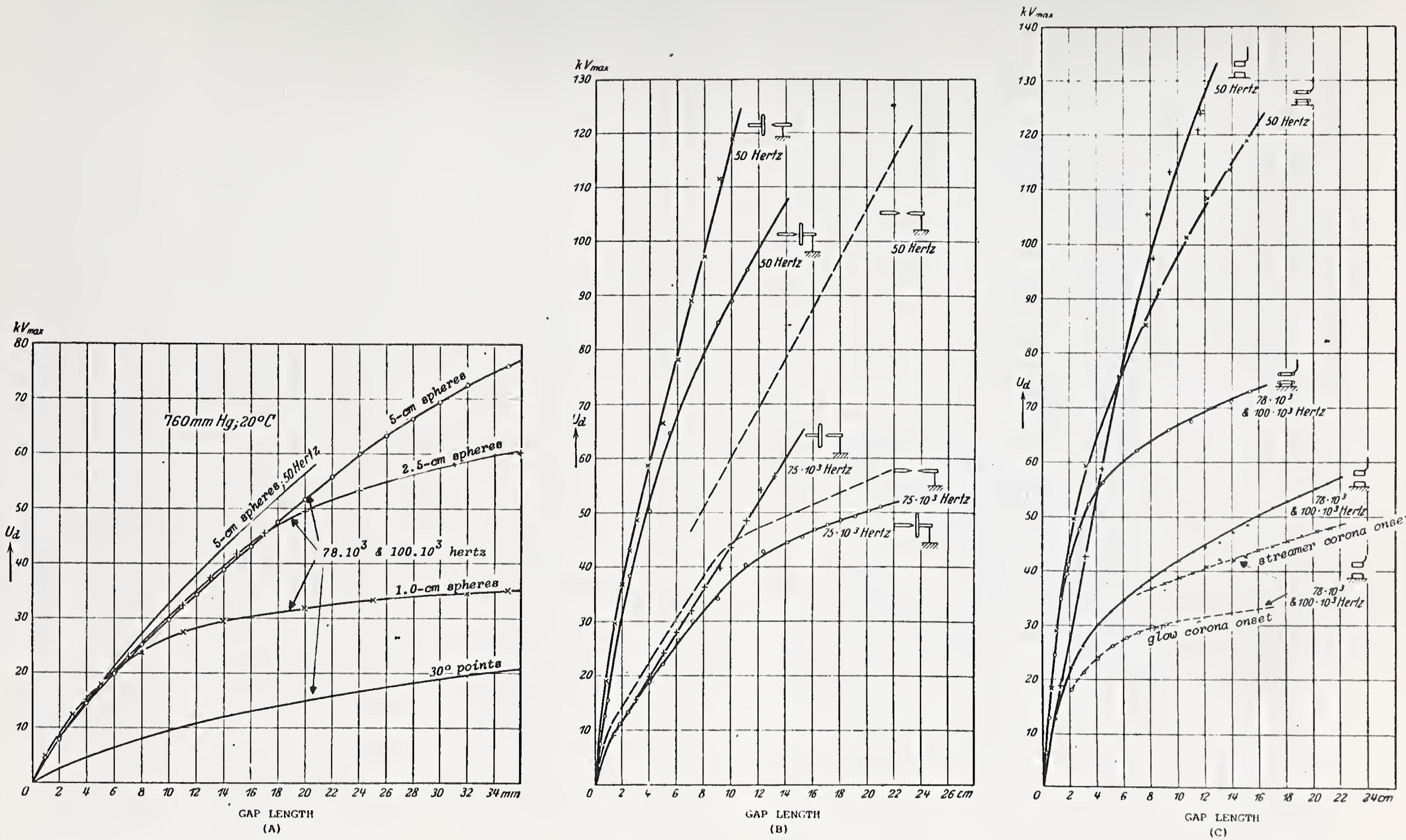


Figure 4 Effect of Frequency on Voltage Breakdown: (A) between 5, 2.5 and 1 cm diameter spheres and between 30° points; (B) between points and planes; and (C) between plane surfaces with rounded and with sharp edges as indicated. (From Kampschulte[3])

calculating the breakdown voltage as a function of gap length and frequency which agreed very well with his experimental data over the frequency range .1 to 10 MHz. It appears that in his work sufficient space charge to achieve a reduction in breakdown voltage with frequency required an external source of ionization.

While Fatechand and Zhukov worked with gaps at most a few centimeters in length and with frequencies in the megahertz region, the fact that space charges associated with corona discharges at 60 Hz on power transmission lines are significant at appreciable distances from the lines themselves had been demonstrated by Carroll and Lusignan [7] in 1927. Their work suggests that even at power frequencies one might anticipate a reduction of the voltage breakdown of a long air gap as a result of space-charge distortion of the electric field between the electrodes under circumstances where disturbing factors such as wind are not significant.

The mobility of "small" ions at atmospheric pressure is accepted as about 2.5 cm/s per volt/cm [8]. Using this value one calculates 3.1 cm as the 28.5 kHz critical gap spacing for which an ion could just cross the gap during a half cycle of an impressed voltage of 250 kV. Thus one would expect that in somewhat larger uniform-field gaps the likelihood of space-charge produced field distortion exists and that for these larger gaps the breakdown voltage at this frequency might be expected to be significantly lower than at 60 Hz.

III. Characteristics of Typical Protective Gap Assemblies

In the course of evaluating the performance of several protective gap assemblies proposed by the contractor for protection of the NRTF Annapolis and NRTF Lualualei VLF tower base insulator assemblies, a limited amount of data on both the 60 Hz and VLF (28.5 kHz) voltage breakdown as a function of gap length for two different electrode geometries as well as some VLF performance data for several variations of a third arrangement were obtained.

In obtaining the values of breakdown voltage reported in this and in the following sections, efforts were made to follow closely the procedure outlined in American National Standard C68.1 Techniques for Dielectric Tests which reads:

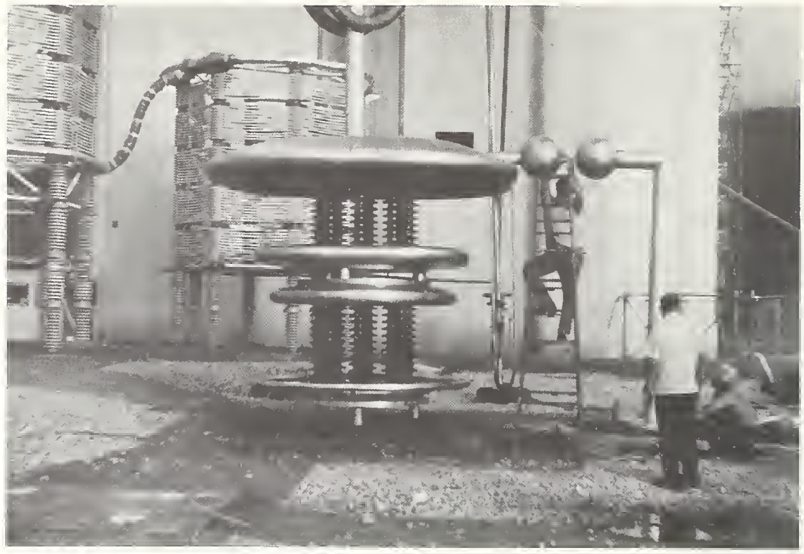
> "4.3 Test Procedure. The voltage should be applied to the test object starting at a value low enough to prevent overvoltages due to switching transients. It should be raised sufficiently slowly to permit accurate reading of the measuring instrument, but not so slowly as to cause unnecessary prolongation of the stress of the test object near the test voltage. These requirements are, in general, met if the rate of rise above 75 percent of the estimated final test voltage is about 2 percent of this voltage per second."
>
> Relative air density corrections were applied but none were made for humidity variations. See Appendix B.

In one protective-gap arrangement both electrodes were spheres of nominally equal diameter; the second was a horn-gap structure similar in general form to that which has seen extensive use in the electric power industry; and in the third, both electrodes were spheres but one was much smaller than the other.

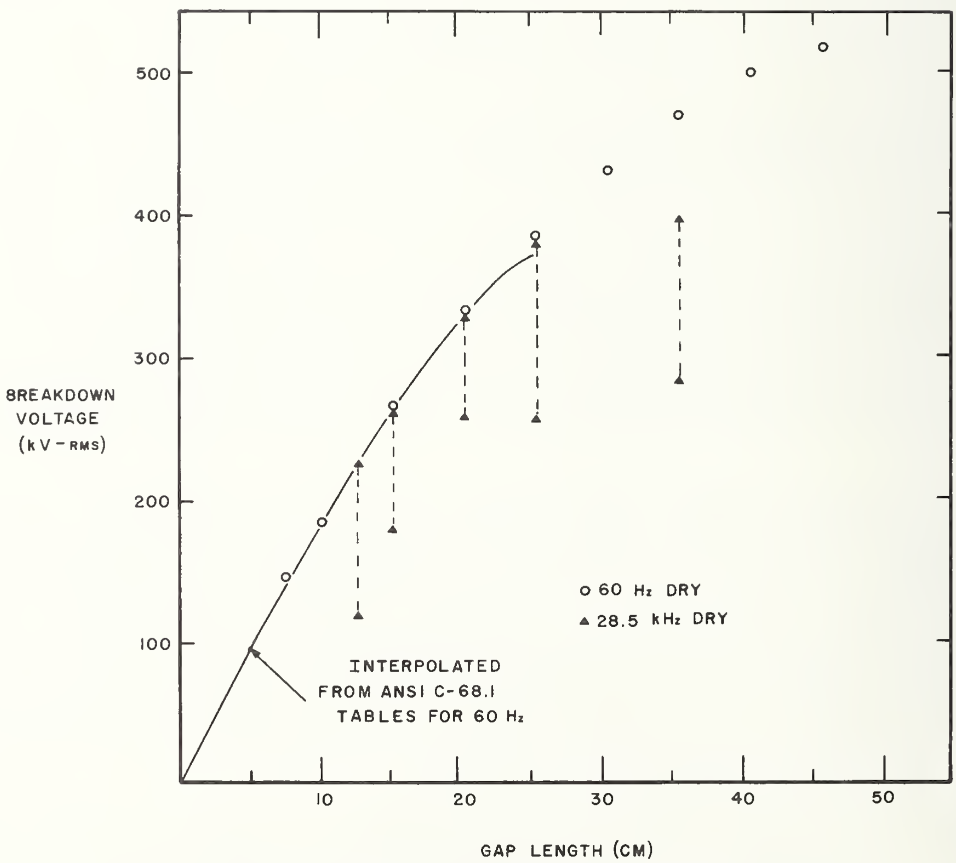
The results obtained with an 18" (45.7 cm) sphere gap mounted as shown in Figure 5 (a) are given in Figure 5 (b). The solid curve was obtained by interpolation from the internationally accepted standard sphere gap tables (ANSI Standard C68.1 and IEC Pub. 52). The agreement with the standard curve is somewhat better than might have been expected since the restrictions on the proximity of the supporting structures specified in the ANSI Standard were not met.

The 60 Hz data points represent the mean of at least three successive trials for which the spread in the values obtained was less than 1%. At the VLF frequency (28.5 kHz) the scatter in the breakdown values at a given spacing was quite large. The data points plotted show the extreme values observed. Of significance is the fact that at the 25-cm spacing two of the five trials resulted in flashovers from the base-insulator top rainshield about 2.5 meters to the ground plane without involving the sphere gap. The other three were flashovers in the gap. At the 36-cm spacing all except two of the five trials resulted in flashovers from the rainshield to ground rather than in the gap. Only gap flashover values are shown in Figure 5.

There is no pre-breakdown corona discharge in a relatively small gap between two large spheres. Thus the development of sufficient space charge to significantly distort the field must depend upon stray ionizing radiation. The experimental results indicate that the probability of such space charge development during the time interval in which the voltage is being raised toward the undistorted-field breakdown value is significant although not high.



(A)



(B)

FIGURE 5 PROTECTIVE GAP. 45.7-CM (18-INCH) DIAMETER SPHERES
(A) MOUNTING ARRANGEMENT, (B) BREAKDOWN CHARACTERISTICS

These tests appear to indicate that there was a greater probability of space-charge development initiated by corona discharges from electrode imperfections or from nearby structures or by other stray ionization sources in the 2.5-m gap between the rainshield and the ground plane than in the 0.36-m gap between the spheres.

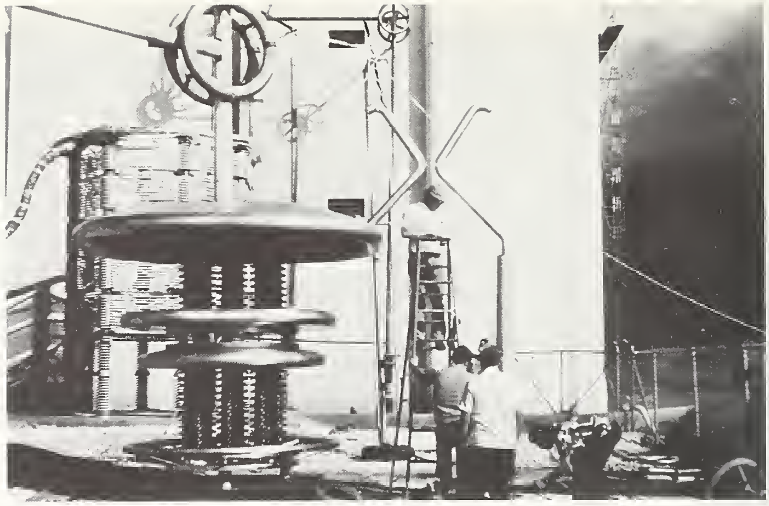
A horn-gap configuration was also studied both at 60 Hz and at 28.5 kHz. The electrodes were constructed of 4" (10-cm) diameter aluminum tubing bent and mounted as shown in Figure 6 (a). The results obtained are plotted in Figure 6 (b). Each data point shown for the 60 Hz experiments represents the average of at least three trials with mean deviations of less than 3%. The scatter in the dry 28.5 kHz test data was quite large; however, all the data obtained for flashovers in the gap fell within the ranges shown on the figure. Not indicated on the figure were several flashovers which occurred from the high voltage electrode or the top rainshield to the ground plane or ground electrode rather than in the gap during dry 28.5 kHz testing at gap settings of 75 cm and larger.

The behavior of the horn-gap configuration was investigated under simulated rain conditions with the results also shown in Figure 6 (b). Flashover seemed always to develop from corona streamers originating at water drops on the high-voltage electrode surface and at both frequencies with the larger spacings there were several flashovers to the ground plane rather than in the gap. However, for flashovers which occurred in the gap the consistency was quite comparable with that of the dry 60 Hz data.

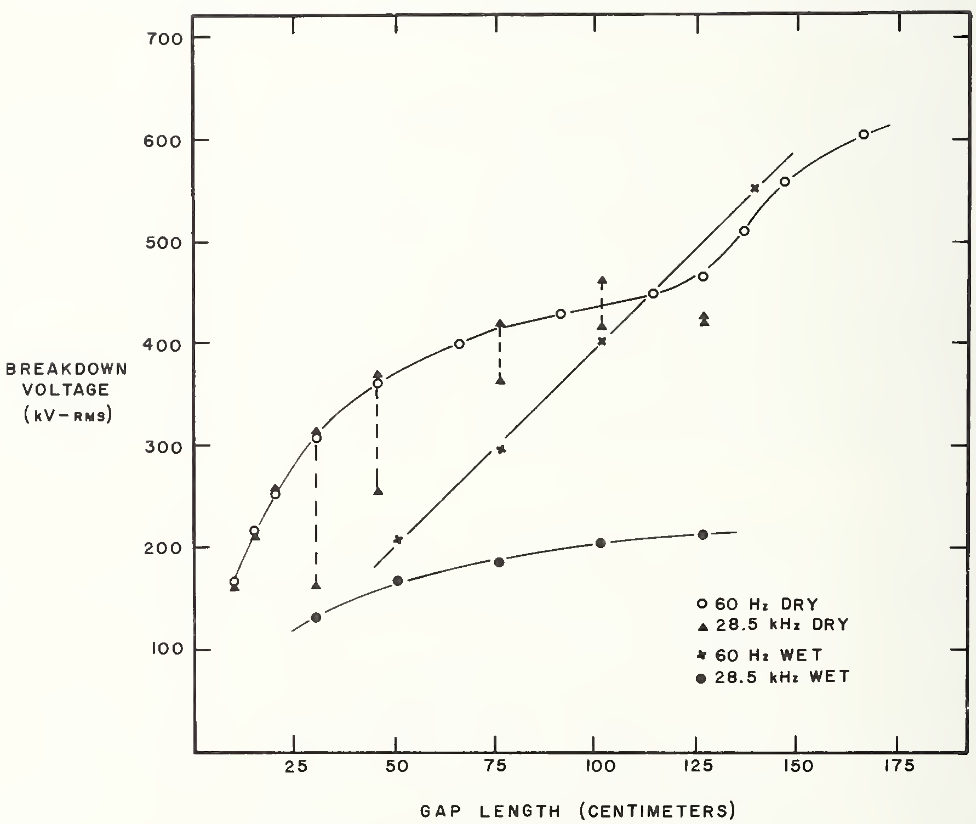
In each of these gap arrangements the performance at 28.5 kHz relative to that at 60 Hz, where the data permit such comparisons, can be explained on the basis of space-charge produced field distortion at the higher frequency. Under dry conditions, the smooth surfaces of the electrodes are not distorted by water droplets and the breakdown voltage appears to be independent of frequency--except for a rather significant percentage of what might be called anomalous flashovers which occur at 28.5 kHz. Under wet conditions the water droplets on the electrode surfaces act as corona sources and provide a copious supply of ionizing electrons and the breakdown voltage at 60 Hz as well as at 28.5 kHz is reduced. However, at the larger gap spacings the space-charge field distortion discussed in Section II is significant only at VLF and the breakdown voltage is very much lower at 28.5 kHz than at 60 Hz. The anomalous flashovers which occur at 28.5 kHz under dry conditions are to be explained as indicated above.

Several modifications of an asymmetrical sphere-gap system in which the high voltage electrode was one of the 45.7-cm spheres and the ground electrode a much smaller sphere were investigated at 28.5 kHz only. Figure 7 (a) shows a typical arrangement and Figure 7 (b) presents the results.

It is believed that the quite consistent performance exhibited when the grounded sphere was 2.5 or 5 centimeters diameter resulted from an ample supply of ions in the gap. Audible corona from the small ball prior to breakdown was always present. Note that under dry conditions with grounded sphere diameters of 7.5 and 15 centimeters, the scatter in values was comparable to that observed with the symmetrical sphere gap. Under wet conditions where water droplets on the spheres distorted the surfaces, the breakdown voltages appeared to be very nearly independent of the diameter of the grounded sphere.



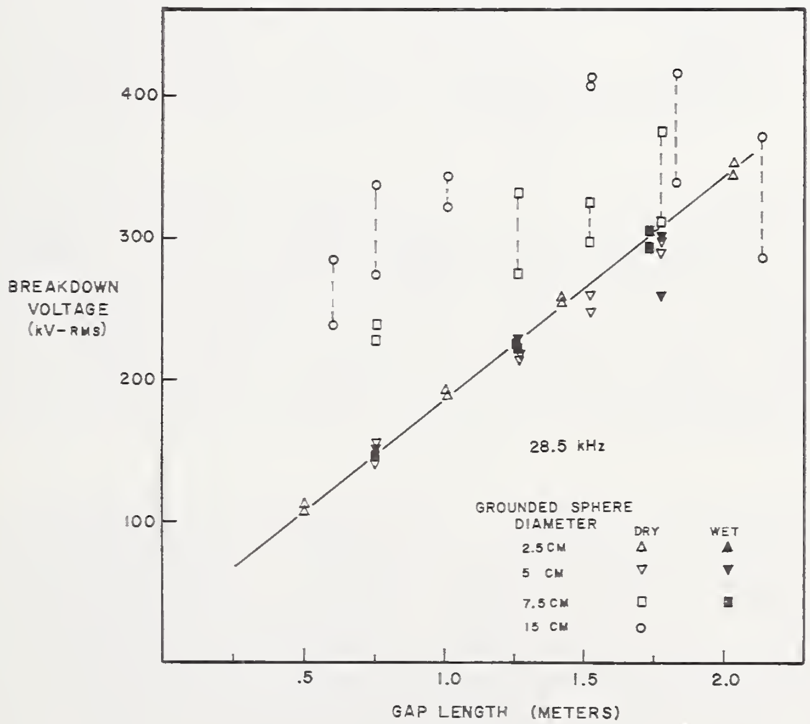
(A)



(B)

Figure 6 Horn Gap: (a) Mounting arrangement, (b) Breakdown characteristic

(A)



(B)

FIGURE 7 PROTECTIVE GAP. ASYMMETRIC SPHERES. (A) MOUNTING ARRANGEMENT. (B) BREAKDOWN CHARACTERISTICS

IV. VLF Performance of "Standard" Gaps

In the design of apparatus and structures for use in power-frequency high-voltage systems, engineers rely heavily upon characteristic curves showing breakdown voltage as a function of gap spacing for guidance in deciding upon safe spacings between components. In addition to this use, the well-documented data for sphere and so-called "standard" rod gaps make them useful as voltage measuring devices.

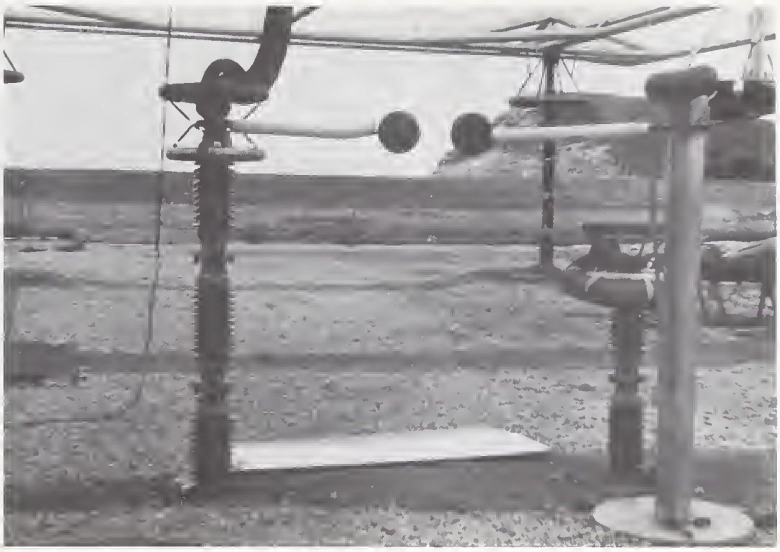
In order to provide a comparable basis for facility design at VLF, several electrode arrangements for which the 60-Hz performance is well documented were studied at 28.5 kHz. These included a 25-cm sphere gap, a horizontal rod gap and a rod-plane gap.

The 25-cm spheres used were heavy brass spheres with sparking surfaces in excellent condition. Care was taken to make certain the supporting structure met the requirements of the standards documents which apply to the use of sphere gaps as standards for voltage breakdown measurements (ANSI C68.1 and IEC No. 52). The test procedures recommended in the standards were followed as closely as possible. Corrections were applied for relative air density but none for humidity. (See Appendix B). Figure 8 (a) provides the details of the mounting arrangement used and Figure 8 (b) shows the results obtained.

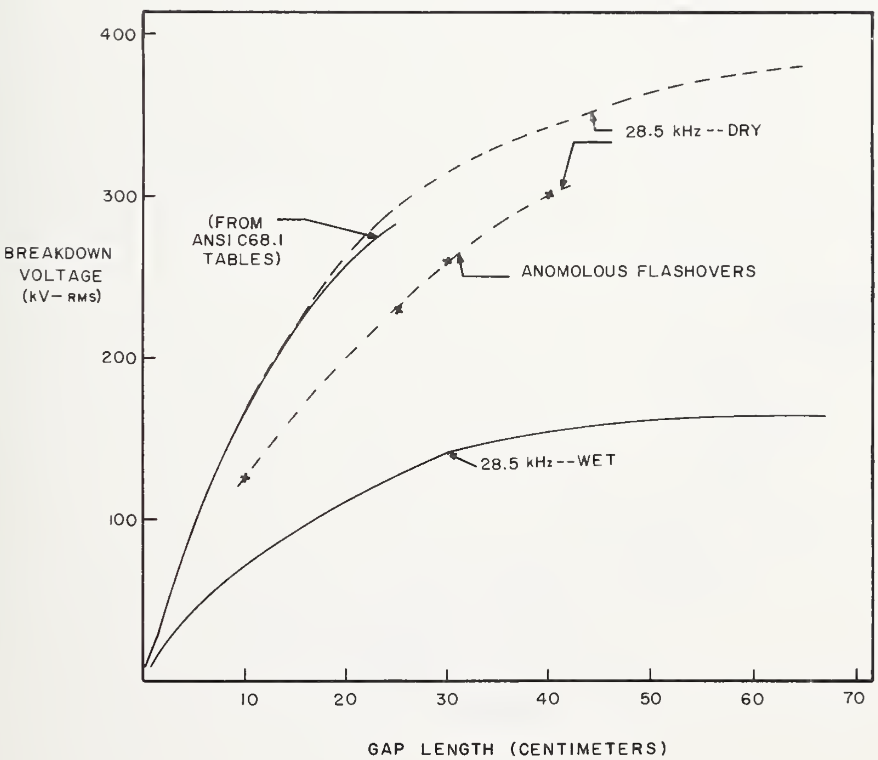
It is significant to note that except for a few anomalous flashovers, attributed to chance space-charge-induced field distortion, the breakdown voltage is the same at 28.5 kHz as at 60 Hz for spacings up to a sphere radius. The radius spacing is the limit for which a sphere gap is recommended as a measuring instrument. The significance of the difference between the 60 Hz and 28.5 kHz curves for larger gap spacing is open to question, since as the spacing is increased the influence of the surroundings becomes more important, and the extent of that influence is not known in either case.

This good agreement between the VLF and 60-Hz performance was not found in the case of "standard" rod gaps as Figure 9 (b) indicates. Figure 9 (a) shows the physical arrangement which met the clearance specifications for a standard rod gap (C68.1, p. 24) up to 1 meter gap length. The reduction in breakdown strength at 28.5 kHz relative to that at 60 Hz increases markedly with increasing gap spacing for gaps more than a few centimeters in length. It appears that the copious supply of ionizing electrons resulting from the corona discharge at the ends of the rods is adequate to produce significant space-charge field distortion.

Additional data were obtained for a sphere gap using the 45.7-cm diameter aluminum spheres previously tested as a protective gap. The sparking surfaces of these spheres were in good condition, however, it was not feasible to meet all the standards specifications for mounting them. The mounting arrangement is shown in Figure 10 (a) and the results of the testing are plotted in Figure 10 (b). In view of the fact that the dimensions and spacing of the supporting structures used for the VLF tests did not comply with the standards, the significance of the apparent reduction in the maximum values of breakdown strength at VLF relative to 60 Hz for gap lengths greater than the radius of one of the spheres is open to question. Unfortunately, a test series at 60 Hz with the same physical arrangement was not feasible. However, the results shown in Figure 5 obtained with a mounting arrangement where the influence of the proximity of the supporting structures should have been even more disturbing, lends confidence to the assumption that the interpolated curve for 60 Hz in



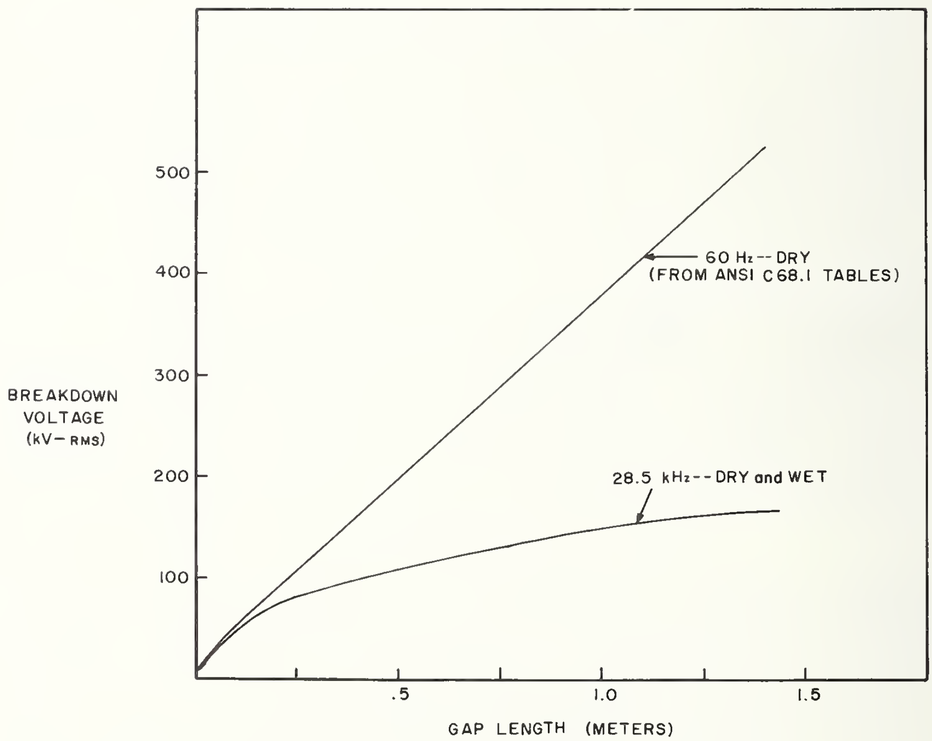
(A)



(B)

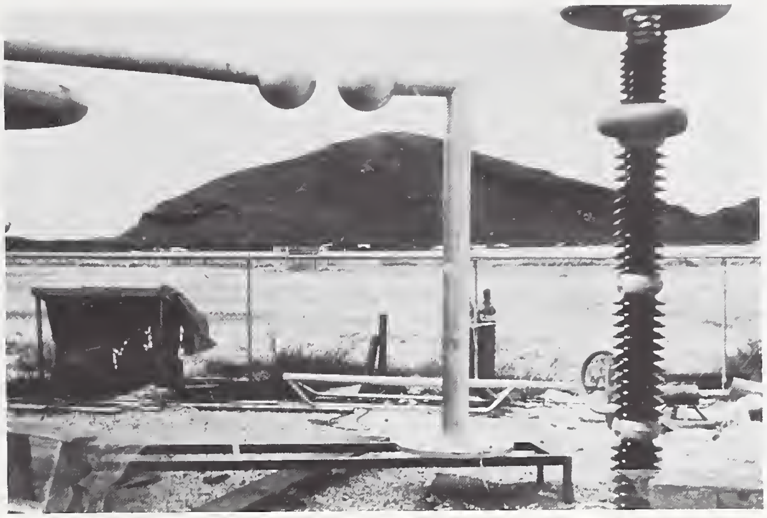
Figure 8 25-cm Sphere Gap: (a) Mounting arrangement,
(b) Breakdown characteristic

(A)

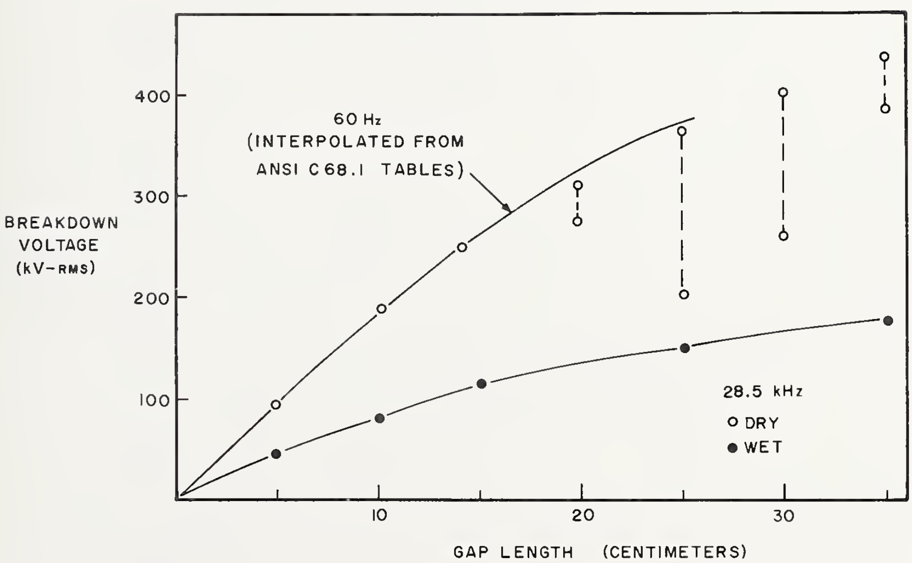


(B)

FIGURE 9 "STANDARD" (1/2-INCH SQUARE) ROD-ROD GAP: (A) MOUNTING ARRANGEMENT, (B) BREAKDOWN CHARACTERISTIC



(A)



(B)

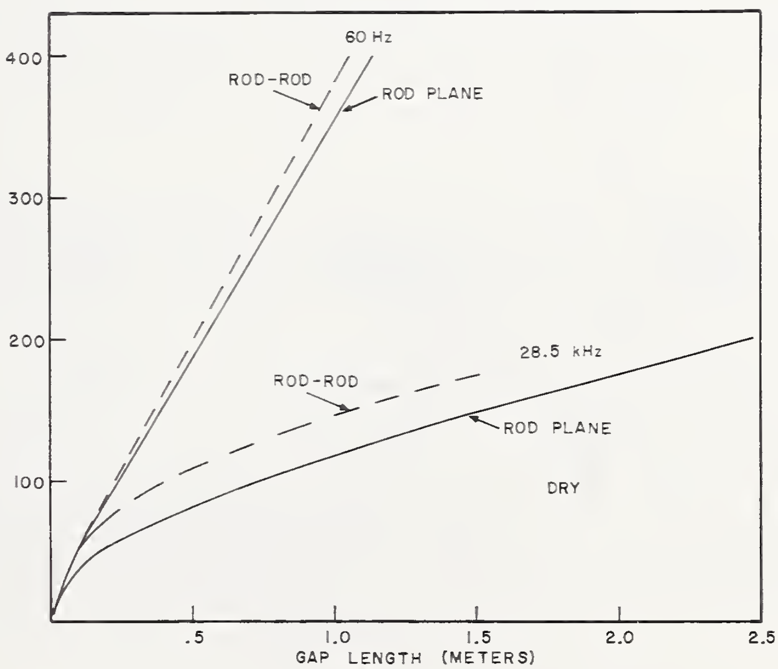
Figure 10 45.7-cm Sphere Gap: (a) Mounting arrangement, (b) Breakdown characteristic

Figure 10 (b) is not seriously in error.

VLF breakdown data for several rod-plane and sphere-plane gap configurations were obtained. The physical arrangements and the results obtained are shown in Figures 11 and 12. In those cases where 60 Hz data are available for essentially identical geometries, they are included for comparison.

The rod-rod characteristic could not be extended above about 170 kV since at higher voltages the flashover was preferentially over the longer path from the high voltage rod to the ground plane rather than to the grounded rod. Similar problems set an upper limit to the range of sphere-plane spacings for which data could be obtained. At higher voltages than those shown in Figure 12, the flashover path terminated on the sphere support rather than on the sphere itself. These results, together with those shown in Figure 13 for round rods with hemispherical ends which showed approximately sphere-gap characteristics up to spacings and voltages at which significant pre-breakdown discharges developed, and the "standard" rod-gap results at the higher voltages, are in accord with the space-charge field-distortion theory already discussed.

(A)



(B)

Figure 11 "Standard" (1/2 inch Square) Rod-Plane (A) mounting arrangement. (B) characteristic. (Rod-rod curves replotted from Fig. 9 for comparison. 60 Hz rod-plane data from Bellaschi and Teague[9])

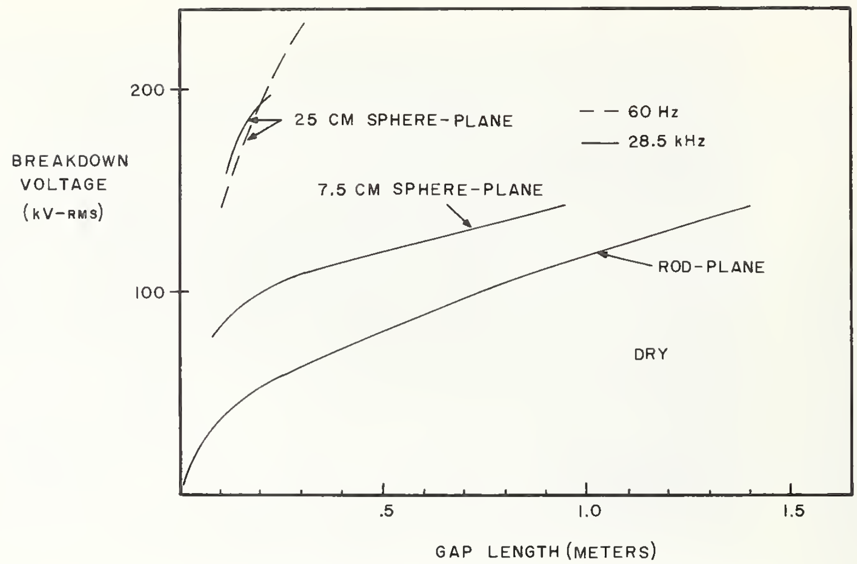


FIGURE 12 SPHERE-PLANE CHARACTERISTICS (ROD-PLANE CHARACTERISTIC REPLOTTED FROM FIGURE 11 FOR COMPARISON. 60 Hz DATA FROM BELLASCHI AND TEAGUE[9])

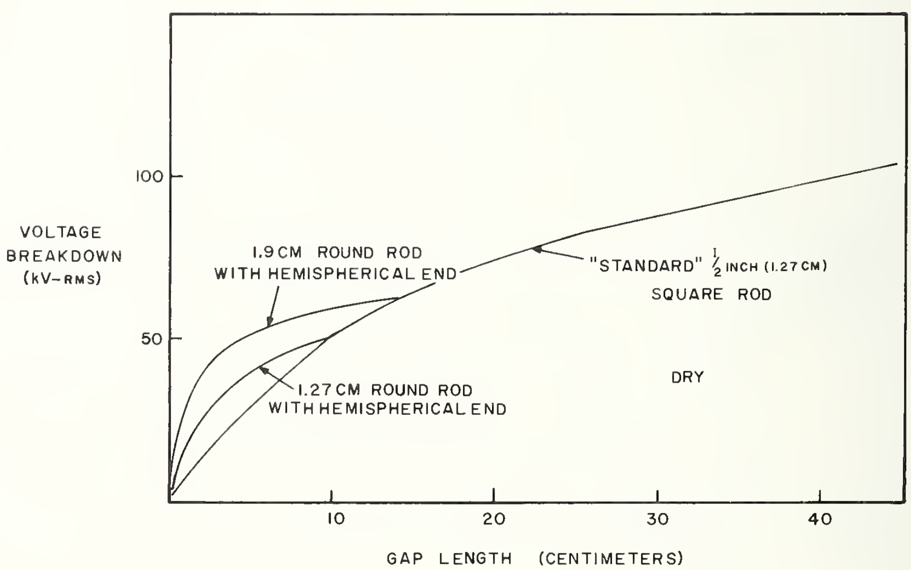


FIGURE 13 EFFECT OF ROD-END GEOMETRY ON ROD-ROD GAP BREAKDOWN CHARACTERISTICS

V. Conventional Protective Gap Systems

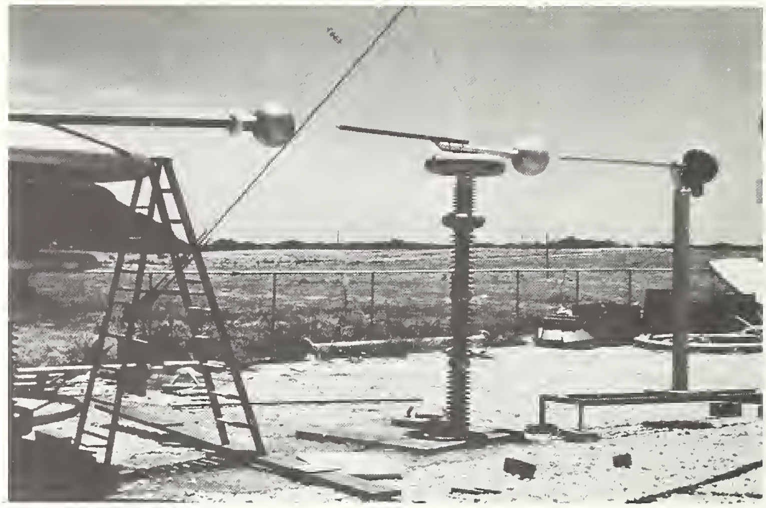
The protective gaps supplied with the original base insulator assemblies for the NRTF Annapolis and NRTF Lualualei VLF antenna towers were found to flash over occasionally at VLF voltages substantially below the design values. It was not possible to increase the spacing sufficiently to prevent anomalous flashovers without sacrificing completely the protective aspects. The high-voltage electrode of the gap was the outer rim of the top rainshield which had a major diameter of about 4.3 meters and a minimum radius of curvature in the vertical plane of about 7.5 centimeters. The ground electrode was a 10-cm sphere supported at the horizontal level of the rainshield by a 7.5-cm vertical rod.

Efforts to improve the performance by substituting electrodes with larger radii of curvature were only partially successful.

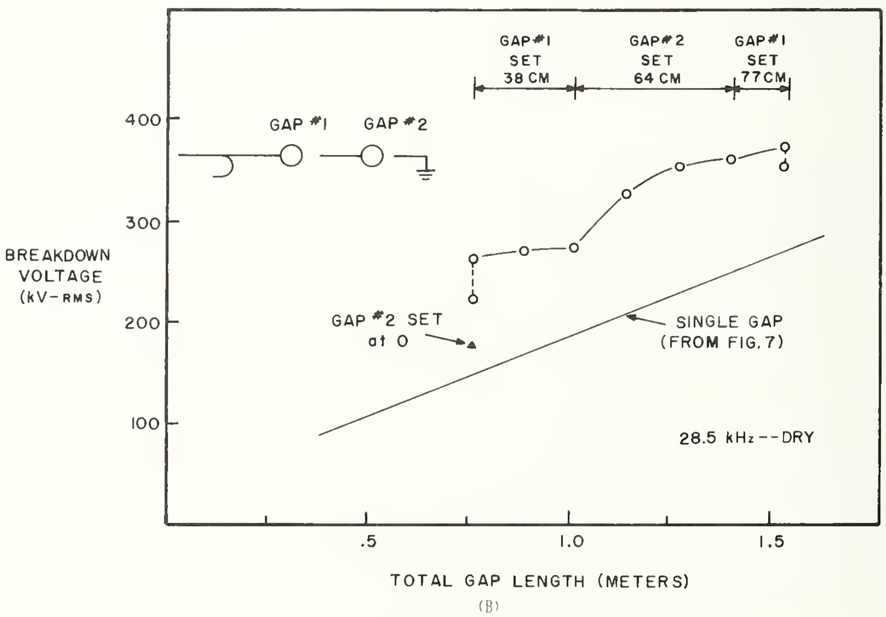
In the course of the redesign of the base insulator assembly, several different protective gap configurations were studied. Two of them, the 45.8-cm sphere gap and the horn gap were investigated both at 60 Hz and at VLF with the results indicated in Figures 5 and 6. Several gaps in which the electrodes were spheres but of unequal diameters were also investigated at VLF (see Figure 7).

Consideration of the performance of these various gap assemblies at 28.5 kHz in view of the conclusions regarding space-charge field distortion which could be drawn from the literature search led to the further conclusion that for the application at hand it was probably not possible to design a single gap operating at normal atmospheric pressure which would provide overvoltage protection and yet withstand the desired operating voltages under both dry and wet weather conditions without occasional anomalous flashovers.

The performance of the gap assembly consisting of a 47.5-cm diameter sphere as one electrode and a 2.5-cm or 5-cm sphere as the other was such as to nearly meet the requirements and suggested investigation of two such gaps in series. The dry flashover results of this investigation are shown in Figure 14. The limitation appeared to be the radius of curvature of the high voltage electrode which under rain conditions resulted in streamer formation from water droplets. However, all flashovers were in the gaps and, as shown in the figure, it was successfully demonstrated that the breakdown voltage for two such gaps in series is significantly higher than for a similar single gap of equivalent total length. It is believed the fact that the effect on breakdown voltage of the same incremental change in gap length was different for the two gaps resulted from lack of equal division of the total voltage between them. Further study of this configuration was discouraged by the results of a wet test during which there was extensive streamer development from water droplets on the high-voltage sphere at about 250 kV with flashovers occasionally to the ground plane as well as across the gap assembly.



(A)



(B)

FIGURE 14 DOUBLE ASYMMETRIC GAP ASSEMBLY: (A) MOUNTING ARRANGEMENT. (B) BREAKDOWN CHARACTERISTICS

VI. Multiple-gap Assemblies

A. The Rod-plane Array

Several versions of a multiple-gap assembly have been studied. The first of these, shown in Figure 15 consisted of short gaps between hemispherical electrodes. Under dry conditions the performance of this array with VLF appeared to be entirely satisfactory; however, rain droplets on the hemispheres seriously reduced the flashover level. An array which exhibited very nearly the same flashover values either wet or dry is that shown in Figure 16. The performance of such a system is highly dependent on the degree of uniformity achieved in distributing the total voltage over the individual gaps in the array. However, even when these efforts were only partially successful the overall performance of the assembly proved satisfactory at VLF.

The improved version of this rod-plane multiple-gap assembly (Figure 17), which had more nearly uniform voltage distribution and in which some adjustments were made in individual gap lengths in an attempt to compensate for the nonuniformity which remained, provided quite acceptable performance as shown in Table 1.

TABLE 1

Flashover Voltage of
Rod-plane Multiple-Gap Assembly
Shown in Figure 17

(See Appendix C for voltage distribution and gap settings)

Diameter of hemispherical rod ends (cm)	Dry Flashover (kV)	Wet Flashover (kV)
1.3	268	234
1.6	290	242
1.9	327	243

The effect of variations in the radius of curvature of the rod end was also studied using a single section (Figure 16) with the results shown in Table 2.

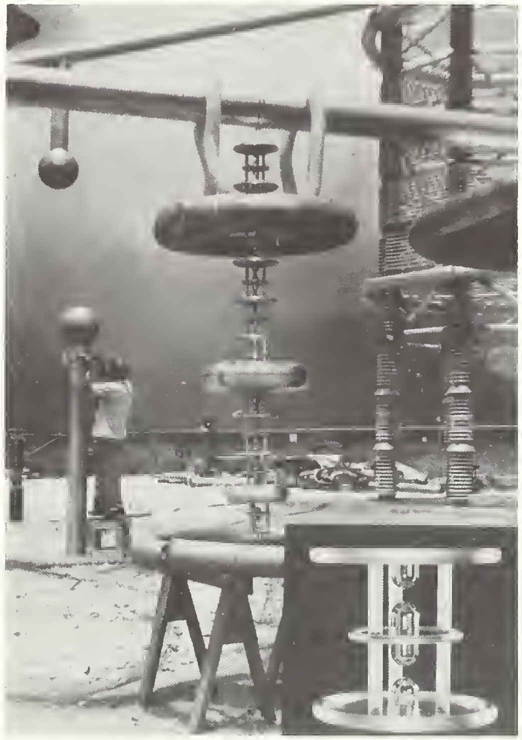


Figure 15 Prototype uniform-field multiple-gap assembly. Inset shows single section.

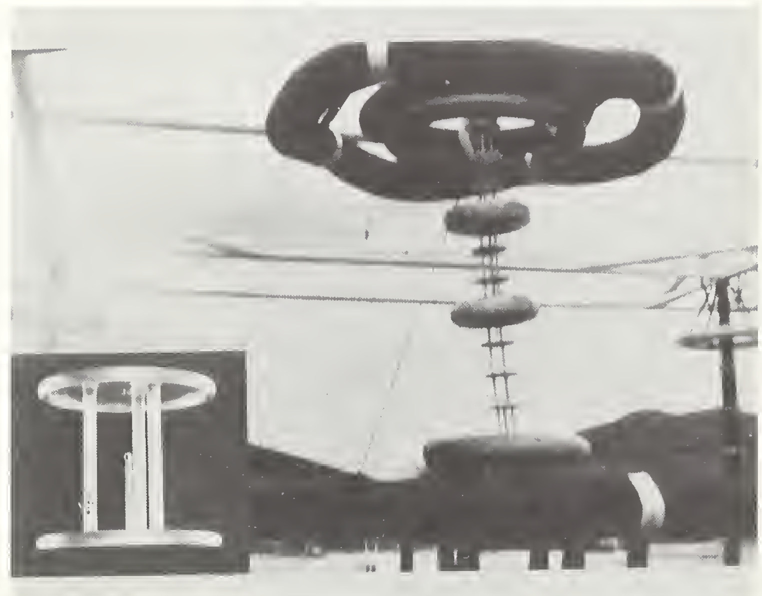


Figure 16 Prototype rod-plane multiple-gap assembly. Inset shows single section.

Figure 17 Multiple rod-plane gap assembly

Figure 18 Rod-ring gap

TABLE 2

Effect of Rod-End Curvature On Breakdown Voltage

Rod	Gap (cm)	Average Breakdown Voltage (kV)	
		60 Hz	28.5 kHz
1.3-cm cap nut on a .95-cm diameter round rod	10.9	47	49 (47 wet)
	8.3	38	40
	7.1	33	33
1.3-cm round rod with hemispherical end	10.9	49	51
1.9-cm round rod with hemispherical end	10.9	60	61 (47 wet)
	8.3	48	49

The data at 28.5 kHz were obtained at the NRTF Lualualei test facility while the 60 Hz data were obtained in the laboratory at the National Bureau of Standards. The values given are averages of at least six trials, and are probably correct within 3% under the precise conditions of the test. The small differences between the corresponding 60 Hz and 28.5 kHz values are probably the result of systematic errors arising from the effect of nearby conducting objects (which could not be made identical at the two locations) on the field distribution between the electrodes. However, these systematic errors remained constant in either location and thus at either frequency so that the variations with gap distance and with rod geometry are significant.

Over this range of gap settings, the breakdown voltage is demonstrated to be independent of frequency as could have been predicted from the results plotted in Figure 9 which show a marked effect of gap length on the frequency influence.

These results and those obtained with the complete assembly support the conclusion that the breakdown is initiated by corona discharge from the rod. Thus the breakdown voltage increases with increasing radius of curvature of the electrode surfaces when dry but, since the water droplets on the electrode surfaces act as corona sources, the breakdown voltage is very nearly independent of the radius of curvature under rain conditions.

It appears that a breakdown voltage nearly independent of weather conditions can be achieved with a multiple gap arrangement of this type if the radius of curvature of the rod end and its spacing from the plane is such that a pre-breakdown corona discharge develops under dry as well as wet conditions.

Of passing interest because of the contrast it demonstrates between 60 Hz and VLF corona phenomena is the result of an experiment with a single section of a wire-plane gap structure. This was prompted by work reported by Cookson and Farish in 1972 [10] which took advantage of the "ultra-corona" or "Hermstein glow" phenomena on a fine wire to greatly increase the breakdown strength of an air gap. In their experiments a 1.6-mm diameter wire, in the form of a 0.125-meter diameter hoop was suspended over a plane conductor and the 60 Hz dry breakdown voltage for the wire-plane gap so formed was found to be well over twice that of a standard rod-plane configuration at the same spacing. This advantage when dry disappeared under simulated rain conditions since then flashover was initiated by corona streamers off water droplets on the wire and the behavior was essentially that of a rod-plane gap.

Since a degree of shielding from the rain is provided by the gap arrangements of Figure 18 and since water would drop from the bottom of a ring mounted as shown, whereas the expected sparking point is at the top, a 8.4-cm gap of that design (Figure 18) was tested dry both at 60 Hz and at 28.5 kHz with the results shown in Table 3.

TABLE 3

Rod-ring Gap Performance

Frequency	Breakdown Voltage (kV)
60 Hz	∿ 100
28.5 kHz	38

As shown in Table 2, the breakdown voltage for the same length gap with a 1.3-cm hemispherically ended rod is about 40 kV. Thus the ring-plane gap exhibits a breakdown value at 60 Hz well over twice that for the rod-plane gap in confirmation of the findings of Cookson and Farish. However, since the breakdown voltages for the rod-plane and ring-plane gaps are not significantly different at 28.5 kHz it appears that the ultra-corona type of discharge either does not exist or simply does not influence the breakdown at VLF.

B. The Rod-rod Array

Anticipating a significant polarity effect in lightning impulse testing of a rod-plane structure, several rod-rod configurations were investigated to the extent time would permit since a rod-rod gap assembly would be expected to exhibit an impulse flashover characteristic nearly independent of the polarity of the impulse.

The rod-rod gap assembly shown in Figure 19, consisting of ten 6.4-cm gaps, exhibited at 28.5 kHz a dry flashover value of 261 kV and a wet flashover of 218 kV. However, the flashovers under wet conditions were all from the grading ring to ground. It appeared that had time permitted, an assembly of such gaps on a taller structure with more care taken in the design of the grading ring would have shown satisfactory performance at VLF.

An attempt to evaluate the rod-rod concept at VLF with improved field grading was made by installing a rod gap such as shown in Figure 20 in each section of the assembly of Figure 17. This, however, proved unsuccessful in that with the fourteen gaps required, the spacing of each gap could be only of the order of 2.5 centimeters. At that spacing it appeared that periodic bridging of one or more of the gaps by a water stream occurred in the heavy rain tests and the performance became erratic.

Figure 19 Single post rod-rod multiple-gap assembly

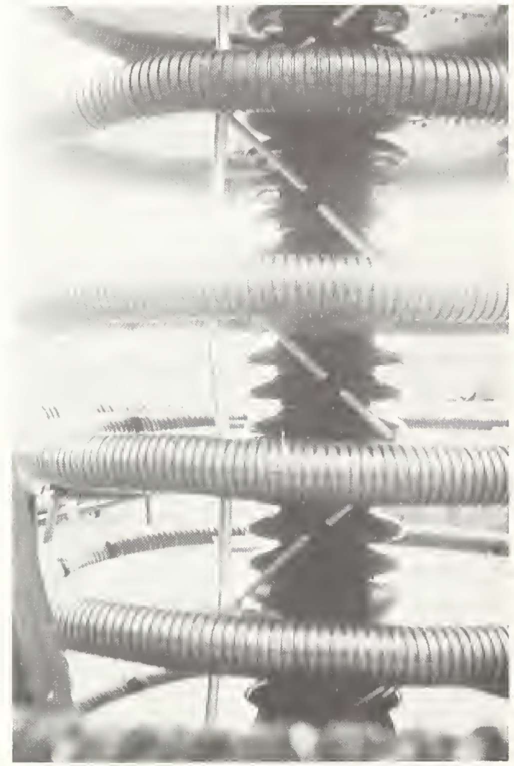


Figure 20 Assembly of Figure 17 modified to incorporate rod-rod gaps

C. Impulse Tests

While it was not feasible to attempt impulse testing of the gap assembly shown in Figure 17, a quite similar assembly which used most of the same components and for which very nearly identical VLF performance could be expected was tested at the Patuxent River Naval Air Test Center facility in March 1975 following the procedures outlined in ANSI C68.1. The results of those tests together with comparative data for the Continental Base Insulator Assembly (CBIA) obtained at the A. B. Chance Laboratory in August 1974, are shown in Table 4.

TABLE 4

Flashover Voltages
Rod-Plane Array
(kV)

	Assured Flashover(1) Gap System	Withstand(2) CBIA	Assured Flashover(1) Gap System	Withstand(2) CBIA
Positive Impulse	700	1490	660	870
Negative Impulse	480	1250	390	1070

(1) Probability of flashover approaching 100%.

(2) Probability of flashover approaching 0%.

Tests of the gap system were made with it mounted adjacent to and in parallel with a mockup of the CBIA. In the CBIA tests its two protective gaps were opened sufficiently wide as to render them largely ineffective. Corrections for relative air density and humidity as called for in ANSI C68.1 were applied. The raw data and atmospheric conditions are recorded in Appendix B.

The impulse voltage wave shape was that specified by American National Standard C68.1: 1.2 μs wave front and 50 μs tail.

As the table indicates, the gap system would provide lightning protection for the base insulator assembly.

Impulse tests of a rod-rod gap assembly were also conducted. The assembly tested differed significantly from those for which limited performance data were obtained at VLF. However, as shown in Table 5 the rod-rod structure does exhibit the advantage over the rod-plane structure in that the flashover voltage is very nearly the same for positive and negative polarity impulses and almost independent of weather conditions.

TABLE 5

Rod-Rod Array* Flashover Crest Voltages

	Dry	Wet
Positive Impulse	685 kV	675 kV
Negative Impulse	695 kV	680 kV

*Eleven 6.4-cm gaps in series.

VII. Summary

A careful study of the literature suggests that one might expect a significant reduction in the dielectric strength of an air gap at a frequency of 28.5 kHz relative to its strength at 60 Hz for gaps in excess of several centimeters if the ion density is sufficient to establish a "trapped" space charge in the gap. Experimental studies of several electrode geometries at 60 Hz and 28.5 kHz have confirmed this expectation.

It has been shown that a gap structure in which there is corona development prior to breakdown exhibits very nearly the same VLF flashover voltage under wet as under dry conditions. It has further been demonstrated that a protective gap array consisting of several short, non-uniform-field gaps in series can be set to protect an insulator assembly, under either wet or dry conditions, from VLF overvoltage and from lightning impulse voltages without the risk of occasional anomalous flashovers during continuous operation at rated VLF voltage. It has not proven possible to achieve such protection and reliability with a single open-air gap.

REFERENCES

1. F. W. Peek, Jr., Dielectric Phenomena in High Voltage Engineering. McGraw-Hill Book Co., Inc., New York, p. 107, 1915.

2. J. M. Meek and J. D. Craggs, Electrical Breakdown of Gases. Oxford University Press, London, Chapter IX, 1953.

3. Josef Kampschulte, "Luftdurchschlag und Überschlag Mit Wechselspannung Von 50 Und 100000 Hertz". Arch. F. Elektro., Vol. XXIV, p. 525-552, 1930.

4. J. K. Hepworth, R. C. Klewe, and B. A. Tozer, "The Effect of Charged Particles on Impulse Corona and Breakdown in a Divergent Field Gap". Proc. 2nd Int. Conf. on Gas Discharges, p. 227, 1972.

5. R.R.T. Fatehchand, "The Electrical Breakdown of Gaseous Dielectrics at High Frequencies". Proc. I.E.E. (London), vol. C104, pp. 489-495, 1957.

6. A. A. Zhukov, "Formation of a Space Charge in a High-frequency Electric Field in Air". Soviet Physics--Tech. Phys. (Trans from Zhurnal Teknichesko, Fiziki), vol. 10, pp. 116-118, 1965.

7. J. S. Carroll and J. T. Lusignan, "The Space Charge That Surrounds a Conductor in Corona". Trans. A.I.E.E., vol. 46, pp. 50-58, 1927.

8. L. B. Loeb, Electrical Coronas. U. of California Press, Berkeley, p. 415.

9. P. L. Bellaschi and W. L. Teague, "Impulse and 60 Cycle Strength of Air". Elect. Eng., vol. 53, pp. 1638-1645, 1934.

10. A. H. Cookson and O. Farish, "Breakdown of Wire-Plane, Disc-Plane, and Rod-Plane Gaps in Air". Proc. Int. Symp. on High Voltage Technology, Munich, p. 273, 1972.

Appendix A

ANNOTATED BIBLIOGRAPHY ON AIR-GAP BREAKDOWN AT FREQUENCIES ABOVE 60 Hz

(Arranged Chronologically)

Books

"Dielectric Phenomena in Electrical Engineering," F. W. Peek, Jr. McGraw-Hill Book Co., Inc., New York (1915) pp. 106-107. Mention of the effect of frequency.

"Fundamental Processes of Electrical Discharge in Gases," L. B. Loeb. John Wiley and Sons, Inc., New York (1939). Qualitative interpretation of experimental data showing reduction in breakdown voltage with increasing frequency.

"Electrical Breakdown of Gases," J. M. Meeks and J. D. Craggs. Clarendon Press (Oxford), (1953) pp. 374-382. A brief summary of the literature to 1953.

"Electrical Coronas," L. B. Loeb, U. of Cal. Press (Berkeley), (1965) pp. 569-571. A brief discussion of the physics involved leading to a reduction in flashover voltage with increasing frequency.

Journal Articles

Clark, J. C. and Ryan, H. J., "Sphere Gap Discharge Voltages at High Frequencies." Proc. Am. Inst. EE 33 (1914) II, 937. Data for 7-inch spheres at gap spacings up to 1 inch and at frequencies of 123, 255, and 612 kHz. In the frequency range covered the high frequency breakdown was about 4.5 kV below the 25 Hz values over the range 20-50 kV.

Goebeler, E., "Über die dielectrischen Eigenschaften der Luft und einiger fester Isoliermaterialien bei hochgespannter Hochfrequenz." Arch. Eleck 14 (1924) 491. No difference was observed between dc and 100 kHz for 2 cm sphere and plate electrodes at spacings up to 0.4 cm. With a needle gap a significant difference between 500 Hz and 10^5 Hz (at 1.5 cm spacing) was recorded.

Reukema, L. E., "The Relation Between Frequency and Spark-over Voltage in a Sphere-Gap Voltmeter." J. Am. Inst. EE 46 (1927) 1314. With 6.2 cm spheres spaced from 0.5 to 2.5 cm, some decrease in sparking voltage was observed when the frequency was changed from 20 to 60 kHz. 425 kHz values did not differ from those at 60 kHz. 425 kHz values did not differ from those at 60 kHz.

Gutton, C. and H., "Sur la d'echarge électrique en haute frequence." Comp. Rendus 186 (1928) 303. Coaxial cylindrical electrodes at 0.5 mm Hg pressure at frequencies of 5 x 10^4 to 10^8 Hz.

Kampschulte, J., "Luftdurchschlag und Überschlag mit Wechselspanuung von 50 und 100,000 Hertz." Arch Elektrotech 24 (1930) 525. Data for 1, 2.5, 5, 10, and 15 cm spheres as well as 30° points at spacings up to 3.4 cm and frequencies of 50 Hz and 75 and 110 kHz. Also given are data for point-to-point, rod-to-rod, and point-to-plane gaps up to 20 cm spacings at 50 Hz and 75 kHz (differences between the 50 Hz and 75 kHz values were of the order of a factor of 2 at the wider spacings). Data are also given for 1-5 cm diameter round plates with round and also with sharp edges at both frequencies as well as results of flashover tests of insulating solid materials mounted between such electrodes.

Lassen, H., "Frequenzabhängigkeit der Funkenspannung in Luft." Arch. Elektrotech 25 (1931) 322. Uniform field gaps using 2.5 cm spheres and 3 cm plates up to 0.5 cm spacing. Demonstrates the existence of a transition region both above and below which breakdown voltage is independent of frequency. (Transition was to a lower breakdown voltage at the higher frequencies).

Miseré, F., "Luftdurchschlag bei Niederfrequenz und Hochfrequenz an verschiedenen Elektroden." Arch. Elektrotech 26 (1932) 123. 5, 10, and 15 cm spheres at spacings up to 7 cm and with frequencies of 50 Hz and 428 and 850 kHz. The effect of frequency was larger with the smaller spheres amounting to about 20% at 6 cm spacing with the 5 cm spheres. Data are also given for 1.64 and 2.26 cm spheres to 18 cm spacing and for points and plates to 35 cm spacing. (A factor of 3 in breakdown voltage at 20 cm spacing is shown for points).

Müller, F., "Der elektrische Durschlag von Luft bei sehr hohen Frequenzen." Arch. Elektrotech 28 (1934) 341. 1 cm spheres up to 1/2 cm spacing at frequencies of 9×10^5 up to 2.5×10^7 Hz. Data agree with Lassen except that evidence of a gradual increase in breakdown voltage following the transition region is shown.

Fucks, W., "Zündung bei Wechselspannung und bei pulsierenden Bestrahlung." Zeit. Phys. 103 (1936). 709. A purely theoretical paper without presentation of experimental data.

Thompson, J., "Sparking Potentials at Ultra-High Frequencies." Phil. Mag. 23 (1937) 1. Results for frequencies in the range 2×10^6 to 10^8 Hz at pressures below 10 mm Hg.

Luft, H., "Überschlagspannungen bei Hochfrequenz mittlerer Wellenlänge an einfachen Anordnungen." Arch. Elektrotech 31 (1937) 93. 5 and 10 cm sphere gaps to 6 cm spacing at 50 and 4.6×10^5 Hz; points and point-to-plane gaps to 30 cm spacings at frequencies of 50 and 3.8×10^5 Hz. (With the point electrodes at 25 cm spacing a factor of about 3 in breakdown voltage was recorded).

Böcker, H., "Die Durchschlagsenkung bei Hochfrequenz." Arch. Elektrotech 31 (1937) 166. A purely theoretical paper based on space charge considerations leading to what the author calls satisfactory agreement with the experimental work of Lassen.

Seward, E. W., "The Electric Strength of Air at High Frequencies." J. I.E.E. (London) 84 (1939) 288. 1/2 cm spheres at 50 Hz and 109, 600, and 900 kHz. 1.4 cm spheres at 50 and 600 kHz maximum spacings of 40 cm. An explanation of the results is offered on the basis of space-charge accumulation.

Jacottet, P., "Zur Frage der Messung von Hochfrequenzspannungen und Stoszspannungen kürzester Dauer mit der Kugelfunkenstrecke." Electrotech Z. 92 (1939) 60. This appears to be simply a summary of uniform field data from a number of authors.

Ganger, B., "Der Hochfrequenzdurchschlag verdichteter Gase." Arch. Elektrotech 37 (1943) 267. 1/2 and 5 cm spheres and 25° points vs. plate at frequencies of 120 and 345 kHz. Measurements are given for several gases at 40 atmospheres pressure.

Hale, D. H., "The Breakdown of Gases in High Frequency Electrical Fields." Phys. Rev. 73 (1948) 1046. Theoretical study which is claimed to be in good agreement with experimental data for frequencies greater than 10^7 Hz at very low pressures.

Fatehchand, R.R.T., "Positive-ion Formation in Air Prior to High-Frequency Breakdown." Nature 167 (1951) 566. Demonstrates that a large positive ion current can be collected by a probe in an air stream flowing through a gap subjected to high frequency voltage prior to breakdown. Gap widths less than 1 mm and frequencies in the 2-20 MHz range.

Fatehchand, R.R.T., "The Electrical Breakdown of Gaseous Dielectrics at High Frequencies." Proc. I.E.E. (London) C104 (1957) 489. Gaps of the order of 0.1 mm at frequencies between 3.5 and 30 MHz. Demonstrates that at pressures below atmospheric the high-frequency breakdown voltage does not fall below the 50 Hz value until the amplitude of the + ion oscillation has become much smaller than the gap width. Explanation given in terms of positive ion accumulation based on measurements of ion currents as outlined in his 1951 paper (above).

Zhukov, A. A., "Formation of a Space Charge in a High-Frequency Electric Field in Air." Soviet Phys.--Tech. Phys. (Translation from Zhur. Tekh. Fiz. 35 (1965) 151). Study similar to that of Fatehchand (above) but based on what the author considers an improved technique. Gaps of 0.6 to 1.8 mm and frequencies of 1.5 to 10.0 MHz.

Rasquin, W., "Einfluss von überlagerten hochfrequenten Wechselspannungen auf die niederfrequenten Durchschlagspannungen von Luft." ETZ - A, 87 (1966) 272. The results of experiments in which 50 Hz and 150 kHz voltages were superimposed on coaxial cylindrical electrode systems are reported. With a 9 cm outer cylinder and a 3 mm inner electrode breakdown apparently dependent on the peak voltage reached, but with a 1 mm center electrode breakdown occurred with a 2 kV, 150 kHz signal superimposed on a 50 kV, 50 Hz voltage while without the 150 kHz signal 80 kV at 50 Hz were required for breakdown.

Zhukov, A. A., "Positive Space Charge and Reduction in Breakdown Voltage in the First Critical Frequency Region." Soviet Phys.--Tech. Phys. (Translation from Zhurnal Tekhnich. Fiz. 37 (1967) 710). Discussion of mechanism of electrical breakdown in parallel-plane gap ($\approx$ 1 mm) at atmospheric pressure and frequencies between 0.1 and 20 MHz -- based on space-charge considerations.

Feser, K., "Influence of Corona Discharges on the Breakdown Voltage of Air Gaps." Proc. IEE (London) 118 (1971) 1309. Results are reported with 50 Hz and with lightning and switching surge voltages applied to 40, 50, and 70 cm rod-plane and rod-rod gaps. In some cases a large scatter in breakdown voltage (up to 30%) was observed which was a function of the electrodes' shape (a point or 2 cm sphere) spacing and waveform. An explanation for the results is offered on the basis of the corona mode at the gap electrodes.

Formal Reports

Bright, A. W., "Corona and Breakdown at Frequencies up to 12 Megacycles per Second." British Elect. and Applied Industries Res. Assoc. Report, Ref. L/T 229 (1950). Not readily available in this country and therefore not reviewed.

Muehe, C. E., "AC Breakdown in Gases." Lincoln Laboratory, Massachusetts Institute of Technology, Technical Report No. 380, 26 Feb. 1965. Deals with electrodeless breakdown at microwave frequencies but contains a bibliography of nearly 200 entries (1891-1963) which covers the entire frequency spectrum.

Fournell, H. D., "Das Entladungsverhalten Von Luft In Koaxialen Zylinderelektrodenanordnungen Bei Gleichzeitiger Beanspruchung Mit Gleich-Und (Sinusförmigen) Wechselspannungn." Doctoral Thesis, Rheinisch-Westfälischen Technischen Hochschule Aachen (Germany) 1968. An extensive study of corona and breakdown in a coaxial cylinder geometry with superimposed direct and alternating voltages of frequencies: 50,500, 13×10^3, 30×10^3, 154×10^3, 760×10^3 and 1.7×10^6 Hz.

Appendix B

DATA TABULATION

The data plotted in the figures in the body of the report were corrected for relative air density in accord with the recommendations of ANSI C68.1; however, no corrections for humidity were made since none are available for VLF and those recommended for 60 Hz apply only to electrode geometries which differ significantly from those used in this study. For this reason, the uncorrected data obtained in the more significant series of measurements, together with the atmospheric conditions as recorded are tabulated in this appendix.

"STANDARD" (1/2" SQUARE) ROD-ROD GAP

Date	Barometric Pressure (millibars)	Wet Bulb (°F)	Dry Bulb (°F)	Gap (cm)	Observed Breakdown Voltage (kV)	Standard Deviation (unbiased %)
		Dry, 28.5 kHz				
5/17/74 AM	1014.3	69	80.5	19.9	74.5	1.3
	1013.7	69.5	82.0	50	110	.9
				90	141	1.4
				120	159	.9
				140	166	1.4
				30	86.5	1.0
PM	1012.6	69	79	10	49.9	2.0
				4.9	29.6	2.4
5/18/74	1015.5	67.5	75.5	10	51.0	1.6
				4.9	30.2	1.3
				90	140	.7
		Wet, 28.5 kHz				
5/18/74	1015.5			10	52.1	3.1
				4.9	28.6	1.4
				19.9	73.7	1.5
				30	86.7	2.2
				90	143	.9

NOTE: Each of the first six values of breakdown voltage tabulated above is the mean of 10 observations. Each of the others is the mean of at least 5 observations.

25-cm Sphere Gap
Dry, 28.5 kHz

Date	Barometric Pressure (millibars)	Wet Bulb (°F)	Dry Bulb (°F)	Gap (cm)	Observed Breakdown Voltage (kV)	Standard Deviation (unbiased, %)
5/15/74 AM	1013.2	69.5	71.5	2.5	52.6	.8
	1015.0	70	76	3.0	60.7	5.1
				4.1	83.7	1.2
				4.9	95.9	1.6
				7.0	130	.9
				7.0	110*	---
				10.0	169	1.2
				10.0	126*	---
	1014.5	68.5	79	12.45	195	1.4
PM	1013.8	73	82	15.0	214	.7
Late PM	1013.8	69	78	15.0	219	.8
				19.9	261**	.9
				19.9	180*	---
				19.9	238*	---
				19.9	193*	---
5/16/74 AM	1014.6	70.2	80.2	19.9	264	.5
				24.95	293	.5
				24.95	228*	---
				29.9	312	.7
				29.9	260*	---
PM	1012.6	69	75	35.0	333	.5
				40.0	340	1.0
				40.0	302*	---
				45.1	357	.4
				45.1	308*	---
				50.0	362	1.4

*Single measurement not included in the mean.

**Mean of 6 observations. Each of the other values is the mean of 10 observations.

MULTIPLE-GAP IMPULSE TESTS

Rod-plane Array	Barometric Pressure (millibars)	Wet Bulb (°F)	Dry Bulb (°F)	Observed "100%" Flashover Voltage (kV crest)
Positive Impulse Dry	1018	56	68	682
Negative Impulse Dry	1018	56	68	440
Positive Impulse Wet	1018		68.5	680
Negative Impulse Wet	1018		68.5	410
Rod-rod Array				
Positive Impulse Dry	986.5	62	67.5	665
Negative Impulse Dry	985.5	61	65	680
Positive Impulse Wet	985		63.5	675
Negative Impulse Wet	985		63.5	680

Appendix C

GAP SETTINGS

IN TEST OF

MULTIPLE ROD-PLANE GAP ASSEMBLY

Gap Number (#1 is bottom gap)	Percent of Total Voltage Across Gap	Gap Length (cm)
1	8.8	3.8
2	7.1	3.8
3	8.2	3.8
4	8.0	3.8
5	7.5	3.8
6	8.4	3.8
7	8.7	3.8
8	8.5	3.8
9	11.1	6.4
10	12.1	6.4
11	11.7	6.4

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			14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Measurements of the electrical breakdown of both quasi-uniform and highly nonuniform-field air gaps at a frequency of 28.5 kHz are reported. Gaps between a variety of electrode geometries ranged from a few centimeters to over two meters in length.

Breakdown voltages significantly below the corresponding 60 Hz values were observed with electrodes for which appreciable pre-breakdown discharges occurred, and a pattern of "anomalous" flashovers at considerably lower than the normal breakdown voltages was noted with quasi-uniform field gaps. The results obtained appear to correlate well with the data found in the literature for higher frequencies but lower voltages.

On the basis of the gap behavior observed, a prototype protective gap system designed for application to the tower base insulator assembly of a VLF (15 to 30 kHz) radio transmitter was tested and found satisfactory.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Air gap; electrical breakdown; insulator flashover; lightning protection; VLF antenna; voltage breakdown

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