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PERFORMANCE OF SIMPLE INSULATOR SHAPES UNDER HEAVILY CONTAMINATED CONDITIONS

by

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SUMMARY

Flashover voltage, scintillation current and AC resistance of a number of simple insulator geometries--rods, discs and cones--have been measured under contaminated conditions. Results have been compared with porcelain suspension insulators. Tests were made in a high density, conducting mist and correlated with the resistivity of the contaminant solution.

With such tests it seems possible to optimize insulator geometries. Flashover voltage of about twice that for conventional 6" porcelain suspension insulators have been demonstrated for small diameter cones on rods. While maintaining the same clearance distance* for an insulator design the effectiveness (per unit length of additional creepage distance) decreases with an increase in creepage distance. This is especially true in the vertical orientation. An increase in insulator diameter decreases effectiveness. Small diameter rods perform well.

Current measurements and photographs of scintillation and partial flashovers provide insight into insulator performance. Scintillation and arcing currents may lead to tracking and erosion of plastic insulators. Optimized design can reduce such currents by as much as twenty times. (This paper is to be presented at the IEEE Winter Power Meeting, NYC on 4 Feb., 1971 as recommended by the IEEE Group on Electrical Insulation.)

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*The distance between electrodes--the arcing distance.

KEY WORDS

insulators, flashover, contamination

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INTRODUCTION

The characteristics of simple insulator shapes under heavily contaminated conditions have been investigated with three major objectives in mind.

1. Improved understanding of the performance of insulators under contaminated conditions.
2. The development of optimized insulator geometries to operate in contaminated environments especially at very high voltages.
3. The development of insulator geometries which will most effectively utilize tracking and erosion resistant plastics.

The last two objectives are independent althoug it is possible that plastic insulators may ultimately be used even at the highest voltages.

Elastomeric bushings have been used for many years on outdoor instrument transformers. More recently tracking and erosion resistant elastomers and plastics have been used in a wide variety of outdoor applications including low voltage line insulators, fuse and cut-out supports, cable terminations, switchgear supports and bushings. The development of track and erosion resistant elastomers and plastic made possible the use of such materials in outdoor high-voltage applications. The author helped to develop the inclined plane, liquid contaminant tracking and erosion test[1] which is now widely used in the evaluation of track resistant materials. As development of organic insulators progressed it became apparent that a test for the performance of insulator geometries was also needed.

Conventional ceramic and glass insulators and bushings have been evaluated extensively in contamination tests designed to represent performance under adverse environmental conditions. Such studies have become especially important as transmission line voltages have increased. In the near future, system voltages may reach 1.5 megavolts. In general, the artificial pollution tests have lacked reproducibility or have been very time-consuming. The development of a high density, conducting mist test, which is described in a comparison paper[2], provided a rapid means for evaluating insulator geometries. Since scintillation and arcing current can be measured quantitatively, the new test also provided a means for judging the performance of plastic insulators as well.

INSULATOR GEOMETRY

The geometry of line insulators and apparatus bushings has evolved for over a hundred years as illustrated by hundreds of U.S. patents and a vast body of technical literature in many languages. About 60 years ago a technical breakthrough was made when strings of individual suspension insulator units were introduced. Over the years various modifications have been introduced, many of which were intended to contribute superior performance* under contaminated conditions. For a long time such designs were evaluated primarily by service trials, which required very long times and depended upon subjective opinion. For about the last ten years more sophisticated techniques for evaluating porcelain and glass insulators have been developed. However, most of this effort has been directed to studies of rather complex insulator shapes which have evolved over the years.

A more fundamental evaluation of fundamental insulator geometries under contaminated conditions seemed appropriate. Simple insulator shapes can be most easily fabricated from plastics with track resistant capabilities** although glass has been used also. Straight rods of various lengths and diameters were investigated first. Simple discs of various diameters were then added to these rods and spaced in different ways. The discs were modified by bands around their periphery to make cylinders. Finally, simple cones (inverted funnels) were substituted for the discs. The plastic models were often fabricated with RTV silicone to fill corners (fillets) or otherwise modify the simple geometry. A variety of such construction are pictured in Fig. 1.

In the beginning, cones were cut from plastic and glass funnels to be slipped over plastic rods. When an intrinsic advantage in the cone construction was discovered, 3 and 5-inch cones were molded from ethylene-propylene rubber (EPDM) which could be slipped over a plastic rod and spaced with EPDM separators. Several varieties of such construction are shown in Fig. 2.

* Many concepts and different opinions have existed. Some support designs which will be easily washed by rain to prevent contaminant buildup. Others contend that natural "washing" is ineffective and long paths with special geometries are needed.

** Polymethyl methacrylate (PMMA), polytetrafluorethylen (TFE), polyethylene (PE), special track resistant modified epoxy resins, room temperature vulcanizing silicone rubber (RTV) and ethylene-propylene-diene monomer rubber (EPDM) have proved to be most useful.

The concepts of basic insulator shapes can be illustrated by simple line drawings as shown in Fig. 3. Modular creepage distances (over the surface) are indicated by an "X". Modular spacings are indicated by an "S". The total spacing and creepage distances for the geometries in Fig. 3 are listed below:

Fig. 3	Spacing	Creepage
(a)	2S	2X
(b)	2S	6X
(c)	2S	8X
(d)	2S	$2\sqrt{2}$ X (2.8X)
(e)	2S	2X + $4\sqrt{2}$X (7.6X)

It is apparent that configuration (c) sacrifices clearance to gain creepage distance and that (e) has the best of both. Practical insulators may combine features of these line drawings. A rounded disc design which is a combination of configurations (b) and (d), is commonly used. General Electric Insulator Department 15KV polymer tension insulator (trademark "Gepol") is of this type and has a deep almost sinusoidal profile. Several others of many possible modifications are shown in Fig. 4. Study of these line drawings can lead to several observations.

1. Discs or cones can be crowded together, as in (a) and (b), until arcing will take place preferentially across the gaps rather than along the surfaces. The same effect will occur if the diameter of the discs is made large relative to the spacing.

2. Disc or cones may be spaced so far apart that creepage distance may be decreased too much, e.g., (c).

3. Configuration (d) emphasizes creepage to the detriment of clearance and may also in practical configurations provide a trap for dirt deep inside the narrow cones.

4. Configurations (e), (f) and (g) are representative of porcelain suspension insulator designs if the central vertical line is considered to be a conductor (the hardware). Configuration "g" is characteristic of one common type of fog insulator. A trade-off between creepage and clearance distance is achieved by changing the length and the spacing of the vertical lines (ribs).

Presumably some sort of optimum size and spacing can be achieved for each type of geometry. Moreover, the orientation (vertical, horizontal, etc.) of the insulator surfaces may also be important. Obviously, an investigational approach is needed and has been the basis of this program.

The investigation can be divided into three parts.

1. Visual observation with photographic record.
2. Flashover voltage studies.
3. Leakage current measurements.

The techniques used have been described in a companion paper[2]. The results are discussed in the following three sections.

VISUAL OBSERVATION

In support of very extensive visual observations more than 2000 photographs in color of scintillation*, partial flashover* and complete flashover of many types of insulator shapes have been taken at different voltages in tap water, 0.1% salt and 1.0% salt, high-density mists. Some of the results with straight rods and porcelain suspension insulators have been described in the comparison paper[2] to illustrate the test method used.

It is possible here to include only a few typical photographs. For example, three 11" long** vertical rods at 38KV in tap water mist are shown in Fig. 5. Only about the top half of these rods are covered with scintillation (the bottom halves are dark and cannot be seen). Both material and diameter affect the visual results. A correlation with current measurements will be described later.

When discs are added to a rod the visual characteristics change. A small 4" diameter disc, 7" from the top of a 36" long rod does not have much effect, as shown in Fig. 6 (only about one-half of the rod is visible). Most of the scintillation is on the rod and the numerous partial flashovers (streamers) are interesting. When the disc is increased to an 8" diameter,

*Scintillation is characterized by many, rather short low intensity arcs which bridge short gaps over small dry areas on a contaminated insulator surface. Partial flashover is a longer higher energy arc, which leaves the surface but does not completely bridge the insulator. Partial flashover often takes place from skirt to skirt so as to bridge part but not all of the insulator. Such long arcs are sometimes also called "streamers". Unfortunately, no well-defined definitions for these terms have common acceptance.

the amount of scintillation is decreased and a radial scintillation pattern can be seen on the disc (Fig. 7). Both rod and disc have a reasonably uniform stress distribution. When the disc is increased to a 16" dia. (Fig.8), the stress distribution is no longer uniform and concentrates just below the disc on the rod. In this case the 8" disc is optimum.

All of the foregoing pictures were taken with a camera exposure of one second so as to record multiple streamers and scintillation. If the photographic exposure time is reduced to 1/60 second (Fig. 9) only two streamers are observed which probably occurred at about the two peak voltages of a single 60 Hertz wave. Visual evidence of stress concentration is common also with multiple discs on rods in the vertical position. Similar effects are observed with the Gepol polymer tension insulator in the vertical position.

Voltage also affects the pattern of the scintillation. Figs. 10 and 11 show a horizontal rod with one 8" dia. disc placed 7" from the left (ground) end of a 36" long rod. At 60KV (Fig. 10) voltage stress concentrates on the disc (the rest is dark) with a curious scintillation pattern of concentric rings. At 100KV (Fig. 11) the scintillation pattern has become radial with more evidence of streamers. Such a radial pattern often precedes flashover.

Distribution of the mist on the test insulator will also influence the visual evidence as shown in Fig. 12. A slightly uneven distribution of the mist causes uneven stress distribution across 9 polyethylene cones in series on a 33" rod. Some of the details are interesting. In Fig. 12, partial flashover can be seen between the lip of the bottom cone and the bottom (high-voltage) electrode. A similar limited flashover takes place between the lip of the second cone from the top and the middle surface of the cone beneath it. Scintillation on the rod under the second cone is also evident. The light on the translucent cones is due partly to light transmitted from the rod but also may be caused by scintillation on the inside of the cones. The considerable drip from the edges of the cones is not illuminated, and cannot be seen in this photograph. However, it is interesting that streamers generally do not follow this drop pattern. In Fig. 13, a more even distribution of mist has been achieved as shown by the even glow of the scintillation on all of the cones. Partial flashover is taking place between the second and third cones on the right side of the photograph. Flashover is imminent and is likely to take place when the mist is cut off. As drying progresses, the limited flashovers become larger, will skip from place to place and ultimately may span three or more cones. Finally, complete flashover will take place, although it may be necessary to repeat the wetting and drying cycle several times before flashover occurs.

Many more examples could be included but it is hoped that the foregoing illustrates the usefulness of visual observation and photography in determining voltage distribution and the events which lead to flashover. Transparent or translucent models are particularly useful in such visual studies.

VOLTAGE FLASHOVER

Data for the flashover voltage of several simple insulator geometries is compared with 6" dia. porcelain insulators and a commercial "Gepol" polymer insulator* in Tables I, II and III for 0.1% salt water mist, 1.0% salt water mist and tap water mist. The calculated flashover stresses, based upon the creepage (surface) distance** have been included also in the tables. Results are reported for both horizontal and vertical orientation and the horizontal/vertical ratio has been calculated.

Orientation

The Gepol polymer insulator, as noted earlier, is actually a number of somewhat rounded discs (sinusoidal shape) along a central core. In the horizontal position it has a higher flashover voltage than the two 6" porcelain suspension insulators even though the clearance is shorter--7" compared to 11". Of course much of the clearance distance of the porcelain

* Gepol is General Electric's tradmark for a cast track-resistant epoxy resin around a glass fiber tension core. It is suggested for use on circuits up to 15KV and is recommended for use <u>only</u> in the horizontal position. The design evaluated is an early model. A modified design is now in production.

**The dimension at the left of the insulator description is the clearance distance. The cones in this case were molded of ethylene-propylene rubber (EPDM).

suspension insulators is taken up by the metal hardware*. In the vertical position, the flashover voltages are lower. A comparative summary for some of the data is interesting.

	Flashover Voltage								
	tap water mist kv			0.1% salt mist KV			KV		
	Horiz.	Vert.	H/V	Horiz.	Vert.	H/V	Horiz.	Vert.	H/V
7", Gepol polymer insulator	51.25	28.75	1.8	25	14	1.8	10	9	1.1
11", porcelain	41.75	33.75	1.2	21.75	17.5	1.2	9	10	0.9
11", rod	35	31.25	1.1	20	17.25	1.2	11.75	10	1.2
11", 4-5" cones	85	70	1.2	43.75	35	1.2	23.75	22.5	1.0
11", 4-5 1/8" discs				40	27.5	1.4			

The disc-like Gepol polymer insulator and the 4 plastic discs on an 11" long, 1" dia. rod have a much lower flashover voltage in the vertical position. If contaminant running down the vertical surface is responsible it might be expected to influence the results on a vertical rod. However, the effect of orientation on the straight rod is not marked. It seems more likely that the leakage current pattern on the discs tends to increase in density at the inner diameter to produce arcing as shown in the photograph (Fig. 8). Such arcing progresses with an increase in voltage and leads to flashover. Similar effects are not apparent with the cones. The increased

* These values are the clearance distance which generally is the same as the arcing distance. However, with porcelain suspension insulators the arcing distance is decreased by the metal cap on the top unit. For 6" diameter units this decrease aounts to 1 3/8".

No. of 6" Units	Clearance Distance - In.	Arcing Distance - In.
1	5 1/2	4 1/8
2	11	9 5/8
4	22	20 5/8
6	33	31 5/8

creepage distance with the cone construction may help but does not appear to be the only beneficial factor. The reentrant profile of the cones seems to have an intrinsic advantage. The results with frustrums (solid cones) in Table I bear out this observation.

When rims are added to the outer periphery of the 5" dia. discs to make cylinders (Table I) the flashover voltage depends somewhat upon the width of the rim (the depth of the cylinder) as summarized below:

11" Insulator (Vertical)	(0.1% salt mist) Flashover Voltage KV	Flashover Stress KV/inch
4 discs alone	27.5	0.97
1" wide rim on discs	30	0.83
2" wide rim on discs	26.75	0.61

When the rim is made too wide, clearance is sacrificed to the detriment of flashover performance. The implications in respect to the design of ribs on the underside of porcelain suspension insulators is obvious.

Effect of Insulator Length

Results from Table I along with additional data are plotted in Figs. 14, 15, 16, and 17 to show the effect of both clearance and creepage distance on the flashover voltage for several geometries in both vertical and horizontal orientation. From the functional point of view, the flashover voltage versus clearance distance (Figs. 14 and 16) is most important. However, the plots against creepage distance (Figs. 15 and 17) give an idea of what might be called the "efficiency" of the geometry.

The superiority of the cone construction is apparent. When plotted against clearance distance (Figs. 14 and 16), the cone constructions have about twice the flashover voltage of the rod or the porcelain suspension insulators. Because the creepage distance is greater for the 5" cones than for the 3" cones the flashover voltage versus clearance is greater for the 5" cones. When plotted against creepage distance the comparison reverses.

From the point of view of unit creepage distance, the larger the diameter of the insulator the poorer the performance (Fig. 15). In the horizontal position the performance of the Gepol polymer insulator is superior to the porcelain suspension units and comparable to the cone construction.

Variable Creepage Distance - Same Clearance

It is obvious that the creepage distance and flashover voltage can be increased by adding ribs, discs, cones, etc., in the same clearance distance. As discussed in reference to Figs. 2 and 3, this approach must ultimately reach a practical limit and needs to be investigated. Various numbers of 3" and 5" diameter molded EPDM cones were evenly spaced on an 11" rod with EPDM cylindrical spacers. Flashover voltage for both horizontal and vertical orientation are plotted versus number of cones in Fig. 18*. In the vertical position the flashover voltage increases and then decreases as the number of cones is increased. From the data available the 4-5" cone and the 5-3" cone construction is optimum. For this reason these two constructions were used in the other parts of the investigation.

In the horizontal orientation the available data do not indicate a maximum with an increasing number of cones. However, doubling the number of cones increases the flashover voltage by only 25%.

The results plotted against creepage are shown in Fig. 19.

Contaminant Resistivity

Some of the results in Tables I, II and III have been plotted in Figs. 20 and 21 to permit easier visualization of the effect of the contaminant resistivity on flashover voltage. If linear plots are assumed, the results can be expressed by the following equation:

$$E = A R^n$$

where: E = flashover voltage, KV
A = constant
R = resistivity of the contaminant solution, ohm-cm
n = the slope of the curves in Figs. 20 and 21.

* The data are somewhat limited but the trend is apparent. The dashed lines indicate a degree of uncertainty.

The values of "n" from Figs. 20 and 21 are tabulated below:

	Vertical "n"	Horizontal "n"
7", Gepol polymer insulator	0.27	0.37
11", 2-6" Porcelain	0.27	0.35
11", 1" Dia. TFE rod	0.27	0.26
11", 5-3" cones	0.27	0.32
11", 4-5" cones	0.32	0.32
Average	0.28	0.32[5]
33", 1" dia. TFE rod	0.34	
33", cones	0.32	

There is an obvious relationship between the flashover voltage and the resistivity of the contaminant solution in the mist. In turn this means that flashover voltage is a function of the leakage current which must be related to resistivity of the contaminant on the surface. Some of the relationships are examined in the following section.

LEAKAGE CURRENTS

The measurement of leakage currents on insulators under contaminated conditions (see the companion paper Ref. 2) provided a "break-through" in the understanding of the performance characteristics. In earlier test methods, the contaminant dried out so rapidly that scintillation was sporadic and very difficult to measure. By increasing the volume (density) of contaminant applied to the insulator surface much of this problem was overcome so that more continuous scintillation could be achieved. Even so, the scintillation current varied with time as shown in Fig. 22(a). The 1/5th second exposure in the photograph shows many current waves. However, after the development of some skill it became possible to record the maximum current value in this dynamic situation. In Fig. 22(b) the schematic sketch shows an "a" and "b" peak. The significance of current waves is discussed more fully in the companion paper[2]. In summary, it is believed that during the start of the increasing voltage cycle, current starts to flow but at the same time liquid contaminant is vaporized from the surface. Consequently, the current reaches a peak "a" and then decreases. When the surface becomes sufficiently dry, arcing (scintillation) takes place across the dry areas so that current again increases. The composite scintillation currents form the "b" peak. The dynamics of the situation will change the size, position and shape of both the "a" and "b" peaks. Much information can be gleaned from the several hundred scope pictures of the current waves measured in this program, but the analysis is too detailed for presentation here.

It is possible to plot the average maximum currents as a function of voltage. Such plots for several 11" long rods are shown in Fig. 23. The current at low voltages is sinusoidal (dashed curves) but as the voltage is increased scintillation starts and the current wave assumes the shape characterized in Fig. 22. It should be noted that the results in Fig. 23 were obtained with a steady mist. At the lower voltages scintillation did not take place. The scintillating "b" peak current is plotted as a solid line in Fig. 23. The current on the quartz glass rod is relatively large. It is apparently wet better* than the polymethylmethacrylate (PMMA). The diameter of the rod influences the current in an interesting fashion. At the higher voltages the current on the 1" dia. rod is greater than would be indicated by simple geometric considerations. These results should be compared with the photographic evidence in Fig. 5. Despite the relatively large current on the 1" dia. rod it does not glow as brightly as the 1/2" dia. rod. Correlation of the leakage current with flashover voltage is better as summarized below:

	(Tap Water Mist) Flashover Voltage-KV		
	Horizontal	Vertical	Ratio H/V
11" - 1/4" dia. PMMA rod	47.5	44	1.1
11" - 1/2" dia. PMMA rod	42	38	1.1
11" - 1" dia. PMMA rod	39	33	1.2
11" - 0.8" dia. Quartz rod	34	30	1.15

It becomes apparent once again that the smaller the diameter, the better the performance.

*After some surface scintillation, the contact angle of water on all surfaces including pplytetraluoroethylene (TFE) drops to a very low value. Nevertheless, surface effect is sometimes apparent.

As the program developed it was found that the most "critical" conditions for flashover and maximum current could be obtained by using a very high mist density and then allowing the surface to dry with the spray removed. (See the companion paper[2].) As a corollary it was found that scintillation could be developed over a much wider voltage range and that the sinusoidal current* generally was linear with voltage at least at the lower values. In many, but not every case, the values of the "a" and "b" peaks of the scintillating current can be plotted as a power function over a fairly large voltage range (Fig. 24). In this instance, the maximum value of the sine wave increases as drying progresses, possibly indicating an increase in surface conductivity. Fig. 25 illustrates two other commonly observed phenomena. As the voltage approaches flashover, the current may increase markedly. As drying takes place during test the value of the "b" peak is higher. The latter effect is more often observed with the longer insulators where more "streamers" are observed. The streamer phenomena sometimes are observed in another fashion as shown in Fig. 26. In this case, two current "modes" can be observed as drying takes place. The higher or "max" mode apparently is related to streamers and the "min" mode to surface scintillation. These two modes may overlap as shown in Fig. 26 so that it sometimes becomes difficult to distinguish between them.

Visual observations can often be related to sometimes quite complex current modes. A complex current versus voltage curve is shown in Fig. 27. In this case it becomes impossible to plot a power relationship although in some cases an exponential relationship can be detected. The break in the sinusoidal current curve is noteworthy also. Such anomalies are observed most often in tap water and 1.0% salt water mists.

Almost 300 charts of current versus voltage have been made in this program so it becomes necessary to correlate results. In Fig. 28 the scintillation current for both 11" and 33" long TFE rods has been plotted as a function of voltage in three different contaminant mists. These data can be described by the expression:

*The sequence in which sinusoidal and scintillating currents is observed is reported in the companion paper[2].

$$I = kE^n \qquad \text{Where } I = \text{"b" peak current}$$
$$k = \text{constant}$$
$$E = \text{voltage}$$
$$n = \text{constant}$$

In order to describe and compare such data it is possible to tabulate the value of "n" and the current at one voltage. Such data are contained in Tables IV, V and VI. Current at 10KV for the Gepol polymer insulator and 11" long insulators and at 30KV for the 33" long insulators have functional significance since these are the line-to-ground voltages which might be used.

Many observations can be made about the results in Tables IV, V and VI. Unfortunately, the value of the exponent "n" seems to vary in a fashion which cannot be correlated well with other characteristics. The values of the current at 10KV (and 30KV) are interesting. For example, the current for the vertical Gepol polymer insulator may be up to 20 times that in the horizontal position. The current at 10KV can be related quite well to the conductivity of the contaminant solution as shown in Fig. 29. In this figure the solid lines follow a linear (exponent = 1) relationship. All of the data except that for the rod (dotted) are reasonably linear.

It can be argued that it is more significant to compare voltages at a constant current particularly for plastic insulators which may be subject to tracking and erosion (a function of the current). This approach is taken in Table VII. Comparisons are made at .010 and 0.100 amps. These values were selected arbitrarily because the current which may cause damage undoubtedly varies with different materials and is in fact not known quantitatively. For plastic insulators it is important, of course, to select materials which are tracking and erosion resistant.

Resistance

From the leakage currents at low voltage, it is possible to calculate a single value of AC resistance*. Such data are tabulated in Tables VIII, IX and X, along with the calculated value of resistance per inch of creepage

* Even in tap water mist the sinusoidal current is essentially in phase with the voltage. However, the wave shape of the scintillating current may give the impression of an out-of-phase relationship.

length. From these tables an interesting comparison of horizontal versus vertical orientation can be made as shown below:

	Ratio of resistance Horizontal/vertical orientation		
	Tap Water Mist	0.1% salt mist	1.0% salt mist
7" Gepol polymer insulator	3.1	3.2	1.9[5]
11", 2-6" Porcelain	1.5	1.6	1.1
11", dia. TFE Rod	0.8(?)	1.0	1.0
11", 5-3" cones	1.5	2.0	1.0[5]
11", 4-5" cones	1.4	1.4	0.9

As for all of the rest of the characteristics, orientation has a major effect on the resistivity of the Gepol polymer insulators. Except for the rod, the effect of orientation with the other shapes is quite different in the tap water and 0.1% mist as compared to 1.0% mist. It would seem that the way in which the current increases in density as it flows from the outer periphery to the narrower diameter in the center is an important factor.

The resistance of the insulator can be related quite well to the resistivity of the contaminant solution as shown in Fig. 30. In this figure the solid lines indicate a linear relationship (slope = 1). The results for the 11", 2-6" porcelain suspension insulators have an almost linear relationship but the results for the 11" long TFE rod have a slope of 0.78. It is not likely that experimental problems will explain all of this difference.

CONCLUSIONS

Without the speed and effectiveness of the high density conducting mist test it would have been impossible to have made so extensive a study of the performance of insulator geometries under contaminated conditions. However, it is fair to ask how useful the results may be with a test which admittedly does not reproduce field conditions (the mist density is much higher than in service). It may well be that the test does exaggerate such things as the effect of orientation but such effects have been observed in service. On the other hand, it is increased conductivity on the insulator surface which affects field performance under contaminated conditions. This condition is achieved in the high density, conducting mist test.

No one test can represent all of the types and degrees of contamination which are found in service. By using contaminants of different resistivities, it is possible to estimate the effect of different degrees of contamination. Fortunately, the order of ranking for different insulator shapes is about the same whichever contaminant solution is used. Tap water is convenient to use but the voltages are relatively high. On the other hand the 1.0% salt mist is so severe that the flashover voltages may be lower than would be expected even under the worst field conditions.

While voltage flashover and insulator resistance can be measured with reasonable repeatability, the current measurements are quite variable. Nevertheless, the current measurements contribute to an understanding of the flashover mechanism.

Visual observations especially with transparent and translucent models, also contribute to an understanding of the flashover performance.

Even for the models it is important to use tracking and erosion-resistant materials. For example, an unfilled, non-track resistant epoxy has failed after a few minutes of test. For actual use it is extremely important to use tracking and erosion-resistant materials. The high density conducting mist test has been used to study erosion but these results are not discussed here.

Geometry

It should be possible to relate the performance of simple insulator shapes so as to better understand the performance of insulator geometries now in use. Such data also may provide the basis for mathematical models and such effort is to be encouraged.

From the experimental point of view it is apparent that creepage distance alone may be misleading as a criterion of insulator quality. As creepage distance is increased, the improvement in flashover strength (per unit length of additional creepage) decreases. In the vertical position an optimum creepage distance may be quickly reached beyond which the flashover voltage actually decreases. If the diameter of the insulator can be kept relatively small, the performance improves particularly if creepage distance is not sacrificed. The cone geometry is effective in this respect. The unexpected superiority of the deep cone configuration, which cannot be explained entirely by an increase in creepage distance, is worthy of particular note. Simple straight rods perform surprisingly well also.

Results with the high density, conducting mist test indicate that flashover voltages up to twice those now obtained with conventional insulators may be possible with small diameter, cone configurations. Simple, small diameter rods might provide an inexpensive alternative, although they may need to be relatively long to reduce leakage currents especially if plastics or elastomers are used. In any case, the potential improvements in geometry need to be checked with other test methods and confirmed with service trial in a variety of adverse field environments.

Practical Insulators

In the work described only limited effort has been made so far to produce "practical" insulators. It seems obvious that such efforts could be very productive. Elastomeric EPDM skirts, in modular construction, are already being used in General Electric's Termi-Matic cable terminations. Deep cone shapes for this application are under consideration. The possibilities in other applications also need to be investigated. The greatly decreased leakage current, potentially by a factor up to twenty times, is especially attractive for elastomeric and plastic insulators. Elastomers and plastics can be fabricated so as to optimize geometry and strength in ways not easily possible with glass or ceramics.

It is recognized that conservative design may dictate the continued use of porcelain or glass, particularly at very high voltages or for applications requiring great reliability, until plastic insulators develop a background of satisfactory service. Some of the concepts developed in this report also can be applied to porcelain designs. The high density, conducting mist test should be particularly useful in rapidly evaluating such innovations and comparing them to a wide variety of more conventional designs now available.

Good performance under contaminated conditions is important but not the only requirement. Insulators and bushings must also have adequate impulse voltage breakdown, mechanical strength, etc. Such factors were not a part of this program but need to be considered.

ACKNOWLEDGMENTS

Part of the work described has been supported by General Electric's Ultra High Voltage (UHV) Project under the sponsorship of the Electric Research Council through funding by the Edison Electric Institute. The interest and support of John Anderson, Project UHV, is gratefully recognized. General Electric's Insulator Products Department supplied the Gepol polymer insulators and the GE Insulating Materials Department (IMD) provided the molds and the EPDM cones used in the program. The encouragement of IMD's R.W. Williams and R.A. Ward has been especially helpful.

The help of R.L. Gingrich and J.M. Atkins, General Electric Research and Development Center, in carrying out the test development and the experimental program, contributed in large measure to the success of the work described.

Table I

Insulator	Creep in.	Min. Flashover Voltage (0.1% salt water mist) KV Horiz.	Vert.	Ratio H/V	Flashover Stress KV/inch Horiz.	Vert.
7", 15KV Gepol polymer insulator	15	25	14	1.8	1.67	0.93
11", 2-6" Porcelain	14	21.75	17.5	1.2^5	1.56	1.25
11", 1" dia TFE Rod	11	20	17.25	1.2	1.82	1.57
11", 5-3" cones	21	40	32.5	1.2^5	1.91	1.55
11", 4-5" cones	30	43.75	35	1.2^5	1.46	1.17
		(repeat)	37.5	1.1^5		1.25
11", 3-4" frustrums	16.5	--	21.75	--	1.32	
11", 4-5 1/8" discs	28.5	40 (?)	27.5	1.4^5	1.45	0.97
11", 4-8" discs	40	>40*	30			0.75
11", 4-5" X 1 1/4" cyl.	36		30			0.83
11", 4-5" X 2 1/4" cyl.	44		26.75			0.61
33", 6-6" Porcelain	42		45			1.07
33", 1" dia. TFE Rod	33	57.5	45	1.3	1.75	1.36
33", 15-3" cones	61	107.5	84	1.3	1.76	1.38
33", 10-5" cones	80	112.5	95	1.2	1.41	1.19

*Dielectric puncture at interface between rod and disc.

Table II

Insulator	Creep in.	Min. Flashover Voltage KV Horiz.	Min. Flashover Voltage KV Vert.	Ratio H/V	Flashover Stress KV/inch Horiz.	Flashover Stress KV/inch Vert.
		(1.0% salt mist)				
7", 15KV Gepol polymer insulator	15	10	9	1.1	0.67	0.60
11", 2-6" Porcelain	14	9	10	0.9	0.64	0.71
11", 1" dia. TFE Rod	11	11.25	10	1.1	1.02	0.91
11", 5-3" cones	21	18	17.5(?)	1.0	0.86	0.84(?)
11", 4-5" cones	30	23.75	22.5(?)	1.05	0.79	0.75(?)
33" 10-5" cones	80	55	52.5	1.05	0.69	0.66

Table III

Insulator	Creep in.	(Tap water mist) Min. Flashover Voltage KV Horiz.	Vert.	Ratio H/V	Flashover Stress KV/inch Horiz.	Vert.
7", 15KV Gepol polymer insulator	15	51.25	28.75	1.95	3.4	1.9
11", 2-6" Porcelain	14	41.75	33.75	1.25	3.0	2.4
11", 1 " dia. TFE Rod	11	35	31.25	1.1	3.2	2.8
11", 5-3" cones	21	72.5	48.75	1.5	3.4^{5}	2.3
11", 4-5" cones	30	85	70	1.2	2.8^{5}	2.3
33", 6-6" Porcelain	42		85			2.0
33", 1" dia. TFE Rod	33		90			2.7
33", 15-3" cones	61		185			3.0
33", 10-5" cones	80		192.5			2.4

Table IV

(0.1% salt water mist)

Insulator	Creep in.	$I = AE^n$ slope-n Horiz	Vert.	Amps at 10KV Horiz.	Vert.
7", 15KV Gepol polymer insulator	15	2.1	3.1	.037	0.27
11", 2-6" Porcelain	14	2.4	1.8	.075	.090
11", 1" dia. TFE Rod	11	1.3	1.9	.079	.098
11", 5-3" cones	21	1.7	1.8	.026	.043
11", 4-5" cones	30	1.7	1.9	.025	.022
11", 3-4 frustrums	16.5		2.1		.082
11", 4-5 1/8" discs	28.5	2.5	1.9	.028	.031
11", 4-8" discs	40	2.7	1.5(?)	.010	.033
11", 4-5" X 1 1/4" cyl	36		2.1		.017
11", 4-5" X 2 1/4" cyl	44		1.9		.046
				Amps at 30KV	
33", 6-6" Porcelain	42		1.9		0.150
33", 1" dia. TFE Rod	33	1.3	1.7	0.100	0.138
33", 15-3" cones	61		1.5		.041
33", 10-5" cones	80	1.4	1.2	.032	.036

Table V

(1.0% salt water mist)

Insulator	Creep in.	$I = AE^n$ slope-n Horiz.	Vert.	Amps at 10KV Horiz.	Vert.
7", 15KV Gepol polymer insulator	15	1.3		0.650	F.0*
11", 2-6" Porcelain	14	1.2		F.O.	F.O
11", 1" dia. TFE Rod	11	?	1.65	0.250	F.O
11", 5-3" cones	21	1.0		0.250	0.385
11", 4-5" cones	30	1.6		0.220	0.260
				Amps at 30KV	
33", 10-5" Cones	80	1.1	?	0.295	0.183(?)

*F.O - Flashover

Table VI

(Tap water mist)

Insulator	Creep In.	$I = AE^n$ slope-n Horiz.	Vert.	Amps at 10KV Horiz.	Vert.
7", 15KV Gepol polymer insulator	15	3.6	NA	<.001	.023
11", 2-6" Porcelain	14	3.2	NA	.006	.015
11", 1" dia. TFE Rod	11	3.0	NA	.009	.009
11", 5-3" cones	21	1.4	NA	.005	.005
11", 4-5" cones	30	2.2	NA	.001	.003
				Amps at 30KV	
33", 6-6" Porcelain	42		NA		.013
33", 1" dia. TFE Rod	33		3.1(?)		.010
33", 15-3" cones	61		NA		.010
33", 10-5" cones	80		NA		.005

NA - Is not a power function (exponential function?)

Table VII

Insulator	Creep in.	(0.1% salt water mist) KV at .010 Amps Horiz.	Vert.	KV at 0.100 Amps. Horiz.	Vert.
7", 15KV Gepol polymer insulator	15	5.7	3.5	16.3	7.1
11", 2-6" Porcelain	14	4.6	2.2	11.8	10.6
11", 1" dia. TFE Rod	11	1.9	3.1	12.3	10.3
11", 5-3" cones	21	10	6.3	29	16.3
11", 4-5" cones	30	6.9(?)	9.4	23.5	22
11", 3-4" frustums	16.5		4.4		11
11", 4-5 1/8" discs	28.5	8.3	5.4	21.5	19.5
11", 4-8" discs	40	10	5	24	18.5
11", 4-5" X 1 1/4" cyl	36		7.8		24
11", 4-5" X 2 1/4" cyl	44		6.0		15
33", 6-6" Porcelain	42		12.8		27
33", 1" dia. TFE Rod	33	6.7	6.7		26.5
33", 15-3" cones	61		16.3		55
33", 10-5" cones	80	21	16.3	83	51

Table VIII

Insulator	Creep in.	Avg. Resistance* kilo-ohms Horiz.	Vert.	Ratio H/V	kilo-ohms/inch. Horiz.	Vert.
		(0.1% salt mist)				
7", 15KV Gepol polymer insulator	15	20	6.5	3.2	1.3	0.43
11", 2-6" Porcelain	14	14	8.5	1.6	1.0	0.61
11", 1" dia. TFE Rod	11	15	15.5	1.0	1.4	1.4
11", 5-3" cones	21	53	26.5	2.0	2.5	1.2^{5}
11", 4-5" cones	30	43.5	30.5	1.4	1.4^{5}	1.0
11", 3-4" frustrums	16.5	--	14.5			0.87
11", 4-5 1/8" discs	28.5	35.5	31	1.1^{5}	1.2^{5}	1.1
11", 4-8" discs	40	42.5	26.5	1.6	1.0^{5}	0.66
11", 4-5" X 1 1/4" cyl	36.		41			1.1
11", 4-5" X 2 1/4" cyl	44.		28			0.64
33", 6-6" Porcelain	42		34			0.81
33", 1" dia. TFE Rod	33	58	45	1.3	1.7^{5}	1.3^{5}
33", 15-3" cones	61		91			1.5
33", 10-5" cones	80	143	95	1.5	1.8	1.2

*Calculated from sine wave currents at relatively low voltage

Table IX

(1.0% salt mist)

Insulator	Creep in.	Avg. Resistance kilo-ohms		Ratio	ohms/inch	
		Horiz.	Vert.	H/V	Horiz.	Vert.
7",15KV Gepol polymer insulator	15	1.9^{5}	1.0	1.9^{5}	130	67
11", 2-6" Porcelain	14	1.9	1.7	1.1	136	120
11", 1" dia. TFE Rod	11	2.8	2.8	1.0	255	255
11", 5-3" cones	21	4.4	4.2	1.0^{5}	210	200
11", 4-5" cones	30	6.0	6.7	0.9	200	220
33", 10-5" cones	80	18.6	16.8	1.1	233	210

Table X

		(Tap water mist)				
		Avg. Resistance kilo-ohms		Ratio	kilo-ohms/inch	
Insulator	Creep in.	Horiz.	Vert.	H/V	Horiz.	Vert.
7", 15KV Gepol polymer insulator	15	136	44	3.1	9.0	3.2[5]
11", 2-6" Porcelain	14	87	58.5	1.5	6.2	4.2
11", 1 " dia. TFE Rod	11	79(?)	99	0.8(?)	7.2(?)	9.0
11", 5-3" cones	21	220	147	1.5	10.5	7.0
11", 4-5" cones	30	295	208	1.4	9.8	7.0
33", 6-6" Porcelain	42		213			5.1
33" 1" dia. TFE Rod	33		310			9.4
33", 15-3" cones	61		890			14.6
33", 10-5" cones	80		1130			14.1

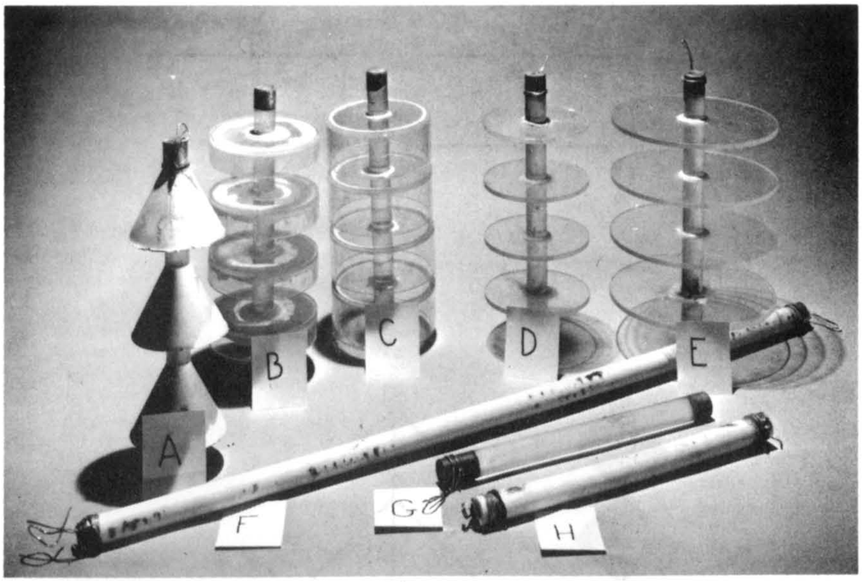


Fig. 1 Photograph of insulator models fabricated from plastic rods, discs and cones.

A-RTV Frustrums (solid cones); B- 5" x 1" cylinder;
C- 5" x 2" cylinder; D-4, 5" Discs; E-4, 8" Discs.
(A thru E are all on 1" dia 11" long PMMA rods)
F-33" TFE Rod; G-11" Quartz Rod; H-11" TFE Rod.

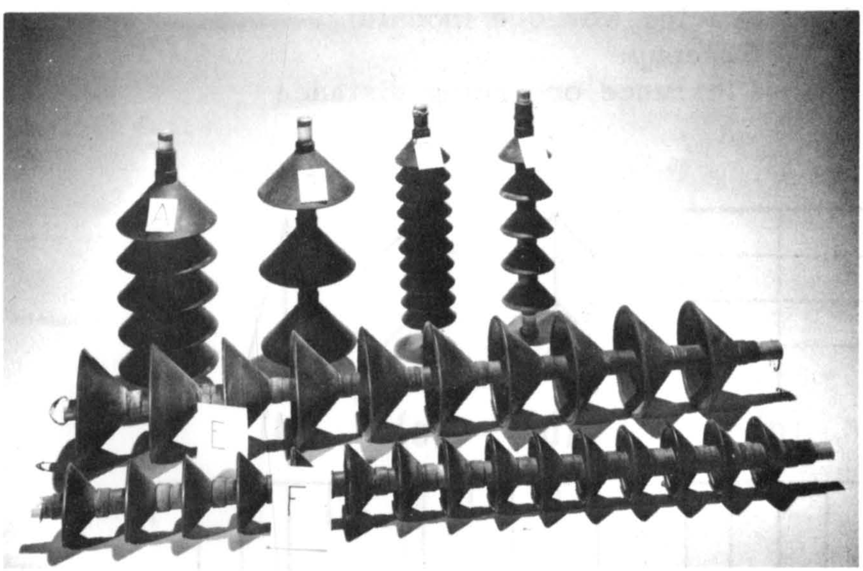


Fig. 2 Insulator models fabricated by slipping EPDM rubber cones on a plastic rod.

A-5, 5" EPDM Cones; B-3, 5" EPDM Cones; C-10, 3" EPDM Cones;
D-5, 3" EPDM Cones (A thru D are all on 11" long rods);
E-10, 5" EPDM Cones; F-15, 3" EPDM Cones (E&F are on 33" long rods).

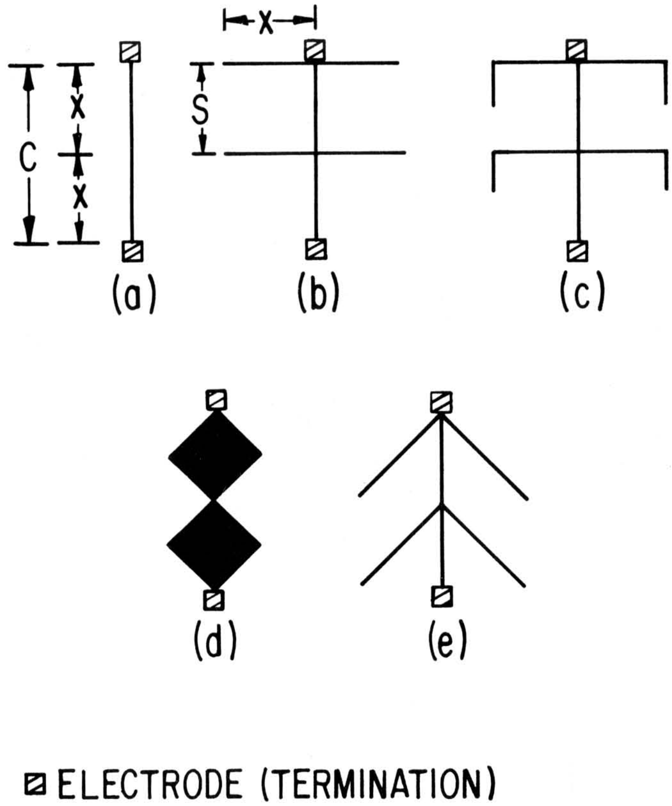


Fig. 3 "Line" drawings of basic insulator geometries.

Two repeating "modules" are illustrated
S - Spacing (for one module)
X - Creepage
C - Clearance or arcing distance

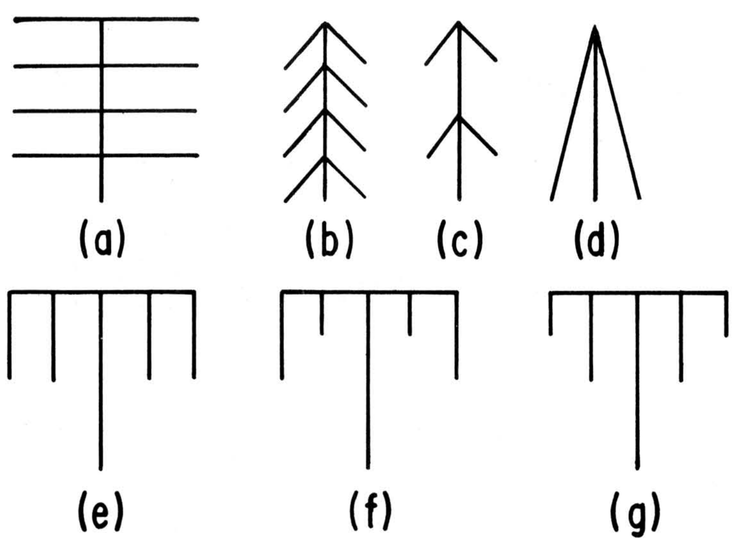


Fig. 4 "Line" drawings of some possible modifications of basic insulator geometries.

The electrodes (terminations) have not been shown. (See Fig. 3)

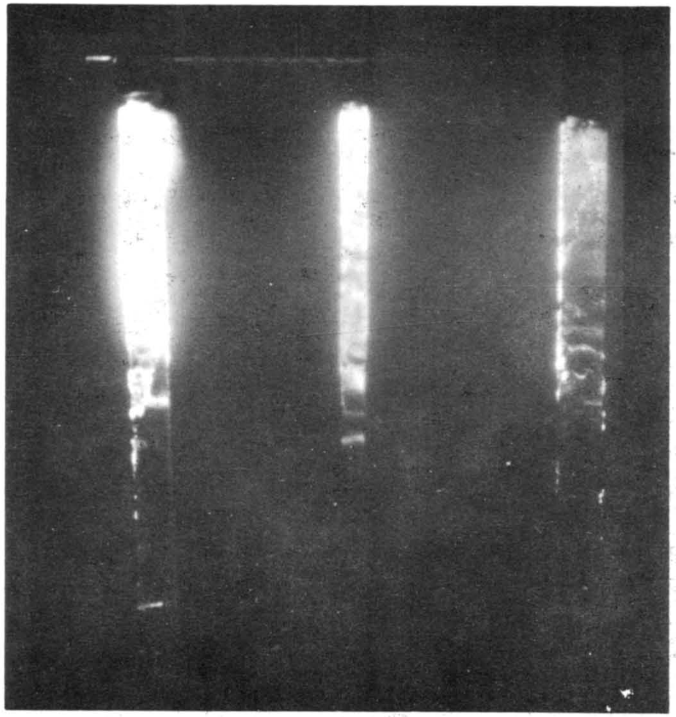


Fig. 5 Three 11" long vertical rods in tap water mist at 38KV.0. 8" dia Quartz glass at left, 1/2" dia PMMA at right.

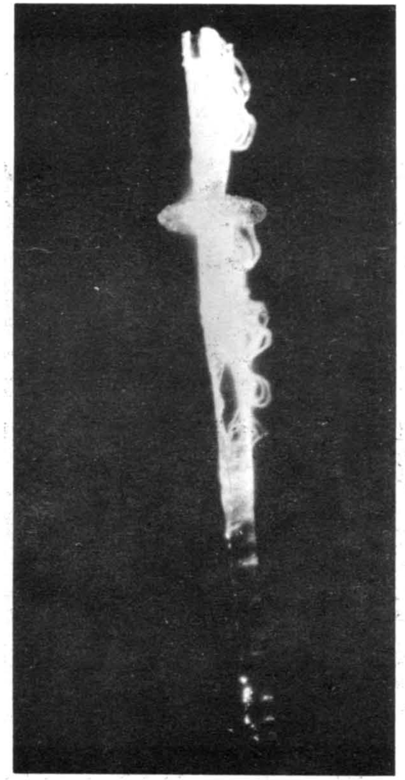


Fig. 6 A 36" long, vertical rod in tap water mist at 125KV. A 4" dia disc has been placed 7" from the top of the rod.

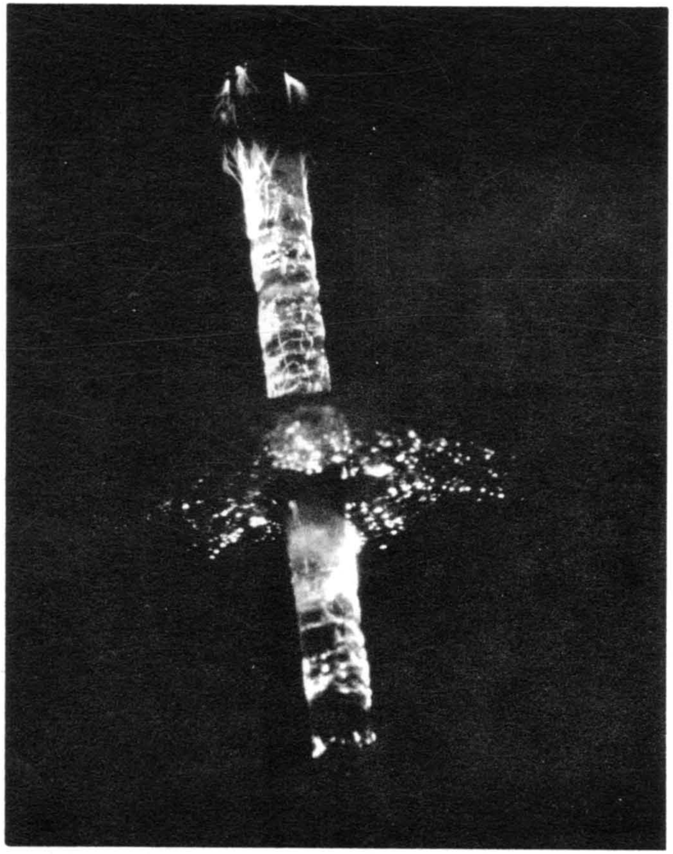


Fig. 7 A 36" long, vertical rod in tap water mist at 120 KV. An 8" dia disc has been placed 7" from the top of the rod.

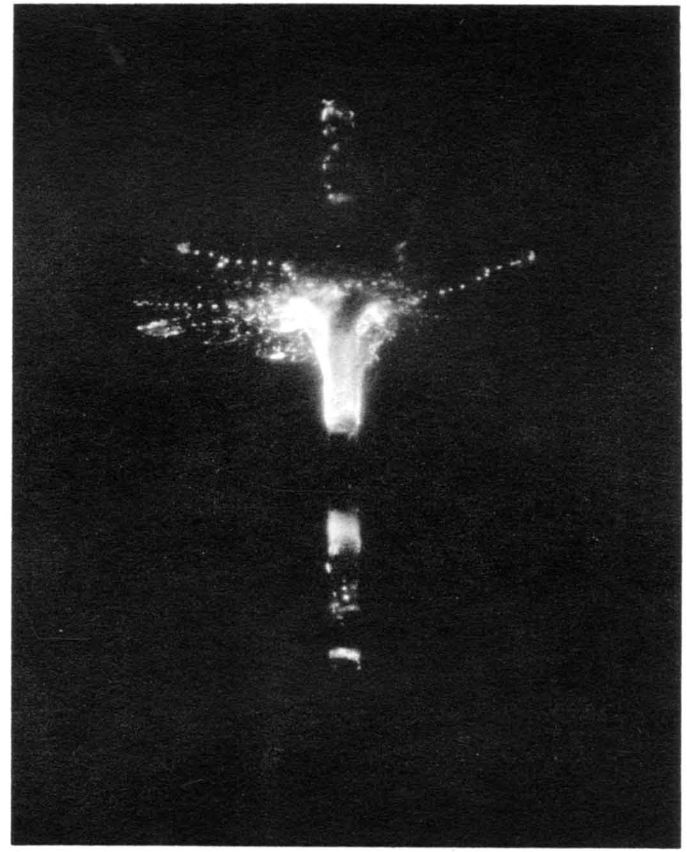


Fig. 8 A 36" long vertical rod with a 16" dia disc in tap water mist at 120 KV.

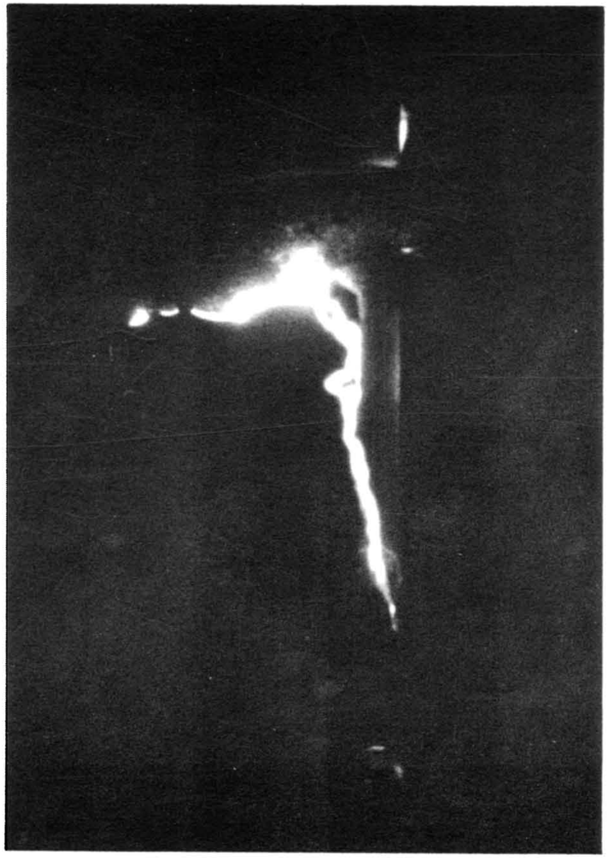


Fig. 9 The same rod and disc combination as in Fig. 8. The photographic exposure time has been decreased from 1 second to 1/60 sec to show just two streamers.

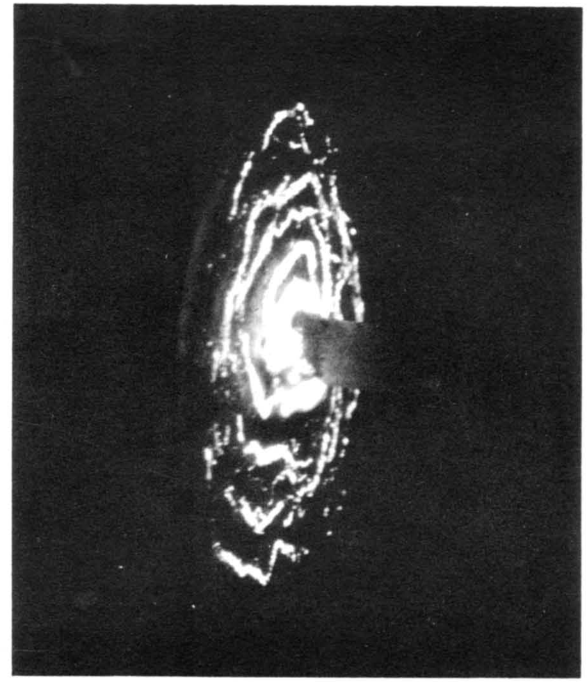


Fig. 10 A 36" long horizontal rod in tap water mist at 60 KV. An 8" dia disc has been placed 7" from the left (ground) end.

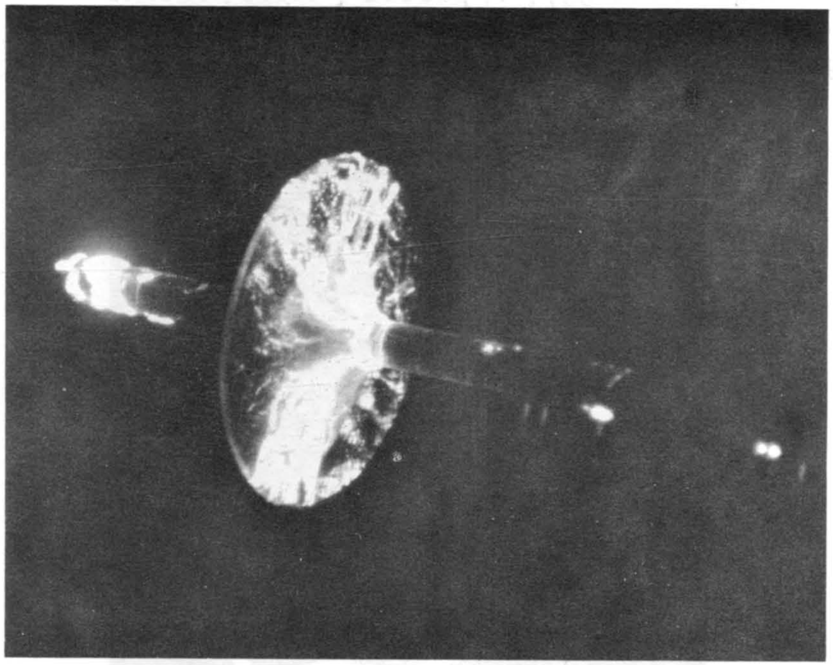


Fig. 11 The same geometry as in Fig. 10 at 100 KV.

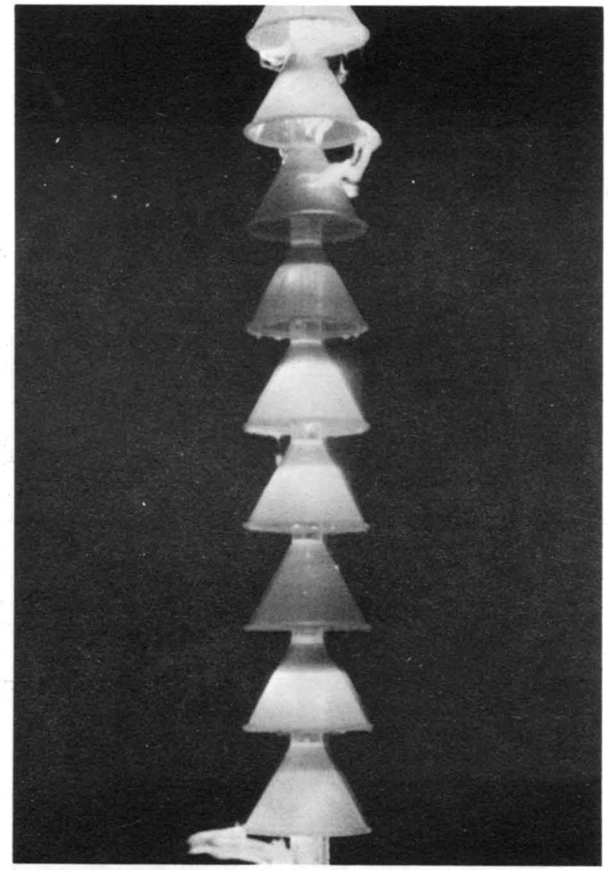


Fig. 12 A 33" long vertical rod with nine 5" dia PE cones. In 0.1% salt water mist at 90KV.

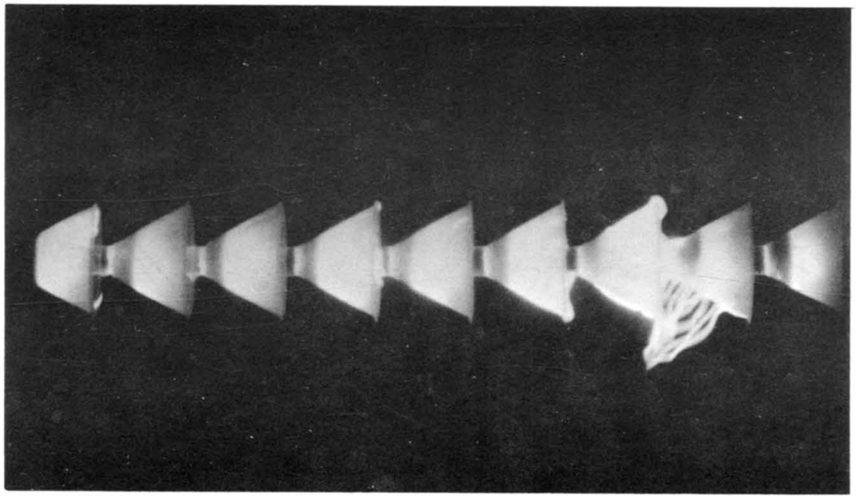


Fig. 13 A 33" long horizontal rod with nine 5" dia PE cones. In 0.1% salt water mist at 120KV.

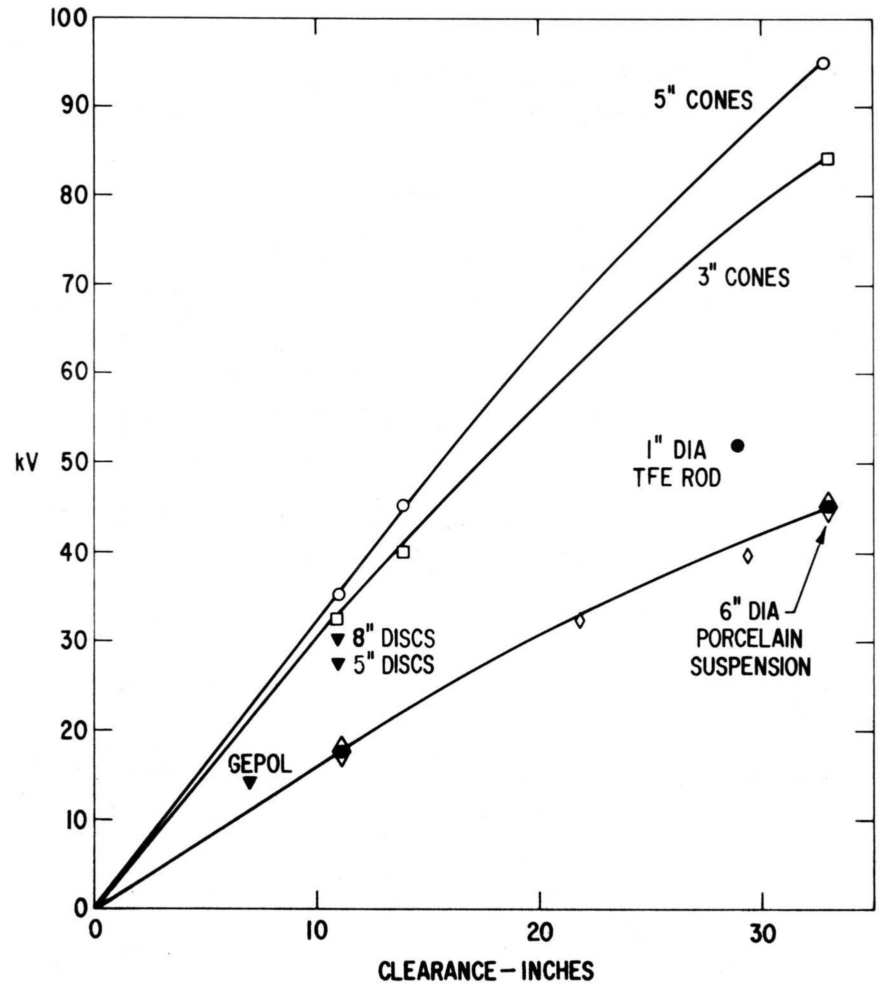


Fig. 14 Flashover voltage vs clearance distance. In 0.1% salt mist - vertical orientation.

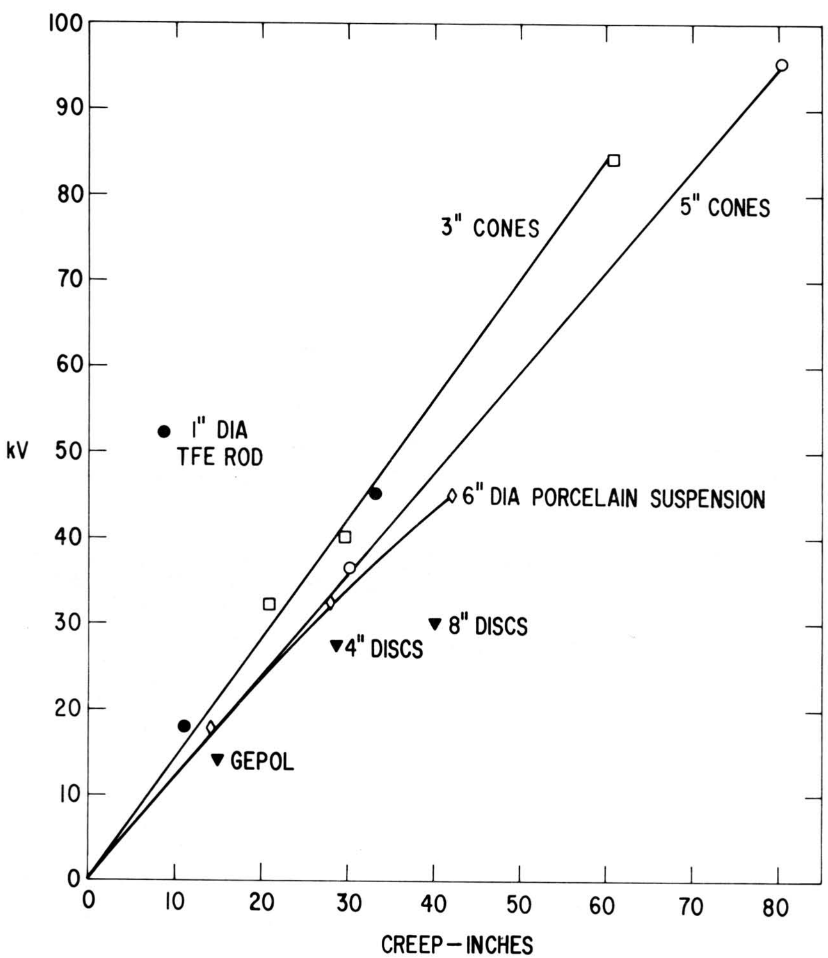


Fig. 15 Flashover voltage vs creepage distance.
In 0.1% salt mist - vertical orientation.

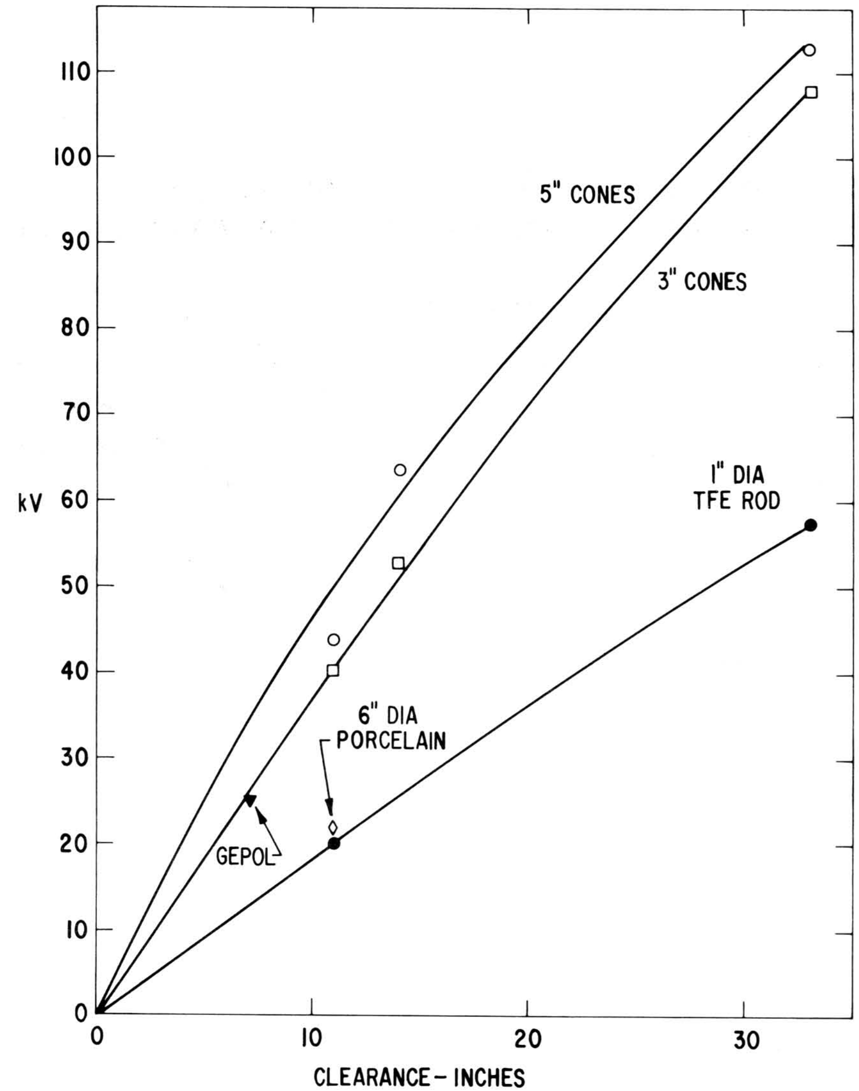


Fig. 16 Flashover voltage vs clearance distance.
In 0.1% salt mist - horizontal orientation.

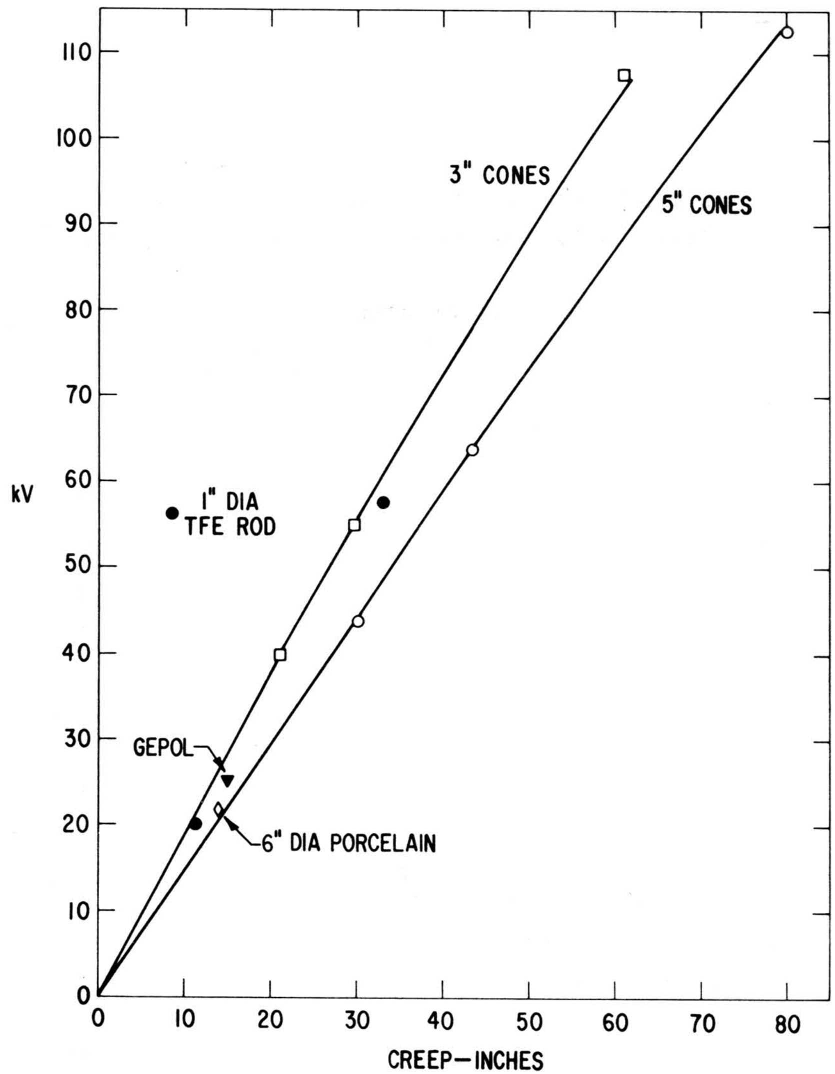


Fig. 17 Flashover voltage vs creepage distance. In 0.1% salt mist - horizontal orientation.

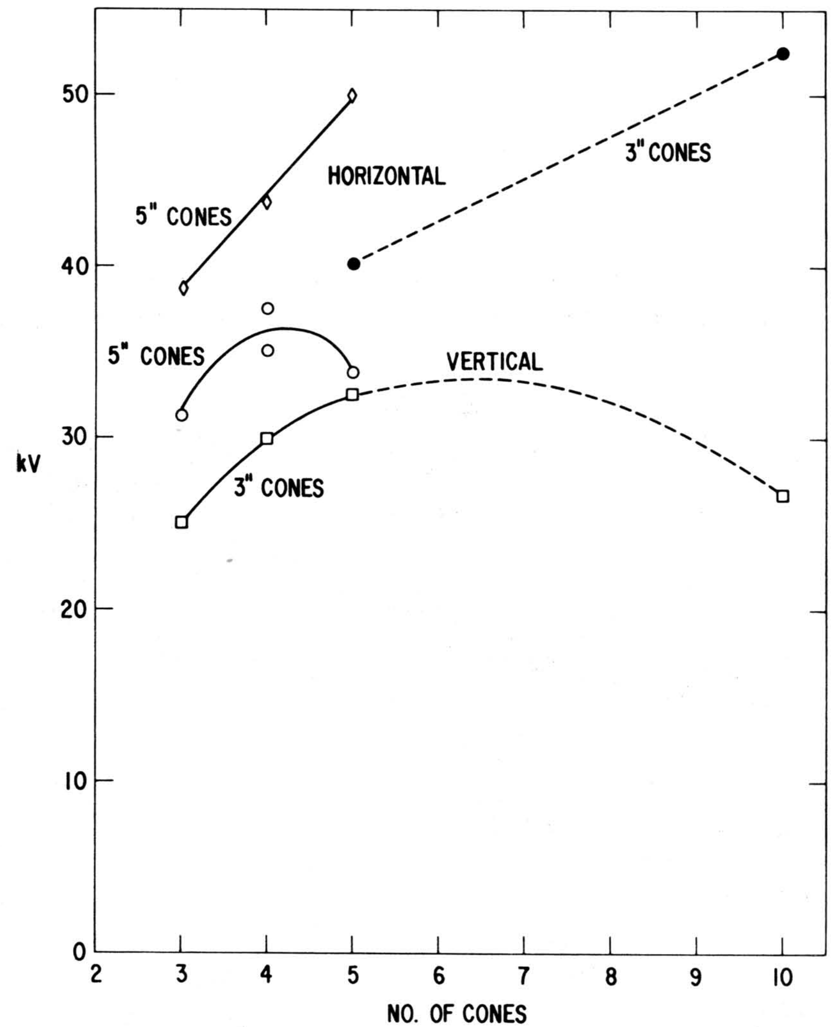


Fig. 18 Flashover voltage vs number of cones on 11" length. In 0.1% salt mist.

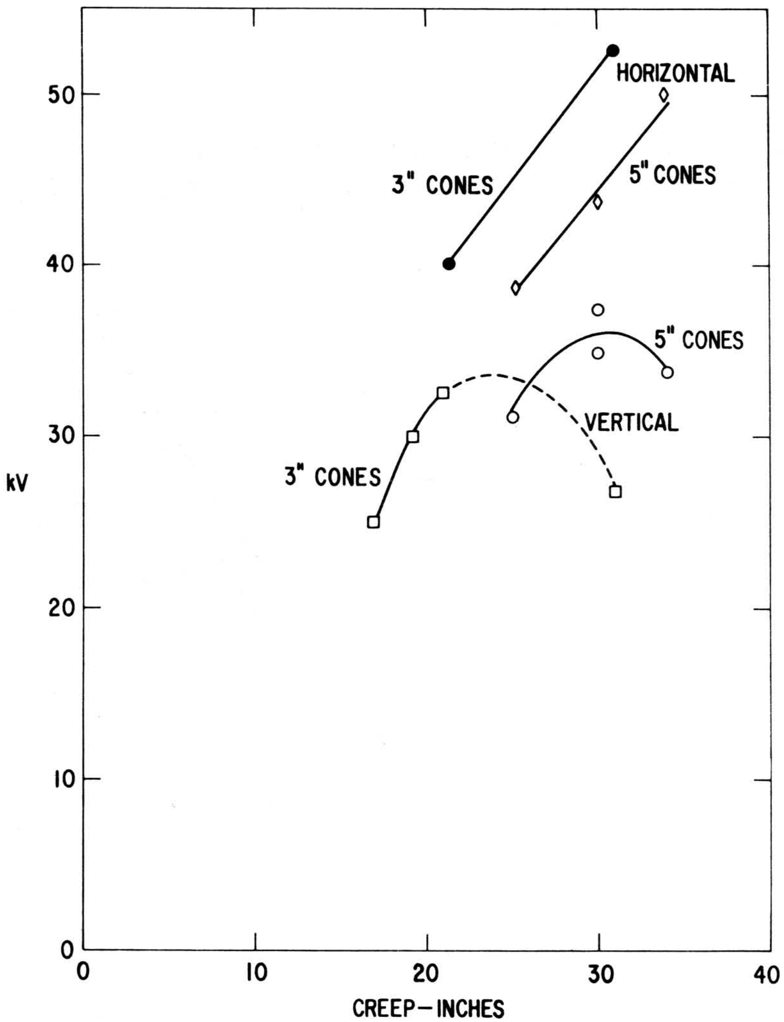


Fig. 19 Flashover voltage vs creepage distance. In 0.1% salt mist - clearance held at 11 inches.

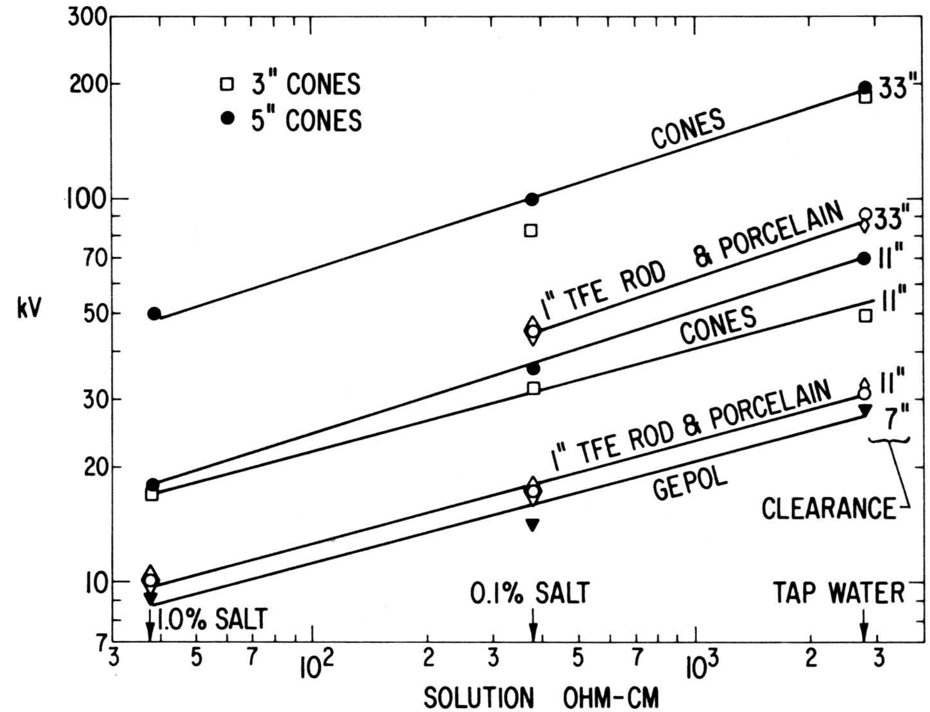


Fig. 20 Flashover voltage vs contaminant solution resistivity. Vertical orientation.

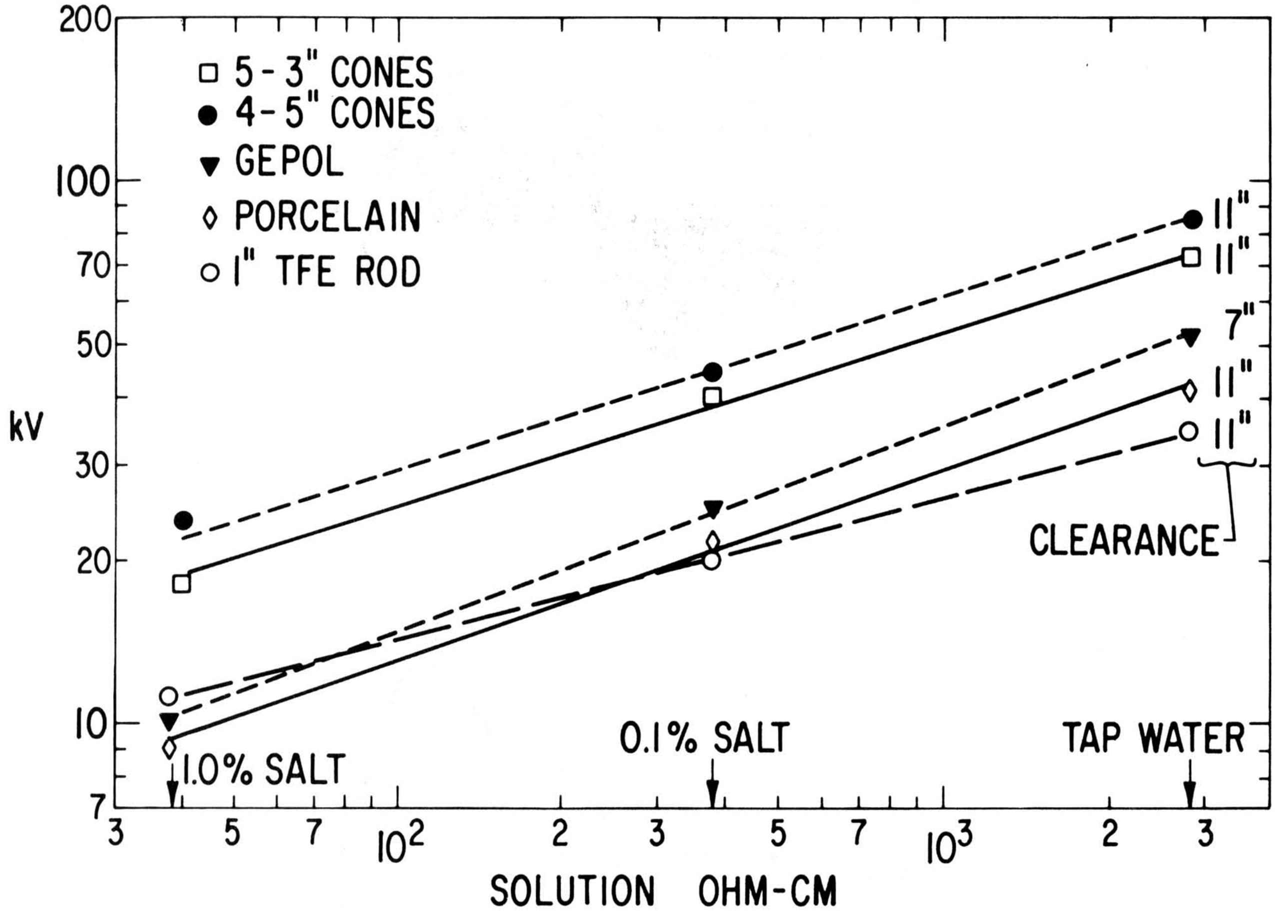
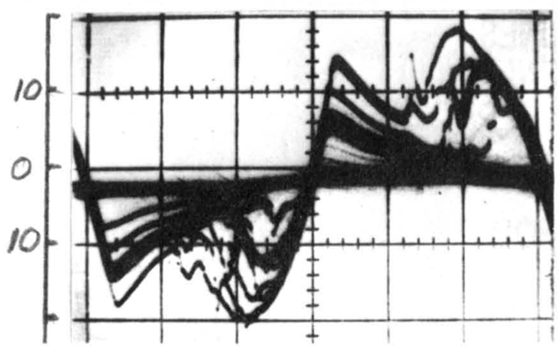
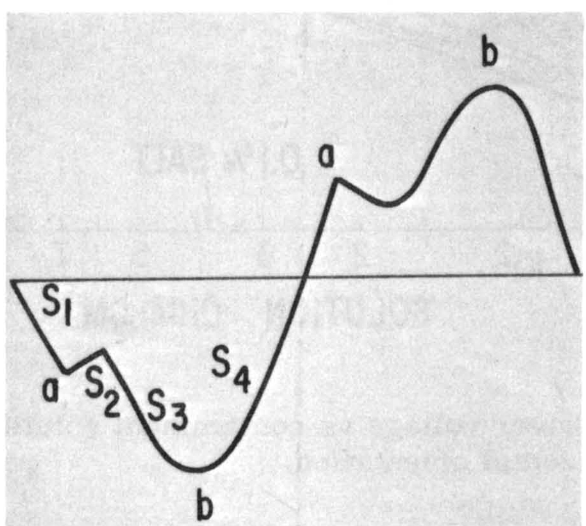


Fig. 21 Flashover voltage vs contaminant solution resistivity. Horizontal orientation.



a



b

Fig. 22 Typical leakage current waves.
(a) Oscilloscope photograph
(b) Sketch to show "a" and "b" peaks.

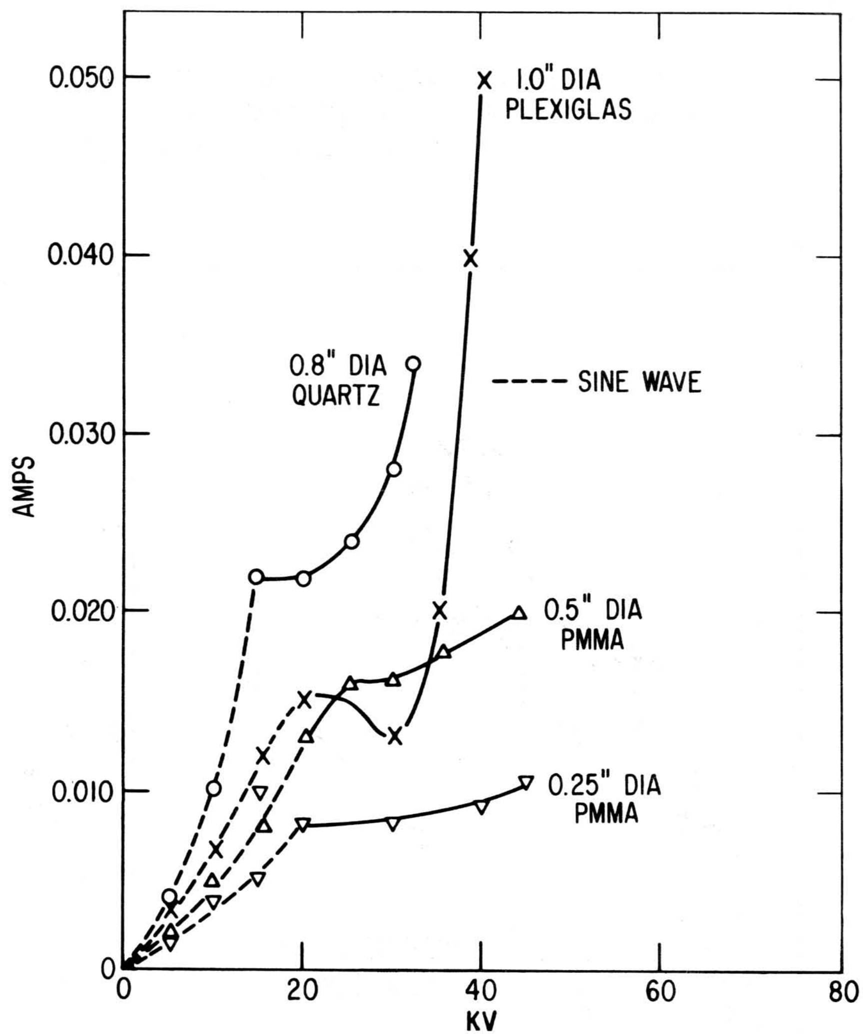


Fig. 23 Current vs voltage - vertical rods in tap water mist at 38 KV. (For these results only, the mist was held steady and not turned off at each voltage step.)

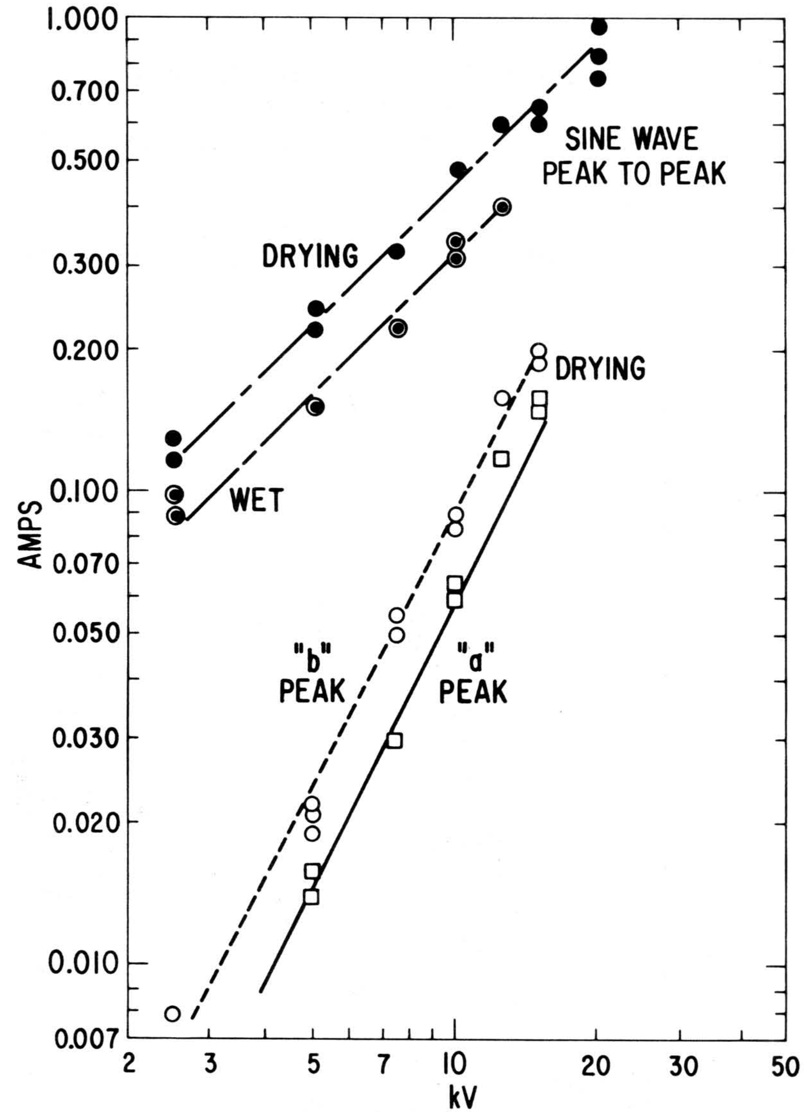


Fig. 24 Current vs voltage. 2-6" porcelain suspension insulators. In 0.1% salt mist - vertical orientation.

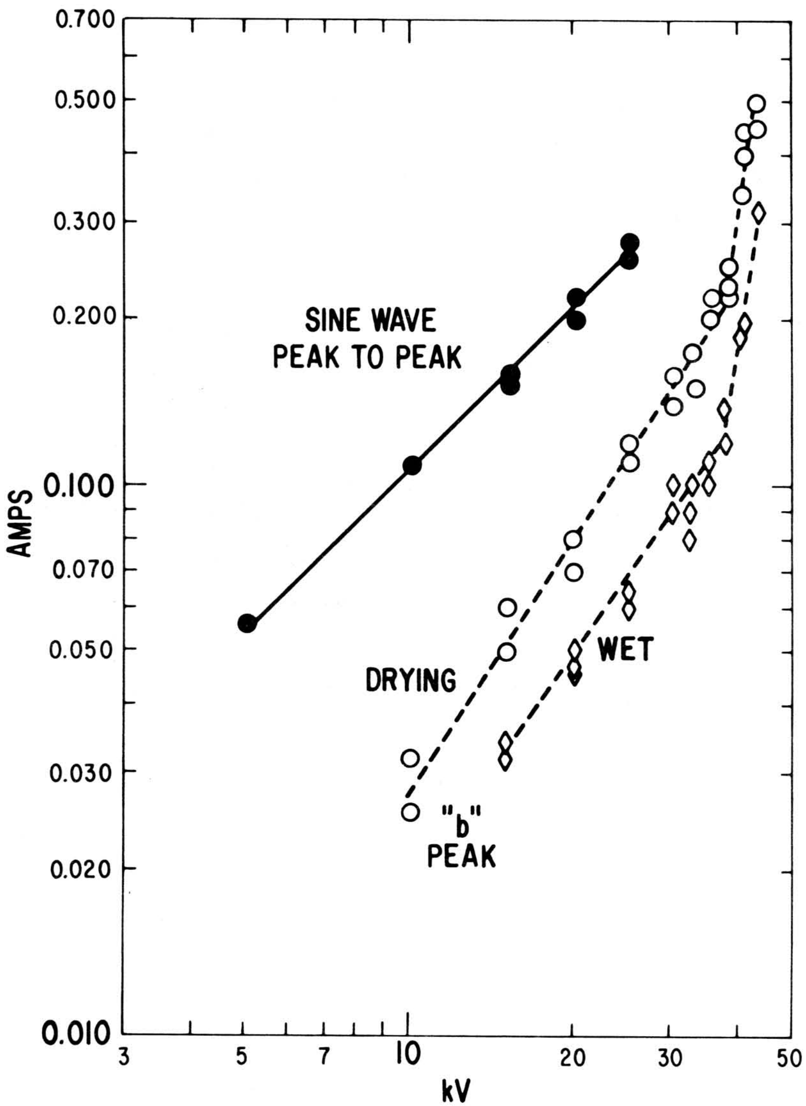


Fig. 25 Current vs voltage.
6-6" porcelain suspension insulators.
In 0. 1% salt mist - vertical orientation.

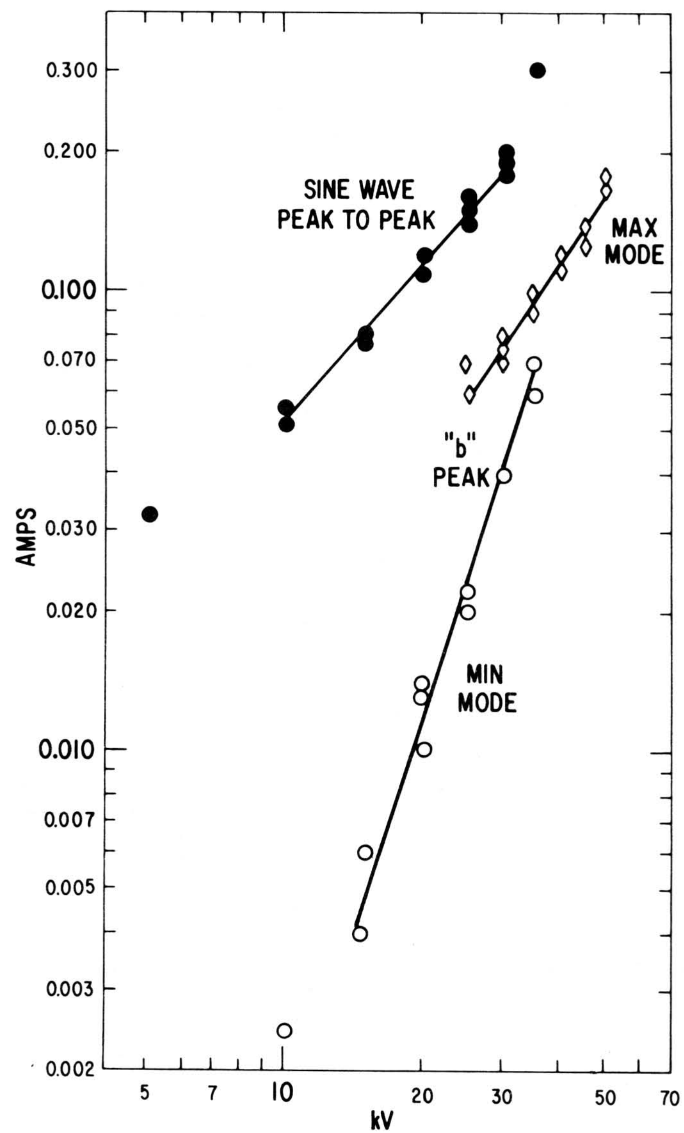


Fig. 26 Current vs voltage.
8-3" cones and 14" length.
In 0. 1% salt - horizontal orientation.

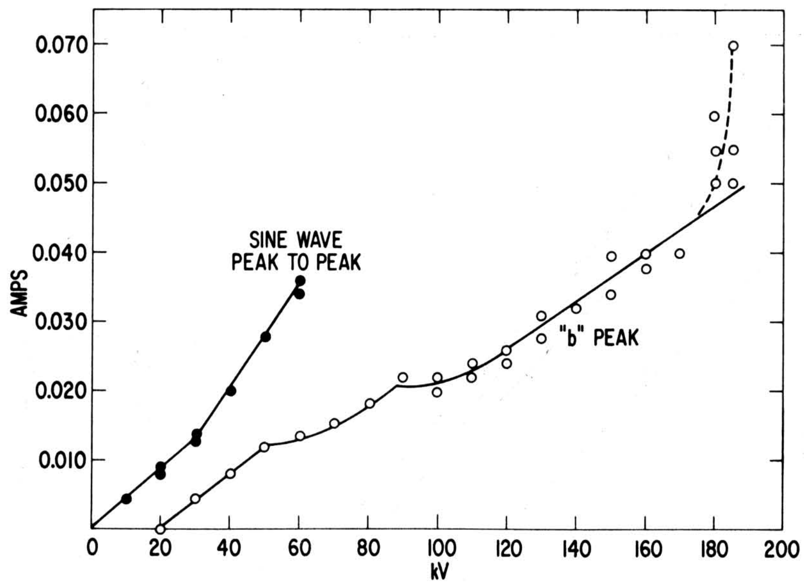


Fig. 27 Current vs voltage.
15-3" cones or 33" length.
In tap water mist - vertical orientation.

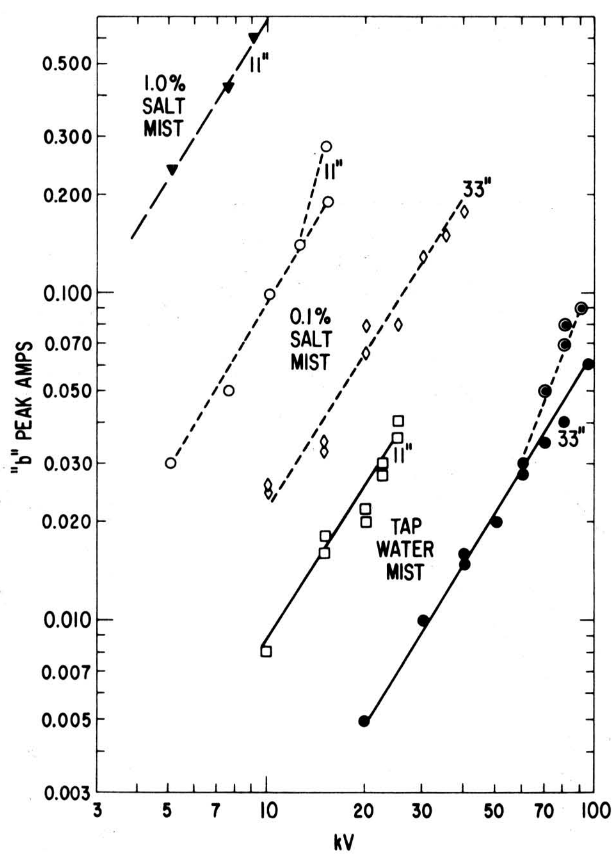


Fig. 28 Current vs voltage.
1" dia TFE rod - 11" and 33" lengths.
Vertical orientation.

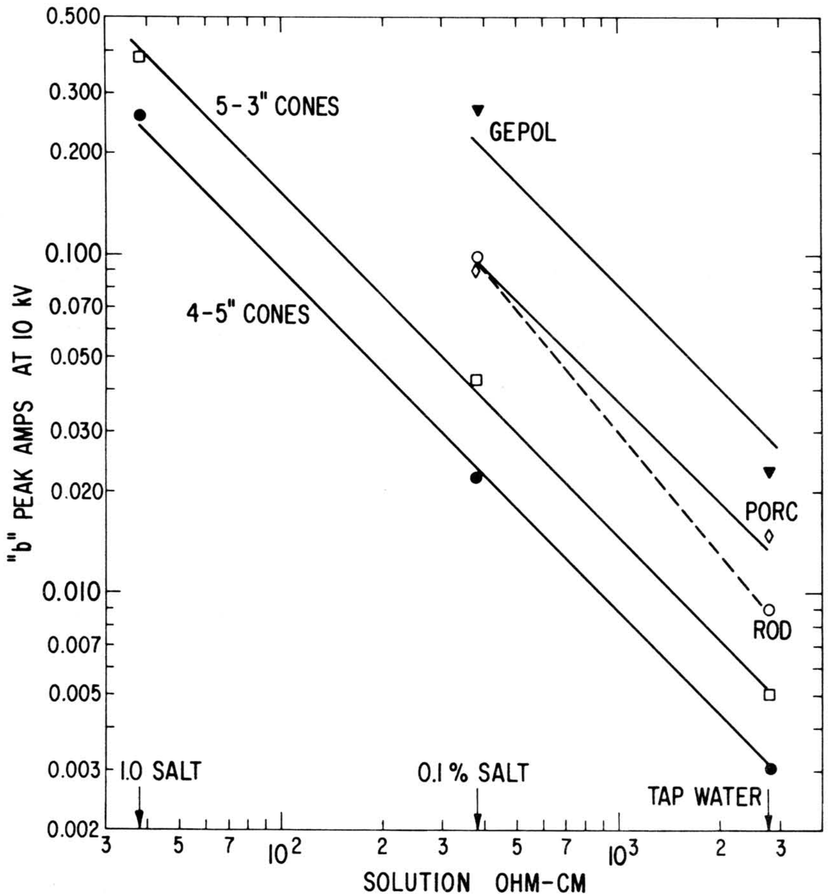


Fig. 29 Peak scintillation current at 10 KV vs contaminant solution resistivity. Vertical orientation.

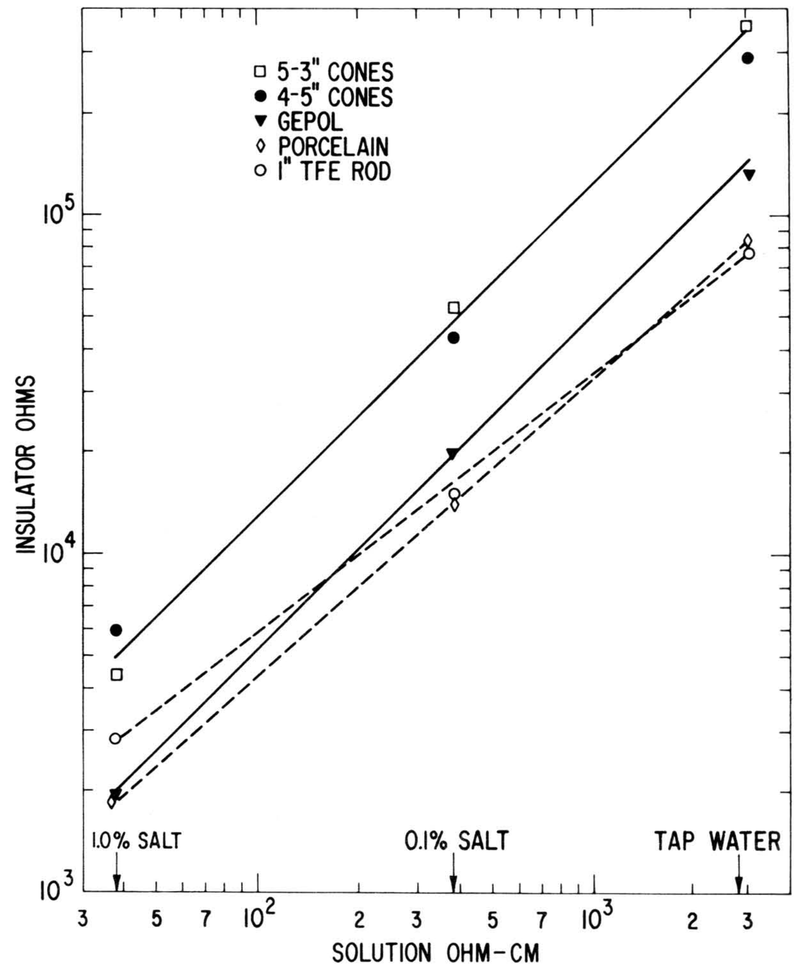


Fig. 30 Insulator resistance (AC at low voltage) vs contaminant solution resistivity. Horizontal orientation.

REFERENCES

1. K.N. Mathes and E.J. McGowan "Surface Electrical Failure in the Presence of Contaminants: The Inclined Plane, Liquid Contaminant Test", Trans. AIEE, Div. Communications and Electronics, Pt. I, 80, pp. 281-288 (July 1961).

2. J.M. Atkins and R.L. Gingrich "High Density, Conducting Mist Test for Insulator Evaluation", IEEE Conference Paper No. 71 CP 236 - PWR (February 1971).