SOME FACTORS RELATING TO THE EARLY STREAMER EMISSION PRINCIPLE

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ABSTRACT

A brief review is given of the means by which additional ionisation has been introduced at the tip of a lightning conductor finial, with a view to increasing the probability of attachment to a downward leader. Attention is concentrated, in present work, on the "early streamer emission" principle, in which corona is initiated by either a steady or pulsed high voltage applied to a finial. The field of an approaching downward leader is simulated, in these experiments, by application of a negative impulse voltage to a sphere, located above the finial. It is shown that a steady corona does not improve the finial performance, under the conditions used, and that a pulsed corona must be applied within a critical time range, in order to be effective. The implications for lightning protection are briefly examined.

1. INTRODUCTION

The passive Franklin rod has formed the standard air termination of lightning protection systems for 200 years. Its range of influence in attracting lightning strokes is limited by the "attachment distance" which is determined by the characteristics of the downward leader. The electric field of the leader (usually negative) induces an electric stress around the tip of the rod, thereby leading to corona formation and, in favourable cases, development of an "answering leader". An extension of the range of influence has been sought in several ways. These include the use of a radioactive source at the tip producing extra ionisation in the air, the shaping of the tip to produce a high stress and, most recently, the use of the "early streamer emission" device in which the rod is activated electrically to produce additional corona which may occur earlier than that induced by an approaching leader.

The use of radioactive sources has long been discredited [1] and many have now been removed. Their ineffectiveness was due to the very low ionisation density that permissible sources could produce around the rod. It was insufficient to increase significantly the intensity of the corona, but it is interesting to note that laboratory experiments [2] have shown that, for a given rate of increase of the electric field at the rod, a radioactive source advances in time the initiation of streamers, compared with the statistically variable initiation time in the absence of the source.

It may likewise be thought that a sharp pointed tip to the rod will be more efficient than a blunt tip in producing streamers, since the electric field near the point is greater than that near a tip of larger radius. Again, discharges are produced earlier from the sharp tip, but the coronas are smaller (since the electric field falls off more rapidly with distance) and they tend to produce a blanket of space charge which discourages further corona development. Also, where the increase in electric field is preceded by a steady field which is also sufficient to produce corona, as with a prominent rod under a thundercloud before a strike develops, then the steady corona so produced has been shown to discourage corona, and suppress leader development, when the rising electric field is applied [3]. Field studies made recently [4] support this conclusion.

The activation of a rod, either by a steady high voltage or by a pulsed voltage, has the merit that a streamer corona may be produced comparable with that produced by an approaching downward leader. Thus, it might be expected that if this corona can be produced by activation at an earlier time than that caused by the approaching leader, then the answering upward leader could also be produced earlier, giving time for greater extension, so increasing the range of influence of the rod.

Alternatively, we may say that the earlier emission of streamers would result, in a laboratory simulation, in earlier or, perhaps, easier breakdown to the activated rod. This approach was used by Bouquegneau [5] who arranged two finials, one passive (Franklin), the other activated by a steady high voltage producing continuous corona, placed at equal distances from a rod placed suspended from above, to which was applied a negative impulse voltage rising to crest in 1μsec and declining to half its peak value in 50μs (Figure 1). He found that sparkover from the suspended rod to the finials occurred with equal probability to each.

A weakness of this test was that the rise-time of the impulse voltage was too short to permit any significant growth of a leader from either of the finials. Moreover, the activated finial suffered from the drawback that the continuous corona inhibited corona growth during the impulse, as noted above. Thus, the tests cannot be regarded as conclusive.

Berger and others [6] [7] carried out large-scale tests at the Les Renardierès Laboratory in which the steady field due to a charged thundercloud and the subsequent descent of a leader, were simulated by placing activated and passive finials beneath a large metal plane, to which a steady and a superimposed impulse voltage were applied. In this case, the activated finial was subjected to a pulsed voltage from an auxiliary supply the nature of which was not specified. The results showed that streamers were initiated at the activated finial at a lower impulse field, and at an earlier time, than was the case with the active finial. However, the velocity of the upward leader, which followed streamer initiation, was exactly the same, at $2 \times 10^4 ms^{-1}$ from both finials. It was shown that the subsequent breakdown, between the plane and active finial occurred about 30μs earlier than it did with the passive finial.

The time to formation of a spark, in the laboratory experiments, may be taken as one indication of the effectiveness of the device, since such a breakdown will only follow if the upward leader from the finial meets either the downward leader (as in nature) or progresses across to the upper electrode of the system in a laboratory simulation. The dependence of this time upon the method of activation used forms the basis of the experiments that have been carried out at UMIST.

2. EXPERIMENTS

2.1 Simulation of field due to downward leader

Berger [6] has shown that the increasing field due to a downward leader can be simulated by the rising voltage front of an impulse reaching crest at about 500μs. Accordingly, the present experiments are based on such an impulse, using a 2.4MV impulse generator connected to a 0.75m diameter sphere placed 0.75m vertically above the tip of the finial under test. The voltage at the sphere thus produced a rising field at the finial tip. In all this work, results obtained with an active finial are compared with those obtained, under the same condition, with a passive (that is, Franklin) finial. The voltage impulse applied to the sphere was always negative.

2.2 Tests with passive finial and finial activated by steady high voltage

The finial was 0.75m tall, mounted vertically at ground level, with a conical tip, of radius 21.4mm tapering over 50mm length to a tip of diameter 2mm.

The finial was first earthed; it was thus passive. Negative impulse voltages were applied to the sphere and the incidence of corona at the tip studied by recording the light emitted by means of a photomultiplier. Thus, each pulse of light emitted by the corona was converted into an electrical signal which was displayed oscilloscopically. An example of such a record is shown in Figure 2; a series of corona pulses produce light pulses which are converted to downward signals on the oscilloscope screen. The time-span, during the application of the impulse field, over which corona was observed, is shown in Figure 3 as a function of crest impulse voltage at the sphere. The two curves show the times of inception of the first and last coronas. For the lowest applied impulse voltages, only one corona pulse occurred; the curves therefore reduce to a single one here. Breakdown of the gap (sparkover) occurred at -490kV.

Positive steady voltages of 10kV, and 30kV were then applied from a separate power supply to activate the finial. The results are shown in Figures 4 and 5. At 10kV the inception times of corona were reduced compared with that for the passive finial; this can be explained by the fact that, for a given impulse voltage at the sphere, the total voltage across the gap and hence the field at the tip, had been increased. Thus, conditions for the first corona were enhanced. At a finial voltage of 30kV separate tests showed that significant steady corona preceded the impulse; here the time to the first corona was increased to a value comparable with that for the passive finial (Figure 5). The total duration of the corona pulses, during the impulse, was not significantly increased by applying the voltage at the finial. The breakdown voltage under the impulse was also increased to 550kV, approximately.

It is evident that the use of a steady voltage at the rod, produced a reduction in the time to first impulse corona only when the voltage was insufficient to produce a preceding corona. Where such a corona was produced, it inhibited further corona under simulated leader-approach conditions, and increased the voltage and field required for sparkover.

Figure 6 shows how the time to breakdown varied with the impulse voltage and with the voltage applied to the finial. It is seen that compared with the passive (grounded) finial case, the time to breakdown was increased, for a given impulse voltage at the sphere as the voltage on the finial was increased to 30kV, in spite of the fact that the impulse voltage required for breakdown was increased by applying voltage to the finial.

It is evident that application of a steady voltage sufficient to produce corona at the rod failed to increase the corona activity under the simulated leader approach.

2.3 Passive finial compared with finial activated by pulsed high voltage

In these tests a positive high voltage pulse, rising to a peak in 1µs and declining thereafter to half the peak voltage in 50µs, was applied to the rod. The time of application could be varied between 40µs and 300µs from the start of the main impulse at the sphere. The amplitude of the pulse was varied up to 40kV; it was thus sufficient itself to set up corona at the rod.

The effect of this pulse on the corona set up by the main impulse is shown in Figure 7. It is seen that, as was the case with the preceding continuous corona discussed in Section 2.2, the presence of the positive voltage pulse did not increase the impulse corona following the pulse, but rather tended to reduce it.

An important parameter here is the time to sparkover. For the particular conditions studied, the time to breakdown of the sphere-finial (passive) gap was 310µs. For the case of the activated finial, the effect of the voltage pulse is shown in Figure 8. The time to breakdown of the sphere to active finial under the main impulse is plotted as ordinate against the time of application of the 1/50µs pulse to the finial as discussed. The time to breakdown for the sphere to passive finial, that is, 310µs, is shown as a horizontal reference line, since no voltage pulse was applied in this case. It is seen that the application of the voltage pulse, in the active case, had negligible effect on the time to breakdown unless it was applied at more than 200µs from the start of the main impulse, that is, within 110µs of the mean time to breakdown of the passive rod. For application times between 200µs and 310µs, the time to breakdown was reduced by a maximum of about 70µs.

The result indicates that the time of application of the activating voltage pulse at the finial is critical in influencing the time to breakdown; over a large period of the rise in field due to the main impulse, it has negligible effect.

The experiment was repeated with a steady negative voltage of -150kV at the sphere, preceding the main impulse; this simulated more closely the conditions in a lightning storm. An example of the results is shown in Figure 9. In this case, the activating voltage pulse at the finial had a small effect when applied at earlier times in the main impulse, but this was, in general, within the statistical spread of the results. In other respects, the results were similar, with the voltage pulse again being required within 100µs of the actual breakdown time for the passive finial in order to effect any significant advancement of sparkover.

3. DISCUSSION

3.1 Effects of steady corona

There are several factors to be considered, in the discussion of these results. For example, where a steady positive voltage was applied to the finial, it could be expected to lead to the formation of a glow discharge around the point, forming a blanket of mainly positive ions. This is a conducting region and, effectively, the radius of the point is increased, so reducing the electric field at the edge of the blanket with consequent reduction in the probability that streamers will form. Earlier experiments in rod-plane gaps with tips of various sizes have shown that where a glow discharge is produced, the voltage needed to produce a sparkover is increased by a factor of 2 and that the transition between a glow and streamers is humidity dependent [8].

Where a finial is located prominently above other structures, for instance on a chimney or mast, the presence of a steady negatively charged thunder-cloud above may lead to similar conditions to those studied here, that is, the formation of a blanket of ions around the point. Where it is less prominent, for instance on an extensive roof, the effect of the field of the cloud in causing corona may be less significant. In all cases, the radius of the tip may affect the size of corona produced. Limits have not yet been adequately defined by experiment, but the present results do not indicate that the ionisation produced by steady corona is helpful in fostering earlier corona, under the influence of an impulse field, or in causing earlier breakdown.

3.2 Effects of impulse corona at the finial

Separate tests showed that a 1/50μs positive impulse applied to the finial produced a single pulse of corona, a few microseconds after the peak, of the order 0.5μs duration, detected by the photomultiplier. Such a pulse is characteristic of streamers. Figure 8 shows that its effect upon the pulses of corona produced at the finial by the field due to the negative voltage at the sphere is to reduce their amplitude. In this respect, the effect of the impulse corona is similar to that of the steady corona, discussed in Section 3.1. It must be assumed, therefore, that the space charge introduced by the pulse of streamers discourages the subsequent development of streamers during the main impulse. However, a change occurs if the finial impulse is applied later in the main impulse, that is, within 100μs of the time at which the gap would have broken down in the absence of the finial impulse. This, occurs at a higher level of main impulse voltage and, therefore, a higher field in the gap, circumstances which, over a limited range, may assist the more rapid formation of a leader.

4 CONCLUSION: IMPLICATIONS FOR LIGHTNING PROTECTION

The present experiments show that, as with provision of a radioactive source, the presence of ionisation around the tip of a finial does not, of itself, create more corona under the influence of the impulse.

It has been shown, however, that the voltage pulsing of the finial during a critical period of about 100μs prior to the time at which the passive finial would have broken down advances the time of breakdown by up to ~70μs. Thus, a device based on the "early streamer emission" principle requires careful adjustment to the variety of conditions which can exist when a leader approaches the finial.

The advance in the time of breakdown implies an increase in the range of influence of the finial in encouraging attachment to the downward leader. Thus, if the answering leader has a velocity of 2×10^4 ms^{-1}[6], then its range can increase by $70 \times 10^{-6} \times 2 \times 10^4$ or 1.4 metre. The velocity of the downward leader depends on the prospective current, but may vary from a few times $10^4 ms^{-1}$ up to 5×10^5 ms^{-1} [9]. Comparison in practice with the passive finial depends on the relationship between the positions of the finials on a structure and the downward leader, but in favourable cases a distance advantage greater than 1.4 metres could be found, though it will vary from one downward leader to another.

5. ACKNOWLEDGEMENT

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6. REFERENCES

1. GOLDE R H, 1977 "The Lightning Conductor", in Golde R H, (Ed) "Lightning" Chapter 17 pp 545-575. Academic Press.

2. ALLIBONE T E and DRING D, 1974 "Influence of radiation on the sparkover of sphere-plane gaps stressed with impulses". Proc. Inst. Electrical Engineers 121, 759-763. For a study of the effects of background ionisation on sparkover, see WATERS R T, JONES R E and BULCOCK J, 1965, "Influence of atmospheric ions on impulse corona discharge", Proc IEE, 112, 1431-1438.

3. ALLEN N L, HUANG C F, CORNICK K J and GREAVES D A, 1988 "Sparkover in the rod-plane gap under combined direct and impulse voltages". Submitted to IEE Proc. A, January 1998.

4. MOORE C B, RISON W, MATHIS J and PATERSON L, 1977 Report on a competition between sharp and blunt lightning rods. Unpublished.

5. BOUQUEGNEAU C, 1985 "Laboratory tests on some radioactive and corona lightning rods" Proc 18th Int. Conf. on Lightning Protection, Munich, 37-45.

6. BERGER G L, 1993 "Determination of the inception electric field of the lightning upward leader" Proc. 8th Int. Symp. on High Voltage Engineering, Yokohama, Paper 70.0L

7. ALEKSANDROV G N, BERGER G and GARY C, 1994 "New investigations in the lightning protection of substations" CIGRÉ Paper 23/13-14.

8. BOUTLENDJ M, ALLEN N L, LIGHTFOOT H A and NEVILLE R B, 1991 "Transitions in flashover characteristics of rod-plane gaps under direct voltages in humid air" Proc 7th Int. Symp. on High Voltage Engineering (Dresden) Paper 42.17.

9. UMAN M A, "Lightning" Academic Press.

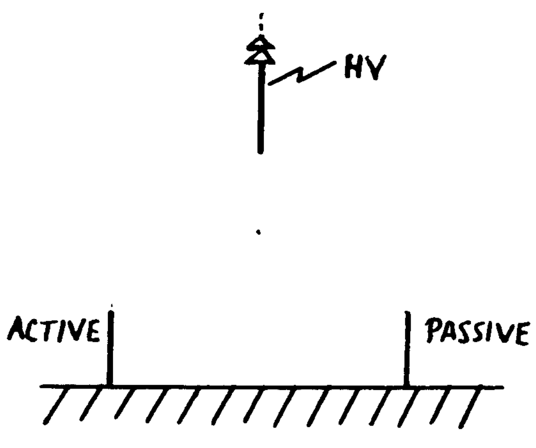

Figure 1 Scheme of experiment of Bouquegneau

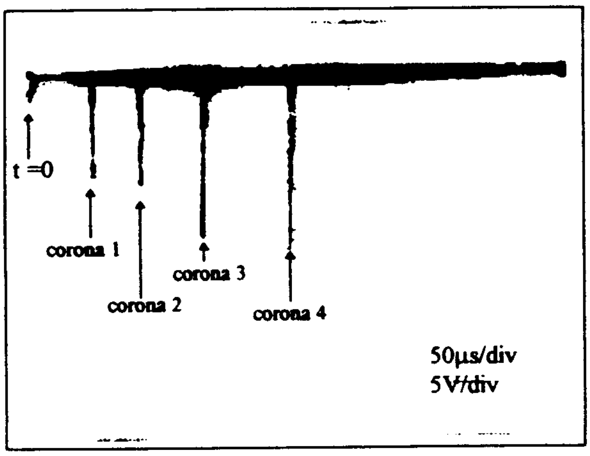

Figure 2 Typical corona observed from tip of passive finial
Negative impulse, 250kV. Photomultiplier record of light emission

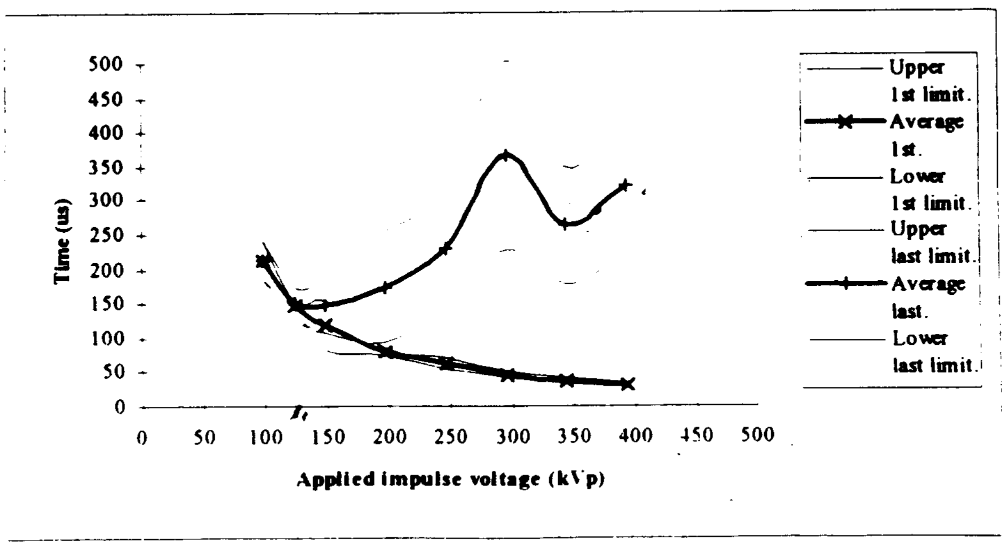

Figure 3 Range of corona inception times, from first to last corona, as a function of applied peak voltage. Passive finial

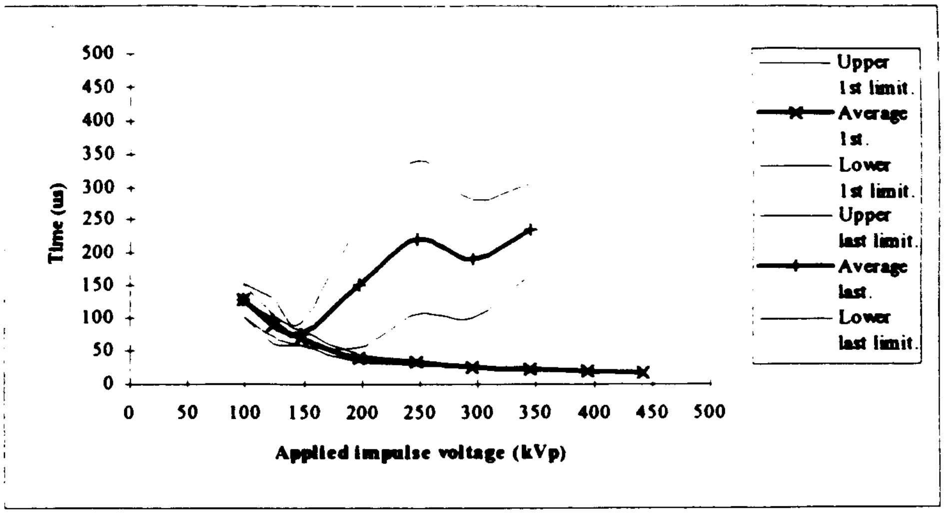

Figure 4 As Figure 3, but with steady voltage of 10kV at finial

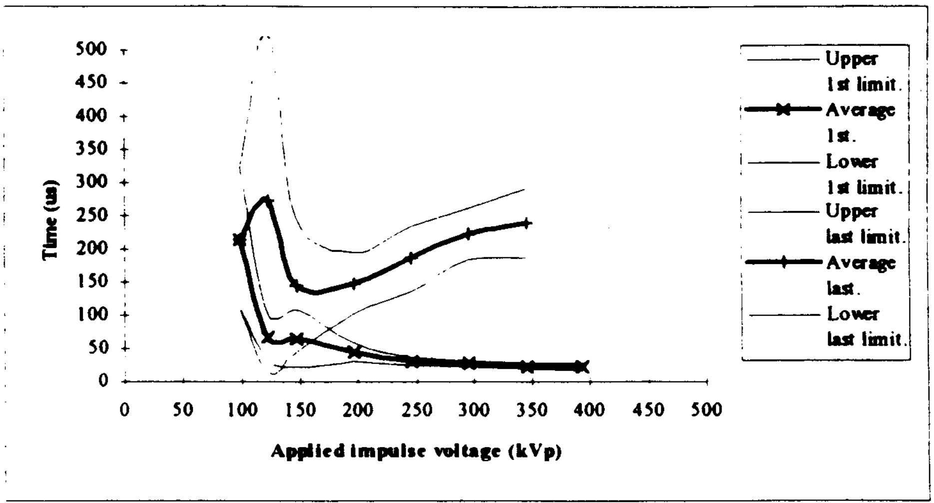

Figure 5 As Figure 3, but with steady voltage of 30kV at finial

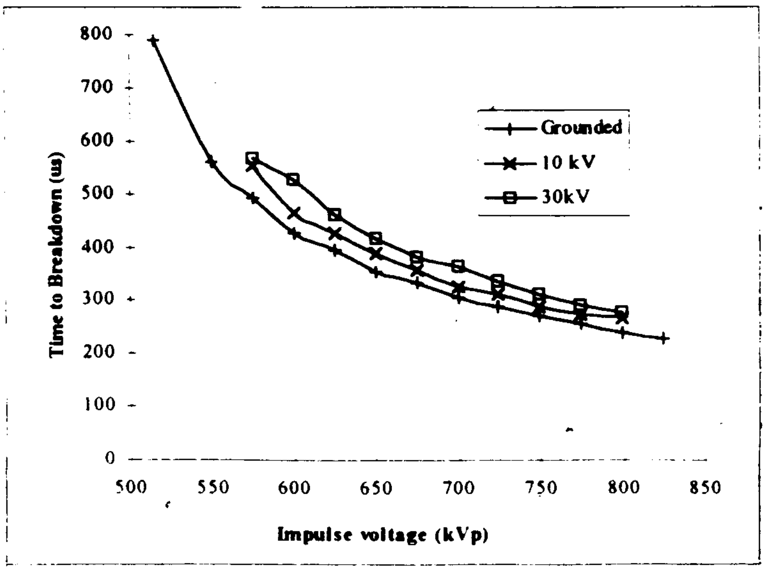

Figure 6 Time to breakdown, for the pre-stressed finial-sphere gap, as a function of applied peak impulse voltage

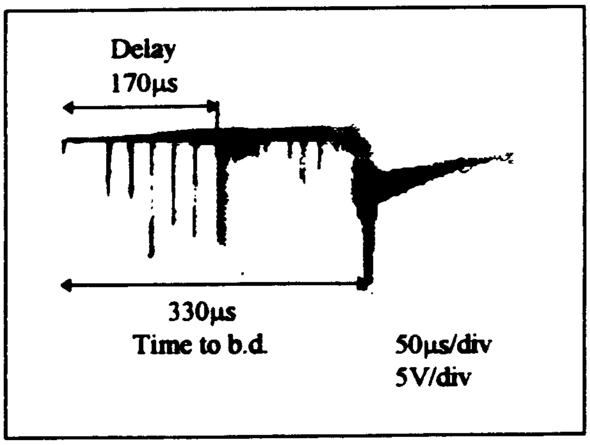

Figure 7 Photomultiplier record showing the effect of the peak at the finial on corona under the influence of the main impulse. Breakdown at 320µs. Compare with Figure 2.

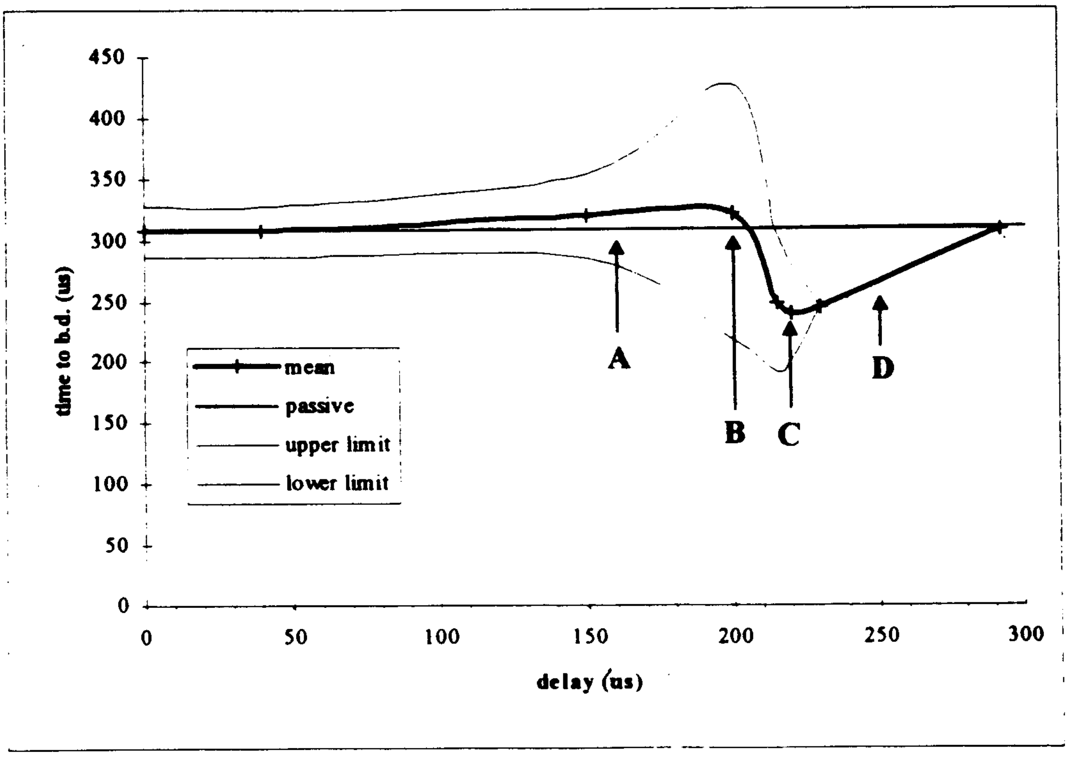

Figure 8 Plot, showing how variation in the time delay to application of finial pulse affects time to breakdown under the main impulse at the sphere. 20kV pulse at finial.

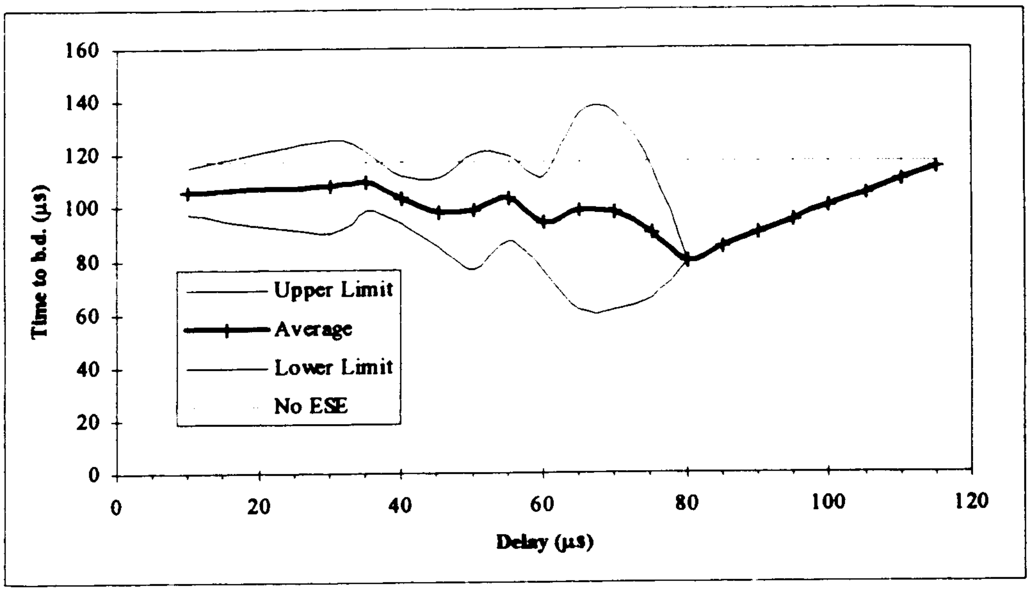

Figure 9 As Figure 8, but with a steady negative voltage of 150kV applied to the sphere.