Dielectric Strength Notes

Note 27

June 1973

HUN Lecture No. 1

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Originally published as
SSWA/JCM/HUN/5

x = Major Items

DIELECTRIC BREAKDOWN AND TRACKING

x The volume/surface area dependency of intrinsic breakdown when this has a finite standard deviation.

SOLID DIELECTRIC BREAKDOWN

Intrinsic breakdown of solid plastic dielectrics.
The pulse life as a function of operating stress.
The high stress useage of thin multilayer film dielectrics.

LIQUID DIELECTRIC BREAKDOWN

Physics picture of some of the breakdown processes.
Electrode area dependency.
Pulse time dependency for uniform or near uniform field conditions.
Point-edge/plane breakdown streamer velocity relations.

GASEOUS DIELECTRIC BREAKDOWN

x Uniform or near-uniform field breakdown :
i DC;
ii Pulse:
  a Townsend avalanche time limited;
  b Streamer transit limited.
Point-edge/plane time dependency.
Pressurised SF6 breakdown fields:
  a Time dependency;
  b Conditioning and whisker rotting.

TRACKING

x Air/solid interface:
  How to make it worse;
  How to make it better.
i DC
ii Pulse
Advantage to be gained from use of freon.
DC Corona - its dangers and prevention.
Liquid, solid interface tracking.
Resistive grading.

EXTRA TOPICS POSSIBLY TO BE COVERED

Very tentative picture of some of the phases of plastic breakdown.
How to break a 6" square of polythene sheet in 200 places.
Very tentative picture of high field streamer breakdown, including a hydrodynamic phase.
A useful light source.
How to track 30 cm with 10 kV with the aid of instant vacuum.

LECTURE NO 1

INTRODUCTION

These lectures will cover superficially the rapidly advancing field of high voltage pulse technology and a few of its applications. Many groups and individuals have contributed to the present state of the art and while I have given an occasional acknowledgment, I am afraid I have been far from diligent in the matter. This is partly because of the speed with which the following notes have had to be produced (three days), but mainly because nearly all the notes of which I had spare copies to bring to Hull have been our own. Thus these were the easiest to refer to and to make available during the lecture course. Consequently I want to apologise to all the other workers in the field for failing to acknowledge their efforts and for not referring to their papers in the open literature. If anyone at Hull wants to refer in more detail to any subject, we can provide copies on loan, or references to most, but not all, of the published work in any specific area.

With regard to the great bulk of the notes (an apt phrase) of which I have provided copies for Hull (in addition to these lecture notes), the majority come via Carl Baum of Kirtland Air Force Base, Albuquerque, New Mexico, who has done a magnificent job of reprinting them. Such copies are much clearer than the originals and are suitable for reproduction. This accounts for the fact that many have two reference numbers. With regard to the remainder, some are recent and of good quality (referring of course to their legibility, not their intelligibility) but a few date from the years BX (Before Xerox) and look as if they had been duplicated by the moist jelly process. Indeed this may actually have been the case and I am afraid there was neither time nor justification for having them retyped, but I apologise in advance to those who try to read them.

Finally I would like to acknowledge that most of the work reported was done by other members, past and present, of the SSWA pulse power group, to whom all the credit is due: any faults that exist are mine. It might be assumed from running an eye down the list of largely internal references given at the back of the later lecture notes that I am the only one at present in the group who can write: a perusal of any of the notes will rapidly disprove this. I can't write, either. However, despite the universal illiteracy of the group, it has managed to make modest contributions to the field from time to time and it is a great personal pleasure to me to acknowledge the fact that we worked as a group and that any success we have achieved was as a group: I just happened to be the one who could afford to buy the ballpoint pen refills.

Summarising, these lectures are a cursory survey of the field and are very largely based on the combined work of the SSWA pulse power group.

I would like to add one personal comment to those who have suffered through the lectures themselves. I could have dealt with half the number of topics in the seven and a half hours and left some degree of comprehension with the audience. However, I have elected to cover, however rapidly and inadequately, all of those areas of the field which are, or may possibly become, of use to the work of the group at Hull University. As such, I aimed to give a general survey, however condensed and confused it may have become. I hope that the stack of single copies of notes will enable those who wish to find out more clearly what I was trying to say on any particular topic and, having perused these, they can contact us to obtain further information and clarification, in the unlikely event that this is forthcoming. To the remainder, who have sat through long tracts of confused and hurried exposition, I can only offer my deepest sympathy and request that if, by accident, they understood any section, perhaps they would be kind enough to enlighten the lecturer as to what it was he was trying to say.

VOLUME/SURFACE AREA DEPENDENCY OF INTRINSIC BREAKDOWN

The treatment given in Reference 1, while being largely concerned with solid dielectrics, is generally applicable. Thus, while solids have a volume effect, most, if not all, of the breakdowns in liquids and gases originate at an electrode surface, in which case an area dependency applies, although, as is explained in the Nanosecond Pulse Techniques note ("NPT"), for conditioned electrodes in gas the area effect is so small as to be practically non-existent. For the case of a chain of many links, where the breaking strength of each individual link has an intrinsic finite scatter, there would be a linear dependency of strength.

As the note, although written eight years ago, is still essentially correct, I will merely update the data in it a little. The distribution which is graphically derived in the note is a Weibull distribution, to which reference should be made by those of a probabilistic turn of mind. The applicability of this distribution function is very wide: indeed, I would hazard an opinion that in real life it is met up with much more frequently than the better publicised Gaussian one. Certainly it is a very good approximation to the distributions found in dielectric breakdown, spark gap firing voltages, mechanical strength, etc. In particular the distribution curve is considerably faster falling on the upper side, which is in intuitive accord with many real life situations - such as the distribution of salaries and other vitally important issues. As is explained in the note, if the intrinsic scatter has a constant standard deviation, then the slope of the breakdown strength against volume or area is constant, too. As is hinted in the note and was subsequently found for mylar in thin sheets, the standard deviation can, of course, change, in the case of thin mylar decreasing to a few percent. When this happens, the slope of the curve decreases very considerably and the volume effect of intrinsic breakdown essentially disappears, the breakdown strength becoming practically constant above some volume. However, even in this situation there is still a finite chance of coming across a sheet with a mechanical defect, or hole, in it, and a new non-intrinsic volume effect takes over. If some electrical or mechanical testing procedure is employed to weed out those areas with such defects in them, this volume effect can be largely removed. The remarkable thing about solid dielectric intrinsic breakdown is not that there is a volume effect, but that over an enormous volume range the standard deviation seems to remain essentially constant (with the exception of very thin films in large volumes).

A second example of the applicability of the note is to the self breakdown voltage of a spark gap. In this case, when the gap is carrying significant but not very large currents, a good gap will have a σ of $\pm$ 3%, or thereabouts, and the distribution is closely a Weibull one. With this distribution, even in thousands of firings there is no real chance of a breakdown occurring at one half of the mean breakdown voltage. However, in real life such low voltage breakdowns can happen, sometimes with percent-like probabilities. These "off distribution" breakdowns are called "drop outs" and visual inspection will show that they are nearly all or all associated with sparks originating well away from the axis of the spark gap, the arc following a long looping path. It is believed that close to the axis metal vapour does not have a chance to condense, or, if it does, the whiskers that grow get knocked by the hydrodynamic shocks from later sparks. However, at some distance from the near axis sites of the vast majority of the breakdowns, long whiskers can grow and these eventually lead to the drop out breakdowns. Thus the breakdown distribution has two components. The issue is one of importance, as in a Marx with twenty such spark gaps as many as 10% of the self breaks can be drop outs occurring at very low voltages. The frequency of drop out breakdowns is a complicated function of electrode material, gas, pressure, current through the gap, and even perhaps gravity, and it has to be controlled in systems using many gaps.

SOLID DIELECTRIC PULSE BREAKDOWN

Firstly there is little or no sign of a time dependency. Jumping ahead, the reason for this can be seen from Reference 13, which mainly deals with the mean velocity of transit of streamers in liquids but also quotes some values for polythene as well. For transformer oil at 100 kV the time to close over, 0.1 cm, is about 70 ns from a point to a plane. In polythene the time is 5 ns. While the proper transit time has to be calculated by integrating as the streamer moves away from the metal electrodes, the ratio stays about the same. In addition to the much higher velocity in polythene, the breakdown field for polythene of a few cc volume is about 2-1/2 MV/cm, whereas in oil charged in about 1 μsec it is more like 1/2 MV/cm. Thus while there are transit time effects in good plastics these are only a percent or so of those in liquids and essentially the breakdown streamer propagation phase can be considered zero, except for large thicknesses of solid dielectric being broken in a few ns. Such streamer velocities were studied in 2 cm thick perspex slabs, where thin holes were introduced part way through and a voltage of 3 MV rising in 10 ns or so applied across the slab. While time resolved measurements were not attempted (it was in the very early days), it was shown that after a very regular growth of small positive bushes the streamer growth went over discontinuously to a much faster mode which travelled at a velocity of up to 1/30th of the local velocity of light. This phenomenon has also been observed in water, where for large gaps the relatively slowly growing, heavily branched bushes from positive edges changed their nature and their velocity of propagation to become much faster and appeared like the more straggly negative bushes. This effect was known as "bush on bush" and suggests that for two very dissimilar materials the negative streamer mode is ultimately the fundamental one and for large voltages or high fields the velocity of this can reach appreciable fractions of that of light.

Thus for solids in most practical situations breakdown is field dependent only and not significantly time dependent. Because there is typically an intrinsic scatter in breakdown fields ($\sigma \sim \pm 12\%$), there is a volume or area effect. The data supporting the contention that there is a volume effect is not extensive but it is reasonably sound and I know of no data that contradicts it. Thus for uniform, near uniform, or very diverging geometries, the volume stressed to 90% of the peak field is estimated and this gives the value of the peak breakdown voltage that the geometry will stand.

In addition to Reference 1, data for some plastics is given in References 2 and 3. One phenomenon that should be mentioned is that while pulse charging gives probably the best measure of intrinsic breakdown strength available, it is possible to achieve a field higher than this using DC with a few materials, typically, and most importantly, polythene. Here, using DC, breakdown fields 20% above those quoted in Reference 1 can be obtained in well arranged tests. This has been studied and can be attributed to charge annealing around the microscopic, probably molecular, scale defect, due to body conduction in the plastic. Thus charge separation occurs along the weakness, reducing the field locally. If such a sample is then put in an LC circuit and rung so that the voltage is reversed, the sample will break at reversed voltages of only 20% of the original applied fields. This is because the annealing charge separation now adds to the reverse applied fields and leads to pulse breakdown at a very low level. The time scale over which this charge annealing takes place is of the order 1 to 10 milliseconds. Other plastics do not show this effect and mylar in particular can be rung nearly 100% without causing it to break after DC charging. DC in this context is 1 min; the effect might show up over longer periods.

Reference 4 gives some data on mylar and was written well before Reference 5, which advances the idea that for large enough volumes of thin sheets of mylar the standard deviation of the breakdown field decreases and the volume effect essentially disappears. The data on which this theory was advanced was notable more by its absence than anything else. However it has been vindicated by fairly recent results from Physics International, where stacks of many thin sheets of mylar of volumes of several hundred cc have shown standard deviations of ± 2% and have breakdown fields essentially on the original curves in Reference 4, thus displaying a much reduced volume effect.

While the breakdown of plastics shows no time dependence it does show a life dependency which, like condensers, is proportional to $(F_{\text{breakdown}} - F_{\text{operating}})^8$. Thus to get a mean life of a thousand shots, a volume of plastic has to be used at half its single shot breakdown field. The pulse life of mylar was investigated as an example in Reference 6. In this it is shown that given the intrinsic standard deviation and the life law, the distribution of breaks with number of pulses at constant field could be calculated. It was also speculated in Reference 5 that there was a direct relation between the standard deviation of the single shot breakdown fields and the life law power. It was shown that for a volume of thin stacks of mylar only just into the volume independent region, the life law was more like a 16th power. This speculation received strong additional support when the life law found for the above tests at Physics International was a 50th power, or thereabouts. Thus from the single pulse breakdown data of a set of samples of a plastic of the same volume, the mean breakdown field and the slope of the volume dependency in the region of the sample volume can be determined. A guess can be made of the life law (an 8th power if $\sigma \sim \pm 12\%$) and then the distribution of breaks with number of shots at a constant pulse amplitude can be calculated: not too bad a return for some modest effort.

LIQUID PULSE BREAKDOWN

The following is a very brief description of what we believe are some of the stages involved in liquid breakdown; these ideas were developed about seven years ago. The model starts with whiskers of lengths in the range 10^{-5} to 10^{-4} cm on the electrode surface. Field emission from these either boils the liquid at the tip of the whisker or warms it so that its surface tension decreases to a low level. A bubble then develops at the tip, where it is hydrodynamically unstable in the large local electric field. The electrostatic pressure at the point is estimated to be in the range 30 to 300 atmospheres. This causes the bubble to elongate and become 10^{-3} to 10^{-2} cm in length. The velocity of this hydrodynamic phase is quite low but because the distances moved are small, the time can still be short. When the sharp bubble has lengthened enough the field at its tip becomes big enough to start the streamer phase proper, which then accelerates out away from the shielding effect of the adjacent electrode.

The range of parameters given above applies for the span of breakdown fields usually encountered with reasonable pulse charging rates in the range several microseconds to tens of nanoseconds. One of the most important phases in this tentative model is the hydrodynamic phase. The existence of this was proved indirectly to our satisfaction by the following experiment. If the hydrodynamic phase is theoretically investigated, a viscosity of order 1 million cgs units will stabilise the bubble against distortion in the applied electric field. We therefore investigated the breakdown of a number of liquids which could be cooled so that their viscosity passed through the range required without crystallisation occurring. Among the liquids investigated were transformer oil and glycerine. For viscosities lower than the critical value, the breakdown had a time dependency and gave field values of the order of 1/2 MV/cm. However, when the temperature was lowered so that the viscosity was greater than about 1 million, the breakdown field rose to 2-3 MV/cm and the time dependency vanished. Thus these experiments showed that the difference between liquids and solids, from a breakdown point of view, is a viscosity of order of 1 million. At the time of doing these experiments there was a brief period of great optimism, as glycerine has a dielectric constant of about 45 and it looked as if (practical difficulties apart) we had a solid of high dielectric constant and high time independent field strength. It was, however, only a couple of hours before it occurred to both Ian Smith and myself to ask the obvious question, and it was quickly shown that the dielectric constant had fallen to about 2 by the time the strength had climbed to those of good solid dielectrics.

Quite recently, some Russian work has confirmed the existence of bubbles at the base of the streamers. In addition the above picture explains why pressurising water to several tens of atmospheres can cause the time dependency to disappear for relatively low fields, and the higher the pressure, the bigger the field at which the time dependency vanishes. This is because the externally applied pressure stabilises the microbubbles against deformation. The picture also led us to coating experiments which for small areas gave dramatic improvements, when used with transformer oil. However, as the coating area increased, the effect became smaller and smaller, producing improvements of only 10% for areas of 10^5 cm^2 or so. This, too, might have been anticipated.

The NPT note summarises the time and area dependency of liquid breakdown and References 7 to 12 cover measurements of the pulse breakdown of liquids for various pulse lengths and electrode geometries and areas.

In the NPT note and Reference 9, the method of calculating breakdown fields in mildly diverging fields, as well as uniform fields, is given. For mildly diverging fields there is usually a polarity term which can be up to about 50% in transformer oil and a factor of 2 for water, with the negative electrode being the stronger. Further work on transformer oil breakdown by Ian Smith, when he went to Physics International has extended the area tested to over 2 x 10^5 cm^2 and investigated very thoroughly oil purity effects, coating, and surface finish. None of these have very much effect and the large area data lies pretty close to the extrapolated curve based on the earlier work at AWRE. The time dependency was also further investigated at Physics International and times out to 50 microseconds were used, and while a more complicated time dependency was found, the basic time dependency can still be expressed as $t^{1/3}$ to an adequate accuracy for design purposes.

For highly diverging fields, ie point/edge plane geometry, the data in Reference 13 is of use. NPT covers the case where higher voltage pulses are applied to point plane gaps in the range 1 to 5 MV with a relation based on data obtained by I. D. Smith at Physics International. This shows that, as we indicated for perspex and water, as the voltage is raised the mean velocity becomes polarity independent, when the applied voltage is large, presumably settling down in the fastest mode.

GASEOUS DIELECTRIC BREAKDOWN

The DC breakdown of near uniform pressurised air is covered in Lecture No. 2, as is the breakdown of SF6 to some extent, and will not be covered here.

The pulse breakdown of uniform gases over a very considerable range is effectively covered by Felsenthal and Proud in Reference 14. There may be delay effects due to awaiting the emission of an initiating electron from the electrodes, but for pressurised bases with rough dirty surfaces there is usually a plentiful supply provided by field emission. In the experiments of Felsenthal and Proud the electrodes were irradiated. They essentially calculate the time the Townsend avalanche takes to build up from an initiating electron to the level at which the avalanche overrides the applied field because of its space charge. The avalanche then accelerates rapidly and significant current begins to flow, the time to do this phase being small compared with the first. The calculations of Reference 14 are in good agreement with the extensive measurements reported. However, the breakdown time that we would use is the time until the resistive phase begins (see Lecture 2 notes), ie the time at which the thin plasma channel first links the electrodes, and the current begins to approach the current that the driving circuit can apply. The measurements reported in Reference 14 take the time until a rather ill-defined current flows and a further time elapses on the records before the start of the resistive phase. However in many cases this time interval is not very long in fast pulsed uniform fields and the hydrodynamic and plasma streamer propagation phases which I believe occur add only a little time to that of the initial avalanche phase. Thus the measurements and calculations of Reference 14 give a lower limit to the time of breakdown, but usually one that is not grossly so. Over most of the range of parameters studied the breakdown field is a fairly low fractional power function of the time. Hence if this time is lengthened a little, the increase produced with calculated breakdown field is rather small. However, under certain circumstances the hydrodynamic and plasma column streamer phase may become the dominant term in the breakdown time. This was first observed by Laird Bradley of Sandia Corporation, Albuquerque. He was investigating the pulse breakdown of uniform pressurised nitrogen gases. These gaps were weakly irradiated by u.v. to provide a supply of initiating photoelectrons from the electrodes. The experiments were in the range of gap spacings 1/2 cm to 2 cm and went up to about 10 atmosphere. As such they were in a different range of parameters to those studied by Felsenthal and Proud and he used pulsed voltages of up to 400 kV. Laird Bradley found that the breakdown field-time relation was as given in Reference 14 for some of the range studied, but for smaller gaps and lower pressures there were significant departures from those calculated essentially only considering the initial avalanche phase. Reference 15 is a note applying the point plane data (discussed below) to these conditions and showing reasonable agreement.

He also found that with a gap operating in this region, ie where the initial avalanche phase had occurred in a few places but the other phases were taking place, the introduction of a substantial burst of u.v. caused the gap to break down in a few ns. This was reasonable on the above picture, because fairly large numbers of electrons would be produced in the body of the gas and these would avalanche in a fraction of an ns and the plasma streamers (which move comparatively slowly) could then link together in line without having to traverse the whole gap separation. This mode of gap triggering is completely distinct from the weak u.v. irradiation used to reduce statistical delays caused by lack of an initiating electron, and from the very much higher levels of energy deposition involved in a laser triggered spark. The range of applicability of this triggering mode is not very large but as the triggering action is extremely quick, under certain conditions the jitter should be tenths of an ns or less.

EDGE PLANE TIME DEPENDENCY

A rather crude relation is given in NPT and Reference 16 for the relation between point plane breakdown fields and time. For air at atmospheric pressure, the data extends out to 5 metres or so and other measurements have carried it down to a few cm for times from tens of ns to a few microseconds. In general it is a relationship which gives answers to 20% for the breakdown fields and is a useful compilation of data rather than an exact physical relation. A differential relation can be derived from this, but the accuracy of it must be expected to be poor. However, this has been used in a number of cases such as in Reference 16, and for the case of partially completed plasma channels reaching out from a transmission line with a short high voltage pulse on it, and answers obtained which are not ludicrously wrong.

Reference 17 gives some data recently obtained for a range of gases at different pressures for small gaps.

PRESSURISED SF_6 BREAKDOWN

This is covered in Reference 18 and also dealt with in Lecture Note No. 2. SF_6 makes a very good spark gap medium and can withstand very large gradients when under pressure, and used with pulsed conditions supporting gradients of the order of 1 MV/cm at about 100 psig.

TRACKING

This is a very large area, on which a great deal of work has been done, but, as far as we are concerned, very little has been written up, certainly not in a systematic way. As there are three media (gaseous, liquid and solid) of interest here, there are three simple interface combinations. In addition, there are at least three cases which can be readily distinguished - DC, pulse, and DC plus pulse - and it is important to note that some remedies which work with DC may actually make the last case worse. Most work has been done on air/solid interfaces, next on liquid/solid, and least on air/liquid. In most cases of tracking the streamer starts from a metal surface, usually at a triple media point; however, this is not always the case. A proper parametric study would cover all the cases for a range of voltages, pressures, and times in the case of pulse tracking; however, life is too short and these notes over-long already. Thus I will outline a few useful remedies, after mentioning some experiments on a tracking set up which were illuminating, or at least were to me.

Tracking is usually considered to be a very variable quantity and as it is affected by moisture, dirt, and time, this is not unreasonable. However, even when these are nominally controlled, it is still pretty variable in the case of DC or pulse charged set ups working in air. If this variability is "intrinsic" then tests with sections of, say, a transmission line, will give optimistic answers compared with the full length line when it is operated; and indeed this can be so. Also when the system is operated a large number of times there may still be a small percentage chance of a track per shot, even when the set up has been modestly overtested for a few shots. The traditional way around this is to provide a really healthy margin against tracking by using overvolt testing. Some of the overtest factors used by us are outlined in the next section.

In the case of a 30 kV megajoule bank, where a track can have dramatic consequences, the feeds to the condensers and the condenser face were overtested by a factor of nearly 3, ie they withstood DC tests near 90 kV. However, in some cases upper limits can be put to the tracking length by doing experiments in which it is made as bad as possible, and this was the aim of the short sets of experiments to be described. The set up was a square of thin copper stuck down to the centre of a large 2 thou sheet of melinex, which in turn was placed in close contact with an extensive earth plane. This central square electrode was pulse charged from a low inductance capacitor of a few microfarads capacity. This was used because as the corona moves out over the surface of the mylar, the capacity of the hot electrode increases greatly and if the DC capacitor is too small, or the circuit linking it to the hot electrode too inductive, the volts on the root of the streamers drops and this is a good way to slow them up or stop them.

With this set up, the resulting streamers were quite visible for some way out from the hot electrode at even 10 kV, but were erratic in length and shape. It was guessed that surface charges deposited on the mylar, by rubbing during assembly or by previous shots, might be affecting the streamers and it was resolved to discharge the surface. This was more easily said than done and a couple of hours was spent in devising a means of doing this simply and quickly. When the surface of the mylar was charge-free, the streamers around the edge of the copper became regular in length and were spaced about equally apart at a spacing of the order of their visible length. As the voltage was increased, the length grew rapidly, but the streamers were still of equal length and spaced about this far apart. The explanation for this is that shielding was taking place and streamers that were slightly longer at any one stage outgrew and killed off their neighbours: the same thing would occur in a forest of trees densely planted at the same time as small plants. The relationship for streamer length was approximately $l_m = 4\ V^{3/2}$ where l is in cm and V is in units of 10 kV. Thus at 40 kV distances of about 30 cm could be tracked. Thus for this worst case of a system rapidly charged from a low impedance voltage source, with no previous charge deposition, very long tracks are possible. In a DC (ie slowly) charged set up, little tracks run out a small way along the surface, depositing patches of surface charge and relieving the stress on the edge. If, however, this charge is removed or reduced substantially, tracking can occur over lengths up to the one given by the above. This happens when a strip transmission line tracks over, because the track removes a lot of the charge locally. Thus, if a system which has tracked is recharged rapidly, it is likely to track again in the same place. To avoid this, the voltage should be worked up again fairly slowly in a number of shots, re-establishing the charge distributions.

Also, in DC charged systems where previous charge distribution has occurred, the tracking distance is much less than that given by the above relation and fairly erratic. However, as the voltage is raised, the micro-tracks get more enthusiastic and may run out into uncharged mylar. Thus DC tracking lengths in normal set ups are much less than l_m but climb to meet it as the voltage is raised to 100 kV or so, and hence show a higher power voltage dependency than l_m . In addition, moist conditions can discharge the surface charge patterns and usually, but not always, increase the chance of tracking.

Consideration of the phenomena outlined above led to some of the following anti-tracking recommendations.

If possible, end both conductors together where the insulation sticks out and avoid the case where an extensive earth plane overlaps the hot strip. This helps DC and pulse tracking.

Use charge deposition intentionally to reduce the field at sharp points or edges. Light weight power packs can be built by providing a perspex cover over the high voltage points. Charge is sprayed on to this and in reasonably dry conditions does not leak away. This charge automatically distributes itself to reduce the field on the conducting components below their coronaring level. Such covers should be "seamless", ie stuck together with simplex (see Lecture 5), not screwed together. However, charge deposition techniques are actually harmful under DC plus pulse conditions, as when the polarity is reversed quickly, the deposited charge adds to the applied field.

A layer of coarse paper (blotting or filter) around the sharp edge of the metal in, say, a copper strip transmission line, carries charge out to its edge, because its surface resistivity is much lower than that of, say, mylar. When a streamer starts out from the paper edge, the potential at its root drops rapidly because it is not attached to metal, and this tends to snuff it out. For lowish voltages this works quite well on its own, but for higher voltages the metal/blotting paper combination should be sandwiched between mylar surfaces, so that the root of the streamer has to move back through the fibres and cannot flash across the surface of the paper. An example of such grading is given in Reference 19.

In this case another trick is also used and this is to make the mylar insulation out of several sheets and separate these at the edge, folding the outside pair back on themselves and separating the others. The streamers then have to run away from each other, reducing their capacity and the energy available to drive them. This trick can be very effective when used in pulse charged systems (see the section in Lecture No 3 on cheap pulse charged 1MV capacitors). The gas in the interstices between the mylar sheets as they separate breaks down but each streamer only has a fraction of the full volts on it and also the internal ones are not connected to metal.

For pulse work, barriers can be erected at right angles to an interface penetrated by two conductors, say. This increases the tracking length greatly for streamers moving across the shortest route at the interface. Such barriers can be simplexed on to the interface, if this is perspex and, properly done, the breakdown can be made to occur between the two metal conductors clear of the interface plus its barriers, before the streamer moving along its tortuous path can complete. This works for pulse voltages up to a million volts or more. For lower voltages, mylar sheets can be twinstuck (a double sided sticky tape) across the interface at right angles to the flash over paths.

Combinations of many of the above tricks can be employed, in most instances, and while the improvement factors they give cannot be multiplied together, at least they are in part additive.

Another class of techniques is to reduce the field on a sharp metal electrode by burying grading conductors in the insulator, just under its surface, and holding these at intermediate potentials with a resistive divider. This is a bit cumbersome, but quite effective.

Yet another class of solution is to provide a compliant seal onto the surface so that a zero or extremely thin air space results along part of the insulator surface. This has been done quite a lot recently by German plasma physics groups, using square section silicon "O ring" compressible gaskets. This approach needs good engineering and a degree of cleanliness, and some care in design, otherwise a solid dielectric switch may be created unintentionally when a pulse passes the joint.

Another class of palliatives is to use a high molecular gas, such as freon, to flood the region. SF_6 can be used, but is considerably more expensive. As freon is much heavier than air, it can be poured into a bag surrounding the equipment. However, making gastight seals through the bag is rather difficult and for a permanent set up something better is usually worth while. The level of the freon can be simply found by floating an air-filled balloon on it, or by lowering a lighted match into it, when a white cloud of smoke will float at some level in the mixed air/freon layer. By introducing the gas at the bottom of the bag via a spreader, freon can be conserved and the interface made pretty sharp.

There are a couple of points about freon worth making. Used in large quantities it can be a hazard, as in a laboratory it may accumulate on the floor, and crawling about in labs or large vessles where freon is in extensive use is not to be recommended. Smoking in air/freon mixture can produce phosgene, and should not be done. On the other hand, a little sparking or corona in freon produces only minute amounts of noxious products and in the normal laboratory is no hazard. Freon is no good in spark gaps, as carbon is produced which deposits on the walls of the gap; SF_6 is much better.

Reference 20 is a brief collection of some data on the pulse breakdown of freon and freon/air mixtures. Also given is the tracking gradient of a Marx in air and a lower limit to the degree of improvement achieved by putting it under freon. In general, in complicated situations such as Marx generators, strip lines, etc., an improvement of about 1.6 is usual. In situations which approximate more nearly to uniform field conditions, higher factors can result, and a peaking capacitor improved by a factor of nearly 2. In genuine uniform field conditions, the factor is more like 3 for pulsed voltages.

Freon, being electro-negative, is very good at suppressing DC corona from sharp points, etc.

LIQUID/SOLID INTERFACES

The tracking problems of these are serious, especially as pulsed voltages of several million volts may be involved. Techniques have been developed for coping with most situations, but to cover them would be a lengthy business and not likely to be of immediate interest to Hull University. In the case of high voltage air cored pulse transformers, the tracking problem can be greatly eased by impregnating the transformer with a dilute copper sulphate solution. As the pulse volts rise on the thin metal sheets forming the windings, current flows along the thin liquid sheet resistors, charging the capacity of the insulant between it and the turn beneath. A diffusion type solution applies to this set up and the very high fields which would result at the edge of the copper are graded over a few millimetres during the pulse rise time. High dielectric constant layers can also be used to reduce the high fields at the edges of thin metallic sheets, in contact with plastic sheets.

The outline of the lecture calls for a discussion of a tentative picture of some of the phases of solid plastic breakdown: however, on thinking about it further, it seemed the points I was going to make were either obvious or very contentious. I will be pleased to discuss the naive ideas with anyone really consumed with interest after the lecture.

"How to break a 6" square of polythene in 200 places". When I put down this topic, I had forgotten it had been referred to in any of the notes and I was relying on my memory of what was done. Consequently I am afraid I got it wrong. The sheet was broken in 600 places, not 200. The experiment is briefly outlined towards the end of Reference 1.

TENTATIVE PICTURE OF STREAMER BREAKDOWN

Early work which led to the light source described briefly below gave rise to one model of the air breakdown process. In these experiments a surface discharge was used. Figure 1 shows a schematic cross-section of the set up. The top sheet of mylar is thin (a couple of thou or so). The potential of the trigger is initially at V during the charging of the condenser. It is then shorted down to earth by a switch and a very large field develops at the HT copper electrode, which is typically 5 thou thick. Field emission provides copious initiating electrons and a very energetic avalanche discharge moves across the top of the mylar. These avalanches lead to a number of plasma channels (~ 8) forming across the gap between the electrodes and then most of the energy (~ 60%) of the condenser dumps into these in about 200 ns. The point of interest here is the stages of formation of the plasma channel. The very high gradient driven Townsend avalanche crosses in a few ns and has dimensions of a few mm. 20 ns Kerr Cell photographs showed that, after a period, relatively low luminosity channels formed which were uniform end to end. These grew brighter but not very quickly. At this time the current (which was much less than that which flowed in the main discharge) would take hundreds of nanoseconds to heat the volume of air to plasma temperatures. During this phase the temperature was a few thousand °K. However, at this stage a very thin, very highly luminous core developed along the axis of the glowing hemicylindrical worms linking the electrodes. These were not completely straight in general but had gentle bends and kinks in them. However, the plasma channel thread followed these perfectly. What was calculated to have taken place was that the warmed half worm-like regions nad expanded slightly, sending a rarefaction wave towards their axes. This could have lowered the density here by a factor of 10 to 100. The rate of heating of this central low density core was then an order of magnitude and a half higher than the main mass of ionised fairly weakly conducting worm. The central core thread then reached plasma temperatures quickly and its resistance ceased falling, and the way the resistance could then fall further was by expanding the cross sectional area of the plasma column in a hydrodynamic-radiation shock, and the resistive phase was started, during which the real energy was deposited. Thus in the surface discharge channels a hydrodynamic phase (the rarefaction wave) reduces the density and then the limited rate of delivery of energy can heat a small low density volume quickly to plasma temperatures, by which time the resistivity essentially stabilises at a few milliohm / cm. In this case the transition happens simultaneously along the whole length of the ionised region, because the degree of ionisation and intermediate declining resistance is uniform along the channel.

In the case of breakdown in, say, uniform field breakdown, an electron is emitted from the cathode and a Townsend avalanche sets out. After about 20 generations, during which the electrons drift with a velocity characteristic of their mobility in the applied field, the space charge dominates the applied external field and the avalanche speeds up, the degree of initial ionisation becomes much greater and the gap is quickly crossed. The current starts to rise through the region of amps; however, most of the voltage is across the initially weakly ionised region near the cathode. The current down the ionised region has to be constant, so the heating rate is rather bigger close to the electrode. This region also has the smallest cross-section. This region quickly expands and the root of the plasma starts at the site of the original initiating electron. The highly luminous plasma streamer then grows out across the gap. This sequence is deduced from streak image intensifier photographs for uniform breakdown over longish gaps in nitrogen at 1/3rd atmosphere. These records were shown to me at Strathclyde University, but they are not responsible for my interpretation of their very nice records. Thus, once again, a hydrodynamic phase would seem to enter into the breakdown process, before a plasma channel is established to move across the gap. This tentative picture is far from being well established. Moreover it sidesteps the physics of the propagation of the plasma channel streamer tip and whether this, too, involves a very rapid hydrodynamic phase, or whether, when the plasma channel is established as a highly conducting sharp projection, a new high field rapid ionisation process sets in at its tip.

It should be stressed that the above is a summary of my personal views about what is going on. They should not be taken as much more than opinions or, at best, a working model with which to play.

A USEFUL LIGHT SOURCE

The above surface sparks provide a useful light source. From the 20 ns Kerr cell photographs when the plasma channel was expanding through the resistive phase, the total volume was known. The current voltage records gave the energy deposited and confirmed that the energy density corresponded to a temperature of about 3 ev. The velocity of expansion of the channel (typically about 3 x 10^5 cm/sec in this case) confirmed this energy density. In addition, the luminosity of the channels measured in the photographic region gave a temperature of about 2 ev with modest accuracy. The superficial area of the 8 channels was about 5 cm^2. After the completion of the condenser energy deposition phase, the shock continues to move outwards and the plasma cools. By the time the temperature has fallen to about 1 ev, the Rossland mean free path becomes larger than the radius of the hot channel. The luminosity then falls quickly, partly because of the T^4 term in the Stefan-Boltzmann equation, but also because the emissivity is rapidly decreasing from unity. The measured light pulse had a duration at half luminosity of 0.4 μsec, in reasonable agreement with the calculations. This short duration was a desirable feature from the application for which the light source was designed. The light energy radiated was calculated to be about 1 joule of a black body spectra, with a peak around 1000 angstroms. Subsequently a 200 cm^2 area source was built and used to take reflected light 0.4 μsecond exposure photographs at 100 feet, as I recall.

Surface guided sparks were also made using pulsed high voltage sources, when the trigger strap was unnecessary. The letters "SSWA" were made in guided sparks about 1 foot long, except that the bar in the letter "A" was omitted: I told you we couldn't write.

Reference 21 is the only one I have been able to find dealing with these light sources and in it these are only briefly covered, I am afraid.

HOW TO TRACK 30 cm WITH 10 kV WITH THE AID OF INSTANT VACUUM

Figure 2 shows the set up. Aluminised mylar links the electrodes and an external switch closes the hot electrode to a low inductance capacitor. A brief low level current flows as the aluminium layer melts and then partially vapourises. Its density at this time is like unity and it expands to 10^{-3} gm/cc when it is roughly in pressure equilibrium with the air, but it overshoots by about the same density factor, producing a mm thick layer of instant vacuum. The voltage across the electrodes is still essentially 10 kV and this low pressure gas layer breaks down for distances up to 30 cm at 10 kV. At slightly smaller distances, multichannel discharge arcs occur, and for considerably shorter lengths an essentially uniform sheet of plasma is generated. This starts below the aluminium, but bursts through this because of Taylor instability. The plasma front can move at 3 cm/μsec, providing a large bank is driving the set up, when few thou aluminium foils can be used as the primer layer. Low energy flash radiographs proved that the aluminium remnants were left way behind the luminous front, travelling at rather less than 1 cm per μsec and in a sadly disorganised state.

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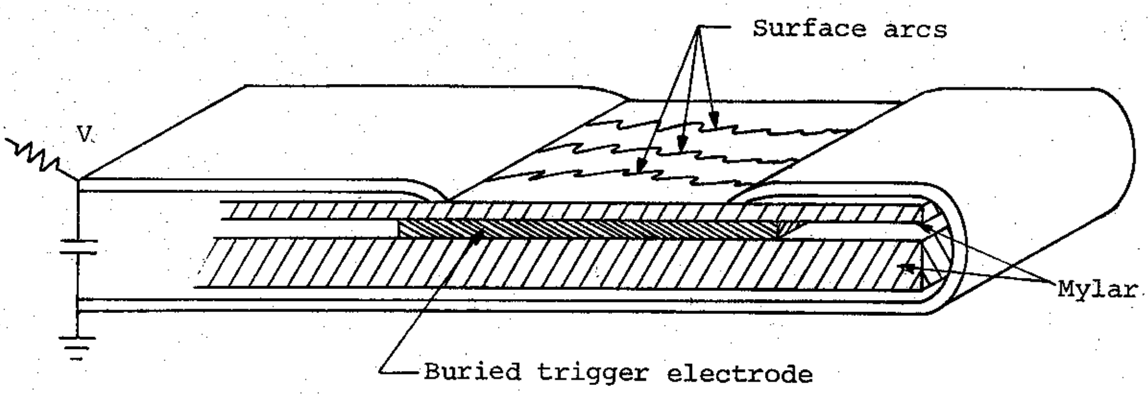

Initially at HT potential rapidly switched to earth

Width of electrodes ~ 60 cms

Spacing apart ~ 1.8 cms for 10 KV

For light source condenser

V ~ 10 KV No. of channels ~ 8

Energy in channels ~ 30 joules

FIGURE 1

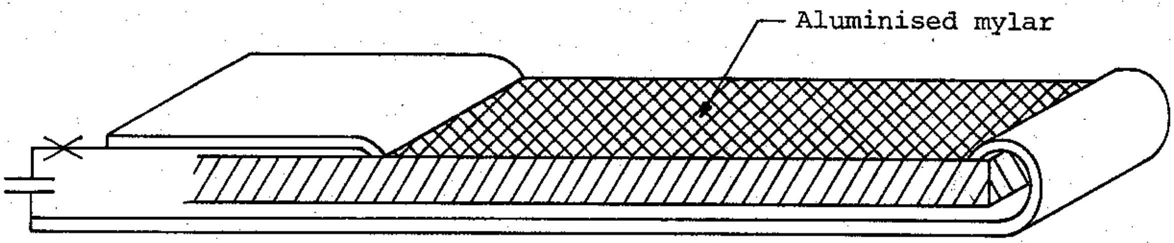

FIGURE 2