High Voltage Notes

Note 4

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PULSED SURFACE TRACKING IN AIR AND VARIOUS GASES

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1 INTRODUCTION

This short study of surface tracking was partly a return to some simple experiments performed several years ago and partly in the hope of providing a zero work function surface covering a large area. The potential application for this is in molecular gas lasers, where a uniform background of electrons is required before a large amplitude multiplying voltage pulse is applied. Such a background of electrons can be provided by u.v. pre-ionisation, but an alternative approach is to drift the electrons from an array of hopefully zero work function surface sparks through the gauze cathode of the laser discharge cell and across this. It is this objective (yet to be tested) which provided the necessary impetus to investigate surface tracking and the characteristics of the subsequently produced surface arcs. As these investigations were rather developmental in nature, the accuracy of the measurements is not very high and also, as usual, the range of parameters studied rather limited. However, even with the above limitations, the data obtained in three weeks or so may be worth recording.

2 HANDWAVING PHYSICS BACKGROUND

In the work done several years ago, it was found that under certain conditions pulsed surface tracking became quite regular. These conditions were that the impedance of the source had to be low, so that as the surface sparks moved out, the voltage at their roots did not drop. More importantly, the surface of the insulator (typically mylar - UK - melinex - USA-) had to be properly discharged between the applied pulses. In addition, the longest tracks were obtained with the thinnest mylar backed closely by an earthed plane. Under these conditions the tracks' originating along a sharp metal electrode resting on the top of the mylar were quite regular in length and spaced about their length apart. As the applied voltage pulse was increased, the length of the tracks increased fairly rapidly and some 30 cm was tracked with an applied pulse of about 40 kV. The normal very irregular tracking lengths usually observed experimentally were shown to be due to patches of charge laid down by previous discharges, in the case of pulsed voltages, or small incomplete discharges where an edge in contact with a surface is DC charged. Indeed, in the case of DC, it is only because small length discharges occur as the voltage is raised, so depositing charge, that tracking lengths much smaller than the one mentioned above can be used. However, without precautions the process is erratic and humidity-dependent, leading to the normal experience of erratic behaviour. As examples of what can be achieved either way, the following cases may be of interest. For a thin metal strip transmission line with the insulator sticking out 2 1/2 cm beyond the two edges, using every trick known, 100 kV DC was held between the electrodes in air. However, with a metal edge and an extensive metallic backing, a 10 cm length can be tracked, using a power pack with a reversible 6 kV voltage, and a condenser and switch.

Considering the possibilities for the initial deposition of surface charge of either sign before the pulse is applied, the following five conditions can be delineated, the order being in the direction of increasing tracking length for a given voltage.

a Surface charge deposited of the same sign as the voltage applied to the sharp metal edge. This charge can either be intentionally deposited by stroking the surface with a flexible, thin metal brush, while this is attached to a power pack, so that the mylar is charged up with reference to the metal backing; or the other way is to pulse the edge a number of times with increasing voltage, each pulse depositing more charge by small surface discharges. As the aim of this investigation was to produce long tracks, this condition was not investigated.

b When a surface track has been closed over the mylar surface, a highly conducting arc results and the surface potential rises to that of the spark channel. However, as the condenser feeding the arc discharges, the voltage falls and at some point the arc extinguishes. This then leaves the surface charged up more or less linearly from the earthy end to the pulsed voltage electrode at a voltage which is a function of the resistance in series with the arc, but typically is a few kV to over 10 kV. If it is desired that another surface track result when a second voltage pulse is applied, then the applied pulse has to overcome this residual charge. However, this initial charge density is quite reproducible and the threshold tracking voltage is, too.

c In this case the surface is discharged carefully between each firing and in a sense this is the most fundamental tracking mode. It should be mentioned that discharging a surface is not all that easy but, as was mentioned above, stroking the surface softly with an earthed metallised brush was found to be simple and effective.

d If the polarity is reversed between firings, the surface charge deposited at arc extinction now aids the propagation of the streamer and a lower tracking voltage will be found than for a completely discharged surface.

e The surface may be charged intentionally with charge of the opposite sign to that of the voltage pulse applied to the sharp electrode. Very long tracking distances can then result. However, where the mylar sheet has been chosen to be as thin as possible, this initial DC charge cannot usefully exceed the applied opposite polarity pulse in magnitude and the useful minimum ± voltage to track a distance is obtained.

In all the above it is assumed that the insulator film is dry and does not carbonise. In practice, mylar seems to be very good in this respect for the gases studied. In addition, its surface resistivity is very high, providing the relative humidity does not approach 100%. Those who have disassembled pulse or DC charged systems, days after their last use, and have collected a shock off the mylar will be able to attest to the very long self discharge times that can occur.

In terms of the experiments to be described, a fair number of experiments were performed in air, using condition (c) and the functional dependency of the track length on mylar thickness, applied voltage pulse amplitude, and duration, was determined. A small amount of work was done with the surface track operating in the condition (b) but the main work was done using the surface track operating in condition (d) which gave the lowest voltage for a given track length under conditions which could be operated in a sealed system. While condition (e) would have given even longer tracks, calculations suggested that it would be very difficult to charge a large area of mylar a few thou (mil) thick by noncontact methods. The alternative, of a charged little mechanical bug gently stroking the surface while it was moving about, was also daunting under the space constraints imposed by the possible application. Thus condition (d) was selected to investigate the dependency of the tracking length as a function of voltage and pulse duration, for a range of gases and mixtures of interest.

To conclude this section, a few observations and speculations about the nature of the surface discharges will be given.

As the pulse voltage is raised (with the surface discharged between shots), at first a very dim glow is observed, reaching out from the edge. At a somewhat higher voltage this glowing region moves out from the sharp electrode and when it becomes a couple of cm long, bright channels begin to form, linking it to the electrodes. At a pulse large enough to track, say, 10 cm, a number of quite bright channels link the 2 cm faintly glowing uniform region back across the 8 cm to the sharp metal electrode. These observations are obviously made when the surface discharge does not link all the way across the surface. The width of the leading faintly glowing region given above is approximate, but is typical for air, nitrogen, or carbon dioxide. However, for helium, the glowing region can be up to 6 cm long and if this is made to link across to an earthy electrode, the subsequent current is carried in a uniform sheath producing a lovely pinkish uniform glow. This lasts for several hundred nanoseconds, eventually going over into rather diffuse channels.

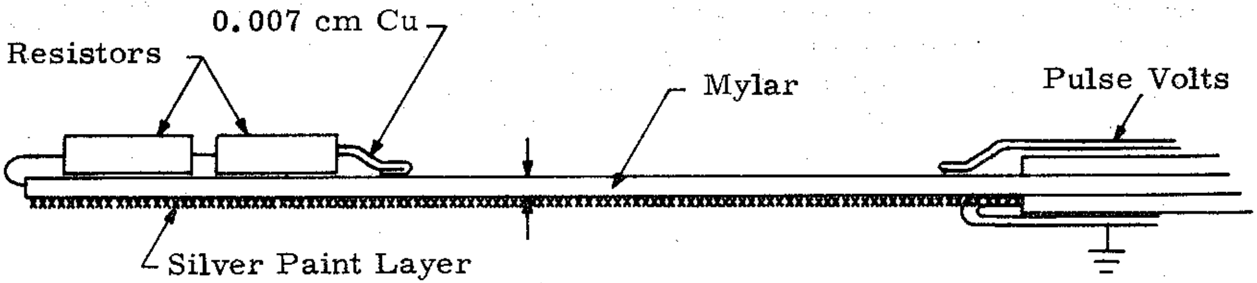
A very tentative picture of the above observations is that in the faintly glowing uniform region, impact and u.v. ionisation cause the gas to become poorly conducting. This layer is probably very thin: visually it is less than 1 mm thick and may be very much less. The energy deposited in this thin layer causes it to heat and expand. A region of pressure very much less than atmospheric results at the plastic surface and the current flowing through this to the advancing front causes the low density gas to heat rapidly and a plasma channel can now be formed. Because of very small surface irregularities, residual surface charge, etc., the formation of the low density zone is not very regular and hence the plasma channel is locally curved and zigzags along the surface. When the discharge links the electrodes, the main current then flows along the preformed zigzag channel. On this picture it would be expected that there would be some constant voltage (that dropped across the faintly glowing head region) which would have to be subtracted from the applied voltage to determine the voltage down the main brightly glowing channel, so as to obtain the relation between the length of this channel and the voltage driving this. As is explained below, the observations agree with this deduction.

3 SOME EXPERIMENTAL ASPECTS OF THE TESTS

When using mylar film of a few thou thickness, the earthy backing electrode must be in very close contact with the underside of the mylar. Even a fraction of a thou of air decreases the capacity in this area and leads to more irregular tracking. Initially aquadag was used to make intimate backing between the earth electrode and the mylar. As the resistance was quite high, this aquadag layer had to be backed by thin aluminium foil. However, a better solution is to use silver paint. The conducting paint we use is that supplied for making electrodes on conducting paper for solving two-dimensional electrostatic problems. Two coats of this provide a layer about 2 thou thick, with a resistivity of about a tenth of an ohm a square. The layer is quite tough and can be flexed without changing its resistance. It can take significant currents for reasonable times, without blowing up. The time integral of the current density squared for blow up is about 10^{-4} of that of silver.

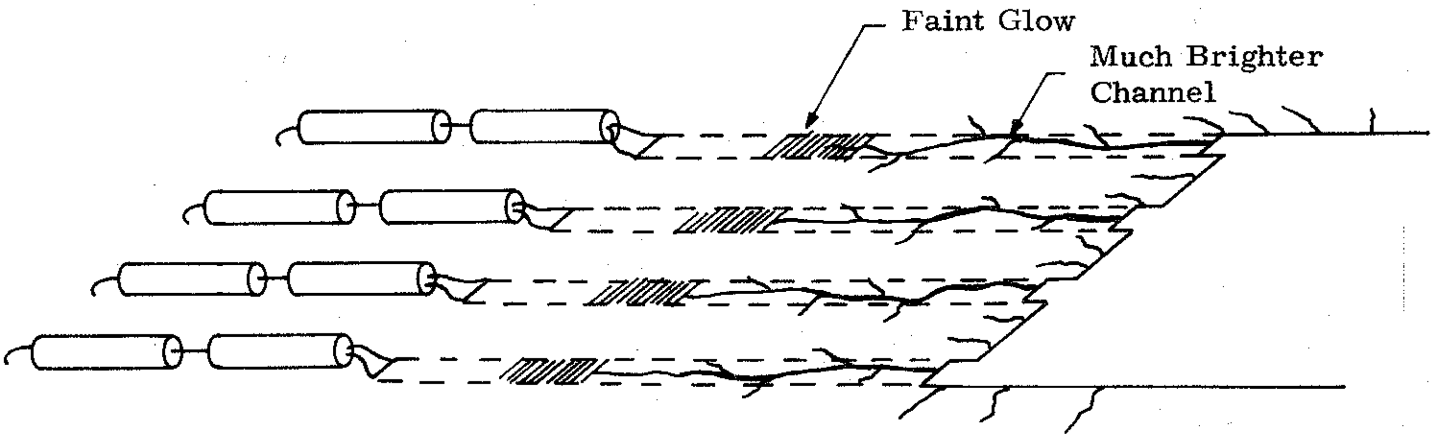
The sharp metal electrodes have been made out of 3 thou copper lightly sprung against the top of the mylar layer. Figure 1 shows a cross-section of a typical set-up.

The capacity feeding the channels is 0.043 microfarads and the switch is a simple mechanically operated one. The inductance in the circuit is about 150 nH. The duration of the applied pulse is controlled by a series of resistor chains (R) which are placed in parallel with the surface track, the circuit being given in Figure 1. The current in the surface arc, if closure results, is controlled by a series resistor (S).

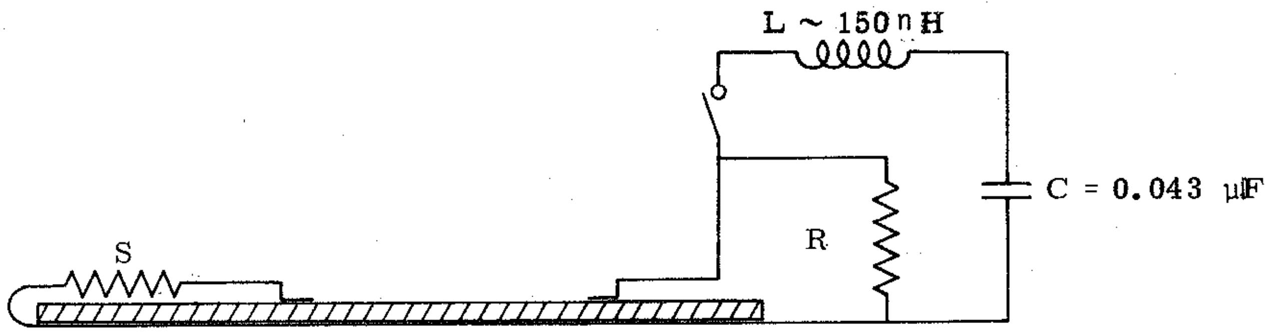


Note Vertical Dimensions Exaggerated

CROSS SECTION OF EXPERIMENTAL ARRANGEMENT



OBLIQUE VIEW OF SETUP WITH 4 UNDERSTRAPS
SHOWING INCOMPLETE CLOSURE TRACKING



CIRCUIT

FIGURE 1

In some experiments a single channel was used, but in most of them an array of 4 or 6 parallel earthy straps were provided, so as to produce data on the ability to light a series of parallel channels and also to increase the statistics of channel formation.

Apart from fairly short channels, it was found that there was little polarity effect in all the gases, except helium. Using the reversing condition (d), sometimes the negative edge required more volts than the positive (nitrogen), but for other gases or mixtures the reverse was true. In general, the difference was less than 10% and seemed to decrease with increasing voltage and track length. For helium, the negative edge gave completed arcs much more easily than for the positive edges. Since for the envisioned application it was very desirable that the applied pulse be negative, the results are quoted for this polarity. However, the positive edge results would be very similar for track lengths over about 5 cm.

It was noticed that there was some hysteresis. That is, when an arc had been struck and the voltage reduced, the voltage at which the complete tracking stopped was a bit lower than when the voltage was raised until restrike occurred. This was despite every effort to discharge the surface (condition (c)). Either the discharging was not complete or there were free ions or excited molecules around which helped the surface discharge slightly. The effect of the latter would be most likely to be felt on the copper electrode, perhaps in helping this to emit electrons to start the discharge. In any event, for reasonable tracking distances the effect was small, again being less than 10% and mostly less than 5%. Because the track is zigzagged (for the pulse durations of most interest) there is a significant standard deviation in the closure voltages, even when everything else is kept nominally constant. Ideally a lengthy series of shots should have been done under every condition and the mean and standard deviation obtained. However, life is short and the criterion used was that the voltage applied should cause closure in about 80% of the shots. Because of hysteresis, care had to be exercised to allow for this and the effect of this and other uncertainties is that the error in any figure quoted can be ± 5% or more. The standard deviation of the observations is probably more like ± 3%. For the application under consideration this was more than adequate.

4 SURFACE TRACKING RESULTS

4.1 AIR

Condition (c) Tracking

With discharging the surface between each shot, the following relation was found to give answers with about ± 5% of the observed ones:

$$\ell = 1.6(V - 5.5\,\delta^{1/3})t^{1/4}$$

where ℓ is the distance tracked in cm

V is the peak applied voltage in kV

δ is the thickness of mylar in thou (10^{-3} inch)

t is a time in μsec equal to discharge time constant of the condenser circuit divided by 6, i.e., the time width of the pulse at 87%

I must apologise for the weird mixture of units, but they happen to be convenient. The range over which the parameters were varied was as follows:

ℓ was varied in general from 4 cm to 12 cm

δ was varied from 1 thou to 30 thou

While δ is specifically for mylar, a short series with polythene suggested that for this parameter the capacity was the important factor and that hence 1 thou polythene was equal to 1.12 thou of mylar: however, this was not established with any great accuracy.

The time parameter ($\equiv RC/6$) was varied between 0.1 and 1.6 microseconds. I must particularly apologise for this parameter. The early work had suggested a 1/6th time dependency; thus the initial choice of RC/6. When this section of the work was done I did not have a pick-up-suppressed 'scope to hand, so could not measure the delay between time of application of the pulse volts and the time the track closed. Later on a Tektronix 'scope became available, but because it is rather pick-up-sensitive and I now have some doubts about its time of triggering, the results from it were not completely reliable. However, they indicated that the closure time did roughly obey the 1/3 power law but were a factor of 2 to 3 shorter than the time parameter as defined above, instead of about twice as long, as the 1/3 power would imply. Thus the absolute time of closure of the surface track is not very certain but is of the order of a half of the time parameter and there is no sense in re-analysing the records using RC/3. I am very sorry about this and can only suggest the t be considered a time like parameter whose significance is not exactly clear.

The relation was also very roughly checked against some long distance tracking data at 160 kV and gave answers roughly in line with these results.

While the results of these (and some later work referred to below) favoured a $t^{1/3}$ dependency, a power significantly above or below this value would have given quite a reasonable fit, with a change in the threshold voltage value of $5.5\,\delta\,1/3$ kV. Thus the time power is not determined with great accuracy. Moreover, for times longer than about 5 μsec, the time dependency vanished.

Some study of the effect of the width of the understrap was made. Where this was wide and the time parameter around 1 μsec or less, a number of channels formed, the spacing being dependent on the mylar thickness. For 1 thou mylar these were on average about 1/2 cm apart, and about 1 1/4 cm apart for 10 thou mylar. Using 3 thou mylar, the effect of reducing the width of the understrap was roughly investigated. Down to 0.5 cm width of understrap there was no change in required voltage; below this there was a very slow increase in threshold voltage, so that at 1 3/4 mm width the constant 5.5 had risen to maybe 6.0, but, again, this change was not investigated for a wide range of parameters.

Other than Condition (c) Tracking

A rather shorter series of tests was performed with conditions (b) and (d). In condition (b) the track was started by discharging the surface and the voltage determined which allowed at least 4 subsequent tracks to occur. In these experiments 4 or 6 understraps were used, each 1/2 cm wide and either 2.5 or 1.25 cm between edges. In air, where a track failed to form, it strayed out on all subsequent shots.

In condition (d), the voltage on the capacitor was reversed between each shot. Again the length was varied between 4 and 12 cm and the time parameter varied between 0.3 and 5 microseconds. Only 2 thicknesses of mylar were used, 2.8 and 5 thou. Again the results could be adequately fitted by a relationship

$$\ell = k(V - 5.5\,\delta^{1/3})t^{1/4}$$

where $k = 0.85$ condition (b)
$= 1.6$ condition (c)
$= 2.2$ condition (d)

4.2 OTHER GASES

The gases used were carbon dioxide, nitrogen, and helium, and some mixtures of these. In these mixtures the notation used is the volume percentages of the gases in the order - carbon dioxide, nitrogen, helium. Thus pure carbon dioxide is 100/0/0 while pure helium is 0/0/100.

The data was obtained for only one thickness of mylar - 5 thou. The length was again varied between 4 and 12 cm, while the time parameter was varied between 0.3 and 5 thou.

Apart from pure helium, nearly all the data was reasonably fitted by a $t^{1/3}$ dependency, with the reservation that above or around 5 microseconds the tracked length became independent of time. The data for a 5 thou mylar thickness and with voltage reversal between each shot (condition (d)) could be fitted by relations of the form

$$\ell = k(V - V_{th})t^{1/4}$$

where the values of k and V_{th} are as given below in Table I.

TABLE I
k, V_{th} VALUES FOR 5 THOU MYLAR, NEGATIVE EDGES

	V_{th}	k
Air	10.3	2.7
100/0/0	11.1	1.0
0/100/0	10.6	1.6
0/0/100[x]	10.5	2.8
10/10/80	12.6	1.8
25/25/50	12.4	2.0
50/0/50	12.2	1.55

[x] The value for helium was obtained only for ℓ = 8 cm. For 4 cm, the values of k were considerably higher, but the definition of when a sharp channel formed from the glow phase was very uncertain. Values for ℓ = 12 cm could not be obtained because of very long length tracking taking place at the pulse feedthrough into the gas cell. Thus the helium values are of very limited use.

The values in Table I are those obtained from fitting the individual sets of data points. However, because of the hysteresis and other effects, the scatter of experimental values would have allowed a range of nearly equally good fits. Because of this, a simplified set of values is almost as good. These are given in Table II.

TABLE II
SIMPLIFIED k, V_{th} VALUES

	V_{th}	k
Air	10.5	2.8
100/0/0		1.0
0/100/0		1.6
0/0/100		2.8
10/10/80	12.5	1.75
25/25/50		2.0
50/0/50		1.6

These values were used in calculating the tracking voltages and the results compared with the original 72 sets of data for gases other than helium and the 8 cm data for this gas. The overall average error for each gas was within ± 2% and the average standard deviation for each result ± 5%. Of this, some ± 3% would be expected in the experimental scatter of each point, the rest being due to errors in the simplified relationships.

With regard to the earlier data quoted for air and independently measured, these give for 5 thou $V_{th} = 9.7$ kV and $k = 2.2$. The larger value of $k = 2.7$ quoted in Table I arises because a value of $V_{th} = 10.3$ was found from the second set of data. Over the range of lengths studied, the two different sets of parameters give results within ± 2 1/2% of each other and therefore the differences fall within the experimental errors. A wider range of parameters would have shown which fitted better, but time was not available to do these experiments.

With regard to the behaviour of the mixtures, a few points can be seen by plotting the data on a triangle for, say, 10 cm track length. These show that the carbon dioxide tends to dominate the mixture. This was further shown by some data at 10 cm for a 50/50/0 mixture which gives a value for k much closer to that of carbon dioxide than that for nitrogen.

A second and somewhat surprising result was that for the n/n/100 - 2n mixtures the trend of k is not uniformly upwards as n decreases. Indeed, the values for the 10/10/80 mixtures are consistently slightly below 25/25/50 instead of being above it as would be expected.

The third result is that, helium apart, all the gases and mixtures need more volts to track a given length than air does. The reason this is a bit surprising is that the attachment coefficient in air (due to the oxygen) is much higher than for pure carbon dioxide and very much higher than for the other gases. However, nature, as usual, resolutely refuses to be simplistic.

This completes the section on tracking voltages. It should perhaps again be repeated that the relationships are only good to some ± 5%. In addition, if the voltage is raised 10% above that given by the relations, 6 tracks will result essentially every time for a 6 strap array with both polarities.

5 VOLTAGE DROP DOWN ARC AFTER TRACK CLOSURE

After the track closes the 2 metal electrodes, a current flows, determined by the value of the series resistor S. This resistor is added for 2 reasons. 1) It keeps the current flowing for many microseconds with reasonable values of the main capacitor. 2) It reduces the requirement for simultaneity in closure of the surface tracks. This is because a track closing does not rapidly discharge the capacitor but ensures the voltage stays up on the pulse charged electrode. The only thing that then causes failure to close of a track of different length is cross-tracking from one channel to another. Where the understraps are separated by 2.5 cm and the length of the track is 10 cm, adjacent channels can be different in physical length by at least 3% and still not affect the formation of both channels on each shot.

Because spark channels can be formed with gradients of 1 kV/cm or even less down them, their behaviour is substantially different from ordinary arcs. In addition, because typically several kilohms are in series with the spark channel, the resistive phase formula is inapplicable, even during the tracking phase.

By measurement it was found that the voltage across S differed from the voltage applied to the electrode fed by the capacitor by a voltage ΔV (kV). As the capacitor discharges, this difference of voltage remained more or less constant, rising only some 20% by the time of spark extinction. Thus over the portion of the waveform of interest to me, from the point of view of practical application, it is possible to assume a constant voltage drop from end to end of the weak spark channel. This voltage difference was found to be a function of arc length and current flowing (i.e., value of resistor S).

A short series of tests in air gave quite a good fit to the relation

$$\Delta V = 0.25\, S^{0.46} \quad (\ell - 1.5)$$

where ΔV is in kV
S is in kilohms
and ℓ is in cm.

In the experiments ℓ was varied from 5 to 15 cm and S from 2 to 16 k-ohm, where this was possible. For the longer lengths and the higher resistances, the arc channel either did not form or went out discontinuously while the source voltage was falling.

A rather more limited series of measurements was made for the value of ΔV for various gases and mixtures, for a track length of 10 cm. Within the experimental error of about ± 10%, the results can be collected into two sets and the average values given in Table III. No data was taken for pure helium. The applied voltage pulse was some 10% above the reversing voltage criteria given in the previous section. In a short separate series of tests, it was shown that ΔV was independent of the applied pulse over the range of 25% or so studied.

TABLE III
AVERAGE VALUES FOR ΔV FOR VARIOUS GASES AND MIXTURES

S (kΩ)	Gas/Mixture	
	100/0/0 0/100/0 50/50/0	10/10/80 25/25/50 50/0/50
2	3.9	3.0
4.2	5.1	4.4
8.2	6.3	6.1

The power dependency for the helium-containing mixtures is close to that of air, while that for the carbon dioxide, nitrogen and equal ratio mixture is lower, being about 0.36.

The above measurements were made with only one time constant of discharge (an RC of about 20 microseconds). It is possible that the approximate constancy of the voltage drop down the arc channel during the pulse is only true for times of this order. The rate of delivery of energy to the channel is typically 1 to 2 kilowatts per cm (assuming a uniform voltage gradient down the channel) at the start of the pulse, dropping by about a factor of 5 shortly before the time of channel extinction. Crude calculations of the various cooling mechanisms of the channel suggest that diffusion of cold molecules into the channels is the main cooling mechanism, with radiation and thermal conduction being rather smaller but still significant terms. Using visually determined estimates of the channel radius, the theoretical estimates of the cooling rates give values around 1/2 kW/cm, in reasonable but possibly fortuitous agreement with the observations. However, this model implies that for rather different time scales from those used experimentally, the channel voltage drop may not remain roughly constant.

CONCLUSION

Approximate relationships are provided for the voltage pulse required to track mylar surfaces for various conditions of initial surface charge. After surface track closure the behaviour of the arc can be pretty closely approximated to by a constant voltage difference between the electrodes. This voltage difference is given as a function of track length for air and current limiting resistor value for various gases and mixtures. No great accuracy is claimed for the relations, but they provide a good basis for estimating the conditions necessary to track a surface in multichannels and to sustain the current in the channels for many microseconds, with a known voltage drop down the channels.