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APPLICATION OF SURFACE ELECTRICAL DISCHARGES TO THE STUDY OF LIGHTNING STRIKES ON AIRCRAFT

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1. INTRODUCTION

For a number of years, aircraft carrying instruments have enabled a large quantity of information to be obtained on the characteristics of in-flight lightning strikes. Whether we consider the NASA programme on the F106 aircraft, [1] the US Air Force programme on the CV580 aircraft [2] or the French programme involving the Transal 04, [3] [4] the results of all three are unquestionably comparable. The main readings taken were recordings of discharge currents in one or several points, and recordings of the electrical and magnetic components of the resulting electromagnetic field. Wherever possible, readings were taken of the current or electromagnetic field within the structures of the aircraft. We now know that a lightning strike phenomenon on an aircraft involves extremely varied discharges, the intrinsic properties of which are very different from one another. Several characteristic phases are observed when an aircraft is struck by lightning.

a) The first is a preparatory phase, which lasts approximately 10 seconds just before the actual strike occurs. The aircraft flies through a high atmospheric field during this phase, and the emission of positive or negative corona discharges can occur in different places around the structure. The balance between these positive and negative corona currents contributes to the evolution of the global potential of the aircraft. During this initial phase, the discharges that act on the aircraft involve very low currents, i.e. in the region of a hundred microamperes.
b) The next is the attachment phase, in which we know that the aircraft simultaneously emits positive and negative streamer and leader systems. This phase is important, as it produces repeated high amplitude pulses on the structure of the aircraft, with an extremely short rise time. The discharges corresponding to this phase are of the streamer or leader type (or both together), and correspond to currents of between a few amperes and several hundred amperes.
c) If the aircraft is flying close to the ground, return current phenomena can be expected ; under these conditions, this will correspond to a very high current pulse since peak values of 100,000 amperes can be reached. Note that this return current phase is rare, and in any case has never been recorded on an aircraft.
d) In most cases, after the attachment phase, a discharge phase occurs between two cloud zones with charges of opposite polarities ; this corresponds to discharges known as junction phenomena. These discharges

involve high currents, which can reach 50,000 amperes with rise times as short as a few nanoseconds.

It is clear that such aircraft programmes will be very difficult to repeat, partly because of the experimental difficulties involved, but mostly because of the financial costs of such programmes. For this reason, and before considering the possibilities of creating models of lightning strikes on aircraft in flight, it would be interesting if we could use electrical discharges capable of simulating the actual in-flight phenomenon in a much more accessible manner. [5] [6]

It is obvious that the corona discharges occurring during the preparation phase are very easily accessible under laboratory conditions, since they involve low amplitude currents and discharges with only a small extension. It has recently been discovered that the attachment phase, which corresponds to the streamer or leader type discharges, can be simulated under laboratory conditions by using pulse generators with peak voltages of several megavolts, capable therefore of simulating electrical discharges of up to 15 metres in length. Note that, using such facilities, the first bileader type discharge was produced in the EDF Renardières laboratory in 1989. [7]

There is also the technique of triggered lightning strikes [8]. This technique, which consists in launching small rockets from the ground, towing an electric wire, enables real lightning strikes to be produced. This technique has an extremely interesting future, since we are already taking steps to use it to trigger lightning strikes at an altitude ; these strikes will therefore be similar to those observed on aircraft. The purpose of this document is to consider the characterisation of surface discharges which, as they are easy to produce under laboratory conditions, provide a facility which is fully complementary to that of artificially triggering lightning, in an attempt to understand the mechanisms involved in lightning strikes on aircraft. These discharges are very small in size. As we will see below, they enable a very precise instrumental record to be obtained, and provide access to the very detailed intrinsic characteristics of these discharges ; we also know that these discharges have properties which are fundamentally very similar to those involved in aircraft lightning strikes, particularly with respect to propagation speed, intrinsic internal field and current involved. ONERA has been using this technique for over ten years, and this has enabled us to make an immense amount of progress in the field of basic understanding of the phenomenology of discharges. [5] [6]

2. GENERAL CHARACTERISTICS OF A SIMPLIFIED SURFACE DISCHARGE

2.1. IMPLEMENTATION PRINCIPLES

Experimentation in the field of electrical discharges is certainly not a new field of investigation, since Toepler was responsible for such work at the beginning of the century. Referring to Figure 1, we consider the main properties of these surface discharges.

The experiment carried out by Toepler consisted in using a thin dielectric plate, beneath which was placed a grounded metal electrode. By means of an electrode located above the dielectric plate, a high voltage is applied

with a variable value VO. We know that as long as VO remains below a critical value, a perfectly isotropic streamer discharge becomes established, in the form of a circle with the electrode as its centre.
If the voltage applied exceeds this peak value, the configuration of the surface electrical discharge changes, and sparks are generated ; these sparks take the form of a propagated channel, with a limited streamer zone in front of it.

Under these conditions, the most simple diagram that can be provided is that of a discharge, which therefore consists of a filament A, preceded by a streamer zone which can be of varying lengths, bearing in mind that the complete unit can propagate either continuously or discontinuously. The same experiment can be repeated, not using a polarised electrode to initiate the process this time, but instead using a method which consists in depositing either positive or negative electrical charges on the dielectric plate, and placing a grounded initiation electrode in front of it.
Figure 2, obtained at ONERA by S. LARIGALDIE, shows the appearance of a surface discharge obtained using a very thin dielectric (a few hundred microns). The discharge structure that appears is highly arborescent, which reveals a large number of spark channels ; the mean distance between these spark channels appears as a constant value. We now know that this mean distance between channels is a direct property of the thickness of the material and of its intrinsic properties. However, it is easily understandable that the study of such a discharge is particularly difficult, due to its complexity and to the non-conservation of the current in the discharges. At ONERA, we had the idea of simplifying the method in order to be able to create an elementary discharge that was as linear as possible, so as to be able to determine its basic characteristic.
The diagram in Figure 3 shows the principle of this type of experiment. The dielectric plate used is again one whose thickness can vary between a few hundred microns and a few millimetres, with a metal strip on one side to enable the propagation of the discharge.
The positive or negative polarity electrical discharges are added on the other face of the dielectric, using a metal comb made up of corona emitting points ; this comb can be connected to a variable high voltage supply.
When the electrostatic charging process of the plate has been completed, the metal comb is removed, and it is merely necessary to earth a floating electrode which is also used to measure the current. It is clear that, under these conditions, it is extremely easy to measure this type of discharge since, in addition to the possibility of easily connecting a current sensing probe in the earth return circuit, it is also possible to add facilities for electromagnetic detection and cinematographic recording at different frequencies, in the close environment of the discharge. This method has been in use for several years at ONERA.

2.2. CURRENT WAVEFORM

The discharge current is directly connected to the generation voltage used to charge the dielectric plate. As soon as the floating electrode is earthed, a breakdown current is established with a waveform as shown in Figure 4.

Curve 1 shows the evolution of the current of an undisturbed electrical discharge, i.e. which propagates from the floating electrode to the end of the electrical strip. Three distinct phases are identified. First, there is a current build-up phase, in which the current starts at zero and finally reaches a peak value (80 amperes on the figure), in a time which is often far shorter than a few tens of nanoseconds. The next phase involves a very slight decrease in the current during the actual propagation of the electrical discharge. Finally, after a period of a few hundred nanoseconds, the current decreases more rapidly during the phase consisting of the relaxation of the charges deposited on the electrical plate.

The waveforms corresponding to curves 2 and 3 are related to disturbances imposed on the path followed by the discharge. In the case of curve N° 2, a dielectric object has been placed in the channel of propagation, and the current pulse corresponds to the by-passing of this dielectric object by the discharge. Conversely, if the path of the discharge is disturbed by a conductive object (curve 3), a secondary pulse is observed that can reach extremely high current values in very short rise times. This secondary pulse obviously corresponds to the discharge of the polarised conductor specimen.

2.3. CONSTITUTION OF A SURFACE DISCHARGE

Through the use of electronic image converters, it has been possible rapidly to obtain a fairly precise idea of the general shape of this discharge. The two photographs in Figure 5 show a recording obtained with this type of image converter. It is perfectly clear that the discharge consists firstly of a filament zone, and secondly of a more widely spread header zone. When considered in detail, this discharge can be structured into several different zones, one of which (defined by AB) corresponds to a "streamer" zone. This zone AB is followed by a "transition" zone, which extends to point C and which then appears between two other zones, firstly CD, and secondly DE.

The diagram of Figure 5 constitutes the basis for a more accurate description of these different zones. The evolution of the drop in potential V along this discharge has been plotted. It is clear that the streamer zone AB corresponds to an initial plasma zone in which the electrical field is in the region of 1.1×10^6 volts per metre. The electron density of the medium is approximately 10^{15} electrons per cubic centimetre, and the electron temperature is approximately 20,000 K.
Point B corresponds to a zone in which the mean gas temperature exceeds 1 500 K. The result is an explosion of electrons around this discharge, and the generation of a transition zone between point B and point C, which corresponds to a very sharp increase in the electron density (N_e = approximately 10^{18} electrons per cubic centimetre), and in which the internal electrical field is also high, since its value is approximately 4×10^6 volts per metre.
Point C corresponds to the beginning of the thermalisation rating, in which the gas temperature approaches the electron temperature, and in which the number of ions will reach 10^{18} per square centimetre. This thermalisation zone concludes with the emergence of the actual channel of sparks which

will connect this leader zone to the initiating electrode. This entire system can therefore propagate at speeds on the order of 2×10^6 metres per second, either discontinuously in the case of negative polarity discharges, or continuously for positive polarity discharges.

3. APPLICATION TO THE STUDY OF AIRCRAFT LIGHTNING STRIKES

Thanks to these surface discharges, it has been possible to experimentally show a complete series of typical discharges that can occur during the general process of aircraft lightning strikes.
In reality, modifications made to the experimental apparatus make it possible to successively consider the establishment of leader or streamer type discharges, return-stroke type discharges, two-directional type leader discharges, and also recoil-streamer type discharges.

3.1. REPRESENTATION OF THE LEADER-STREAMER PHASE

In reality, this leader-streamer phase is perfectly represented by the study of surface discharges such as those shown in paragraph 2.
Among the phenomena demonstrated, we have shown that the propagation speed of such discharges could be variable according to the voltage applied to the dielectric, but would nevertheless always be between some 10^5 metres per second and some 10^6 metres per second - these values are absolutely identical to those known to be reached by lightning leaders.
The most important point obtained during these experiments concerns the rise time of the current wave. We have indeed been able to experimentally show that the electromagnetic radiation threshold that is detectable in presence of such discharges exists only at the beginning and end of the surface discharge. Consequently, this means that the electromagnetic radiation could only be associated with the rapid rise time of the current obtained either at the beginning or at the end of the surface discharge.
This point is of paramount importance, since it has made it possible to understand the electromagnetic radiation properties of lightning discharges in a natural environment. This concept of a rapid rise time has been in particular used to create an electromagnetic interferometer, capable of following the propagation of discharges between clouds in both time and space. [9]
In particular, and as demonstrated elsewhere, we now know that the initiation of a discharge between clouds occurs according to the two-directional leader model recorded during aircraft lightning strikes. [10] [11] .

3.2. REPRESENTATION OF THE RETURN-STROKE PHASE

A relatively simple modification of the original surface discharge experiment enabled us to produce a laboratory representation of a return-stroke type discharge phase. It was merely necessary to complete the previous experimental set-up (described in paragraph 2) by adding an electrode connected to a high energy capacitor, in turn connected to the earth. The experiment therefore consisted, as explained in paragraph 2, in triggering a leader type discharge by means of the spark gap at the top ; once the leader discharge had reached the lower electrode, a return wave

was immediately initiated, therefore causing the discharge of the capacitor which had been charged in the channel of the preceding leader. Under these conditions, it was possible to produce an extremely high energy electrical discharge, with properties which were sully similar to the return stroke of natural lightning.
As an example, we have included two curves in Figure 6 to show the evolution of the electrical currents measured on the capacitor and the floating electrodes. In the capacitor current pulse, the emergence of a very fast pulse can be seen, with an over-oscillation which subsequently tends to become identical to the current wave observed on the floating electrode. In the same way, it was possible to use small capacitive antennae, located along the path of the return-stroke, to show the potential variation laws in several points along the discharge channel.
These evolutions of potential are shown by the different curves in Figure 7. It can therefore be seen that this potential, which starts when the leader touches the capacitor electrode, with a field distribution related to the leader phases, will therefore lead to the establishment of a field curve with a higher value, and show the superimposition of an oscillating value of the electrical field. This experimental set-up has also made it possible to directly observe the geometry of the discharge channel. In particular, we have been able to use an interferometric holography technique at ONERA to enable channel diameter fluctuations to be observed over extremely short periods of time. As an example, we have provided an idea of the evolution of this channel in Figure 8, for build-up times of between 50 and 500 nanoseconds as from the instant when the return-stroke is established. It is particularly clear that, during this phase of some 500 nanoseconds, the diameter of the channel has changed from approximately one millimetre to three millimetres.
All of these measurements, current, potential, holography and also spectroscopy of the discharge, have enabled us to record the intrinsic parameters necessary to produce a theoretical model. This theoretical model was able to be assessed by numerical calculation.

3.3. APPLICATION TO THE TWO-DIMENSIONAL DISCHARGE PHASE

In the same way, the experimental set-up used for the surface discharges was easily modified to enable the generation of two-dimensional discharges, identical to those recorded during lightning strikes on aircraft. The method consists in using two dielectrics, charged to different potentials.
The installation of a floating conductor between the two dielectric plates makes it possible to generate a surface discharge which initiates from each side of the interface, showing the dual propagation of a positive leader and a negative leader.
The photograph in Figure 9 gives an idea of the type of two-directional discharge produced in this way. A complete study is currently in progress in order to acquire the most accurate knowledge possible of the properties connected with these types of propagation.
The use of surface electrical discharges can also be extrapolated to the examination of recoil-streamer type discharges that occur on aircraft.
In this case, the experimental equipment concerned comprises three dielectrics separated from each other, and the middle dielectric has its conductive plate connected to the earth : the zones on either side are

charged with potentials of positive and negative voltages. The obtainment of recoil-streamer type discharges can be considered in the following manner :
the two dielectrics on either side are charged, and when a state of equilibrium of the charges is reached, the two generation devices are removed and a discharge is initiated on one of the interfaces. The result is the propagation of a two-directional discharge, as specified earlier, with, for example, a negative discharge propagating on the left-hand electrode and a positive discharge on the middle electrode. When this positive discharge reaches the extreme right-hand zone, a recoil-streamer type process will be able to be established. We are currently in the process of providing instrumentation for this experiment. The objective is to establish a viable mechanism which could explain the readings obtained on lightning-struck aircraft.

4. CONCLUSION

We have just demonstrated that the laboratory studies carried out on surface discharges have proven to be extremely profitable to the increase of our knowledge on aircraft lightning strike phenomena. The preliminary phase consisted in creating surface discharges with properties that are absolutely identical to those of the streamer or leader type discharges that occur during the phase leading up to natural lightning or aircraft lightning strikes.
The fact that the initiation times of these discharges could be perfectly controlled, and most of all the ability to pre-determine the path followed by the discharge channels, meant that it was possible to produce a highly dedicated high-performance instrumentation system.
Simultaneous measurement of the electric current, the electric field, and spectroscopics of the discharge channel made it possible to create reliable theoretical models. More particularly, we were able to obtain and demonstrate a very thorough knowledge of the electromagnetic radiation mechanisms involved in a discharge.
We now know that simple modifications can be made to the basic set-up, in order to obtain electrical discharges of different types. An additional study has already been carried out, with the aim of examining the return stroke type process. At ONERA, we are currently in the process of making a third type of modification to this equipment, with the objective of carrying out a detailed study, firstly of two-dimensional leader type discharges, which correspond to the attachment phase of the lightning strike on the aircraft, and subsequently of the recoil-streamer type discharge phases, which are extremely important for the study of the electromagnetic disturbances that can occur on aircraft.

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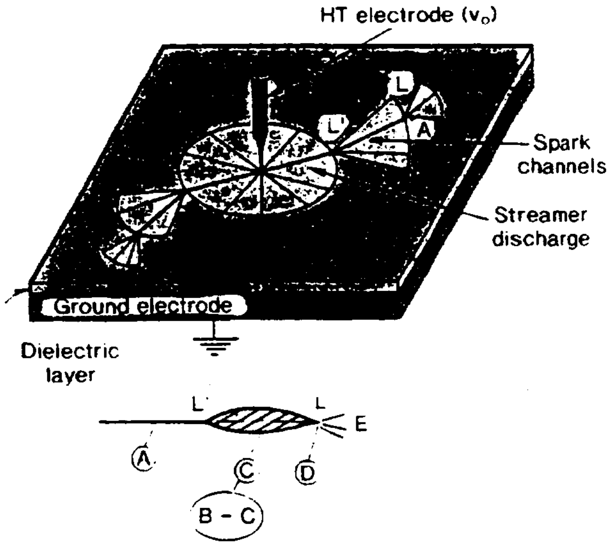

Figure 1
Surface discharge propagation.

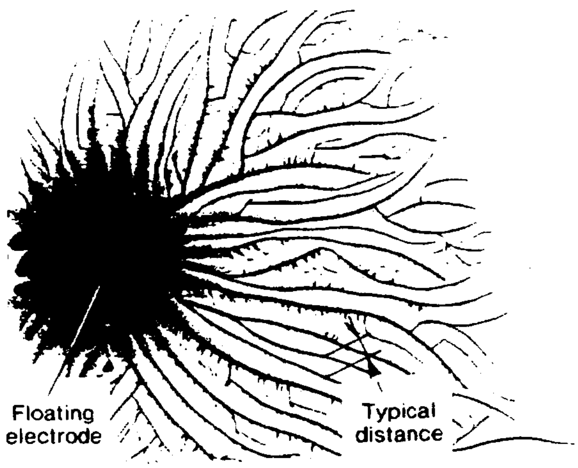

Figure 2
Photography of an electrical surface discharge.

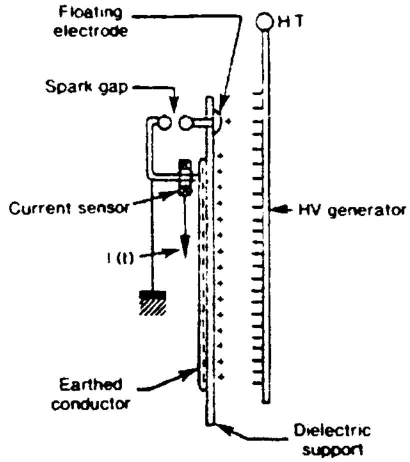

Figure 3
Surface discharge experiment.

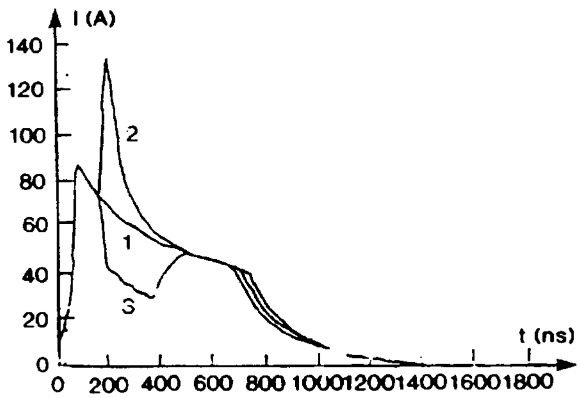

Figure 4
Current waveforms.
1) Normal. 2) Conductive obstacle.
3) Dielectric obstacle.

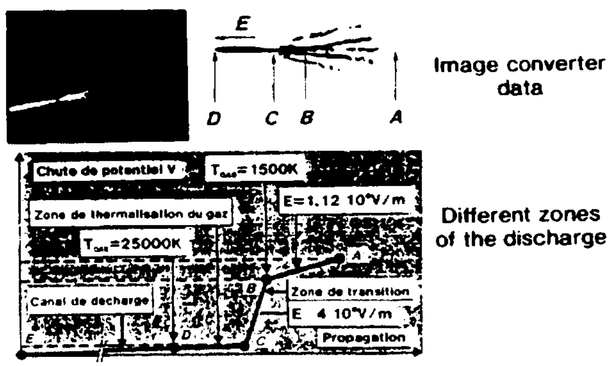

Figure 5
Surface discharge structure.

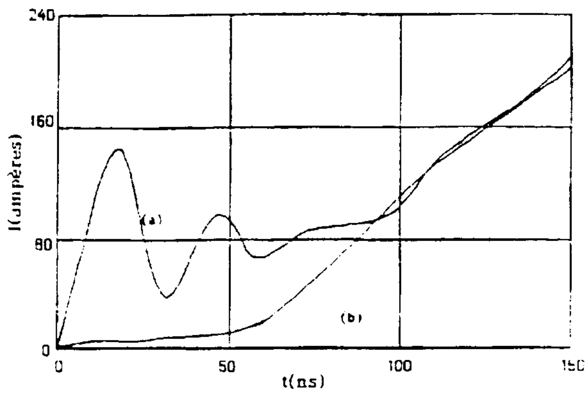

Figure 6
Discharge currents.
a) At the capacitor level.
b) At the upper electrode level.

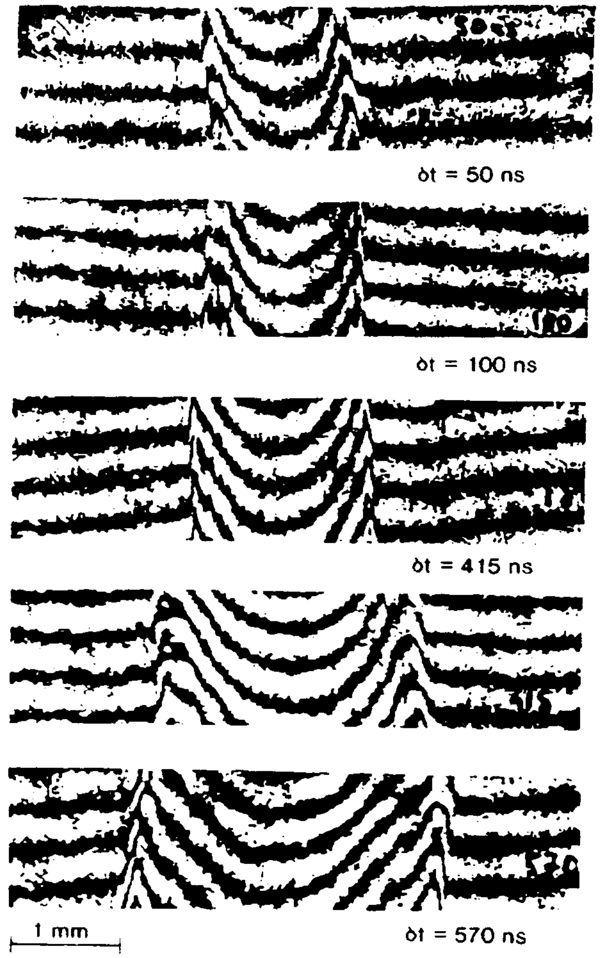

Figure 8
Return-stroke channel observed by holography.

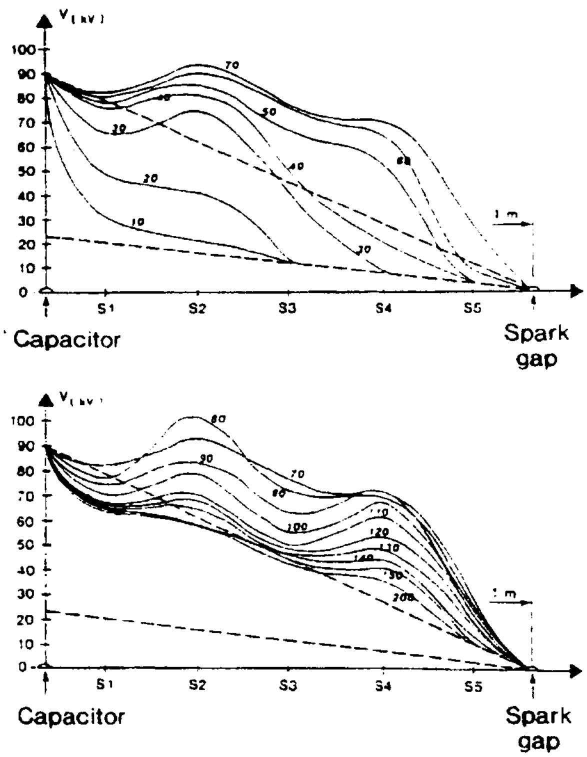

Figure 7
Voltage variations at different locations.
Voltage: 90 kV. e: 2 mm.

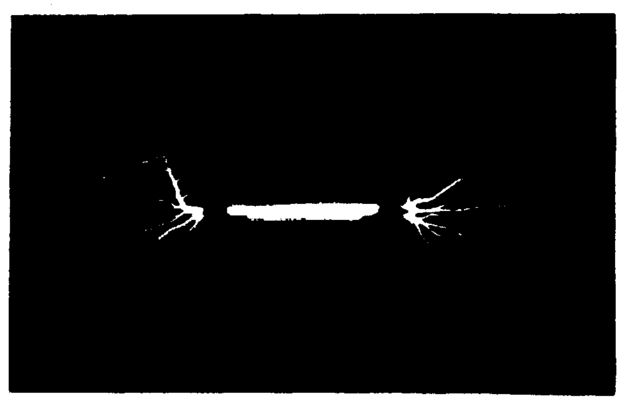

Figure 9
Example of a bidirectionnal leader obtained on a dielectric support.