THE USE OF HIGH-VOLTAGE PHOTOGRAPHY AS A TECHNIQUE FOR DETECTING SUBSURFACE ELECTRICAL INHOMOGENEITIES IN MATERIALS

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ABSTRACT

The controversy over the ability of High-voltage photography to detect subsurface electrical inhomogeneities independent of surface smoothness has been addressed. A method was devised in which one or more samples could be tested under exactly the same conditions with controlled deviations in surface smoothness. This method was also used to examine the ability of the photography to resolve differences in the conductivity of materials which have no surface correlations. The findings of this study indicate that it is possible to detect subsurface electrical deviations and that materials of differing resistivity can also be detected to some degree. Finally, a theory is advanced which offers an explaination for the observed dependence of the discharge on frequency, the occurance of unexpected areas lacking discharge and which provides a mechanism by which materials of differing resistivities can be detected independant of other parameters.

INTRODUCTION

High-voltage Photography is known by several names: Corona Discharge Photography, Electrical Discharge Imaging, and most popularly Kirlian Photography. The technique first gained fame as a result of the work of Semyon Kirlian who began his studies in Russia in the 1930's.[1] His work was with living subjects and resulted in the Russian idea of a bioplasma.[2] Here in the United States Dr. Thelma Moss, of the University of California at Los Angles was greatly influenced by the Russian work and her work has brought much attention to the technique with which she claims to detect an unknown life force.[3] In attempts to learn more about the process scientists were forced to apply the technique to better understood physical materials. This lead to the important advances in the 1970's in understanding the technique and its use in materials testing.

High-voltange photography is a process where a photograph of an object is taken in complete darkness, using an induced corona discharge to expose the film. The simplest type of device for making these pictures is shown in Figure One. With this device the object to be photographed is in direct contact with the film, although in others it is not. Under the film is an insulation plate, usually glass, that helps protect the object from over-exposure. Under the insulation is an electric conductor, such as a copper plate, and connected to the copper plate is a high voltage power source.

The method of the formation of corona discharge has been well studied and is a well known phenomenon.[4] The applied high voltage current causes electrons to jump into the air gap between the cathode and the object, which serves as the anode. When these electrons acquire enough energy, they begin to travel across the air gap toward the anode, ionizing the surrounding air and producing an avalanche effect along the way. The density of the positive ions left behind soon becomes sufficient to pull some of the electrons back from the anode and recombination events occur, causing the emission of light which exposes the film. Electrical breakdown occurs across the gap as a result of the propagation of additional avalanches by the secondary processes described by Tiller.[5]

In their study of High-voltage photography, Boyers and Tiller show that the pattern of the positive-negative streamer formation is strongely dependent on pulse width, the number of pulses and the interelectrode spacing, and is weakly dependent on the type of electrode material.[6] Here perhaps the most important, and often subtile, parameter is the interelectrode spacing. It is defined as the distance from the cathode to the anode, but it is extremely varible over the surface area due to deviations from absolute smoothness.[7] In Figure Two, the effect is evident in the great detail of the surface relief in the photographs of the two coins.

Lord goes a step further in his studies and describes the use of High-voltage photography as a technique for materials testing. He proposes that the technique can be used to reveal or amplify surface and subsurface conditions of the material being tested. He also suggests that it is sensitive to impurities and porosites in the material.[8] In one of the experiments described by Lord and Petrini, a nickel specimen with hardness indents is photographed on both sides. The photograph of the indented side shows the indents as light areas surrounded by dark circles. The opposite side, with no visibly or mechanically detectable indication of the indents, reveals the indents as black spots surrounded by gray areas.[9] Nielsen and Schackelford suggest that this indicates deviations from surface smoothness as opposed to evidence of subsurface stress.[10] However, another extremely interesting experiment performed by Lord and Petrini is not so easily explained. In this experiment an aluminum bar with milling marks is polished smooth until no evidence of the marks are detectable either by visual or talysurf profileometer inspection.[11] Interestingly a high voltage photograph of the bar reveals the milling marks, which Lord attributes to the technique's detection of the subsurface internal state of the metal.[12]

It is apparent that a controversy has developed between the two Californian teams of reseachers. Lord and Petrini claiming that High-voltage photography can be used to detect subsurface characteristics of materials,[13] while Nielsen and Schackelford hold that their work can be explained by micro-deviations in surface smoothness.[14] It is the purpose of this study to end the controversy and determine the status of the technique. The primary goal of this research is to establish proof of the ability of the photography to detect subsurface characteristics of a material independent of surface characteristics, and secondly to determine if differences in the electrical characteristics of materials can be detected.

MATERIALS AND METHODS

. A diagram of the equipment used in this study is shown in Figure 3. The gain of the amplifier is used to set the maximum applied voltage. The applied voltage could be held relatively constant by observing the length of streamers through the spark gap but was difficult to measure with any accuracy. The frequency of the output voltage was controled by the oscillator and the pulse width by a tap switch. This power source is connected to the photographic device previously described so that breakdown occurs in the air gap between the object to be photographed and the copper plate. With this apparatus, photographs were taken of various materials under different conditions. Exposures were made on 4 x 5 Kodak Tri-X pan sheet film and directly on photographic paper.

The first sample consisted of a pencil drawing of a fish on paper. Other photographs were taken of a polycrystaline silicon plate with boron doped crystal interfaces at varying frequencies. Here it was hoped that the slightly higher electric field produced at the interfaces could be detected. Due to the complexity of the silicon sample, it was decided that experiments were needed of samples with more obvious electrial gradients.

Objects of differing electrical characteristics were sandwiched between two sheets of opaque graphite paper which were sealed with photographic sealing paper. In one, a hole was cut in a third piece of graphite paper and filled with a piece of plain paper cut to a nearly a perfect fit as possible. This was then sealed between the graphite paper as described. In another, an aluminum triangle approximately 2.5 cm in height was sandwhiched in the graphite, this was followed up by placing several one centimeter triangles between the graphite to determine resolution. Finally liquid graphite was painted onto an Aluminum foil square, over which another square was placed and the whole thing was sandwhiched between the graphite paper as described.

However, none of these set-ups control for the surface deformation caused by the sandwiched material or for the interelectrode spacing. A method was therefore, devised in which one or more samples could be tested under exactly the same conditions with controlled deviations in surface smoothness, using a cleaved plate of mica on which deposits were made (Figure 4). A material such as copper is deposited to a desired depth on one plate, another material can then be deposited in any manner so as to test the effects of varying the thickness and conductively. A second plate and glycerine are used as a protective covering which is sealed with wax. The wax also forms an air gap in which discharge can occur. With this set-up, photos can be taken from side A to illustrate differences in interelectrode spacing and surface relief or from side B to control for these parameters. This method was also used to examine the ability of the photography to resolve differences in the conductivity of materials which have no surface correlations.

Using this device a series of photos were taken of two 500 A thick depositions of copper and Bismuth which were deposited so as to overlap. The first layer was of copper followed by Bismuth, a second layer of copper and then a second layer of Bismuth. Photos were taken from side A in which the interelectrode spacing and surface relief had a maximum variance of 1500 A, and from side B in which the surface relief was held constant.

Since the reflectivity of a material is a factor in the image produced, a more concrete analysis of the photographs was derived by counting the number of streamers in a square centimeter of each area shown in figure 5. The averages were obtained from six counts from 500 to 1400 Hz in one series and five counts from 1000 to 1800 Hz in the second. These frequency ranges encompased the upper limit at which discharge would occur for the sample.

RESULTS

Figure 6 shows the pencil drawing of a fish on paper. Note the lower part of the tail, which had been erased and redrawn. The erased area shows up clearly but differently than the other. A photo taken at 1000 Hz of the silicon plate is show in Figure 7c, the discharge pattern reveals no correlations with the chrystal interfaces. At ten Hertz the same plate has a dramatically different discharge pattern. This photo clearly shows the depression of the silicon plate in the center due to the heavy ground on top, which reduces the air gap toward the center. There is a low density of streamers and the occurance of indistinct shadows typical of glow discharge. The density of the streamers and glow discharge is seen to increase at 100 Hz (Fig. 7b), but the depression pattern ;is lost. Finally a complete dominace of streamers is seen at 1000 Hz (Fig. 7c). In figure 8, a picture is taken of the same plate after it was cracked, the crack can be seen extending across the middle of the photos taken at higher frequencies (approx. 1000 Hz).

A picture of the graphite sandwich with the cut out is shown in figure 9. The area of the hole can clearly be seen in the center of the photograph as an area of high discharge surrounded by an area of poor discharge. The 2.5 cm aluminum triangle is seen in the upper left hand corner of figure 10a, as an area of no discharge surrounded by areas of discharge. The 1 cm triangles are barely visible in the center of figure 10b. The sample of the aluminum foil sandwiching liquid graphite and which is itself sandwicked by the graphite paper, is shown in figure 11. The aluminum area is clearly seen as being without discharge, while the center area of graphite appears exactly like that of the surrounding graphite paper.

Photographs of the deposition samples taken from side A, are shown in figure 12. Ignoring the first copper deposition, no distinct border is seen to illustrate differences in the thickness or type of material. Photos of the same sample taken of side B in which surface relief is controled are seen in figure 13. The area of the second bismuth layer has a different pattern than the others, being dominated by larger more diffuse streamers. A graph of the average streamer density for an area over the entire frequency range in which discharge occured, verses resistivity is shown in figure 14.

In the photographs the effect of varying the voltage was that of shifting the frequency range over which discharge occured, but no other effects were observed. The frequency however, had a major effect on the amount of discharge produced for a given material. This was seen in all cases and is shown in figure 7, 12 and 13. It was also observed that, different materials produce discharge over different frequency ranges. Another general observation is illustrated in most of the photographs. Here a large portion [illegible] of the photographs have an unexplained area lacking discharge (Example figure 7).

DISCUSSION

To illustrate some of the parameters affecting the pattern of corona discharge produced, a picture of a leaf is shown in figure 15. The surface relief is greatest along the veins of the leaf, here the ridges act to increase the local electric field and hence decrease the sparking potential, creating more discharge along the vein. Increasing the air gap decreases the discharge in the area, but also increases the density of the streamers in a clustering manner because there is more time for branching of the main streamer channel. Note the density of the streamers from the aluminum ground plate is gradually decreasing, while the pattern becomes more diffuse due to the tilt of the plate.

The erased area of the fish drawing which clearly shows up in figure 6, could indicate the presence of un-erased graphite and a lower conductance, or the ridge formed by the pencil trace. This question could be answered by testing similar samples against a control in which a trace is formed by a stylus. Experiments with the silicon plate were unsuccessful, possibly due to the resolution of the technique. However, the dependence of the discharge pattern on the frequency of the applied voltage, and the presence of the depression pattern are very important (figure 7). The depencence of the discharge on frequency was noted by Nelsen[15] but has not been understood, and will be discussed later.

The ability of the photography to detect the depression of the silicon plate is in itself very interesting, but the manner in which the pattern is formed is even more fascinating. In figure 7a, this pattern is made up mostly of glow discharge but also of streamer discharge. The discharge is confined within gradients resembling an interference pattern, instead of appearing as gradual density changes as would be expected. This phenomenon is unexplained, but may involve the effects of an actual interference pattern on the local concentration of photoionization, resulting in discrete areas of discharge.

In the photographs of the hole cut out of a piece of graphite paper sandwiched inside two other pieces (figure 9), the pattern produced may indicated the surface geometry, since a ridge would be developed only at the edge of the cut, forming the outline of the hole. In the photos of the aluminum triangles, one would expect an indietinct border between the area of the aluminum and the heavily discharged area of the graphite, because the bulge in the surface relief would tend to be rounded. Here, aloo the pattern of the aluminum is markedly different from the surrounding graphite, completely lacking discharge. The limit of the resolution of the photography using my equipment, is illustrated by the barely visable 1 cm triangles in figure 10b. It is clear then, that the chrystal interfaces are not within the resolution of my equipment, providing one explaination for the enability to detect them.

The most interesting photographs from the graphite paper series where those of the sandwiched aquadag (liquid graphite), and aluminum foil. The aluminum area is clearly seen to be without discharge, while the center area of the aquadag appears exactly like that of the surrounding graphite paper (figure 11). If this were a surface effect, one would expect a gradual transition from the pattern of the graphite paper to that of the aquadag. The aluminum area should appear intermediate to the other two areas. Instead, areas of graphite appear the same regardless of thickness, and the aluminum area is dramatically different. Note also, that the aquadag is seen through the aluminum. In my opinon, this is strong evidence of the photography's ability to distinguish between the electrical characteristics of materials regardless of the surface geometry.

Even so, more conclusive results are desired. To achieve these results, it is essential that surface effects are controled. The sample set up previously described and shown in figure 4 accomplishes this goal. The deposition of the samples on the rigid mica plate controls the surface relief since the mica determines the surface (from side B). It also controls the interelectrode spacing (air gape) to some degree due to the rigidness of the plate. It was discovered, however, that the plate could be tilted due to inconsistancies in the thickness of the wax used to seal the sample, resulting in a gradual gradient in the thickness of the air gap. The set-up also has the advantage of allowing different materials to be photographed under exactly the same conditions.

The detection of the copper and bismuth deposits through the mica plate proves that subsurface characteristics can be detected. In this sample there are no surface correlations with the deposits since the surface of the mica determines the surface relief and interelectrode spacing. The image is not merely formed as a result of streamers arcing from the ground plate through the mica plates and sample. Since there is no air gap between the deposits and the mica plate, streamers in the area of the sample must be generated from the surface of the mica. That the pattern is not caused by any changes in the surface relief is supported by the lack of differences in the discharge pattern for the area in pictures taken of side A, where the surface relief has a maximum variance of 1500 A.

When the average streamer density of the areas illustrated in figure 5 are compared, a possible correlation is seen between streamer density and the resistivity of a material (Figure 14). To explain this occurance, one must keep im mind the dependence of the discharge on frequency. In the course of my study, it was noticed that for a given sample, discharge would occur only over a specific range when the voltage is constant. The amount of discharge would increase to a peak with an increase in frequency to a limit, and then decrease with increased frequency.

Varying the voltage only had the effect of shifting the frequency range at which discharge occured, but this occured only to a certain point beyond which further increases in the voltage had no visible effect. A possible reason for this behavior was suggested when it was discovered that the frequency range at which the discharge occured, could be dramatically increased by adding a large resistance to the sample. It then became clear that as the impedence of the tranformer changed with the frequency and load, the current passing through the sample was changing. As the frequency increases the load on the tranformer increases and the current passing through the air gap increases. If the quenching time of the discharge streamer is on the same order as the frequency, then the streamer may not be able to quench between pulses, and recombination events would be inhibited until the discharge stopes. Therefore, one would see an increase in discharge with frequency due to the the increase in current up to a maximum point, followed by a decrease in the discharge with further increases in the frequency. The validity of this theory can easily be determined by conducting experiments in which the resistance of the sample is changed, controling the current through the sample.

The above reasoning may also explain the patches of no discharge which occurs in nearly all the photos taken. Boyers and Tiller[16] suggest that this pattern is caused by buckling of the film, but I find this unlikely in some of my set-ups. There seems to be a strong correlation of these areas with the ground contact to the aluminum ground plate. If this is the case, then the contact is being detected thorugh the air gap, two mica plates, the sample and an aluminum plate one milimeter thick. The ability to detect this area may be due to the extremely strong elctric field and current flow from the contact, which may produce a region where the charge density remains high and does not quench even at low frequencies. This theory can easily be tested by completely eliminating film buckling with glass film and by carefully controling the location of the contact.

CONCLUSION

The findings of my study support the work of Lord and Petrini. It is possible to detect subsurface electrical inhomogeneities in materials which have no correlation with the surface characteristics. It was found that areas of differing electrical characteristics produce different discharge patterns as was seen in the aluminum-aquadag sample. Prelimenary data from this study also suggests that materials of different resistivities can be detected by finding the average streamer density over the entire frequency range at which discharge will occure for materials and graphing it against the resistivity of the material. Finally, a theory is advanced suggesting a possable explanation for the observed dependence of the discharge on frequency, and for the occurance of unexpected areas lacking discharge. This theory also offers a mechanism by which the resistance of a material can effect the type of discharge pattern produced, resulting in the detection of materials of different resitivity.

ACKNOWLEDGEMENTS

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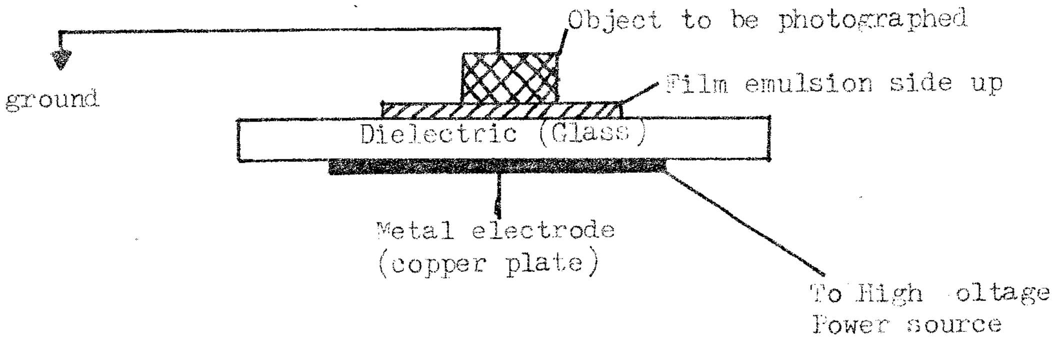


Figure One

A Simple Device for Making
High Voltage Photographs

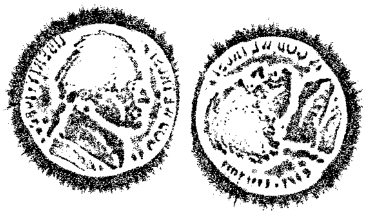


Figure Two

Negative of coins taken using High-Voltage Photography. Exposed directly onto photographic paper. Darker areas are most intense areas of light. Pale area of face results from direct contact with the emulsion surface.

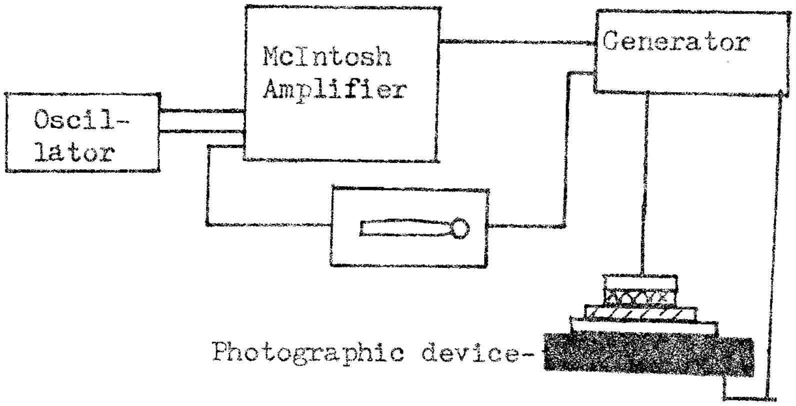


Figure Three

Equipment used to make
High-voltage photographs

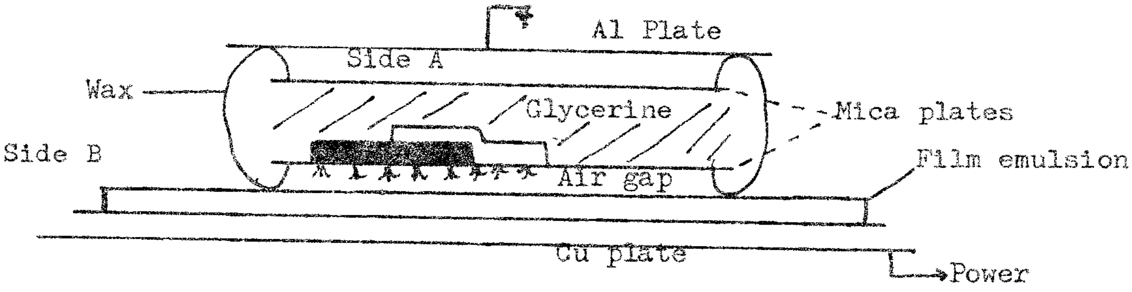


Figure Four

Sample set-up used to test one or
more samples under the same conditions
while controlling for surface relief.

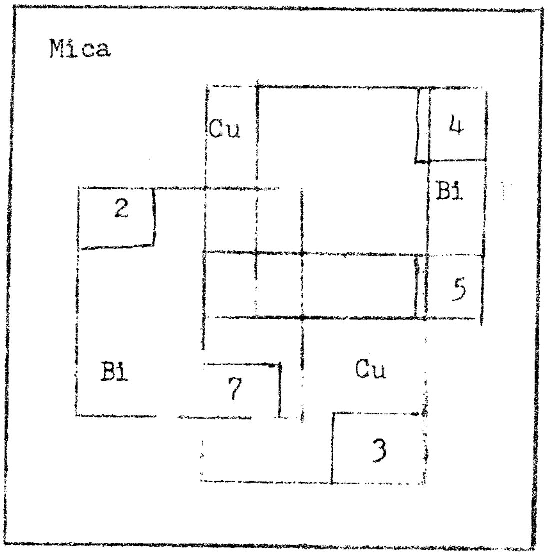
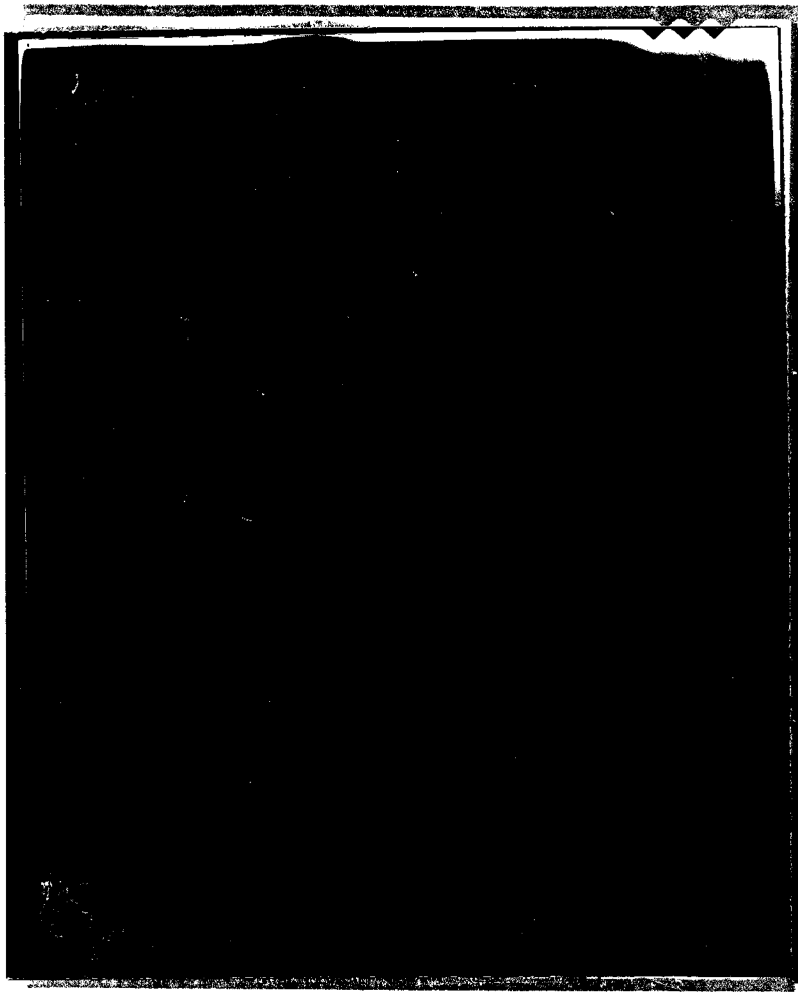


Figure Five

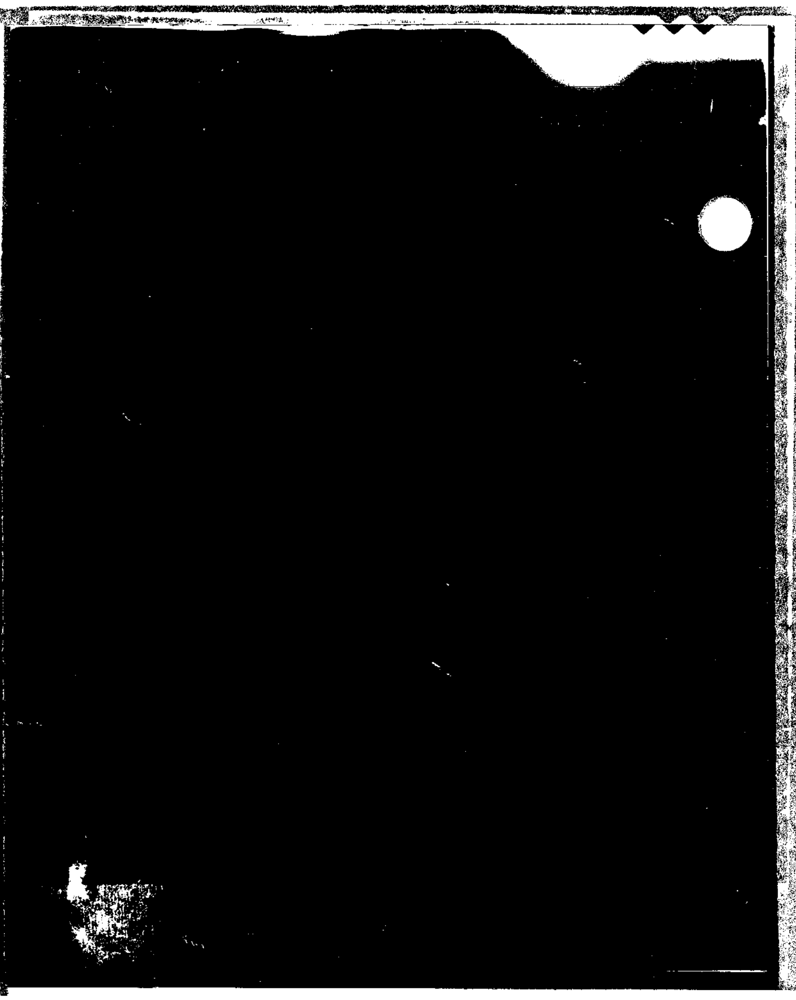
Count areas used to quantify the amount of discharge for a material.

Figure Six

High-voltage photograph of a pencil drawing of a fish on paper. Note the lower portion of the tail which had been erased and redrawn.



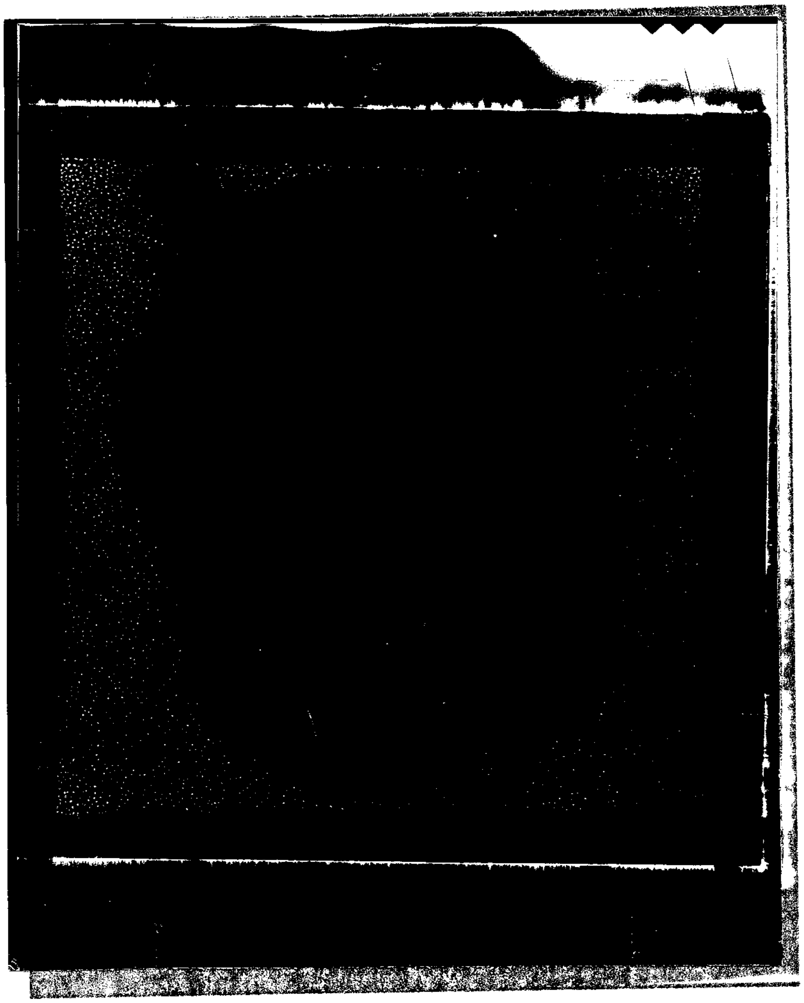
A (10 Hz)



B (100 Hz)

Figure Seven

High-voltage photographs of a Polycrystaline Silicon plate with boron doped interfaces. The deformation of the plate is seen in A. Note changes in the streamer pattern with frequency.



C (1000 Hz)

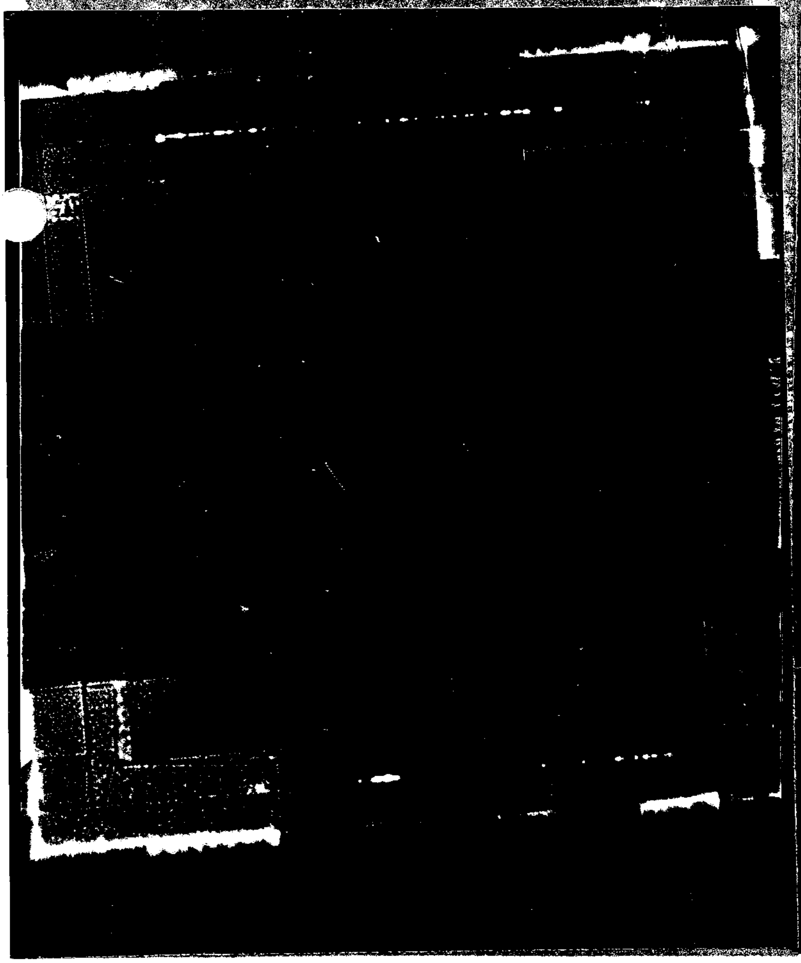


Figure Eight

Photo of the same silicon plate after it was cracked. The crack can be seen extending through the middle of the picture. Taken at 1000 Hz.

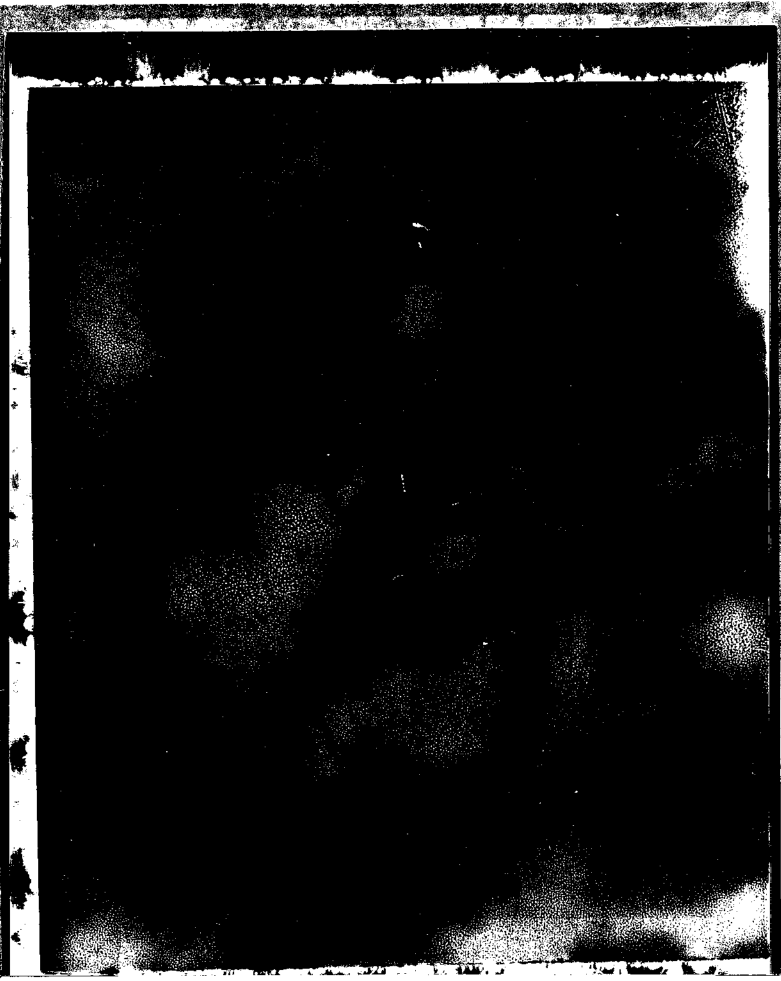
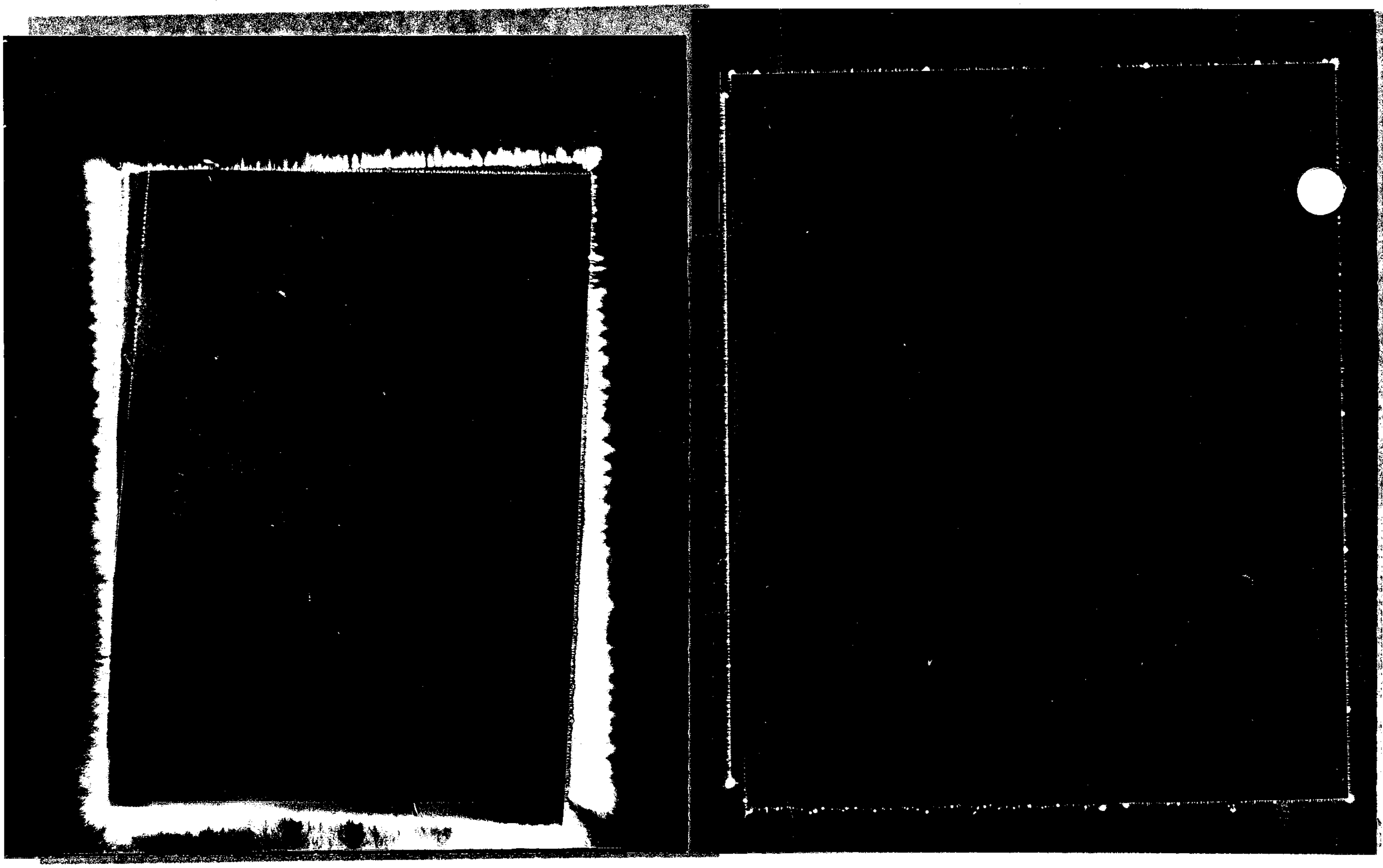


Figure Nine

Picture of a hole cut in a piece of graphite paper and sandwiched within two other pieces of graphite paper. The outline of the hole is clearly shown in the center of the picture. Taken at 1000 Hz.



A
2.5 cm

B
1.0 cm

Figure Ten

Photographs of Aluminum triangles sandwiched between two sheets of graphite paper. The large triangle in the upper left hand corner of A. The smaller triangles are visible as heart shaped black areas in the center of B. Taken at 1000 Hz.

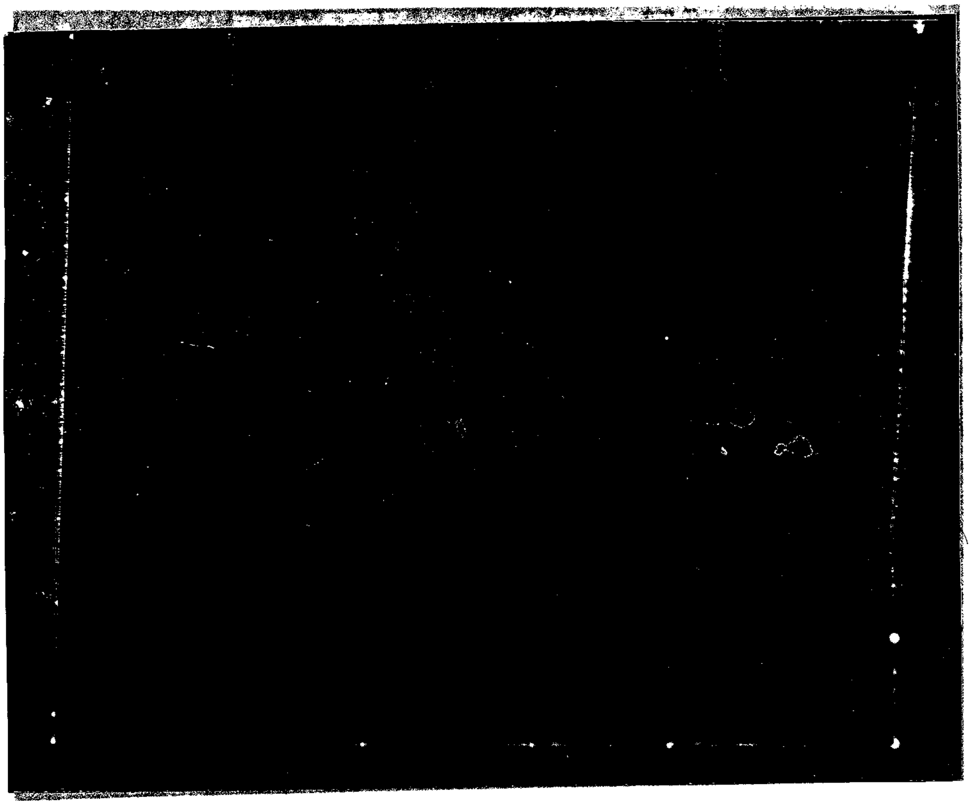


Figure Eleven

This photograph is of aquadag painted between two squares of aluminum foil and sandwiched between two sheets of graphite paper.. In all cases, the areas of graphite produce the same discharge pattern, which is completely different from the pattern produced by the aluminum.

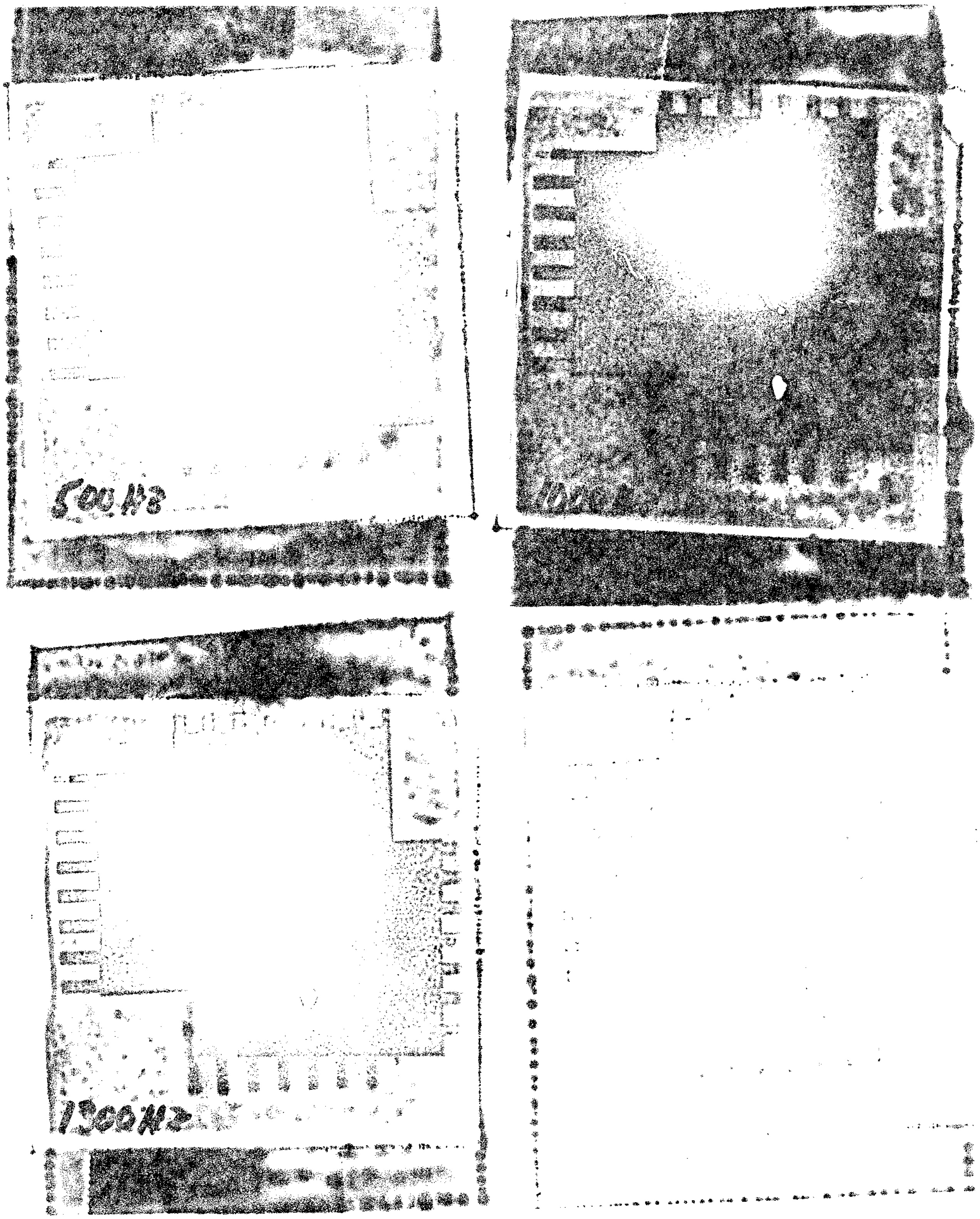


Figure Twelve

Negative prints of copper-bismuth deposits on mica, taken from side A so that the surface relief is not controled. A at 500 Hz, B at 1000 Hz, C at 1300 Hz, D at 1600 Hz.

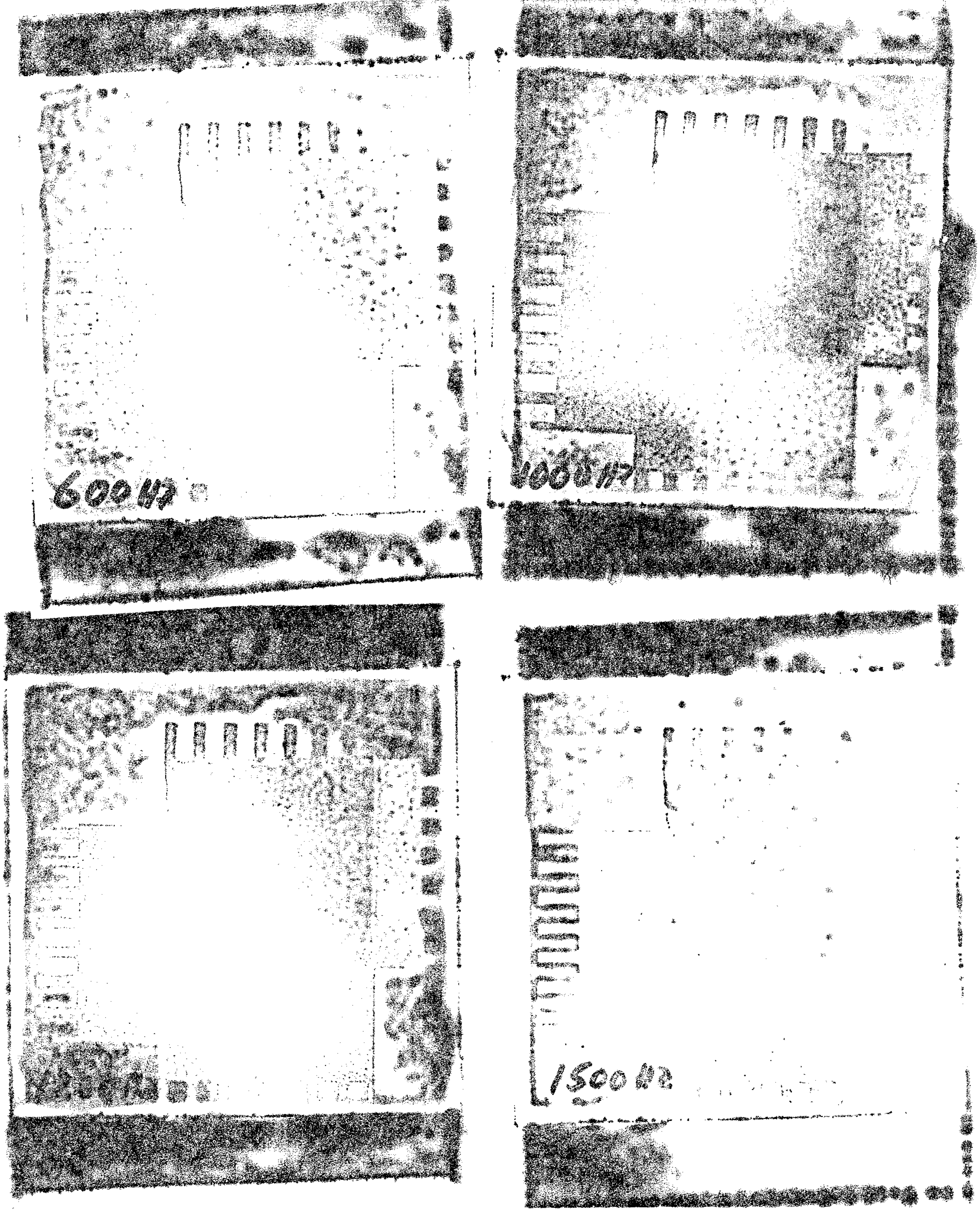


Figure Thirteen

Negative prints of copper-bismuth deposits on mica taken from side B so that the surface relief is controled. A at 600 Hz, B at 1000 Hz, C at 1200 Hz, D at 1500 Hz.

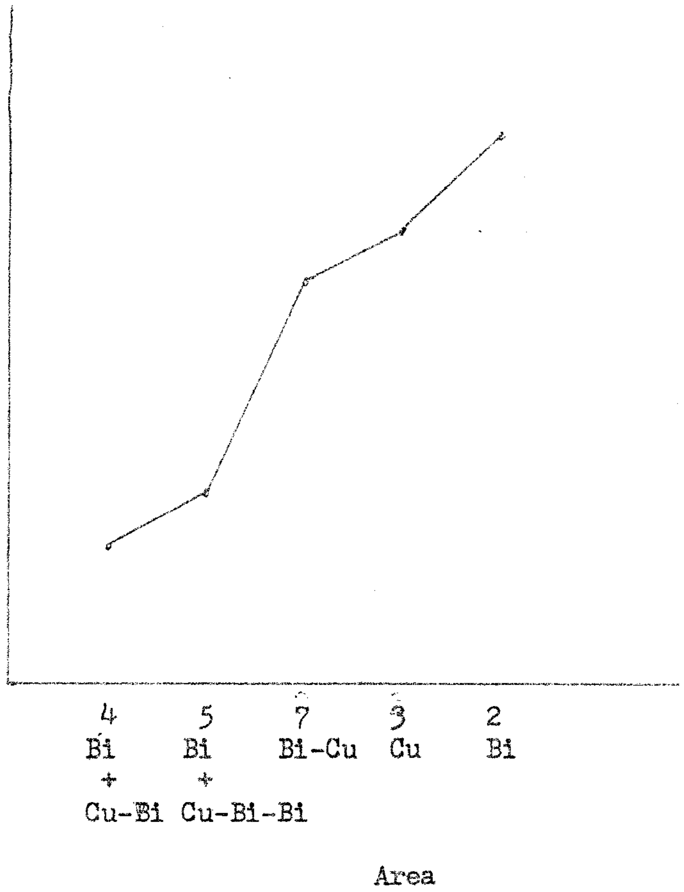


Figure fourteen

Graph of materials verses streamer density. Materials are shown in order from the mica surface. For example, area 7 is composed of a copper layer over bismuth on mica. Hence the bismuth layer has the greatest effect on the discharge. But due to diffusion the resistivity can vary widely in the areas and is unknown. The dramatic difference between areas 4 & 5 compared to 3 & 2 is due to the tilt of the mica plate, resulting in a smaller streamer density for 4 & 5. These results are highly ambigous, but areas with more Bismuth have higher discharge densities.

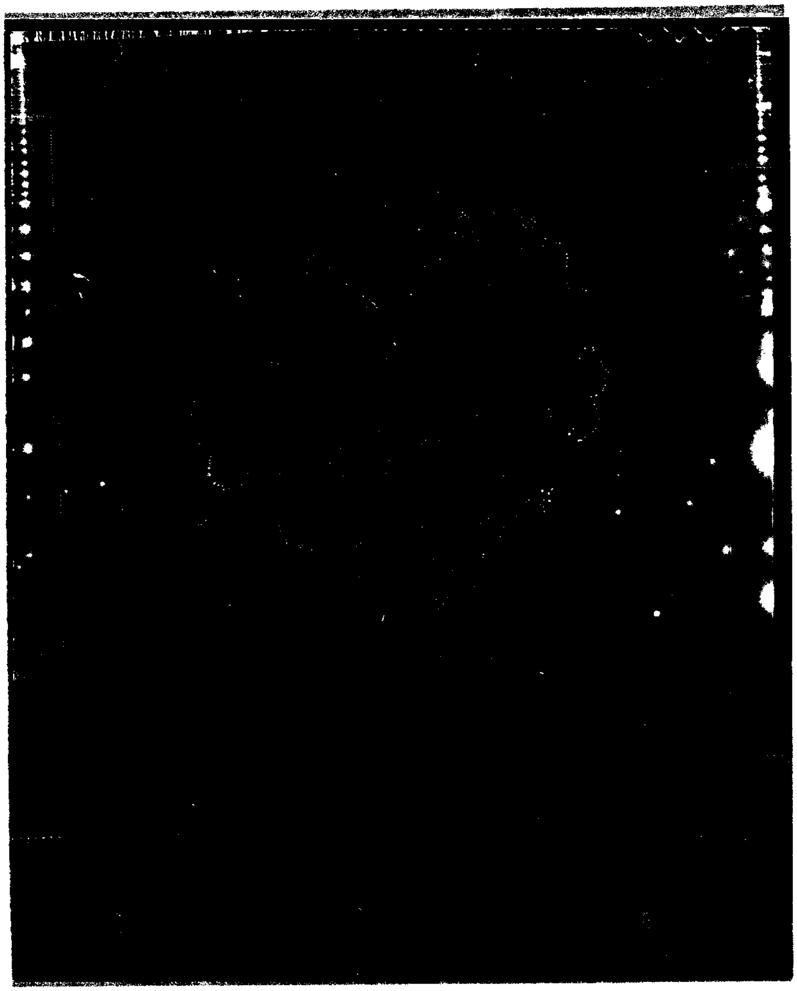


Figure Fifteen

High-voltage photograph of a leaf, illustrating several parameters affecting the discharge pattern produced.

FOOTNOTES

[1] William A. Tiller, *Kirlian Photography: Its Scientific Foundations and Future Potentials*. (William A. Tiller, 1975), pp. 3-9.

[2] Ibid.

[3] Thelma Moss, *The Probability of the Impossible: Scientific Discoveries and Explorations in the Psychic World*. (Los Angeles,Ca.: J.P. Tarcher, Inc., 1974), pp. et passim.

[4] Tiller, pp. 3-9.

[5] Ibid.

[6] D.G. Boyers and W.A. Tiller. 1973. "Corona Discharge Photography" J. of Appl. Physics. 44(7): 3102-3112.

[7] Ibid.

[8] David E. Lord, *Electrical Discharge in Gases—A technique for detecting Metal anomalies*. (Livermore, California: University of California, June 6, 1979), pp. 3-6.

[9] David E. Lord and R.R. Petrini, *High-voltate photography applied to Non-destructive Testing*. (Livermore, California: Lawrence Livermore Laboratory, Oct. 8, 1975), p. 2.

[10] N.J. Nielsen and J.F. Shackelford, *Non Destructive Inspection of of Surface Topography by Electrical Discharge Imaging* (Davis, Calif.: College of Engineering, Uni. of Calif. at Davis, to be published in Inter. Advances in nondestructive testing, vol. 8), p. 12.

[11] Lord and Petrini, p. 3.

[12] Ibid, p. 5.

[13] Ibid, p. 2.

[14] Nielsen and shackelford, p. 12.

[15] Niels Jacob Nielsen, Electrical Discharge Imaging. Thesis for Master of Science. (Davis, Caliv.: Univ. of Calif. at Davis, 1978), p. 35.

[16] Boyers and Tiller. p. 3108.