Materials and Methods

Numerous devices and techniques for discharge production and observation were tried before a suitably repeatable method was developed. This last apparatus was the only one which produced quantifiable results. Its development is best traced by a brief description of each of the earlier devices, along with representative examples of the results they produced. These results are of value in illustrating some of the general characteristics of electrical discharge photography.

1. The Remote Camera Method

In this earliest system, the upper (supply) electrode was a sheet of glass with a transparent conductive coating of tin oxide applied to one surface. A thin sheet of clear mylar was used to insulate the tin oxide surface from the adjacent test sample, which, for illustration, was a silver dollar (figure 6).

A view camera loaded with Polaroid film was positioned over the test assembly. When power was applied to the system, a blue-white discharge appeared on the surface of the coin. This discharge was visible to the unaided eye in a darkened room through the transparent supply electrode and was photographed by the overhead camera. This is shown in figure 6, along with a schematic of the system used to produce it. The power source was a Macintosh MC350 power amplifier driving an ordinary twelve volt automobile ignition coil which was connected to the electrode assembly. One thousand hertz square waves were fed to the Macintosh input from a Hewlett-Packard 3310A signal generator. Neither the air gap spacing between the coin and the mylar sheet insulator nor the magnitude of the applied voltage was known. Purity of the output signal from the transformer was not monitored.

To make an exposure, the lab lights were turned off, and the Macintosh and signal source turned on. The Macintosh gain control was then advanced until the onset of visible ignition was observed. Then, the shutter on the overhead camera was opened and a time exposure of several seconds' duration made. At the end of the exposure, the system was shut off and the room lights restored. The film was then removed from the camera and developed. Intense amounts of ozone were produced when this system was operating, and poor impedance matching between the Macintosh and the ignition coil frequently caused the Macintosh to overload and trip its circuit breaker. Occasionally, the mylar insulation would burn through, causing the glow discharge between the mylar and the sample to degenerate into an arc between the sample and the tin oxide/glass electrode. This would destroy the electrode, disfigure the sample and overload the ignition coil and the Macintosh. Ignition coils would repeatedly fail under load. Despite these flaws, the system demonstrated the production of an alternating current discharge in the small air gap separating two high voltage electrodes.

2. Early Direct (Contact Mode) Camera-less Method

For these tests, the mylar sheet was replaced with a piece of Kodak Kodalith Ortho Type #3 (#2556) copy film, A.S.A. 16. Thickness of this film was not known. The transparent electrode was replaced with a simple flat metal plate which held the film, emulsion-side down, against the test sample. No overhead camera was used. The sample was a 1/4" thick plate of 1000-series aluminum which had a thermal quench crack running across it. Again, an automobile ignition coil was used to drive the system, but this time the coil was fed from a small 50 watt Bogen CHS50 public address amplifier. It performed adequately even though it had only one-eighth the power output capability of the Macintosh. By using less power, arcing-over and ozone generation were almost completely eliminated. This move to lower power was made possible because of the superior sensitivity of this "direct contact mode" system. One thousand Hz sine waves from an H-P 3310A signal generator served as the signal source for the Bogen. Figure 7 shows a schematic of the system, along with a sample exposure.

To make an exposure, the lab lights were turned off. In total darkness, a piece of the Kodak film was inserted between the supply plate and the sample. Then, the amplifier -- previously adjusted to adequate output -- was turned on for several seconds. (The signal generator was permitted to run continuously, whether or not the Bogen was on.) The film was then directly exposed by the discharges in the gap between the film itself (which served as the insulating dielectric in these tests) and the sample surface. At the end of the exposure, the Bogen was shut off and the film extracted from the device. It was stored away safely for subsequent development. Then, the room lights were turned back on.

During these tests, ignition coil output voltages were estimated by connecting an oscilloscope across the high voltage coil terminal and ground. This oscilloscope was good only for estimation purposes because of its age and condition, but was an inexpensive step in the right direction. An exposure of 8 seconds' duration made at about 800 volts (peak) is given in figure 7. In this figure, the film was returned to its original position against the sample surface after processing. Dark areas on the otherwise transparent negative are regions where breakdown and ignition occurred in the air gap. This air gap between the sample and the film was produced by the simple use of Scotch tape applied to the ends of the sample. Hence, an air gap of two tape thicknesses was produced but not measured. At the time of these tests, the Paschen dependence of ignition onset had not been realized, so air gap thicknesses were not recorded.

Despite the simple experimental setup, I was able to locate a tiny crack in the aluminum sample which had escaped my previous inspection. A positive print enlargement of the film negative in the region of this crack is given in figure 8. Comparison photos of the crack, made by light and scanning electron microscopy, are also included in figure 8. A "zyglo" dye penetrant crack detection test was then performed on the sample, which also confirmed the location of the crack. This demonstrated that electrical discharge imaging could indeed be used as a crack detection tool. Although edge-enhanced corona ignition had occurred at the edges of the crack, Townsend breakdown had also occured in planar regions between the sample and the film where the Paschen criterion was met. Hence, the test could also be used to map out warpage or other small deviations from perfect flatness. Fine surface texture was also resolved by the test. Polishing scratches which are obvious in the conventional light microscope shots in figure 8 show clearly in the discharge image as well.

Similar tests were run using Kodak Kodacolor II #620 color print film instead of the Kodalith sheet film, but no real advantage was gained. Observation of the discharge image negative under a conventional light microscope revealed that the color film did not have better resolution than the Kodalith. Several beautiful color prints were prepared from the negative, however, displaying the characteristic intense blue color of the discharge. These prints, while dramatic, are not included here because they cannot be photostatically copied.

3. Vacuum Chamber/Remote Camera Method

Lord and Petrini had assembled a plexiglas vacuum chamber to contain their sample and electrode assembly so that tests could be made at reduced pressure and in controlled atmospheres, if desired. When I visited their lab in 1976 to observe this device, they explained how the reduction in pressure permitted an increase in the gap width to the point where several centimeters separated the electrode and the sample under test. This would permit visible electrical discharge to be generated all across the surfaces of a non-planar test sample. No quantification of the effect of pressure on gap width required to cause ignition at fixed voltage was offered by Lord and Petrini at the time.

A schematic of a similar system constructed in our laboratory along with one of the only photographs to be prepared by this method is shown in figure 9. A partial vacuum was maintained in the chamber so that an external camera could photograph the process. The test sample was the same cracked aluminum block as before, and the crack is in evidence in the photograph. The power source and test procedure were the same as those previously described under heading #2, with the addition of the vacuum apparatus to the system. The gap between the transparent mylar dielectric and the sample was doubled, as permitted by the lowered pressure. Since fine detail wasn't resolved by the test, and since this apparatus was difficult to manage, it was not used further.

4. Refined Direct-Contact Apparatus

This apparatus was similar to that used in the early direct mode tests. However, several changes were made. A Hewlett-Packard Model 200 CDR sine wave generator was used to produce 1000 hertz sine waves which were amplified by the Bogen as before. The ignition coil was discarded and replaced by an Altec Lansing (Peerless #16309) audio output transformer. The output (secondary) taps on the transformer were connected to the Bogen output and the plate (primary) taps on the transformer were connected across the specimen/film/supply plate capacitor. This transformer, used here in reverse, stepped up the Bogen's output voltage by better than a factor of ten. Output voltages of better than 800 volts R.M.S. were attainable with the Bogen operating at the onset of clipping. Polaroid Type 57 high speed (A.S.A. 3000) 4x5 sheet film was used instead of the Kodak film because of its higher sensitivity and convenient instant processing. The metal film holder used with the Polaroid sheets served as the return electrode in the high voltage circuit. A schematic of this system is given in figure 10.

The system was controlled by two switches. One was a safety interlock microswitch for interrupting the line from the Bogen to the step-up transformer. It was tripped by raising the clear plastic lid covering the high voltage circuitry. The other, an A.T.C. "Tankard" programmable timer, connected the output of the sine wave generator to the input of the Bogen for a duration which was set in advance by means of push-buttons on the timer's front panel.

To perform a test, the H.P. and the Bogen were turned on and allowed to warm up. After turning off the laboratory light, the Polaroid film was revealed by pulling the film's protective cover out of the film holder. The sample to be tested was then clipped to one high voltage lead of the transformer, the other lead of which was then clipped directly onto the film holder. The sample was then laid face-down in direct contact with the film emulsion. The exposure was made either by manually keying the safety interlock switch and counting seconds, or by punching the A.T.C.'s cycle start switch. In this case, timing and shutoff of the exposure cycle were automatic. After then removing the test specimen at the end of the exposure and replacing the film's light-tight envelope, the laboratory room lights were turned on again and the film developed in the normal manner.

Typical test conditions were about 500 volts R.M.S. (adjustable from 0 to 800 volts R.M.S. by means of the master gain control on the Bogen), 1000 hertz driving frequency (controlled by adjustment of the sine wave generator), and a power-on exposure time (or "pulse width") of one second. A Fluke 8600A digital multimeter was used to monitor the system R.M.S. voltage as shown in the schematic, and a squirrel-cage blower was used to scavenge any ozone produced by electrical discharges in the safety box. The scavenging system, which drew air from inside the box over a wad of damp steel wool, was never put in service because ozone production was not noticeable at the low power levels used in the later tests. It is not shown in the schematics. The Polaroid print obtained in this fashion is a full-size, left-for-right reversed photographic map of the ionization events which happened at the surface of the sample, when the high voltage was applied.

Figure 11 is a representative shot made at 625 volts R.M.S., 1000 hertz, 10 second exposure time, of a flat aluminum fracture toughness specimen. A normal light photograph of this object is included for reference. Ignition occurred where sharp edges were present and where there were air gaps between the sample and the film. At these regions, the air broke down and became electrically conductive, and the light which was given off as a byproduct of the process then exposed the film locally. Electrical discharge events were conveniently monitored under much more closely controlled test conditions than had previously been attainable.

This new system was not without faults, however. Compare the two photos in figure 12. While all test parameters were identical, figure 12a was timed by manually keying the safety interlock while the Bogen was running. On the other hand, figure 12b was timed by turning on and off the Bogen's main power switch with the interlock shorted. Results identical to those in figure 12a were obtained by keying the system with the A.T.C. automatic timer. Storage scope observations of these two turn on modes are given in figures 13a and b. Figure 13a clearly illustrates distortion of the 1000 hertz waveform by the switch. This distortion was transient and stopped about 0.0025 second after the timing cycle started. Figure 13b is a smeared-out indication of the Bogen's output voltage versus time as the Bogen comes up to full output after being turned on. The sine waves have overlapped to form a continuous exposure because the oscilloscope sweep rate was very slow. But, a slow exponential voltage amplitude buildup to a steady state value can be seen. Time to steady state in this case was about 0.06 second. Since the amplitude of the "dirty" signal produced by the A.T.C. (or the safety interlock) switch was not remarkably different from that of the steady state sine wave, a frequency effect on ignition threshold was suspected. The irregular blotches of ignition in the so-called "sharp turn-on" (i.e., automatically timed or safety interlock-keyed) exposures were set in operation by the transients. I originally believed that the high frequency noise component of the switching transients was the cause of enhanced ignition in small gaps, but later tests with spectrally pure sine wave pulses actually showed the opposite to be true. This effect will be more thoroughly discussed later.

The test surface of the sample had been previously polished to mirror-like smoothness, so the graininess of the transient ignition is actually an artifact revealing the microscopic bumpiness of the

Polaroid film's emulsion surface. The crack imaged by the transient, however, is no artifact. It is plainly visible extending away from the radiused notch cut into the sample. The bright area at the tip of the crack is a dimpled-down, concave region of plastic strain where a large air gap existed between the otherwise flat sample surface and the Polaroid film. No two exposures in this series were exactly the same, due to the variable nature of the "dirty" switching action. Attempts to "clean" the A.T.C.'s mechanically actuated microswitches (to eliminate contact bounce and other switching transients) were unsuccessful. Figure 14 is probably a double exposure since it contains two degrees of gray-scale plus an edge discharge. Contact bounce upon switch closure most likely modulated the 5000 hertz signal into several discrete bursts of different duration and freqency content, causing ignition in different regions.

Small, polished metal discs, which were slightly dished (concave) by residual stresses, were the next test specimens tried. It was found that this test could be used to qualitatively map their concavity. Results are given in figure 15. Next to each discharge photograph is an interferometer exposure of the same sample for comparison purposes. The presence of one or two interference fringes indicates deviations from flatness of not more than one or two μm.

At this stage, nothing could be done about the dirty signal produced by the A.T.C., but work progressed nonetheless on trying to accurately determine the dependence of ignition onset on air gap thickness. To do this, an aluminum specimen was machined which contained a tapered groove. This groove varied linearly in depth from 0 to 10 mils along the sample's length. A sketch of this sample is given in figure 16. Also included is a photograph of the sample -- tipped over on its side, so as to reveal the groove -- resting atop a piece of Polaroid film in the film holder. Figure 17 shows the sample resting in position atop a dummy sheet of film, with the film cover pulled out to the left of the film holder. The clip lead from the transformer has been attached, as has a small chunk of stainless steel, used to help weight down the sample against the emulsion. For reference, another photograph is included which shows the film holder inside the insulating safety box. The transparent lid has been removed and is resting to the left of the box. The transformer can be seen inside the box. (In this picture, the test sample has not yet been connected.)

Under test, the ignition onset was expected to follow the Paschen dependence and start near the shallow end of the groove at lower applied voltages and then extend further out into deeper portions of the groove as the voltage was increased. Figure 18 contains two discharge images in this test series which were both shot at about 675 volts R.M.S. with different exposure times; the interesting thing about these shots was the obvious texturing of the film emulsion. Note that while the angle of the "slant block" (as this test specimen was called) with the film edge varies, the texturing direction does not. This film texture effect serves as a source of caution about misinterpreting such experimental artifacts as hidden test specimen features.

The 664 volt R.M.S. exposure shows ignition in the shallow end of the groove, as anticipated. The groove can be seen extending from the left-hand edge of the slant block across the surface to the point where the groove ignition was extinguished. At that point, the air gap is almost zero, leaving the sample separated from the film holder only by the 4 mil thickness of the Polaroid film. Despite the sharp, as-milled edges of the groove walls, the groove's width limits seem fuzzy and indistinct in places. This is due to ignition which occurred at the groove wall edges because of their sharpness, another illustration of corona production at a surface discontinuity. Note that the light created by this edge ignition left the edge and travelled away from it, only to strike the film obliquely at points distant from the original location of the ignition. Hence, some detailing was lost by this "edge illumination" effect. Any light produced in this manner might also illuminate the metal sample's surface, causing portions of the metal to appear as ignition sites even when they actually were not. This effect is shown in figure 19, which presents a discharge image of a different sample, and a separate sketch of the sample. The discharge image was shot at 600 volts R.M.S., 1000 hertz for 0.10 second. It shows how edge illumination clearly illuminated the air gap all the way around both shallow rings. This light either left the edge to strike the film distant from the edge, or bounced off the shiny machined surface of the circular groove to then strike the film, hence making it appear that non-igniting portions of the groove actually were igniting. This technique was used by Lord and Petrini[12] to illustrate the gap width dependence of ignition brightness. Unfortunately, the resulting data may be distorted by this artifact.

5. Final Direct Contact Apparatus

The problem of signal purity was solved by discarding the electromechanical A.T.C. timer in favor of an all-electronic switching system. A block diagram of the system is given in figure 20. Figure 21 is a photograph of the actual system. To produce a single pulse of sine waves, the sweep reset arming button on the Tektronix #394 scope is punched. This initiates a single-shot horizontal sweep of the scope trace and causes the "+ gate out" terminal on the scope to go from ground potential to +30 volts (open circuit). An in-line voltage divider reduces this to approximately +2 volts which can be fed to the external trigger input of the Hewlett-Packard #3312A signal generator. When the signal generator senses this voltage at its trigger input, it turns on its main sine wave oscillator and begins feeding sine waves to the Bogen for amplification. When the Tektronix has completed its single shot sweep, its "+ gate out" terminal returns to zero volts. This in turn shuts off the signal generator and the cycle is complete. The horizontal sweep circuitry of the Tektronix scope is used as a timing switch to turn on and off the sine wave generator noiselessly. Storage scope traces of a pair of representative pulses obtained in this manner are included in figure 21. These pulses are free of transients or other switching noise. The width of the pulse produced is varied by adjusting the sweep time of the oscilloscope. Milliseond pulses can be produced just as easily and as accurately as pulses of several seconds' duration.

Experimental difficulty was still experienced with this most refined system due to the dirty safety interlock switch and initiatory time lags (see theory section). The first problem was solved by permanently shorting the switch. The second only became a problem because the new, cleaner signal control permitted millisecond range exposure times. It was solved by longer exposure times (greater pulse widths) which minimized exposure variations due to the random time lag effect as explained in the theory section. One second exposure times were found to be adequate in this respect. Solution of these two final problems allowed reproducible, quantitative results to be obtained.

Results

The slant block of figure 16 was used to obtain the relationship between applied voltage and air gap size (necessary to produce visible light emission due to Townsend breakdown). Figure 22 shows three typical discharge images, shot at various applied voltages. The extent of ignition in the gap was measured with a straight edge scale. Earlier measurements made with a scanning densitometer indicated that the extent of ignition was sharply defined and that the simple scale measurement was equally accurate. Knowing the slope of the slant block, the position corresponding to the spot in the gap where ignition stopped yielded a gap distance for a particular ignition event. The corresponding AC R.M.S. voltage was noted, and converted if necessary for comparison purposes, to peak voltage by multiplying by 1.414. The resulting graph of ignition onset voltage versus gap width is shown in figure 23. It should be noted that the data represent the "border line" between visible light emission and no emission as shown in the earlier Paschen plot of figure 3. A few anomalously low data points are not shown as they can be readily ascribed to "shorts" in the system such as dust particles bridging the gap.[6] Similarly, a few anomalously high data points are not included as they can be ascribed to an absence of environmental ultraviolet light, causing a shortage of exoelectron-generated ion pairs in the gap. Scatter in electrical breakdown experiments is commonly reduced by ultraviolet illumination,[5] but this was impossible in the current work due to the presence of photographic film. Therefore, some anomalous data was unavoidable.

Despite this, the general trend of data was clearly defined and is summarized in figure 23.

Discussion

The data shown in figure 23 cannot be compared directly with Paschen curves for air, because of the effect that the Polaroid film has upon the geometry and electrical characteristics of the gap. However, Halleck[13] offers a simple adjustment to Paschen's law which allows accurate prediction of breakdown in gaps which are partially filled with insulating material. His correction takes into account both the thickness and the dielectric constant of the insulating material residing in the gap. Imagine an air gap t mils wide between two flat plate electrodes. Now, insert a sheet of insulating material t_d mils thick, where $t_d \leq t$, into the gap and in close contact with one of the electrodes. The remaining air gap is called t_a, where $t_a + t_d = t$. Define a parameter "β" such that $\beta = t_d/\epsilon_d$, where ϵ_d is the relative dielectric constant of the insulating material. If V_s is the Paschen-predicted Townsend breakdown potential in air of a gap t_a mils wide, then the breakdown potential of the gap containing t_d mils of dielectric and t_a mils of air is $V' = V_s(1 + \beta/t_a)$. One can map out a family of pseudopaschen curves for various values of the parameter β. This has been done in figure 24. For the case of $\beta = 0$, the curves reduce to the classical Paschen curve.

One can also plot the voltage minima in the adjusted Paschen curves versus β. Such a plot is given in figure 25. The data points are from Halleck's experiments. The solid line is from his theory. In my experiments, the minimum breakdown ("corona starting") voltage was at 410 volts R.M.S. (at 60 hertz). Consulting figure 25, this corresponds to a β value for Polaroid type 57 film of about 0.5. One can also plot the air gap widths corresponding to the voltage minima in the adjusted Paschen curves. This is offered in figure 26. Again, data points are from Halleck's experiments and the solid line from his theoretical derivation. In this figure, a β value of 0.5 corresponds to a minimum air gap width of about 1.2 mils, in excellent agreement with the observed value in the previous 410 volt R.M.S. 60 hertz experiment of 1.14 mils. We can conclude that the value of β for Polaroid film probably is quite close to 0.5, and that my experimental results are in good agreement with this literature. Figure 27 is a plot of my data superimposed on a plot of Halleck's modified Paschen curves for β=0 (Paschen curve, no modification) and β=1. Most of the data lies between these two curves, but a variation of breakdown voltage with frequency is seen. Such behavior is not predicted by any theory dealing with Townsend breakdown at audio frequencies, but may be due to ϵ_d being not a constant but instead a function of frequency in this range.

We can solve for the dielectric constant of Polaroid film at 60 hertz with the aid of the Halleck plots and some knowledge of the structure of Polaroid film. A sheet of type 57 is 4 mils thick, about 1/3 of which is a layer of conductive anti-static paint applied to the back surface. This portion of the film is not an active dielectric. The remaining 2.66 mils are dielectric. If β=0.5 and t_d=2.66, then $\epsilon_d \cong 5.2$. This is in agreement with data on other types of film tested by Halleck at 60 hertz.[13]

In my experiments, ignition at the sharp edges of the slant block always happened at lower voltages than those required to cause

Townsend breakdown in the groove of the slant block. As previously mentioned in the theory section, this is qualitatively expected due to the field asymmetry at the edges. Halleck plotted corona starting voltages versus electrode sharpness for different values of β. The results of his tests in this area appear in figure 28 and indicate a starting voltage depression due to sharp edges of perhaps 10% for low-β materials. In my experiments, a similar drop of 10-12% was typical.

Conclusions

My experiments have shown that the behavior of a Kirlian electrophotography device can be predicted with a modified Paschen curve model of Townsend breakdown. This correlation, substantiated by agreement with the literature, permits the use of electrical discharge photography as an engineering nondestructive test for surface flatness. These experiments also demonstrated the test's ability to locate cracks, based on corona enhancement in asymmetric fields.

An anomalous frequency dependence of breakdown voltage was observed, which may have been caused by variations in the Polaroid film's dielectric constant with frequency. However, data from the 60 hertz test were consistent with the literature and permitted a reasonable estimate of the dielectric constant of Polaroid film to be made (ϵ_d=5.2 @ 60 hertz).