MULTICHANNEL SURFACE DISCHARGE SWITCH

by

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ABSTRACT

A system designed to investigate the performance of dielectrics in a multichannel surface discharge switch was built and tested. The apparatus consisted of a constant current charging supply that produced 10 mA at 50 kV, a storage capacitor, a 6-ohm stripline, the surface switch, a matched 6-ohm copper sulfate water load, and diagnostics. Diagnostics to evaluate the dielectric performance included capacitive voltage probes in the stripline, a video camera to record multichannel events on videocassettes, and an optically isolated counter to record the number of events in a test run. Typical operating parameters were: 180 joules per pulse, a peak voltage of 40-50 kV, and a peak current of 7 kA. Dielectric samples were tested by placing them in the switch for 10,000 shots at a repetition rate of 1-1.2 pulses per second. The dielectrics were then compared by observing their erosion, changes in breakdown voltage, and the number of channels that occur during discharges. Further analysis to study possible chemical change in the surfaces of three of the dielectrics was performed using Electron Spectroscopy for Chemical Analysis (ESCA).

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CHAPTER I

INTRODUCTION

A surface discharge switch conducting the same current as many switches in parallel has a very low impedance and avoids the complications of simultaneous triggering of parallel switches. The surface switch owes its unusually low impedance to the geometry of the arc paths. Designed as a section of a parallel planar transmission line, the switch provides minimum impedance change in the current path. This technique can also be applied to a coaxial line if the switch dielectric is available in the form of a cylinder.

This idea is not without drawbacks. Although the surface switch operates much like a conventional, gas-filled spark gap, the added parameter of a dielectric substrate confronts the designer with an even more difficult choice of material combinations with which to construct the switch. A great deal of research is presently being done in the field of spark gaps and several promising combinations of gas and electrode materials have been investigated [1,2]. The material choices in surface switching, however, are less certain. Several investigators have designed systems to

evaluate the performance of dielectrics in a surface switch [3,4], but few have addressed the issue of finding a combination of dielectric, gas, and electrode material that will provide a surface switch with characteristics such as high hold-off voltage, low impedance, low jitter, long life, and short recovery time.

This report describes the first two of a series of experiments designed to determine which combinations of materials will enable the designer to construct a reliable surface discharge switch. The experiments involved the design and construction of a system that allowed the experimenter to interchange dielectrics easily so that each dielectric sample could be tested under identical conditions. The first experiment used a multichannel test switch and the second used a single channel test switch. In each experiment, the dielectric was compared to itself "before" and "after" exposure to many discharges in the test switch. Because the samples were tested under almost identical conditions, they could also be compared with each other. Parameters used to compare the dielectrics were: selfbreak voltage, number of discharge channels per unit length, and erosion of material.

The best candidates from the first two experiments can then be used in a third experiment that will investigate how different gases and electrode materials affect the operation of the switch. The third experiment will rely heavily on research done by other investigators in the field of gas-filled spark gaps.

This report describes the design and construction of the system used to perform the first two experiments described above. The second chapter describes the various system components including the charging system, transmission line, test switch, and water load. The third chapter details the diagnostics, including the low-inductance, capacitive voltage probes located in the stripline. The fourth chapter covers the operation of the system and the dielectric evaluation procedure. The fifth chapter describes the results of the two experiments and the method used to achieve multichanneling without triggering. Finally, three appendices are included. The first is chiefly for future reference: it describes the modifications and operation of the power supply. The second contains a description of how each type of dielectric was prepared for operation in the switch. The third is an example of a SPICE [5] computer analysis program used to evaluate the capacitive voltage probes.

CHAPTER II

EXPERIMENTAL ARRANGEMENT

Desired System Parameters

A surface discharge switch introduces a minimum of additional inductance into the circuit when used in either a stripline or coaxial configuration. There are many low-impedance loads of interest in the field of pulsed power, such as magnetic flux generators, particle beam diodes, and X-ray generators. To transfer power efficiently it is always necessary that the system delivering the power has the same impedance as the load. Power efficiency then dictates that the power delivery system (storage device, switch, and pulse forming circuitry) also has a low characteristic impedance. To minimize the external or leakage fields which often result in a high noise environment and difficult diagnostic problems, and to achieve a low impedance, designers usually choose coaxial lines or parallel planar transmission lines (striplines) to conduct pulsed currents.

The impedance of a coaxial line or a stripline is a function of the dielectric material, and the physical

dimensions of the line. These relationships for the characteristic line impedance, Z_0 , are shown below [6]:

$$\text{coax: } Z_0 = \frac{1}{2\pi} \sqrt{\frac{\mu_0}{\epsilon}} \ln \left(\frac{b}{a} \right) \quad (2.1)$$

$$\text{stripline: } Z_0 = \sqrt{\frac{\mu_0}{\epsilon}} \cdot \frac{t}{w} \quad (2.2)$$

where the dimensions are given in Figure 1, μ_0 is the permeability of free space, and ϵ is the permittivity of the insulating dielectric.

Coaxial Line

Stripline

Figure 1: Transmission Lines

Because low impedance (5-10 ohm), high voltage, coaxial lines and striplines were not commercially available, a stripline configuration was chosen for several reasons: the line would be easier to construct; dielectrics were more readily available in sheet or plate form; and visual access to the gap would be assured. In a coaxial configuration it is usually better, for safety reasons and diagnostics connections, to ground the outer conductor. To avoid breaking the ground conductor with the switch gap, the surface switch would need to be placed as a gap in the inner conductor, inside the insulating dielectric. Since most dielectrics are not transparent, photography of the arc channels would be difficult. The dimensions of the line and gap were chosen so that the line impedance would be 10 ohms or less and so that the electrode width (corresponding to the line width) would be several times greater than the electrode separation. If the width is several times greater than the separation, the electric field between the electrodes will be uniform throughout the greater part of the gap region. Choosing the width to be at least 10 times the separation should meet the preceding criterion.

The dielectric strength of air is approximately 30 kV/cm [7]. The presence of the dielectric in the switch was expected to decrease the voltage that the switch would

be capable of holding off [8]. Even if the effect of the dielectric was weak compared to that observed by Larigaldie, et. al., the breakdown strength could be expected to be no greater than 20 kV/cm. Choosing to operate the system at 50 kV and overvolting the switch by 200 percent requires the gap separation to be at least 1-2 cm. To produce the uniform field in the gap region, as previously described, the width of the line and electrodes would need to be at least 20 cm.

Capacitor Bank and Transmission Line

The capacitor bank for the first two experiments was a single, 0.18 μF , 100 kV capacitor. The capacitor was designed to be connected to a stripline so it was readily adapted to the surface switch system. The stripline conductors were made of 1.27 cm (0.5 in) thick aluminum. The line insulator was cut from 0.635 cm (0.25 in) thick Blue Nylon (cast nylon). Although Blue Nylon has only average dielectric properties when compared to other plastics [9], it was chosen over the others, because it was easy to machine to the desired shape. The relative dielectric constant of Blue Nylon is 3.7 [9], giving a characteristic line impedance of 6.0 ohms. To minimize reflections on the stripline it was necessary to use a matched (i.e. $Z=Z_0$) load which dictated

that the load impedance also be 6 ohms. Hence, taking into account materials considerations, the dimension of the gap and stripline were derived. In summary, the line width was 20.32 cm (8.0 in), the dielectric thickness 0.635 cm (0.25 in), and the length of the line between the series switch and the surface switch electrode was 60.96 cm (24 in).

Surface Switch Design

The surface discharge switch used in the system was designed so that the electrodes and dielectric sample could both be changed easily. In order that the impedance change encountered by a pulse transmitted down the line was minimal, the overall dielectric thickness in the switch was made equal to the stripline insulator thickness. This was achieved by cutting a slot into the line insulator and replacing the line dielectric by whatever dielectric sample was being tested. The top and side views of the switch assembly are shown in Figures 2 and 3, respectively.

The upright structures shown in the side view of the switch were used to press the electrodes and stripline conductor together. At the high frequencies common in pulse situations, the skin depth of the conductor is only several tens of microns. If the electrode and stripline conductor were not pressed tightly together, arcing would occur at the

Figure 2: Surface Switch Assembly--Top View

Figure 3: Surface Switch Assembly--Side View

interface between the two conductors and the dielectric. The upright structures prevented arcing and allowed the electrodes to be replaced by any other electrode design that had the T-slot cut into the end so that the slot would receive the upright structure.

The shape of the electrode edge that touches the dielectric and initiates the arc channels, was an area of some concern. Electrode design in surface switches is usually a matter of construction convenience [4]. One expert opinion on the electrode design was to use any reasonable shape to start with since it might not affect the switch performance at all [10]. As shown in the side view of the switch assembly, the initial design was to cut the electrode edge at a 45 degree angle down to the dielectric. The electrodes were used for a total of over 90,000 shots without appreciable erosion and produced dense multichanneling as desired. The gap spacing between the electrodes was adjusted by positioning the load, as described in the section of this report which describes the water load.

The multichannel electrodes were made out of brass because brass is a common electrode material and is easily machined. Results from the first experiment, together with

research by other investigators [3], indicated that a higher peak current would be needed to damage most of the dielectrics significantly. To increase the channel current without incorporating larger power supplies or higher working voltages, a second electrode design used field enhancement to reduce the number of channels to a single channel. This increased the channel current by 20-30 times. The single channel electrodes were made of aluminum but had tips machined out of K-33 (a copper-tungsten composite material). Experience in gas-filled spark gaps indicated that brass might not be a satisfactory electrode material at the peak currents expected during single channeling (7-8 kA peak) [11] and the modest repetition rate used (1 pps). Top and side views of the single channel electrodes are shown in Figures 4 and 5, respectively. The K-33 electrode tips were held to the aluminum by a blind bolt extending from the aluminum base, so that the tips could be removed for refacing or replacement.

Initial tests with the single channel electrodes indicated that the corners of the electrodes caused significant field enhancement. This field enhancement eventually led to a breakdown, through the line insulator, at the edge of the sample slot. To avoid a recurrence of this fault, the sample slot arrangement was modified in the following

Figure 4: Top View of a Single Channel Electrode

Figure 5: Side View of a Single Channel Electrode

manner. Instead of milling a slot in the line insulator to receive the sample, slots were milled in the electrodes to receive a .0159 cm (1/16 inch) thick sample that was placed directly on top of the line insulator. This eliminated the weak point in the line insulator that resulted from the milling of the sample slot. The gap spacing for the single channel electrodes is fixed by the sample width. For the results cited in this report, the sample width was 3.89 cm (3.5 inches), setting the gap separation at 2.54 cm.

Series Railgap

The surface discharge switch depends on multichanneling to achieve low inductance and low erosion rates of the dielectric and electrode edges. To produce multichanneling across the switch dielectric the switch can be triggered [4,12] or simply overvolted [1]. That is, a fast

pulse with a voltage magnitude of 1.5 to 2.0 times the selfbreak voltage of the switch causes the surface to flash over with many distinct arc channels. This is easier to implement than a triggering system and should produce similar damage to the dielectric and electrodes. Charging the capacitor to a voltage greater than the surface switch breakdown voltage required an additional switch in series with the test switch. This switch was located physically between the capacitor and the stripline as diagramed in Figure 6. The switch was placed at a distance of 3 times the width of the line from the first series switch, so that the current density would become uniform across the width of the stripline conductors before it arrived at the surface switch.

Figure 6: Block Diagram of Surface Discharge Switch System

A pressurized rail gap was used for the additional series switch. By varying the pressure in the rail gap from zero to 30 psig the test voltage in the system could be varied from about 15 kV to 50 kV. The air flow through the rail gap was adjusted so that the air in the gap was exchanged one time each second (corresponding to one time per shot).

Low Impedance CuSO_4 Water Load

Two load designs were implemented in the surface discharge switch system. The first consisted of a matrix of 2-watt carbon composition resistors. The sixty resistors, arranged as 15 resistors in parallel, 4 rows in series, were capable of dissipating 120 watts continuously. The average power output of the system was increased to 250 watts when power supply modifications were completed. Doubling the power capacity of the matrix load was considered, but rejected for two reasons: 1) the assembly and alignment of the resistor holders for 120, 2-watt resistors would have been difficult; and 2) little information was available on the linearity of the resistors when operated in pulsed conditions with over 6 kV potential across each resistor.

A copper-sulfate water load could be made with the advantage that its power capacity could be increased if

future experiments called for higher power dissipation. The load design incorporated into the surface switch system is shown in Figure 7. The load actually consisted of two separate resistors, one above the line insulator and one below. The two-resistor configuration most closely approximated a matched line termination. The upper resistor could be moved along the length of the stripline so that the multichannel electrode gap could be varied from 1 to 4 cm. Each resistor was divided into two cavities as shown in Figure 7.

The copper sulfate solution was pumped from a storage tank, through the load, and back to the tank, as detailed in Figure 8. So that a potential difference would not occur between the storage tank and the load, the lines from the tank were designed to enter the load resistor through the grounded electrodes. A voltage between the tank and load would have resulted in two possible problems: first a safety hazard to personnel that might come into contact with the cooling system; and second, a current flow caused by the potential difference would have caused the cooling lines to radiate electrical noise that might have interfered with the diagnostics.

Figure 7: Top and Side Views of Upper and Lower Water Loads

Figure 8: Flow Pattern Through Upper and Lower Water Loads

The flow rate could be varied to control the temperature increase of the solution as it passed through the load. The amount of solution in the tank could be varied to control the temperature increase in the storage tank during a test run. Table 1 lists typical load parameters during a test run. As shown, neglecting any heat loss from the lines, load, or polyethylene tank, the temperature rise during a typical 10,000 shot test run was only 10.7 degrees Celsius.

TABLE 1

Typical Solution Parameters for the CuSO_4 Water Load

Total Resistor Volume	215 ml
Total Tank Volume	50 l
Flow Rate	40 ml/sec
Power In	250 watts
Typical Test Run	10,000 shots (2.5 hours)
Temperature Rise of Solution As It Passes Through the Resistor Body	1.5° C
Temperature Rise of Solution In Tank During a Test Run (assuming no heat loss from the system)	10.7° C

The resistance of a copper sulfate solution will decrease by about 10 percent of its unstressed value at fields of 18 kV/cm [13]. The electrodes were separated so that the peak electric field during a 50 kV pulse would be about 5.6 kV/cm, so that the resistivity of the solution would be nearly constant during the entire pulse. The width of the cavity was chosen to be the same as the width of the line and the thickness was 1.27 cm (1/2 inch). The volume, cross sectional area, and total resistance then determined the necessary resistivity of the solution. To avoid saturating

the solution, sulfuric acid was added to further lower the resistivity. Solutions of 40 gm of copper sulfate per liter of water can be brought down to resistivities of less than 30 ohm-cm by adding sulfuric acid [13]. The resistance of the solution was measured by applying 120 volts ac at 60 Hz across the load and measuring the current with an ac ammeter. The resistance was calculated from Ohm's law, the rms voltage, and rms current. Measuring the resistance with an ohmmeter is not feasible, because at stresses of less than 10 V/cm, the solution shows a marked increase in resistance, presumably due to plating of the electrodes [13,14].

The final solution was approximately 10 % by volume concentration of sulphuric acid. Materials used to resist corrosion by the acid were: Lucite in the resistor body; Viton O-rings for seals at the electrode; nylon tube fittings; polyethylene tubes and tank; and PVC valves on the tank. Damage due to the acid occurred only on the nylon fittings on the resistor body. The nylon developed crumbled areas that washed out after several months of operation. Teflon fittings would be more resistant to the acid and are available as direct replacements from Swagelok [15].

According to Bishop and Edmonds [13], the only metal that can be placed in a copper sulfate solution is copper.

While awaiting delivery of suitable copper stock, a set of brass electrodes were tried in the load. They functioned well for about 20-30,000 shots. At that time, each electrode began to fall apart as if they had been made out of clay. Finally a set of copper electrodes were installed and have been used successfully for over 60,000 shots before significant erosion occurred. After about 20,000 shots, the surface of the copper appeared to have been covered with tiny crystals. This is probably due either to incomplete plating under high current, pulsed conditions, or a chemical reaction involving the electrodes and the sulphuric acid.

The erosion of the copper electrodes appeared to be more directly related to time of exposure to the solution than to the number of test shots. After 20,000 shots, fine machining marks were still visible on the copper electrode surfaces. During periods of "system-down" time, the electrodes eroded noticeably even though no electrical power was being dissipated by the load.

Charge and Dump System

A 60 kV, 10 mA power supply was allocated for use in the surface discharge investigation. To charge the capacitor as quickly and efficiently as possible without exceeding the 10 mA maximum current rating, it was necessary to

operate the power supply in a constant-current configuration [16]. A simple LC network that achieves constant current charging is described in the literature [17,18]. The network which is placed on the primary of the high voltage power supply is shown in Figure 9. Several calculations and attempts were made to implement an LC network that would limit the output current to 10 mA without using the autotransformer. Finally the autotransformer was added and determined to be the single most important component. A slight change (10-20% of line voltage) would increase or decrease the output current by a factor of two. Careful analysis of the LC network showed that although the output is nearly a constant current, the output current actually varies slightly as a function of the voltage across the capacitor that is being charged. To achieve any designed-for output current, it is necessary to use an input voltage control device, and adjust it until the desired output current is reached.

Another conclusion based on the more detailed analysis of the charging circuit is that a resistor is needed in series with the capacitor that is being charged. This resistor limits the initial current when charging a capacitor and protects the power supply from large, reverse, current surges. The value of the resistor, 1000 ohms, was chosen so

Figure 9: Constant Current Charging Network

that during normal operation the resistor did not decrease the output voltage by an appreciable amount. If a fault occurred in the power supply, the resistor would limit the fault current to 50 amps if the bank capacitor was charged to the maximum test voltage (50 kV). While the power supply was charging at 10 mA, the voltage drop would only be 10 volts--a small fraction of 50 kV.

The dump system consisted of an 8000 ohm dump resistor and a high voltage dump relay. When the relay closed, the capacitor voltage was almost completely discharged in four time constants or $4RC$. The dump relay closed in 80 ms and $4RC=1.4$ ms, assuring that the voltage level would be safe less than 0.1 second after any signal to drop the dump relay. The dump relay, originally rated at 20 kV, was

immersed in an oil tank to increase its working voltage to at least 50 kV. The dump system was designed to discharge the storage capacitor any time the power supply was turned off, or the primary power to the supply was interrupted. The power supply dump and interlock relay logic is described in more detail in Appendix A.

SPICE Computer Simulation

The surface discharge switch system is shown in Figure 10. Although the stripline inductance was very small, the placement of the railgap and water load increased the system inductance significantly. Following is a calculation of the approximate inductance of the railgap, the coupler between the capacitor and railgap, and the water load. A computer analysis program, SPICE [5], was implemented to analyze the circuit model and the results were compared to measurements during the system testing.

The series railgap was not triggered during the first two experiments. Allowing the railgap to selfbreak permitted only one arc channel to occur in the railgap. The arc through the railgap occurred 4.5 cm above the surface of the line insulator, approximating a line above a plane, as shown in Figure 11. Using the length of the line, 7.0 cm, and assuming the arc diameter was about 1.0 mm, the inductance of the railgap was approximated as [19]:

Figure 10: Surface Discharge Switch System

$$L = \frac{\mu \cosh^{-1} \left(\frac{s+a}{a} \right)}{2\pi} \text{ H/m,} \quad (2.3)$$

which gives

$$L = 75 \text{ nH.} \quad (2.4)$$

Figure 11: A Transmission Line Formed by a Line Above a Plane

The other inductances in the loop were approximated as portions of a stripline. The inductance per unit length of a stripline is given by [6]:

$$L/\text{meter} = \frac{\mu_o \cdot t}{w} \text{ Henrys.} \quad (2.5)$$

where t and w are the dimensions shown in Figure 1. The second inductance results from the connection of the capacitor to the railgap. Substituting the dimensions of the connection section ($t = 0.64$ cm, $w = 8$ cm, and $l = 18$ cm) into equation (2.5), yields an inductance of 20 nH. The final inductance occurs as a result of the copper sulfate water load. Approximating the current flow as the total current flowing through the midplane of the resistor body, allows the use of the stripline model of inductance for the water load. The thickness is equal to one line insulator thickness plus two times one-half of the thickness of a resistor body. The length was assumed to be the total length of the resistor body and hardware, and the width equal to the stripline conductor width. These dimensions ($t = 3.0$ cm, $w = 20.3$ cm, and $l = 11$ cm) resulted in a total inductance of 20 nH. The three inductances are listed in Table 2 and, as seen in the table, the total inductance including the internal inductance of the capacitor, is 135 nH.

Using these inductance approximations, the circuit was modeled as the simple one-loop RLC series circuit shown in Figure 12. The use of SPICE computer simulation made it possible to analyze the model with a variety of inductances. Figure 13 is a SPICE plot of the load voltage versus time

TABLE 2
System Inductances

Capacitor Bank	20 nH
Railgap	75
Connection Section	20
Water Load	20
TOTAL INDUCTANCE	135 nH

after the switch is closed, using the total estimated inductance from Table 2 (135 nH) as the value of L in the model.

Figure 12: System Model for SPICE Simulation

Figure 13: SPICE Plot of Load Voltage vs. Time

Figure 14 shows two oscilloscope photographs of the load voltage during a test shot. The surface switch was replaced by a brass conductor during the test shot, so that any inductance due to the surface switch arc channels was not included in the measurement. Note that the 10-90% risetime of the pulse in the SPICE simulation is about 40 ns and that the risetime of the pulse in Figure 14 is about 60 ns. The difference in predicted and observed risetimes suggested that the capacitive voltage probes did not have as fast a response time as they were originally thought to have.

Calibration tests performed on each stage of the capacitive probes indicated that the capacitive divider had a risetime of less than 8 ns. Careful impedance matching between the test pulser and the surface switch stripline would need to be implemented before the actual risetime of the capacitive divider could be measured, in place. The tests also showed that the resistive attenuator distorted the test pulse enough that the risetime of the resistive divider network could not be measured. The waveform of the output pulse exhibited ringing and a risetime that was much slower than the risetime of the test pulse. To measure the load voltage risetime accurately, and determine the actual system inductance, it would be necessary to construct a better resistive attenuator. Careful construction would minimize

10 kV/div

1.0 $\mu\text{s}/\text{div}$

10 kV/div

0.1 $\mu\text{s}/\text{div}$

Figure 14: Capacitive Line Probe Output Pulse

inductance and stray capacitances, improving the step response considerably.

The largest single inductance in the system is due to the series railgap. The railgap inductance could be decreased by triggering the railgap so that multichanneling occurred. The inductance could be further decreased by using a railgap whose construction positioned the current path closer to the line dielectric. The best solution would be to remove the railgap from the system and trigger the surface switch. The system inductance would then be decreased by at least 75 nH, decreasing the current risetime from 40 ns to about 14 ns [20].

CHAPTER III

DIAGNOSTICS

Test and Selfbreak Voltage

The capacitor charging voltage was measured with a commercial, high voltage probe. When the railgap was shorted with a shorting strap, the capacitor charged until the surface switch closed. This was titled the "Selfbreak Voltage" for the dielectric sample in the surface switch. With the railgap in the circuit, the capacitor would charge until the railgap closed. This voltage was titled the "Test Voltage" for a particular test run. By adjusting the sweep speed of the oscilloscope, 5-10 charge sequences could be recorded on one photograph. These were later averaged and recorded as the particular voltage measurement. A typical Test Voltage photograph is shown in Figure 15.

Figure 15: Oscilloscope Recording of Eight Charging Sequences

Load Voltage

A capacitive voltage divider was built into the strip-line to measure the voltage drop across the load. The probe was located between the surface switch and the load, and constructed in the following manner: A 127 micron (.005 in) thick sheet of Mylar was placed on the lower line conductor (ground conductor). Then, a 50.8 micron (.002 in) thick sheet of brass was placed on top of the Mylar, and the line insulator and high voltage conductor were placed over the probe. A thin wire from the center of the brass sheet passed through the Mylar and to the center of a BNC

connector that had been threaded into the ground plate. The two dielectrics (line insulator and Mylar) formed two capacitors in series, with the brass sheet and wire being the center point of the divider. Constructing the divider as part of the stripline resulted in a low inductance geometry, capable of measuring very fast risetimes (1-10 ns). In order to measure pulses of two microsecond duration, a series resistor was used to insure that the charge did not leak off of the capacitor too quickly.

A schematic drawing of the capacitive and resistive divider network, including associated inductances, is shown in Figure 16. The value of R_{atten} was chosen so that the product of R_{atten} and C_{probe} was at least ten times longer than the product of R_{load} and C_{bank} , the time constant of the switch system. The value of R_{atten} was then adjusted so that the total value of attenuation, assuming a 50 ohm oscilloscope impedance, was 10,000 to 1. The inductance of the capacitive probe, L_{probe} , was estimated as the inductance of a section of a stripline. The inductance of the resistive attenuator, L_{atten} , was estimated as a short length of coaxial cable, because the resistor was built into a copper tube with BNC connectors on each end. A SPICE computer plot of the probe input and output voltage is shown in Figure 17.

Figure 16: Schematic of the Capacitive Voltage Probe

Figure 17: SPICE Simulation of Capacitive Probe Performance

Video Tape Recording of the Number of Arc Channels

A black-and-white video camera was used to record the number of arc channels during each multichannel discharge. The intense light produced by the discharge was attenuated by placing several neutral density, photographic filters before the camera lens. During the beginning and end of each test run, twenty to thirty shots were recorded with the video cassette recorder (VCR). These shot sequences were played back, and, using the "pause" feature of the VCR, the number of arc channels on five sequential shots was counted. To establish a repeatable procedure, all visible arc channels were counted, even though the brightness of the various channels varied considerably. The number of channels was averaged for the five shots and the average number was recorded as the number of channels per shot. The number of channels per shot was converted to channels per meter for reporting so that the numbers could be compared to results reported by other investigators.

Optically Isolated Shot Counter

During the process of designing a shot counter to record the total number of shots in a test run, a commercial counter was found that worked very well. The counter had a light source and detector, and was designed to count objects

passing through and breaking the light beam. Discarding the light source and aiming the detector at the discharge region of the surface switch converted the counter to an optically isolated shot counter. The detector was placed outside the experiment's screen enclosure, accurately detecting and counting discharges from a distance of 50 cm. The maximum counting rate of the counter was limited by the mechanical counter to 20 counts per second.

CHAPTER IV

SYSTEM OPERATING PROCEDURE

Multichannel Mode

Multichanneling was achieved by overvolting the surface switch as described on page 13. The percentage of overvoltage needed to cause dense multichanneling was determined experimentally to be about 100 percent. (i.e. the Test Voltage was equal to twice the Selfbreak Voltage.) Because of electrode field enhancement, the initial selfbreak fields of the different dielectrics were all very close to 10 kV/cm. A surface switch gap of 2.3 cm resulted in a selfbreak voltage of 20-25 kV for a G-10 dielectric sample. All dielectrics were tested with the gap set at 2.3 cm and a test voltage of 48 kV.

The preparation of the dielectrics; machining, cleaning, and insertion into the switch, is detailed in Appendix B. For each run, the railgap was shorted and the selfbreak voltage of the sample was measured as described in Chapter III. The test voltage was measured to verify consistency between runs. The run was started and the repeti-

tion rate noted so that average power could be calculated. Finally, a series of 25-50 sequential shots was recorded with the video cassette recorder. The preceding measurements, taken during the first 500 shots, established the characteristics of the sample "before" exposure in the surface switch. The same measurements, taken during the last 500 shots of a 10,000 shot run, constituted the characteristics of the sample "after" exposure.

Single Channel Mode

A single channel investigation was undertaken after the results of the multichannel study were evaluated. Other investigations have shown that a current per channel in the range of 5-10 kA showed a marked increase in erosion rates over currents of less than 2 kA [3]. In order to operate in this current regime, single channel electrodes were designed to concentrate the entire discharge current into one channel. The peak channel current then approached 7-8 kA.

The test procedure with these electrodes was very similar to the test procedure used with the multichannel electrodes. The measurements taken at the beginning and end of the run were: the selfbreak voltage for a gap of 2.5 cm and the test voltage for the run. Because the current per channel had increased by 20 to 30 times, 1,000 shots was

found to damage the dielectrics enough to compare them. After each run, the electrodes were polished with crocus cloth and wiped with methanol.

Evaluation of Dielectric Performance

Evaluating the dielectric performance involved three different comparisons: 1) the "before" and "after" data described in the two preceding sections was compared for each sample, 2) a visual inspection of the damage of each dielectric was made with the aid of an 80 power optical microscope, and 3) several of the samples were studied using Electron Spectroscopy for Chemical Analysis (ESCA). Each sample was compared to itself to determine any degradation of performance that resulted from exposure in the switch. To make a qualitative comparison between the dielectrics, a summary of the data for each sample is tabulated in Chapter V.

CHAPTER V

RESULTS

Multichannel Study

The surface switch system proved to be a suitable vehicle for evaluating the performance of dielectrics in a medium powered surface discharge switch. The switch closed with 20 to 30 arc channels when overvolted. An open shutter photograph of such a discharge across delrin with 45 kV is shown in Figure 18. a discharge across delrin with

Results of the multichannel study indicated that a higher repetition rate, average power, or peak current, was needed to damage most of the dielectrics so that they could be compared more accurately. Only one of the samples compared in Table 3, boron nitride sprayed on a G-10 substrate, was damaged enough to noticeably alter the performance of the switch. Several of the samples showed grooves or eroded arc tracks up to 0.5 mm deep caused by the repeated occurrence of arcs at the damage site. These included Blue Nylon, Delrin, Kapton, and Lucite. Two of the samples, G-10 and Macor, showed no visible evidence of erosion. Boron nitride

Figure 18: Open Shutter Photograph of Discharge Across Delrin

in plate form ablated evenly, resulting in a clean, un-grooved surface.

TABLE 3
Multichannel Results for 10,000 Shot Test

DIELECTRIC MATERIAL	SELFBREAK FIELD (kV/CM)		CHANNELS/METER	
	BEFORE	AFTER	BEFORE	AFTER
Blue Nylon	9.7	9.3	150	140
Boron Nitride (BN)	9.3	9.3	120	120
BN Coating Sprayed on G-10 Base	10.6	5.3	160	150
Delrin	10.3	10.1	140	120
G-10	9.0	8.7	140	160
Kapton	8.8	8.0	150	150
Lucite	10.2	10.2	150	130
Macor	7.5	7.9	120	120

Inspection with an 80 power optical microscope revealed deposits on the surfaces of all of the dielectrics except boron nitride. The deposits, which were heavier at the cathode, appeared near the electrode edges. The deposited material was brass-colored and since brass electrodes were

used, it is reasonable that the deposits were metals sputtered off of the electrodes. ESCA or another technique could be used to determine the exact composition of the materials. Pai and Marton, in a similar study of surface switch dielectrics, used x-ray analysis and determined that the deposited material did include several of the elements from the brass electrodes [21]. The materials they found included copper and zinc, although the relative percentages of each were not included in their preliminary report.

Electron Spectroscopy for Chemical Analysis (ESCA) was performed on three of the dielectrics: G-10, Lucite, and Delrin. The analysis of a virgin sample of G-10 showed the composition to be approximately 74% carbon and 26% oxygen. After 10,000 shots the surface material was found to be composed of 60% carbon and 40% oxygen. Delrin behaved similarly with a decrease in carbon from 75% to 33% and an increase in oxygen content from 25% to 67%. By contrast, the analysis of Lucite showed an increase in carbon from 71% to 77% and a decrease in oxygen from 29% to 23%.

These changes indicate an oxidization of the G-10 and Delrin surfaces, although the analysis was not detailed enough to determine the particular oxygen bonding or the compounds involved. The surface of the Lucite appears to

have carbonized slightly which should have lowered the surface resistivity of the material. Although this would eventually lower the selfbreak voltage, it might be beneficial in that surface charging would be reduced, promoting enhanced multichanneling. It should be noted that, for Lucite, the chemical changes were so slight that the analysis would have to be repeated to verify the results. The surface changes of the three materials, while significant, are difficult to evaluate in terms of performance of the dielectric in a switch. The preceding data taken together with the visual inspection of all the samples, and results from other investigations, indicated that a higher peak current would be necessary to damage the dielectrics sufficiently to make a valid performance comparison.

Two interesting observations resulted from the multichannel investigation. The first involves the preparation of the sample. In preliminary tests, a factory surface of a G-10 plate was used as the sample. After several thousand shots, grooves appeared in several locations from repeated arcing at the damage site. These grooves followed the weave pattern of the fiberglass fabric layer in the G-10. The grooves were not exactly perpendicular to the electrode edge as they were in samples

such as Lucite. This contrasted sharply to the results reported here for a machined G-10 surface. No visible damage could be detected on the machined surface. It is probable that after the epoxy coating on the factory surface completely eroded, the erosion rate would decrease sharply and resemble the data reported here.

The second observation concerns charging of the dielectric surface. Some of the samples appeared to show a strong tendency to build up surface charges during the test procedure. After several hundred shots, the number of channels per shot would decrease until only 2-5 channels would occur on any shot. If the power supply was turned off for one minute after a period of this reduced channeling, and then turned back on, dense multichanneling would occur again for 5 to 50 shots. Dense multichanneling would also resume if a conductive pad was brushed over the surface of the dielectric after a period of reduced multichanneling. Static discharges could be heard during this brushing operation, indicating that the effect was due to "trapped" charges on the surface of the test dielectric. It was found that an air flow across the dielectric surface between the electrodes would remove these charges, allowing the switch to multichannel with 20-30 channels per shot throughout the entire 10,000 shot run. To make the comparison between

dielectrics consistent, the air flow was used during each run, even if a particular sample did not tend to collect charges.

Single Channel Study

The single channel electrodes were used in a limited investigation to determine how the peak current would affect dielectric damage. The two dielectric samples chosen for the single channel study exhibited contrasting damage patterns in the multichannel study. Delrin had shown slight erosion grooves that seemed to follow scratches that existed on the surface prior to testing. Machined G-10 did not show any noticeable damage in the multichannel study. The single channel study did not require the air flow used to remove surface charges during the multichannel study. To determine the effect of the air flow on the damage of the dielectric, one test was performed on Delrin with the air flow, and one test without the air flow.

The arc tracks observed on the samples exposed in the single channel switch were much wider than those observed on the same materials exposed in the multichannel switch. Whereas the grooves caused by arc tracking in the multichannel study were about 1 mm wide, the groove in a single channel dielectric was 5-10 mm wide. No visible difference

could be detected between the Delrin with air flow and the Delrin without air flow. This suggests that at low repetition rates (less than 1 pps) the air flow has no effect, other than to produce denser multichanneling. At higher repetition rates or longer test times, the air might be expected to aid by cooling of the dielectric, increasing the dielectric lifetime. A comparison of the three samples and their performance follows in Table 4.

TABLE 4
Single Channel Results for 1000 Shot Test

DIELECTRIC MATERIAL	SELFBREAK FIELD (KV/CM)	
	BEFORE	AFTER
Delrin without air	9.8	9.8
Delrin with air	9.8	9.8
G-10 with air	9.1	7.9

One interesting observation was made after calculating the selfbreak fields from the oscilloscope photographs. All oscilloscope recordings showed a distribution of selfbreak voltages that varied from 5 to 10 per cent of the average

voltage. G-10, after 1000 shots in the single channel experiment, had a much more consistent selfbreak voltage than before the test. No difference in the selfbreak voltage of the eight sequential shots could be measured on the photograph. This is different than all other runs including G-10 in the multichannel study, in that no sample has shown such a narrow breakdown distribution. Further investigation would be necessary to prove that the preceding effect is a property of the dielectric and not caused by conditioning of the electrode.

CHAPTER VI

CONCLUSIONS

A versatile system capable of investigating the effects of electrode and dielectric materials in surface discharge switches was developed and used for two similar studies. The first study used multichannel electrodes. The second used single-channel electrodes as a technique to increase the channel current and increase damage rates at the dielectric surface. The results from these two studies have lead to the following conclusions:

- 1) Peak currents of at least 7 kA are required to damage dielectrics sufficiently so that they may be compared in less than 10,000 shots.
- 2) Several materials, notably those that have high surface resistivities such as Delrin, G-10, and Kapton, tend to collect surface charges that inhibit multichanneling for the conditions studied.

3) Air flowing accross the surface of the dielectric inhibited this tendency to trap charges well enough that no significant decrease in the number of arc channels with time was noticed at 1 pps for the materials studied.

4) Several materials such as Delrin, Kapton, Lucite, and unmachined G-10, showed a tendency to arc repetitively in a few tracks and cause significant erosion only in those tracks. It is likely that these materials would erode too quickly to make a reliable switch capable of conducting higher current than the test switch.

5) While solid boron nitride ablated very evenly, providing a continuously clean surface, a thin coating of boron nitride sprayed on G-10 was the only surface studied that was clearly unsuitable for a surface switch dielectric.

In light of the findings reported in this study and others [21], several objectives are being considered for future investigations:

1) Higher repetition rates (10-1000 pps) are likely to emphasize problem areas such as surface charging. Finding dielectrics that do not trap charges well, or

finding techniques to liberate these charges quickly, is essential to the development of higher repetition rate surface switches.

2) Triggering by several methods, including preionization with UV and field distortion, should be investigated to determine which method produces more arc channels and less jitter. Dense multichanneling is essential to low erosion rates and low jitter is essential to reliable switching in many systems.

3) By replacing the capacitor bank with a matched transmission line, fast pulses at higher repetition rates can be used to measure breakdown delay times across different dielectrics.

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APPENDIX A

CONSTANT CURRENT POWER SUPPLY

The constant current power supply consists of a Sorensen 60 kV, 10 mA supply, the L-C constant current network, and associated control logic. The output current can be set by adjusting the voltage on the Variac autotransformer. The current meter on the power supply face is not accurate, but the current can be calculated with the following formula:

$$i = \frac{C \cdot V}{t} \quad \text{Amps,}$$

where C is the value of the capacitor being charged in farads, V is the charge voltage in volts, and t is the time to charge in seconds.

A schematic of the present control logic is shown in Figure 19, and a schematic of the Sorensen supply is shown in Figure 20. The power supply can operate only when the power switch on the front panel and the power switch on the remote control are both in the "on" position. The "re-

Figure 19: Power Supply Control Logic

mote on/off" switch on the front panel determines which charge switch is allowed to initiate the charge sequence. With the remote switch in the on position, only the charge button on the remote control can initiate charging. In the off position, charging can be initiated only from the front panel. Initiating a charge sequence does three things: ac line voltage is supplied to the Sorensen supply; the dump relay in the Sorensen is lifted; and 120V ac is supplied to the two ac outlets on the back of the supply cabinet to

operate external dump relays. A charge sequence can be stopped and all dump relays closed by turning off either power switch. A charge sequence will also be stopped if the voltage exceeds the overvoltage level set on the front panel voltmeter. In the locked position, the "dumps locked" switch allows the dump relays to be held open when the "charge" is broken by the overvoltage trip. In the unlocked position, the dump relays will close any time a charge sequence is stopped. After a charge sequence has been interrupted, charging will not resume until the proper charge button is pressed.

Figure 20: Sorensen Power Supply

The power lamp (clear) comes on when both power switches are in the on position. The charge lamp (red) comes on when voltage is supplied to the primary of the Sorensen

supply. When the internal or external interlock lamp (orange) is on, it indicates that voltage is applied to the internal or external dump relays, respectively.

APPENDIX B

DIELECTRIC SAMPLES: PREPARATION FOR TESTING

All dielectric samples were cut and milled to dimensions without the use of any cutting fluids. Before inserting a dielectric sample into the switch, each side of the sample was cleaned by wiping with methanol and paper towels. The edges and bottom surface of the sample, and the sample slot were then coated with a thin layer of transformer oil. The sample was placed in the slot, the electrodes were positioned and the dielectric surface between the electrodes was wiped again with methanol.

Two of the dielectrics, Kapton and boron nitride sprayed on a G-10 substrate, had special preparation procedures. The boron nitride was sprayed from an aresol can onto a machined G-10 substrate. Five layers of boron nitride were applied at intervals of 20 minutes. The Kapton was only available in a 127 micron (.005 in) thick sheet. To increase the thickness of the Kapton sample, so that it would fill the sample slot, transformer oil was applied to the Kapton sheet and it was placed on a Lucite substrate.

The sample combination was placed in the switch and a paper towel used to squeeze air bubbles out from between the Kapton and the Lucite. The Kapton was then cleaned with methanol and paper towels.

Although reasonable precautions were taken to avoid contamination of the samples during preparation and testing, it is possible that the air flow, used to inhibit surface charging, resulted in some contamination during testing. The air flow was "house" air that was ran through a water trap and simple filter and then directed across the dielectric surface.

APPENDIX C

SPICE TRANSIENT SIMULATION EXAMPLE

The following circuit is a model of the surface switch test system and the capacitive voltage probe. The circuit model is shown in Figure 21 and the following pages are a copy of the SPICE input file and a copy of the associated printout from the National AS/6 computer at Texas Tech. The SPICE manual available at Texas Tech has several examples of SPICE models, but it does not contain a good example of a transient solution similar to those encountered in the pulsed power field.

In the following model, the capacitor is given an initial voltage and then the circuit analysis begins as if a switch were closed, connecting the capacitor to the discharge circuit. Table 5 lists the component names and their description for the circuit.

Figure 21: Circuit Schematic for SPICE Example

TABLE 5

Circuit Component Abbreviations and Descriptions

C_{bank}	--	Bank Capacitance
L_{bank}	--	System Inductance
R_{load}	--	Load Resistance
C_{line}	--	Capacitance of upper probe capacitor using line dielectric (Blue Nylon)
C_{probe}	--	Capacitance of lower probe capacitor using Mylar dielectric
L_{probe}	--	Inductance of probe capacitor plate
L_{atten}	--	Inductance of resistive attenuator
R_{atten}	--	Resistance of resistive attenuator
R_{cable}	--	Characteristic impedance of oscilloscope cable


```

1. // JOB
2. // EXEC SPICE
3. //SYNID 00 *
4. CAPACITIVE LINE PROBE
5. *
6. *****
7. *
8. * THIS PROGRAM MODELS THE SURFACE SWITCH CAPACITIVE LINE PROBE. *
9. * THE RESISTIVE ATTENUATOR AND ITS ASSOCIATED INDUCTANCE IS *
10. * INCLUDED. *
11. * A 50 OHM CABLE IS ASSUMED BETWEEN PROBE AND SCOPE. *
12. * *****
13. *
14. *
15. * SYSTEM COMPONENTS:
16. *
17. CBANK 6 0 0.16UF IC=50KV
18. LBANK 6 1 0.135UH
19. RLOAD 1 0 6.0
20. *
21. * PROBE AND ATTENUATOR COMPONENTS:
22. *
23. CLINE 1 2 34.6PF
24. CPROBE 2 0 1.104F
25. LPROBE 2 3 300.0PH
26. LATTEN 3 4 30.0NH
27. RATTEN 4 5 14.2KOHMS
28. RCABLE 5 0 50.0
29. *
30. * ANALYSIS AND PLOT CONDITIONS:
31. *
32. .TRAN 50NS 6.0US UIC
33. .PLOT TRAN V(1) V(5)
34. .END
35. /*
36. //

```

Figure 22: SPICE Input File for AS/6 Computer

```

*****          ***** SPICE 2G.1 (15OCT80) *****          *****

CAPACITIVE LINE PROBE

****          INPUT LISTING                      TEMPERATURE =    27.000 DEG C

*****

*
*****
*
* THIS PROGRAM MODELS THE SURFACE SWITCH CAPACITIVE LINE PROBE. *
* THE RESISTIVE ATTENUATOR AND ITS ASSOCIATED INDUCTANCE IS    *
* INCLUDED.                                                     *
* A 50 OHM CABLE IS ASSUMED BETWEEN PROBE AND SCOPE.          *
*                                                                 *
*****
*
* SYSTEM COMPONENTS:
*
CBANK 5 0 0.18UF IC=50KV
LBANK 6 1 0.135UH
RLOAD 1 0 6.0
*
* PROBE AND ATTENUATOR COMPONENTS:
*
CLINE 1 2 32.6PF
CPROBE 2 0 1.10NF
LPROBE 2 3 800.0PH
LATTEEN 3 4 30.0NH
RATTEN 4 5 14.2KOHMS
RCABLE 5 0 50.0
*
* ANALYSIS AND PLOT CONDITIONS:
*
.TRAN 50NS 6.0US UIC
.PLOT TRAN V(1) V(5)
.END

```

Figure 23: SPICE Output Text

Figure 24: SPICE Output Plot