# THE DIELECTRIC FAILURE MECHANISM OF A HIGH VOLTAGE FEEDTHROUGH

by

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# ABSTRACT

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This paper summarizes the investigation into a series of dielectric failures that occurred in the high voltage feedthrough of an electrostatic spray painting system. The feedthrough, or well, is where the high voltage cable interfaces to the high voltage power supply. Each well failed by forming conductive, carbon paths, called arc-tracks, along its surface. These arc-tracks bridge the distance between the high voltage electrode and ground.

This paper evaluates the field evidence and discusses the relevant literature. The distinctions between solid dielectric breakdown and surface arc-tracking are presented and discussed. A series of experiments is run to determine the necessary conditions for the formation of arc-tracks. Finally,. possible solutions are evaluated and the final solution is presented.

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# LIST OF SYMBOLS

| SYMBOL | | UNITS OR REFERENCE |
|---|---|---|
| e | Electronic charge | C |
| E | Electric field intensity | V/m or KV/inch |
| i(E) | Injection current | A |
| $i_T$ | Thermionic current | A |
| I | Current | A |
| J | Current density | $A/m^2$ or $A/in^2$ |
| k | Boltzmann's constant | eV/K |
| n | Electron volume density | $m^{-2}$ |
| $q_1$ | Linear charge density | C/inch |
| r | Radius | inch |
| T | Temperature | K |
| v | Average electron velocity | m/sec |
| V | Voltage | V |
| $\epsilon$ | Relative dielectric constant | none |
| $\mu$ | Electron mobility | $m^2$/volt-sec |
| $\rho$ | Resistivity | $\Omega$-m or $\Omega$-inch |
| $\sigma$ | Conductivity | ℧/m |
| $\phi$ | Work function | eV |

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# CHAPTER 1

## INTRODUCTION

Several years ago, an insulation problem developed on a line of electrostatic painting equipment. This problem involved the feedthrough or well where the high voltage cable makes contact with the high voltage power supply. The problem was that the well and cable would become arc-tracked and fail dielectrically. This document summarizes an investigation into the causes and possible solutions for this problem.

The electrostatic painting system consists of three parts: a high voltage power supply, an interconnecting high voltage cable, and a gun. See Figure 1. The gun can be either a paint spray gun or a gun for applying powder coatings. The system with the highest failure rate was the system utilizing a paint spray gun and operating at 115KV.

Electrostatic painting is an improvement over conventional spray painting. The major benefit of electrostatic application of paint is that this process is more efficient in the use of paint than conventional spray painting. Its major disadvantage is that it can introduce enough electrical energy into the painting environment to be both a personnel hazard and a fire hazard.

Electrostatic spray painting achieves a higher efficiency in paint usage because it charges the paint by con-

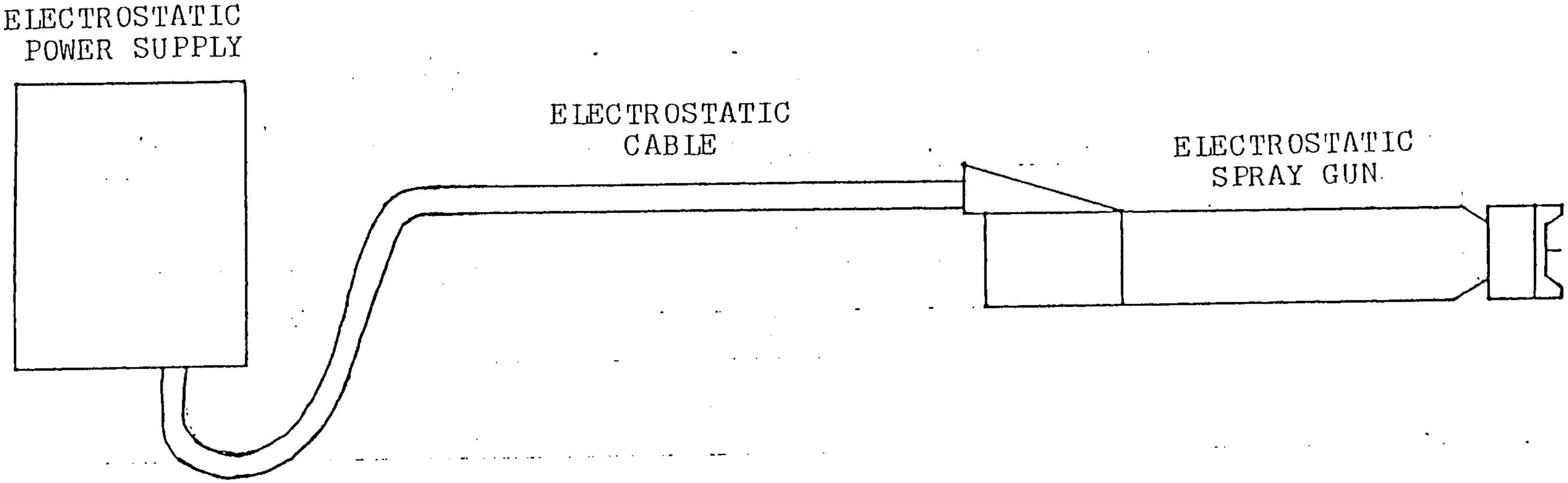

FIGURE 1. BLOCK DIAGRAM OF ELECTROSTATIC SYSTEM

duction. The electric charge, together with the electric field developed from the charging electrode on the spray gun to the grounded piece to be painted, forces the charged paint particles to be attracted to the piece to be painted. Thus the paint doesn't get blown past the piece to be painted. Even paint particles that do travel past the piece to be painted still can follow the field lines to the back of the piece. This effect of painting the back side of the piece is termed "electrostatic wrap."

The increase in painting efficiency means that more of the paint that is sprayed from the gun reaches the piece to be painted. Typical efficiencies for conventional spray applications range from 20% to 40%. With electrostatics, efficiencies range from 60% to over 90%.[1]

The higher efficiency results in reduced paint consumption and an immediate cost savings. However, this increased efficiency also produces several indirect benefits. Since less paint is used, less overall solvent is used. This helps a plant stay within solvent emission limits. The increased efficiency also means there is less paint overspray that can collect on the spray booth and the conveyor. A reduction in overspray also means a reduction in cleanup costs,

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[1] Gerald L. Schneberger, Understanding Paint and Painting Processes (Wheaton, Illinois: Hitchcock Publishing Company, 1979), p. 10.

The major drawback associated with electrostatic spray painting is the introduction of electric energy into the hazardous atmosphere of the spray area. The high voltage electrostatics can constitute both a danger to personnel (as a shock hazard) and an ignition source.

Every electrostatic system has a high capacitance to ground. It is the release of the energy stored in this capacitance that can cause shocks to personnel or that can produce a spark sufficient to ignite solvent vapors. The electrostatic system studied here has discrete resistors spaced along the length of the cable and inside the spray gun, These resistors serve to limit the release of energy from the ground capacitance when the gun's charging electrode becomes grounded. These resistors limit the energy such that this electrostatic system cannot harm personnel nor ignite solvent vapors.

The high voltage cable that connects the gun to the power supply is a coaxial, polyethylene cable. See Figure 2. The outside diameter of the polyethylene is .375". A copper ground braid surrounds the polyethylene and a blue polyurethane jacket surrounds the ground braid for abrasion and chemical resistance. The conductor of the cable is made up of discrete 20M resistors equally spaced along the length. The resistors are connected by a carbon-loaded, conductive PVC tubing. The outside diameters of the tubing and of the resistors are equal. As mentioned previously, the purpose of the resistors is

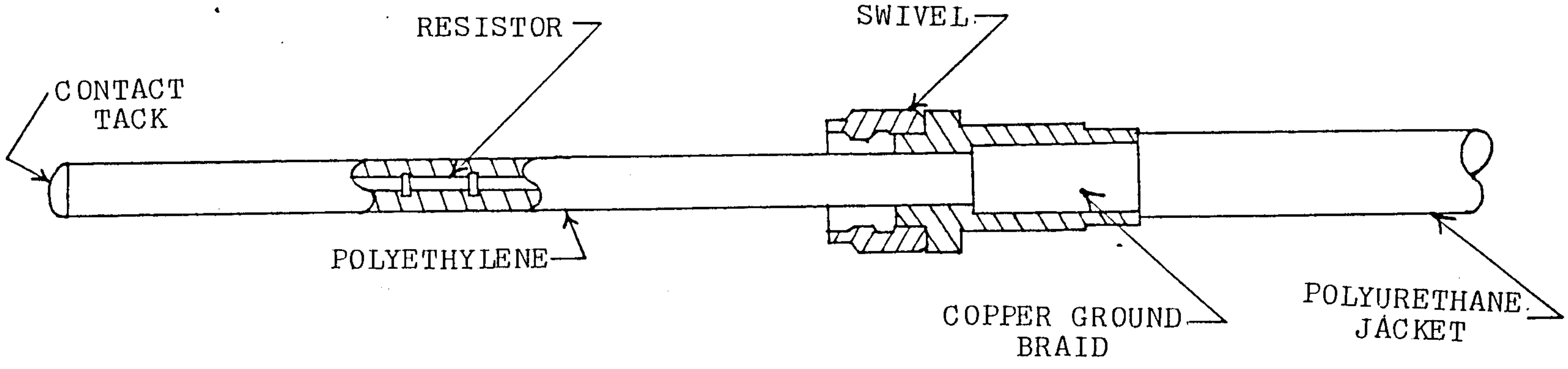

FIGURE 2. HIGH VOLTAGE CABLE CROSS SECTION

to limit the discharge energy delivered to the gun tip, if the gun should become grounded. This is a safety measure that makes the system safe to operate in the solvent-rich, hazardous atmosphere in a paint spray booth.

In order to make the transition from the cable to the high voltage power supply, the ground braid is removed from both ends of the cable and is terminated to female brass fittings. This feature allows the cable ends to be inserted into the power supply and into the gun and still maintain sufficient distance from the tip of the cable to ground. The tip contains a brass contact tack.

The high-voltage power supply is of an all solid-state design and consists of a printed circuit board, a high voltage transformer, and a Cockroft-Watson voltage multiplier. See Figure 3. The first half of the printed circuit board accepts a low AC voltage, rectifies it, and regulates the resulting DC voltage. The regulator output is adjustable to between 10 and 15V. The second half of the printed circuit board takes the DC voltage and uses an astable multivibrator switching circuit to produce a 5 KHz square wave. This square wave is sent to the high voltage transformer.

The high voltage transformer steps the voltage up to 14 KV and sends the high voltage square wave to the multiplier circuit.

The multiplier circuit is a series of diode-capacitor doubling circuits in a cascade arrangement. Each of the ten stages approximately doubles the input voltage.

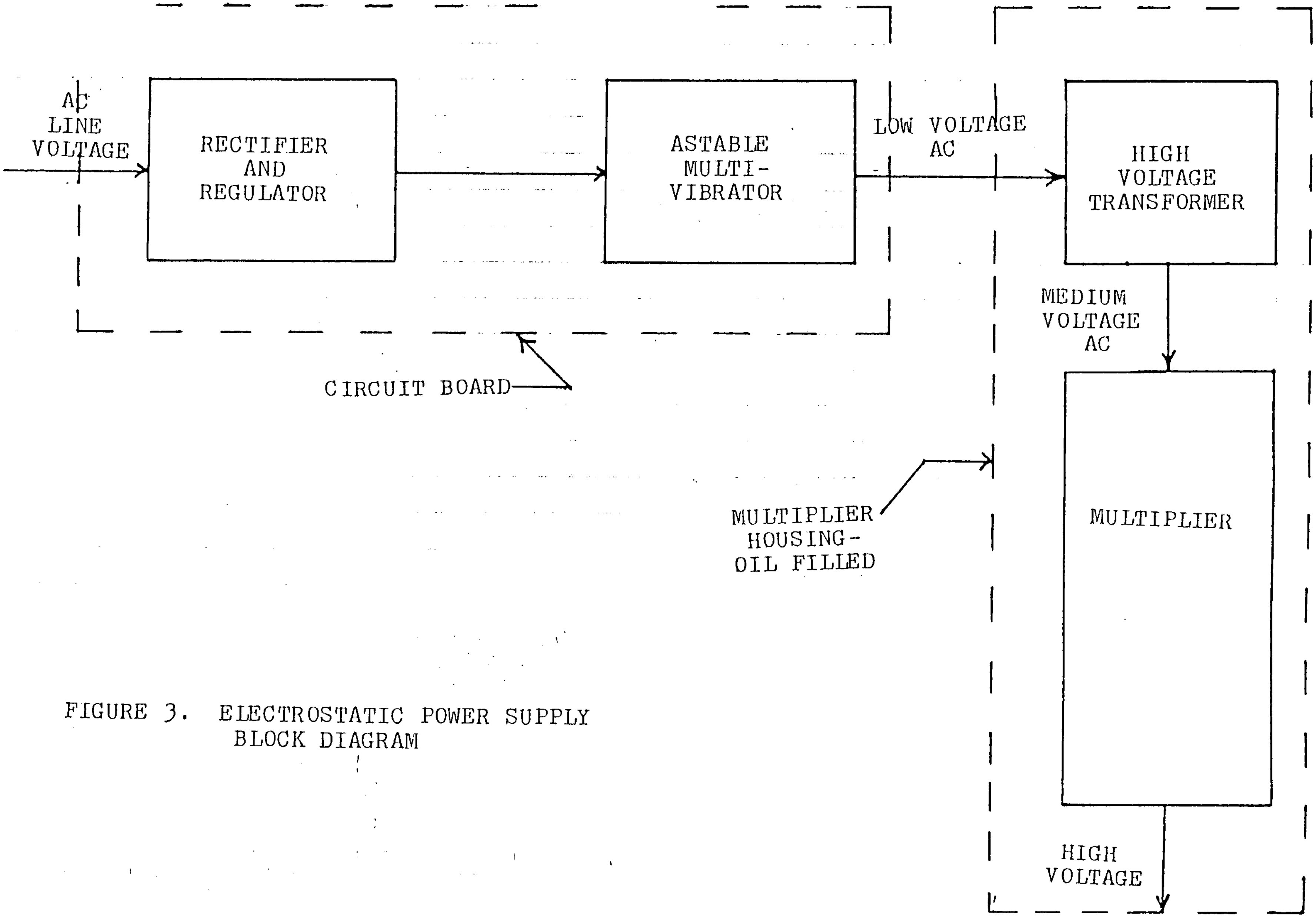

FIGURE 3. ELECTROSTATIC POWER SUPPLY BLOCK DIAGRAM

The multiplier circuit also rectifies the input square wave so that the multiplier's output is a negative 115KVDC. A bleed off resistor of 17GΩ shunts the high voltage output to discharge the capacitors when the unit is switched off.

The polarity of the output voltage of the multiplier is determined by the orientation of the diodes. While a positive voltage could have just as easily been produced, negative voltage has historically been used in electrostatic painting applications.[2]

Both the high voltage transformer and the multiplier are immersed in insulating, transformer oil. The assembly of the transformer and the multiplier are inside a cylindrical PVC pipe. See Figure 4.

To accommodate the connection to the high voltage cable, a dry well is inserted through the bottom end of the multiplier. The well is also made of PVC and has an inside diameter only slightly larger (.40625") than the outside diameter of the cable. The top or high voltage end of the well has a steel spring to make contact with the cable end and to compensate for small variations in the length of the cable end. The bottom or ground end of the well has a brass threaded adapter that connects to the ground braid of the cable as well as to an earth ground. See Figure 5.

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[2] Schneberger, p. 75.

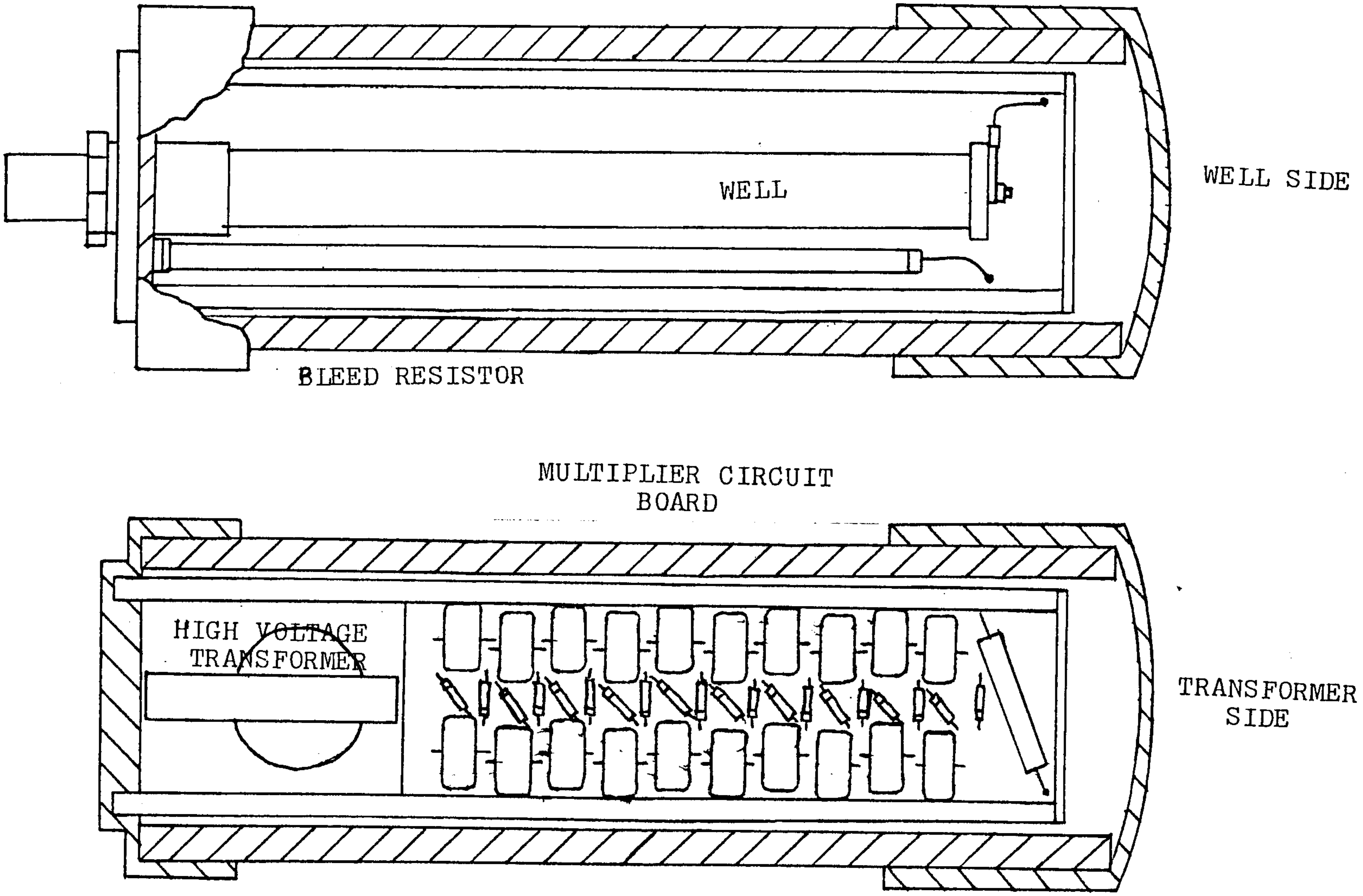

FIGURE 4. MULTIPLIER ASSEMBLY

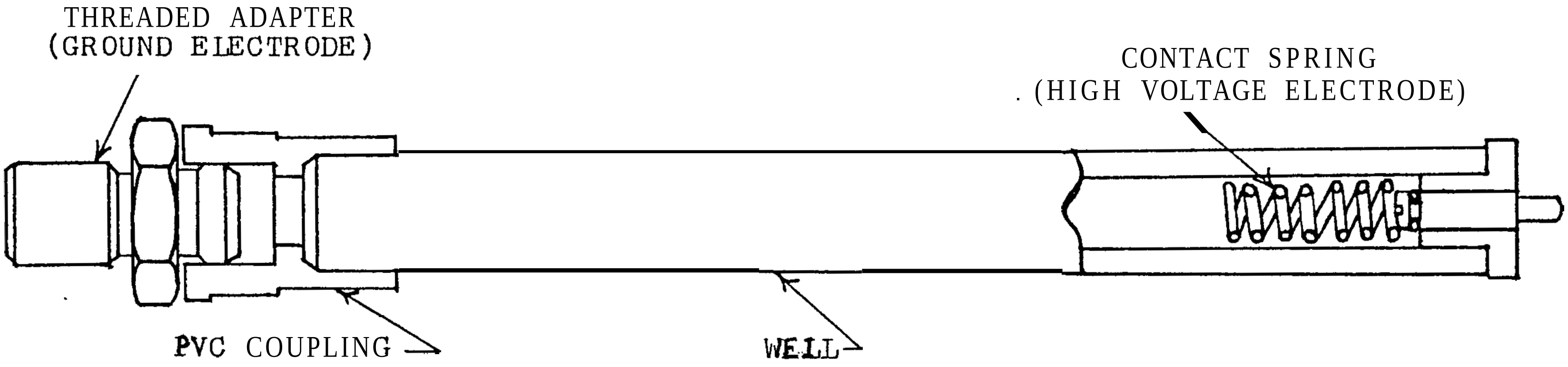

FIGURE 5. CROSS SECTION OF HIGH VOLTAGE WEDTHROUGH OR WELL

The insulation problem began showing up in field units in the fall of 1980, about nine months after the 115KV system was first introduced for sale. It was first noted as a high current condition (>160 microamps) on the power supply's microammeter and a corresponding drop in the voltage at the tip of the gun. The power supply, cable, and gun are designed to have high effective resistances. Therefore, with a current this high, the voltage at the gun tip, available to charge the paint, was essentially zero.

The cause of this high current draw turned out to be current on the inside surface of the well and the surface of the cable end inside the well. Both of these surfaces were normally excellent insulators.

In the less severe cases, when the cable was removed and the high voltage was turned on, visible and audible arcing inside the well was noticed. Often these arcs were of sufficient intensity and duration to register on the power supplies' microammeter.

In the more severe cases, the cable had become so distorted that it could not be removed from the well through the threaded adapter. Also, once the cable was finally removed, and the high voltage was switched on, the microammeter indicated a dead short. The current easily flowed down the surface of the well with no arcing. See Figure 6.

This paper will review the pertinent literature on solid dielectrics and the experiments run to gain insight to the well failure mechanism. It will also develop the cause of the well failure and discuss several possible alternative solutions, as well as the solution finally implemented.

# CHAPTER II

## SOLID DIELECTRIC BREAKDOWN

Breakdown of all dielectrics, solid, liquids, and gases, has been of interest ever since the rise of the electric power industry in the end of the last century. The various investigations into this area have taken many different approaches. Some of these have been strictly empirical, while others have been theoretical. Solid insulation, in particular, has been the most difficult area in which to develop a theory of dielectric breakdown. There are many different mechanisms of solid dielectric breakdown and many variables that have an effect on each mechanism. The following is meant to be only a general introduction to the subject of solid dielectric breakdown.

Solid insulations come in a wide variety of structures and chemical make-up. The highly structured crystals of the alkali-halides (such as sodium chloride and potassium chloride) have been the subject of much theoretical and experimental work. Yet the conclusions reached here are not easily transferred to the real world insulations, just as the alkali-halides themselves have no application in the practical world of electrical insulation. The real world insulations tend to be of amorphous molecular structures and of varying degrees of purities. They tend to be of a wide variety of chemical compositions, from the inorganics, such as mica or the various glasses, to the organic polymers such as polyethylene.

The experimental work that is used to study conduction and breakdown in these insulations also presents many problems. First, there is the type of voltage to be used, d.c., power frequency, high frequency, or impulse waveforms of various shapes. The time of application changes the breakdown strength, as does the rate of rise of the voltage. Conduction can decay with time and can also be field dependent as different charge carriers move at different rates and react to different field strengths. The effects of external discharges, the temperature of the insulation, and the thermal conductivities of the insulation and of the electrodes all have to be taken into account.

As if there wasn't enough confusion already, there are many different mechanisms of conduction and of breakdown. Basically, the theories of solid dielectric breakdown involve two separate methods of breakdown, thermal breakdown and intrinsic breakdown. These two modes have been recognized for many years. If the breakdown occurs as a continuation of the conduction process, it can be classified as thermal breakdown. If the breakdown occurs because of an instability, such as collision ionization, than it can be classified as intrinsic. The classifications are convenient but it is often difficult to force any given situation to fit either of the classifications.

Furthermore, each classification has many theories as to the actual mechanism of breakdown.

It is generally agreed that most dielectric failures encountered in the design and use of electrical machinery can be classified as thermal breakdowns. The time it takes for failure to occur and the type of voltage (steady, 60HZ) applied are two indications. Nevertheless, no real means exists to compare different insulations as to their ability to perform in this manner, other than actual life testing on models of specific apparatus.

In the area of solid insulation, there have been various theories developed. Also, various empirical methods of applying solid insulation have been developed. These empirical methods vary depending on the type of apparatus involved, the type of voltages used and the practices of various manufacturers. But, more significantly, the empirical methods often do not make use of the theories.

Breakdown in a dielectric is hard to define. While it could be thought of as current flow in a normally non-conducting material, it is better to visualize it as an inability of the insulation to hold voltage. While current flow in an ideal dielectric is impossible, current can flow in a real dielectric without causing breakdown.

Non-breakdown current in a real dielectric can be broken into two parts: the conduction current and the polarization current. The polarization current is due to one or more of the three mechanisms of polarization:

1. displacement of the centers of positive and negative charge
2. relative motion of the ions in an ionic crystal
3. rotation of dipolar molecules[3]

Conduction current, on the other hand, is actual transport of charges through the dielectric. In a solid dielectric, these charges are mostly electrons.[4]

Basically, conduction in insulation can be explained by the same equations as in solid-state electronics. For an electric field E, a current density J flows. In solid insulation the current is made up primarily of electrons, although the movement of slow moving positive ions is not unusual. The current density is dependent on the number of electrons, and the mobility of the electrons, as well as the electronic charge. Thus,

$$J = nev \qquad (1)$$

where: $n$ = electron volume density

$e$ = electronic charge

$v$ = average electron velocity in the applied field.

$$v = \mu E \qquad (2)$$

where: $\mu$ = mobility in $m^2$/volt-sec

$E$ = the applied field

Equation 1 can be rewritten as

$$J = ne\mu E = E\sigma \qquad (3)$$

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[3] R.W. Sillars, Electrical Insulating Materials and Their Application (New York: Peregrinus Publishing Co., 1973), pp. 38-40.

[4] J.J. O'Dwyer, The Theory of Dielectric Breakdown of Solids (New York: Oxford University Press, 1964), p. 6.

where: $\sigma$ = conductivity.

Then the resistivity can be defined as the inverse of the conductivity

$$\rho = 1/\sigma = 1/ne\mu \qquad (4)^{5}$$

In solid insulation, unlike in metallic conductors, the resistivity tends to decrease exponentially with temperature.[6]

The dielectric constant, $\epsilon$, is a measure of the amount of polarization in the material. The value of $\epsilon$ at a particular frequency and temperature is enough to tell something about the material. Also the variations of $\epsilon$ with frequency and temperature can tell a great deal about the structure of the material. A large dielectric constant indicates the rotation of large ions under the influence of the field. As the frequency is increased, these large particles lose the ability to follow the field. Therefore the dielectric constant drops. Eventually, only the displacement of the electron cloud will occur, and the dielectric constant will level out at a much lower value.

The variation with temperature is not so well established. However, it is still a good indication of the structure of the material. A dielectric constant that increases with increasing temperature could indicate an easing of the molecular bonds so that the molecules can rotate more

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[5] Jacob Millman and Christos C. Halkias, Integrated Electronics: Analog and Digital Circuits and Systems (New York: McGraw-Hill Book Company, 1972), p. 21.

[6] O'Dwyer, p. 50.

easily. This could be due to a weakening of the structure or the presence of more charge carriers. An€ decreasing with increasing temperature might indicate either a strengthening of the crystal or more energetic molecules that do not follow the field as well. This effect might also indicate a thermosetting type of material if it is not reversible as temperature drops.[7]

As mentioned previously, there are two major categories of insulation breakdown, thermal breakdown and intrinsic breakdown. Thermal breakdown is more frequently encountered and tends to occur at lower voltage levels. Intrinsic breakdown is rarely encountered outside the laboratory. The various theories of intrinsic breakdown predict much higher values of breakdown voltage for intrinsic breakdown than have been encountered even under laboratory conditions.

Thermal breakdown was probably the first breakdown mechanism noted historically. Thermal breakdown simply realizes that every insulation has a temperature above which the dielectric will be unable to support voltage. Macroscopically, the insulation may degrade, change phase, or go through a chemical reaction because of the temperature and the time factor. From an analytic point of view, if the heat entering the dielectric exceeds the amount of heat that can be dissipated, thermal breakdown will result.[8] Thermal

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[7] Sillars, pp. 145-147.

[8] O'Dwyer, pp. 46-47.

breakdown makes no distinction as to where the heat comes from. The insulation could be heated by the $I^2R$ losses in the conductor around which it is wrapped. This would typically occur in power frequency apparatus such as transformers and generators. Or, the dielectric could be heated by conduction or polarization currents in itself. This can occur in high frequency applications or with lossy dielectrics at any frequency. A condition of thermal runaway can occur as the losses increase with temperature, and the heat cannot be dissipated by the dielectric. This condition is aggravated by the decrease in insulation resistivity as the temperature increases. Higher current means even higher $I^2R$ losses and an even more rapid temperature rise.

Intrinsic breakdown is sometimes divided into disruptive or intrinsic breakdown and avalanche or conduction breakdown. However, recently O'Dwyer has advocated a return to a single category, intrinsic or purely electrical breakdown. Regardless of the nomenclature, this type of breakdown is caused by the field strength becoming so high that electrons are stripped from the atoms and conduct current.[9] This condition must occur solely because of the field strength (hence the name purely electrical) and it must happen in a very short time span. In effect, it is the ultimate dielectric strength of the material and it is very hard to

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[9] O'Dwyer, pp. 7-9.

verify, even in the laboratory, because the test specimens will normally fail by thermal breakdown first.

One of the difficulties encountered in the study of dielectric breakdown is the inability of investigators to identify factors that precede breakdown. The intuitive approach is to suspect that conduction current in solid dielectrics is of a similiar mechanism as breakdown current. Then, by studying conduction, insight can be gained into the breakdown process. This train of thought produces the conduction or avalanche theories of intrinsic breakdown. Several of these theories have been well developed. But there is also the disruptive type of breakdown which has almost no formal theories. Instead, both O'Dwyer and Whitehead suggest that electron instabilities exist that allow electron-lattice collisions that are ionizing.[10]

By contrast, semiconductor theories dealing with current in semiconductors postulate that electron-lattice interaction are always non-ionizing.

While thermal breakdown takes time on the order of milliseconds or more to occur, intrinsic breakdown occurs on the order of microseconds. On a microscopic level in the dielectric, free electrons can exist for a variety of reasons such as thermal agitation, impurities, defects, or some absorption of energy. Once the electrons are free of the solid structure, they can be accelerated by the electric

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[10] O'Dwyer, pp. 17-27.

field. The energy the free electrons absorb from the field can be passed to the other free electrons, to trapped electrons, and to the solid structure, i.e., the atoms. If this energy can produce more free electrons and if the free electrons experience a net increase in energy, breakdown can occur.[11] This explanation hints at the avalanche theory, but it is not limited to avalanche breakdown. For example, it could be possible for enough free electrons to exist without the electric field. The field could only be necessary to move them in the same direction.

This type of picture is also easily explained by solid-state theory. While in an ideal dielectric the energy gap between the conduction and the valence bonds, i.e., between the free electron energy level and the bound electron energy level, would be unbridgeable, in a real dielectric, imperfection levels exist that sufficiently narrow this gap. Once the imperfections are there, electrons can rather easily move from a bound imperfection level to the conduction state by one of the mechanisms previously mentioned. In the conduction state, they can receive energy from the field and transfer this energy to each other or to bound imperfection electrons. These bound electrons can either give up the energy to the solid structure or they can use it to jump to the conduction state. If more energy is gained from the field than is

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[11] O'Dwyer, pp. 59-60.

lost to the solid structure, enough electrons are moved to the conduction state so that an electron gas phase can exist. With the continued application of the field, breakdown can occur as the electrons bridge the distance between the electrodes.[12]

Unlike the theoretical aspects of conduction in semi-conductors which support the practical world of solid-state electronics, the theoretical view of conduction in insulation is far from the practical world of insulation of electrical devices. The majority of the work has been done on very pure, crystalline materials such as the alkali-halides. Nevertheless, the theories do offer a starting point. Two theories in particular will be briefly described.

First, there are two low temperature conduction theories, one by von Hippel and one by Frohlich. While both theories predict high breakdown strengths, which have never been fully realized, and an increase in dielectric strength with temperatures, von Hippel assumes that ten times the thermal energy (approximately .025eV) will be sufficient to lift an electron into the conduction band. Frohlich on the other hand uses the binding energy between the electron and the lattice, which is on the order of 10eV.[13]

In the practical world, dielectric strength decreases with temperature. To accommodate this fact, Frohlich

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[12] O'Dwyer, pp. 62-71.

[13] O'Dwyer, pp. 17-26.

has also proposed a high temperature theory (i.e. room temperature and above). This theory proposes that free electrons have a temperature different from that of the crystal structure. Energy transfer from the electrons to the lattice can only happen if the temperature of the electrons is greater than that of the lattice. An electric field can increase the electron temperature so that they can supply energy to the lattice. This would result in further ionization and an increase in the electron concentration. Breakdown would quickly follow. This theory predicts a decrease in dielectric strength with increasing temperature.[14]

The low temperature theory and the high temperature theory are not mutually exclusive. Experiments have shown both theories hold in their respective temperature ranges. In fact, a critical temperature exists for each material which marks the transition from the low temperature behavior, This temperature is usually well below room temperature.[15]

While the intrinsic breakdown theory is well accepted, certain aspects of it are subject to disagreement. The method of generating conduction electrons, the way the electrons absorb energy from the field, whether or not the field alone is sufficient to raise electrons into the con-

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[14] O'Dwyer, pp. 41-45.

[15] A.A. Zaky and R. Hawley, Dielectric Solids (London: Routledge and Kegan Paul, 1970), pp. 147-153.

duction state, and whether or not the free electrons all move in the direction of the field are areas that still need clarification. A further disadvantage of the intrinsic breakdown theory is that it leads to a postulated intrinsic breakdown strength. This value is difficult to find experimentally because other effects, such as edge discharge from the electrodes, cause other breakdown mechanisms to come into play before the intrinsic strength is reached. Lastly, examples of intrinsic breakdown in non-laboratory conditions are rare. Usually, either some other mechanism is the more likely candidate, or the evidence is so disturbed that no mechanism can be identified. Intrinsic breakdown has therefore tended to remain a laboratory theory with little practical applications.

In the real world, many factors have an affect on the dielectric strength of any given insulation/electrode system. Some of these factors are corona, edge or surface discharges, temperature, humidity, and chemical reactions. As was mentioned earlier, it is often necessary to test the actual insulation structure either in full size or in scale models to really determine how the insulation will react. Scale model testing has the disadvantage of accentuating electrode effects so that the test may not be comparable to the full scale.

Because of these concerns, both model testing and specialized, standardized tests are performed for a relative ranking of insulations. ASTM D3638, Standard Test Method for Comparative Tracking Index of Electrical Insulating Materials contains the following disclaimer:

> The conditions specified herein are intended . . . to produce a condition conducive to the formation of surface discharges and possible subsequent tracking. Test conditions are chosen to reproducibly and conveniently accelerate a process; for this reason, they rarely reproduce the varied conditions found in actual service. Therefore, while tracking tests serve to differentiate materials under given conditions, results of tracking tests cannot be used to infer either direct or comparative service behavior of an application design. Rather, tracking test results provide a tool for judging the suitability of materials for a given application. The suitability can only be verified through testing the design in actual end use or under conditions which simulate end use as closely as possible.[16]

Indeed, it may take several standardized tests on a set of different materials to gain a true picture of how the insulations will react in real life. The American Society for Testing Materials (ASTM) currently lists over 25 testing standards for breakdown strength under various conditions and configurations for solid insulation alone. Furthermore, ASTM tests are primarily aimed at the electric power industry and tend to be more concerned about power frequency and impulse testing than for either DC or high frequency voltages.

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[16] American Society for Testing Materials, "Standard Test Method for Comparative Tracking Index of Electrical Insulating Materials," ASTM D3638-77.

# CHAPTER III

# SURFACE DISCHARGES AND ARC-TRACKING

Many of the problems encountered both in applying solid dielectrics and in studying solid dielectric breakdown are due to surface effects. Surface effects include contamination and moisture effects as well as surface corona and several levels of arcing discharges. These effects are often the limiting factor in the application of any solid dielectric.

Creepage distance is one good example. In power transformer design, for instance, a sheet of solid insulation is used from the end of layer of conductor winding to the grounded iron core. This solid insulation also serves as layer to layer insulation, but under failure conditions, failure will almost always occur as a flashover along the surface from the winding to the grounded core. See Figure 7.

Similarly, a common test for the dielectric strength of sheet insulation employs two, two inch diameter brass electrodes with the sheet of insulation under test sandwiched between the brass electrodes. The failure mode being tested for is one of puncture between the two electrodes. As the thickness of the insulation grows, the dielectric strength only increases until flashover becomes the failure mechanism. Increasing the insulation further

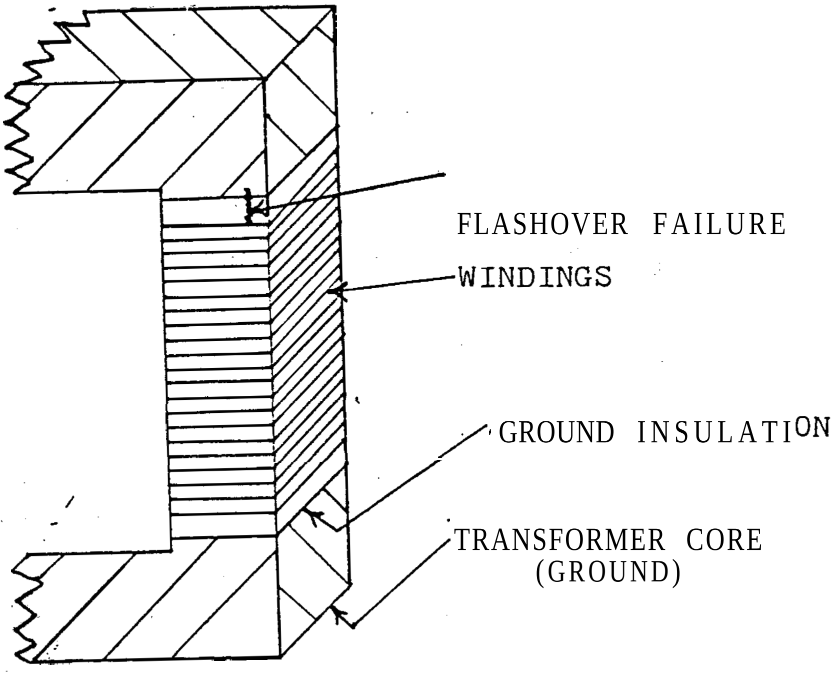

FIGURE 7. GROUND INSULATION FAILURE UNDER TRANSFORMER WINDINGS

produces only a minimal increase in dielectric strength. This is illustrated in Figure 8.

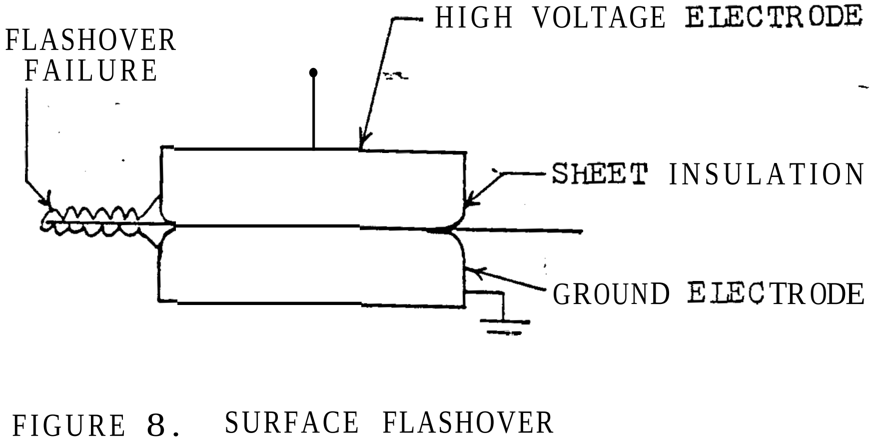

FIGURE 8. SURFACE FLASHOVER IN SHEET INSULATION TEST

Another good example, is the insulation clearance between an isolated point and ground. If the same voltage is applied across the surface of an insulator, much more distance is required to prevent breakdown. Operation in moist or contaminated environments requires even greater distances along the surface. To accommodate this long creepage length, stand-off and suspension insulators typically have fluted or rippled surfaces as do high voltage electrical bushings. Often the design of the fluting produces areas where water cannot lie for use outdoors.

While an insulating surface can usually recover from a single flashover, repeated flashovers can lead to insulation degradation and eventually to insulation failure. Any type of arcing from surface or edge corona to very powerful, high current arcs can cause deterioration of solid insulation surfaces.

Again using the example of the breakdown test using the two inch diameter brass electrodes, corona from the radiused edge of the electrode will cause visible surface degradation. Sometimes, the insulation will fail in this deteriorated ring, rather than under the electrodes.

Similarly, in actual electrical equipment, surface coronas and low level arcing can cause deterioration. The resulting weakness then fails either under an over-voltage transient or when its strength drops below the operating voltage. The exact mechanisms of breakdown vary with the type of corona or arcing and with the insulation material itself. Often, the ultimate breakdown is a thermal breakdown, but this is preceded by many, different effects as the arcing progresses.

There are different ways to classify arcs. They can be by current alone, by voltage alone, or by the energy in the arc (which is voltage and current). While it can generally be said that there are high voltage, low current arcs and low voltage, high current arcs, a more quantitative measure of the voltage and current is necessary.

Mandelcorn has theorized several levels of arcing or discharge based on the power density. These levels he terms low, intermediate, and high. Table 1 lists the respective voltages and currents involved in each level.

TABLE 1

SUMMARY OF ARC DISCHARGE SEVERITY LEVELS

| | SEVERITY LEVEL | | |
|---|---|---|---|
| | Low | Intermediate | High |
| Power Density.(W/cm$^2$) | $10^3$ | 10 | 100 |
| Discharge Voltage (V/cm) | $10^4$ | $10^3$ | 10-100 |
| Discharge Current (A) | $10^6$ | $10^2$ | 1-1000 |
| Temperature ( C) | 100 | 500 | 1,000 |

Also listed in this table is a temperature range that is caused by the heating action of the arc. Elevated temperatures cause deterioration of the insulation by various mechanisms. These mechanisms depend upon the type of insulation material and upon the atmosphere in which the discharges take place. In the extreme, the temperature will cause carbonization, which makes the insulation conductive.[17]

There are also other mechanisms of deterioration, besides heat, for each level. Again, these mechanisms are dependent upon the type of insulation and upon the atmosphere in which the discharges occur. These mechanisms include degradation by UV radiation, by active oxidizers such as ozone, by liberated chemical radicals such as $O^-$, $COOH^-$, and by attack by various acids and other compounds.[18] There are other mechanisms that come into play such as the driving off of volatiles and plasticizers, embrittlement, and even melting in the case of some thermoplastic materials.

The series of tests listed in ASTM for arc-tracking takes a very similar course as Mandelcorn in arc classification by current. ASTM D495 is specifically designed to test for the effects of high voltage, low current arcs close to the surface of the insulation. The test consists of the use of two electrodes placed on the surface of the insulation so that with an applied voltage an arc forms between the electrodes. The electrodes can be either stainless steel strips or tungsten rods. In either case, the voltage is in-

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[17] Lyon Mandelcorn, "The Effects of Electric Discharges Between Electrodes Across Insulation Surfaces, Part 1," AIEE Transactions, pt. III, August, 1961, 482.

[18] Mandelcorn, "Effects of Electric Discharges," 483-485.

creased until arcing occurs. The time until failure is recorded, generally in seconds. This is a particularly severe test and usually fails insulations in relatively short time. Four general types of failure have been recognized.

1. Some inorganic insulations become heated enough to become incandescent. In this condition, they are conducting. However, when they cool, they regain their insulating ability.
2. Some organic insulations burst into flames.
3. Some organics fail by tracking. That is a thin wiry line is formed between the electrodes.
4. Some insulations fail by carbonization of the surface.[19]

In regards to Number 2, it should be remembered that most solid insulations also have structural uses. Therefore, they are considered as failed if they burn.

In the real world, solid insulations are subjected to various types of dirt and contamination as well as extremes of humidity. These conditions usually impair the surfaces' ability to hold voltage with minimal leakage current. Therefore, the ASTM has adopted many tests to evaluate arc and track resistance under controlled contamination and humidity conditions. Table 2 summarizes these tests.

These tests vary in their severity as well as in the type of arc employed. As mentioned previously, D495 uses

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[19] American Society for Testing Materials, "Standard Method of Test for High Voltage Low Current, Dry Arc Resistance of Solid Electrical Insulation," ASTM D495-73.

a high voltage, low current arc with clean, dry insulation. D3638 utilizes a low voltage (<600V), high current arc, with timed drops of aqueous contaminants placed between the electrodes.

TABLE 2

SUMMARY OF ASTM TESTS FOR ARC AND TRACK RESISTANCE

| ASTM TEST | TITLE | POWER DENSITY |
|---|---|---|
| D495 | High Voltage, Low Current, Dry Arc Resistance | Intermediate |
| D2132 | Dust and Fog Tracking and Erosion | Intermediate |
| D2275 | Voltage Endurance | Low |
| D2302 | Differential Wet Tracking Resistance | Intermediate |
| D2303 | Liquid Contaminant, Inclined Plane Tracking and Erosion | Intermediate |
| D3638 | Comparative Tracking Index | Intermediate |

D2275 subjects the insulation surface to partial discharges or surface corona. Corona is a very low level discharge. Either cylindrical or spherical electrodes at high voltage are placed on the sheet of insulation which rests on a ground plane. The corona or the by-products of the corona degrade the insulation until failure. Failure can occur in one of several ways.

> The failure produced by corona may be due to one of several possible factors. The corona may erode the insulation until the remaining insulation can no longer withstand the applied voltage. The corona may cause the insulation surface to become conducting. The corona may cause a 'treeing' within the insulation, which may progress to failure. It may release gases within the insulation that change its physical dimensions. It may change the physical

> properties of an insulating material to embrittle or crack, and thus make it useless.[20]

D2132 subjects the insulation to arcs caused by conduction through liquid-contaminant surface films. Three strip electrodes are placed on an insulation sample which rests on a ground plane. The insulation is covered with a specific dry contaminant and water is continuously sprayed onto the insulation surface for the duration of the test. A phenomenon called "dry banding" occurs where the insulation experiences localized heating (due to conduction) which causes evaporation of the film. Arcing then occurs across the dry band. If tracking occurs, the carbonization further concentrates the field and intensifies the dry banding and the arcing.[21] Insulations can also fail by erosion rather than tracking. In erosion, the arcing volatilizes the insulation, forming channels in the surface.

D2303 is a similar test where the insulation samples are continuously bathed in a special contaminant solution, while under voltage. However, in this test, the arc current is limited by an external resistance to a much lower value than in D2132.

A more severe test is D2302. In this test the specimen and electrode assembly are partially immersed in water

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[20] American Society for Testing Materials, "Standard Method of Test for Voltage Endurance of Solid Electrical Insulating Materials Subjected to Partial Discharges (Corona) on the Surface," ASTM D2275-75.

[21] M. Kurtz, "Tracking," IEEE Electrical Insulation Magazine, May, 1987, 12-13.

while subjected to increased voltage levels (and power levels) until failure occurs.

All of these standardized tests were developed in response to specific problem areas encountered in actual practice. All except D2275 produce power densities in Mandelcorn's intermediate range. This middle third is a very wide range, covering most real world situations.

Various investigations have been performed to investigate the effects of surface discharges and the mechanisms involved in these effects. These investigations usually concentrate on one specific level of discharge. These levels vary, as with the ASTM tests, from the low level surface coronas or partial discharges through successively higher power levels of arcing. One difference between the effects of the different levels is the time to breakdown. Another is the mechanisms involved in the degradation process. The lower power levels, which are also slower, tend to have more mechanisms involved, while the higher power levels tend to create surface temperatures that cause carbonization.

In the low power level caregory, Molter, et al., list five mechanisms that come into play for surface corona: thermal, oxydative, radiative, mechanochemical, and chemical.[22] Dakin, et al., reports electron bombardment to be the primary

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[22] Kevin D. Wolter, Julian F. Johnson, and John Tanaka, "Degradation Product Analysis for Polymeric Dielectric Materials Exposed to Partial Discharges," IEEE Transactions on Electrical Insulation, October, 1978, 327-330.

mechanism with attack by ozone and oxides of nitrogen to be the secondary mechanisms.[23]

In the intermediate power density range, Mandelcorn, Hoff, and Sprengling found no one dominating mechanism other than carbonization or erosion.[24] As mentioned previously, this range is very wide, and at the higher end, almost all insulations failed in very short time.

Little or no work has been published regarding testing in the high power density range. Few laboratories are equipped to handle the combined voltage and currents at this level. Also, few insulations can pass this test.

Another critical parameter is what type of solid dielectric is being tested. Generally, all organic insulations are degraded by discharges. On the other hand, most inorganic insulations are very resistant to deterioration by discharges.

The organics are degraded by several different mechanisms. Under the lower power level discharges, chemical and thermal reactions are prevalent depending on the specific insulation. For instance, polyethylene has a low melting point, and tends to erode or melt under arcing. Also, it is readily oxidized by ozone, by ultraviolet radiation, and by acids formed as by-products of its degradation.[25]

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[23] T.W. Dakin, H.M. Philofsky, W.C. Divens, "Effects of Electric Discharges on the Breakdown of Solid Insulation," AIEE Transactions, pt III, May, 19-54, 160.

[24] Mandelcorn, "Effects of Electric Discharges," 482-486.

[25] Wolter, Johnson, and Tanaka, 327-330.

Other organics are de-polymerized by the arcing. Their molecular chains are broken down and the lighter, more volatile constituents are driven off. Other organics, such as PVC, lose their plasticizer and become less flexible.[26] Some types of Teflon absorb low energy electrons easily because of fluorine's affinity for electrons. This causes the molecular chain to decompose.

Inorganics on the other hand, tend to be very resistant to corona and low level discharges. The surface of most inorganics is only slowly disrupted. There are no volatiles to be driven off. Finally, they tend to have a regular structure, which makes it easier to recombine when a molecule is dislodged.[27]

Mandelcorn, Hoff, and Sprengling have run some tests at higher power level on inorganic insulations. They have found that if the arcing is intense enough to develop surface temperatures of 500° C, carbonization occurs and the insulators allow conduction. However, if the arcing intensity is increased to 800° C, the carbon burns off and the conduction decreases.[28]

In summary, the results of arcing and discharge-are three: chemical breakdown, carbonization or tracking, and

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[26] H.L. Saums and W.W. Pendleton, Materials for Electrical Insulating and Dielectric Functions, (Rochelle Park, New Jersey: Hayden Book Co., 1973), p.81.

[27] Dakin, Philofsky, and Divens, 160.

[28] L. Mandelcorn, R.E. Hoff, and G.R. Sprengling, "The Effects of Electric Discharges Between Electrodes Across Insulation Surfaces, Part III," AIEE Transactions, pt III, August, 1961, 491.

mechanical. By far, the most common is tracking. In a tracking failure, the arcing is intense enough, at least at the end of the process, to carbonize the surface. Current flows through these carbonized tracks, eventually bridging the electrodes and failing the insulation. The great majority of organic insulations (including most phenolics, epoxies, and polyesters) will fail in this way. Those that do not fail by tracking (such as polyethylene or acrylic) will erode or melt as the arcs move across the surface. This process also leads to failure.

The chemical breakdown is a secondary or supplemental effect. Under lower level discharges, the chemical breakdown and subsequent attack can degrade the insulation enough to cause more intense arcing. Or, the insulation's properties change enough that it is mechanically weakened. Thus, it may no longer be able to support weight or it may become brittle and unable to flex with the movement of the conductors.

In most of the standardized ASTM tests and in most of the laboratory investigations, external resistances limit the current available to the arcing. This allows the level of arcing to remain fixed through the experiment. While this is useful in studying the degradation mechanisms in the low and intermediate power density levels, it is not how arcing typically attacks solid insulation in the real world.

In actual practice, especially in power frequency apparatus, the resistance of the insulation itself is the controlling factor for the discharge current. As the surface resistance decreases, the discharge current increases, carrying the reaction into higher power density regions until failure occurs. Two scenarios are presented to illustrate this point for dry and wet conditions.

For a relatively clean and dry surface separating a high voltage electrode from ground, continuous corona occurs near the junction of the high voltage electrode to the insulation surface. This corona erodes the area adjacent to the electrode. If there is a ground point on the other side of the sheet insulation, the erosion will eventually decrease the insulation thickness so that an over-voltage transient will puncture the insulation.

Or, if the nearest ground is at the end of the insulation opposite the high voltage, the erosion increases the likelihood of a flashover occurring during the over-voltage. The flashover starts a carbon track or whisker forming on the surface. Successive flashovers form new tracks or lengthen existing ones. As the carbon tracks grow, they distort the electric field, concentrating the electric field intensity across smaller portions of the insulation. They also provide a low resistance path for the discharge current. Eventually, either an over-voltage succeeds in connecting a track to ground or the electric field becomes high enough that even the operating voltage causes arcing and the tracking reaches ground.

The second scenario again involves an insulating surface separating a high voltage connection from ground. However, in this scenario, the surface is exposed to contamination and moisture. Water being effectively a polar solvent, the moisture disassociates some of the contamination into ions. The water itself also disassociates to a small degree. Now, the ions are free to carry a leakage current over the surface. The current will raise the temperature of the moisture and, where the moisture film is thinnest, the water will evaporate leaving a dry-band. This narrow dry-band will see almost the full voltage across it. It cannot sustain this voltage and arcing will occur. The arcing will form carbon tracks and essentially short out this part of the insulation. The temperature caused by the arcing will cause further evaporation, but the new dry-bands will still be seeing an extremely high field and the arcing will continue to intensify. Failure occurs in short order as the tracks bridge to ground and to the high voltage electrode. The writer personally observed such a failure mechanism that occurred in the bottom of an oil-filled transformer.

# CHAPTER IV

## EXPERIMENTAL RESULTS

The problem with the well in the electrostatic power supplies is clearly an arc-tracking phenomenon. However, not all wells fail, so the conditions that need to exist to start the failure mechanism must be identified. Also, the sequence of events that leads from the initial conditions to final failure must be discovered. Only then, can a solution be identified.

In an effort to investigate the failure mechanism, the initial field evidence was analyzed and a test program was undertaken. The following is a summary of that effort.

The early observations and evidence relating to the well failures included a yellowing of the polyethylene cable and a tarnishing of the brass tack used as the cable termination. These symptoms were accompanied by a "wetness" on the cable and a sharp, acidic odor. In the early stages, with the cable removed, the wells emitted sharp snapping, popping and hissing noises. There were blue arcs constantly visible. The surface of the polyethylene cable was eroded resulting in an alligator-skin appearance. In the later stages, the wells had carbon tracks formed on their inside surfaces and would carry appreciable ($\sim$100 to 200 $\mu$A) current even without the cable present.

Based on these observations and on the literature, the following hypothesis was developed. The degradation process occurs in three phases. In the first phase, a low level corona in the presence of moisture starts to degrade both the cable and the well. Toriyama reports that the corona discharge produces short-lived active radicals such as $O_2^+$, $O_3$ and others that oxidize the surface of the polyethylene producing $H_2O$ and $CO_2$. Furthermore, ozone penetrates the polyethylene and produces carbolic acid.[29]

The increased moisture leads to the next phase which is a wet tracking degradation mechanism. As the moisture collects, especially where the cable is thrust laterally against the inside diameter of the well, the field distribution becomes concentrated around the water. This causes surface discharges or scintillations. Mandelcorn states that wet tracking degradation results from two mechanisms, thermal degradation and the formation of electrically conducting active products.[30] The heat generated degrades both the PVC and the polyethylene. The formation of carbon tracks further concentrates the stress which results in further arcing.

The third phase is one of pure arc-tracking. As more of the well is tracked the stress across the remaining

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[29] Y. Toriyama, et al, "Degradation of Polyethylene by Partial Discharge," <u>IEEE Transactions on Electrical Insulation</u>, August, 1967, 88-89.

[30] Mandelcorn, "Effects of Electrical Discharges," 483.

insulating surface is further concentrated causing more severe arcing. Rapidly, the whole length of the surface is tracked and current flows freely from the high voltage electrode to ground.

There are three conditions necessary for this process to occur. The presence of the cable in the well, the PVC well material, and moisture. Corona is also necessary, but corona at this voltage level (115KV) is almost unavoidable with the allowable dimensions of the electrodes involved (i.e., the contact spring and the grounded cable adapter).

The presence of the cable is necessary because, with the contact spring and its own natural flexibility, it gets somewhat compressed inside the well. This compression forces the cable to assume an "s-bend" shape, so that it contacts the inside of the well at several random locations. The interface between PVC well and PE cable becomes a weak point, concentrating the stress and collecting and distributing the moisture by capillary action.

The moisture is necessary from several aspects. First, it intensifies the corona and helps carry about the by-products of the corona attack. Second, by wetting the surfaces, it allows surface currents to flow, and it causes concentrations of the electric field. Third, when enough moisture is present, it enables the typical scintillation of a wet tracking mechanism.

The PVC well material is necessary because PVC does arc-track and therefore, the well reaches final and permanent failure. There are many materials like PVC that arc-track.

There are also many materials that, while not tracking, will not stand up to the temperatures involved in arcing. There are also materials that are more track resistant than PVC. For the well to progress to permanent failure, the well material must form carbon tracks.

A series of experiments was performed to evaluate this hypothesis.

## Experiment 1

This test involved finding some wells in customer's plants that appeared to be in the early stages of failure. This condition was diagnosed by listening to the well for sounds of popping and hissing. If these sounds persisted after cleaning the well with a suitable solvent (Freon TF), the multiplier assembly was returned to the lab where it could be tested.

Four such multipliers were discovered at the Pontiac Motor Division plant in Pontiac, Michigan. These multipliers were returned to the laboratory where the wells were examined with a borescope. All the wells showed incipient tracks.

Two of the Pontiac wells were reassembled in power supplies and fitted with cables and guns. Two similar control systems were also assembled. All four wells and all

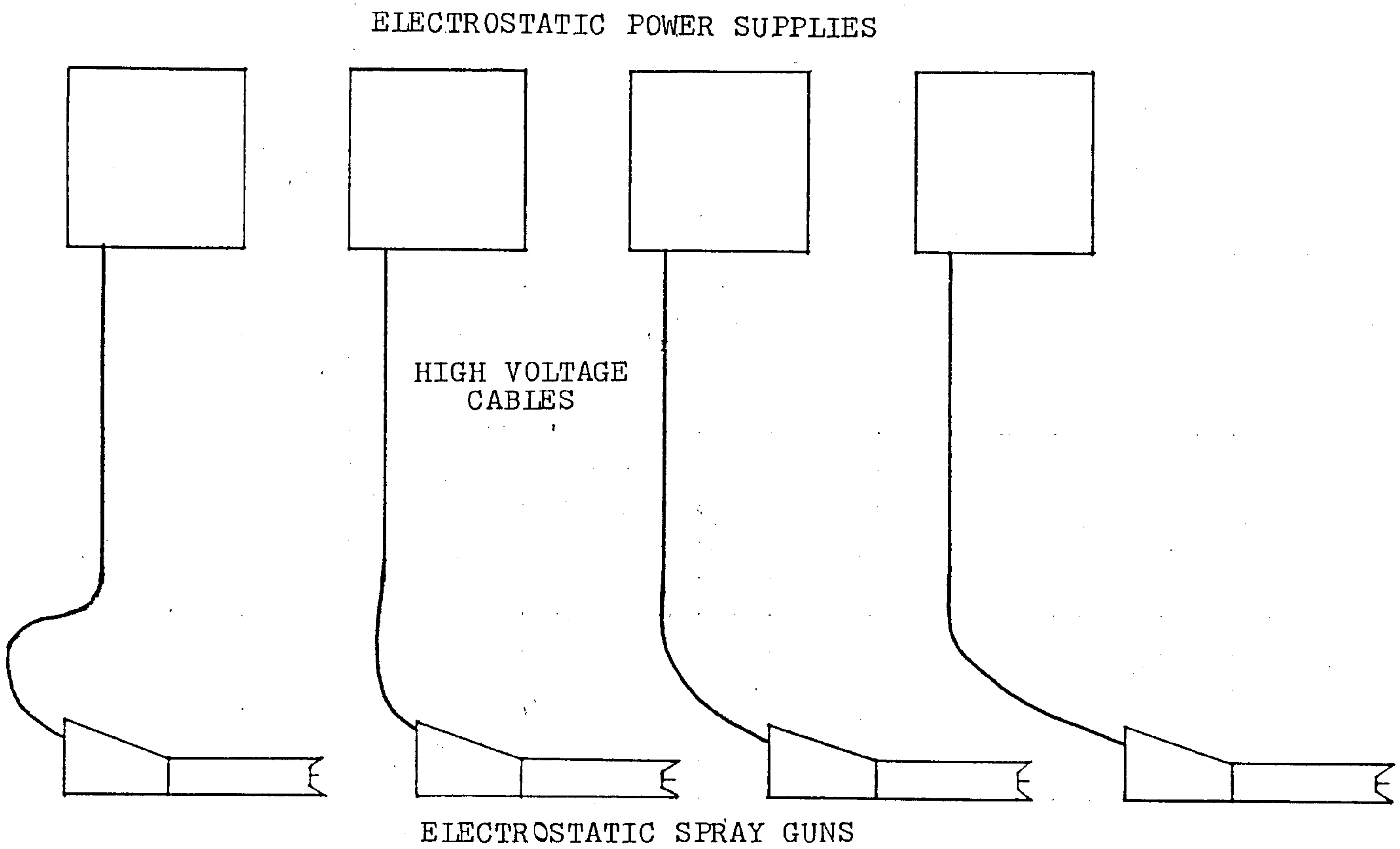


FIGURE 9. TEST SET UP FOR EXPERIMENT 1.

four cable ends were thoroughly cleaned with Freon TF before assembly. The four systems were then operated at full voltage, but were cycled on and off.

The HV cable on one of the Pontiac wells failed to ground in less than 48 hours, but the well was not degrading.

After 6 days with still no increase in current, each of the wells was audibly inspected for signs of arcing. Only the first Pontiac well showed a continuous arcing noise and it also showed a yellowing on the polyethylene of the cable. By day 9, one of the control wells was beginning to hiss and crackle. Also at this time the first Pontiac well would draw 10-20$\mu$A on its inside surface without the cable present. The cable was yellowing especially near the threaded cable adapter (grounded electrode). The second Pontiac well showed a steady crackling and was also beginning to yellow the polyethylene.

After 41 days, no further degradation had occurred and the experiment was terminated. In hindsight, this test was run in an humidity uncontrolled room in the middle of winter. The lack of any ambient moisture prevented the reaction in the well from progressing to the second and third stages.

## Experiment 2

In order to expose new wells to a variety of different moisture conditions, a more controlled experiment was performed. An acrylic plate was used to suspend four inverted wells in a bucket of insulating oil. The high voltage ends of the four wells were connected. Three such buckets were constructed with two standard EPU-9 Power Supplies feeding the buckets. This arrangement is shown in Figure 10. In order to introduce moisture in the wells, some of the cable ends were dipped in water. Since this equipment is used in a paint environment, other cable ends were dipped in a solvent blend consisting of equal parts of methyl isobutyl ketone, toluol, and xylene. Some wells were also left open, without cables. Finally, several wells were operated as controls. This is summarized in the following table.

TABLE 3

SUMMARY OF CABLE END CONTAMINATION USED IN EXPERIMENT 2

| BUCKET | WELL | CABLE |
|---|---|---|
| 1 | A | Clean cable to other buckets |
|  | B | Input cable from EPU-9 |
|  | C | Cable dipped in solvent blend |
|  | D | Open well |
| 2 | A | Clean cable to other buckets |
|  | B | Cable dipped in water |
|  | C | Cable dipped in solvent blend |
|  | D | Open well |
| 3 | A | Clean cable to other buckets |
|  | B | Input cable from EPU-9 |
|  | C | Cable dipped in solvent blend |
|  | D | Cable dipped in water |

Within eighteen hours, two wells showed signs of being in the first stage of degradation. The cable in well 2B, which had been dipped in water, had black carbon smudges

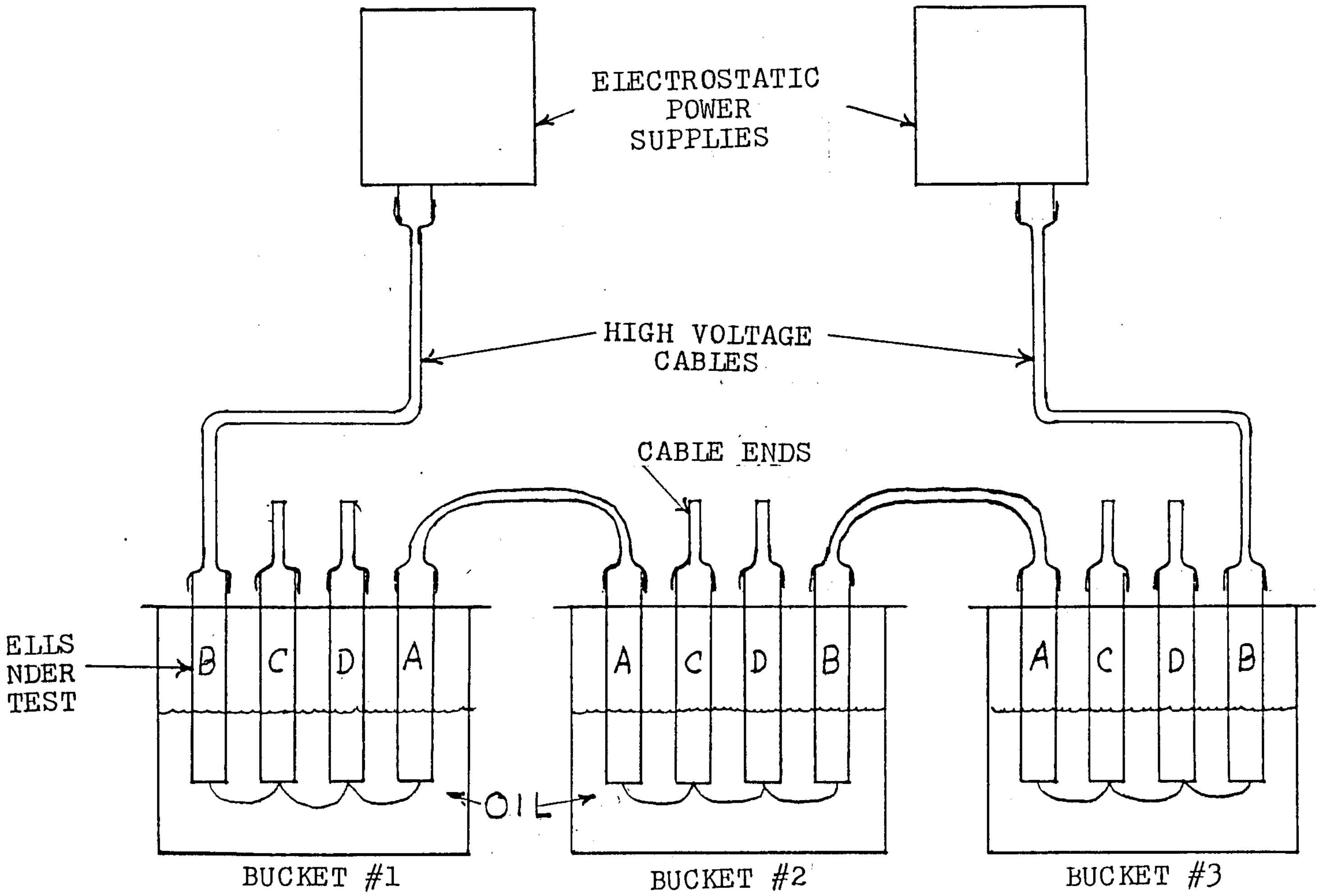


FIGURE 10. TEST SETUP FOR EXPERIMENT 2.

at the tack end and had a yellow stain near the grounded cable adapter. The well itself had visible arcing inside, when it was energized without the cable. However, a borescope examination showed only hair line arc-tracks.

Well 3D, the other well with a cable dipped in water, was further along in the degradation process. There had been enough arcing to raise the temperature of the cable enough to soften it. With the applied force of the spring, the cable had actually swollen or increased its diameter such that it was difficult to remove. Borescope examination showed the well had a single, heavy arc-track.

Both wells and both cable ends were replaced. The cable end that was inserted into well 3D had a teflon heat shrink tube fit tightly over it. Instead of dipping the cable ends in water, 1.0 cc of water was added to each of the wells.

Within 48 hours, well 2B had failed again. This time, the arcing had raised the temperature enough to soften the polyethylene and to swell the cable so that it was unable to be removed.

After another 24 hours, well 3D, which had the teflon heat shrink applied to the cable end, showed evidence of treeing on the polyethylene as well as a yellowing near the ground electrode. Also the teflon had one spot of heat distortion. The well itself had sounds of arcing without the cable. Within 36 more hours, the well and cable had progressed to failure. As with the other wells, the cable had softened and expanded so that it could not be removed. These wells and cables are shown in Figure 11.

Since the two wells that had been left open had not shown any signs of arcing, 1.0 cc of water was added to both wells 1D and 2D. These wells ran for 15 days without any indication of arcing or degradation.

The conclusions that can be drawn from these two experiments are as follows. First, moisture is absolutely necessary to start and to sustain the reaction. Second, an open well, one without a cable, will not begin the failure process, even with water present. Third, the presence of solvent had no effect.

Another experiment was run to evaluate the role that the PVC material of the well plays in the degradation process.

## Experiment 3

The same arrangement used in Experiment 2 was used, but wells made from a glass-melamine material (NEMA grade G-9) were used. The glass-melamine material is much more track resistant than the PVC.

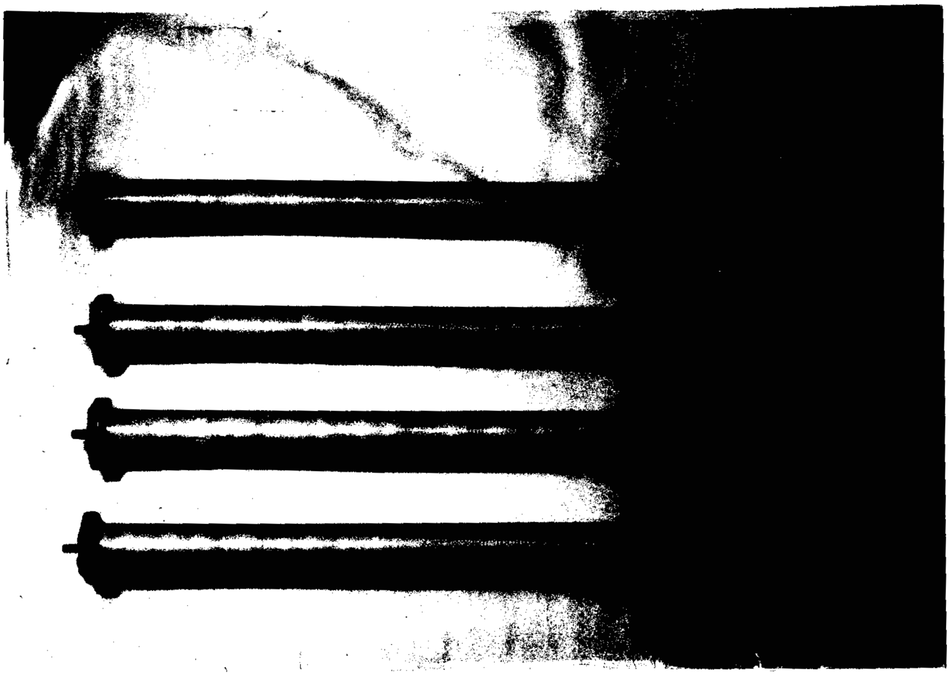
Two glass-melamine wells were constructed by inserting the glass-melamine well into the PVC end coupling. These wells were then installed in the same apparatus of Experiment 2. One of these (B) had 2.0 cc of water added to the well while the other (D) was the control. Two PVC wells were also used, A had the input power cable and C was left open.

After 27 hours of operation, the cables and wells were examined, Well D was unaffected, while the cable in well B showed a yellowing near the grounded, threaded cable adapter. When the test was re-energized, well B drew excessive current. Within 30 minutes, the cable in well B had become alligator-skinned and a hole had melted down to the conductor opposite the grounded cable adapter. The well showed visible arcs when operated without the cable. However, no arc tracks had formed.

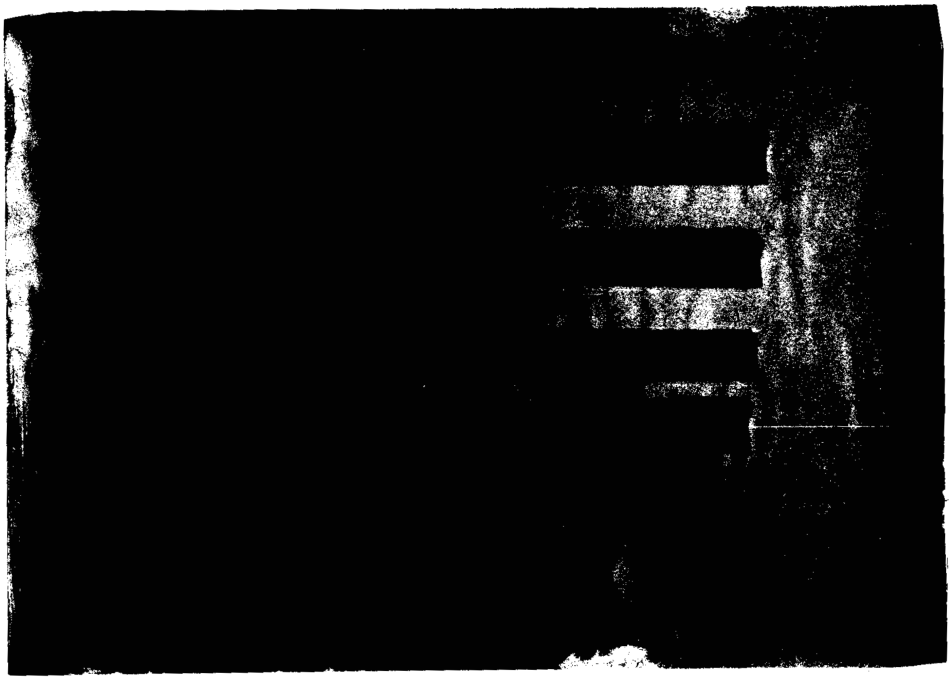
Well B was removed from the test and 4.0 cc of water were added to well D and the test was resumed. Within 2 hours, well D was arcing violently enough to cause ripples in the oil in the bucket. Upon examination, the cable showed severe deterioration opposite the PVC coupling, but showed no deterioration opposite the glass-melamine well. Also, the well showed tracking only on the PVC coupling, not along the glass-melamine.

To eliminate the PVC material, a brass adapter was machined to join the glass-melamine well to the grounded, threaded cable adapter. One well was fitted with this and the test was repeated. 2.0 cc of water were added to the well and a clean cable end was inserted. In 1.5 hours, the well had audible and visible arcs, but there was not tracking. Instead the surface of the cable had become alligator-skinned. These wells are illustrated in Figure 12.

The conclusions of this experiment are as follows. First, the PVC is necessary for arc-tracking to occur. A



a) ASSEMBLED GLASS-MELAMINE WELLS.



b) SECTIONED **WELLS** BEFORE AND AFTER TEST.

FIGURE 12. SAMPLE GLASS-MELAMINE WELLS **FROM** EXPERIMENT 3.

highly track resistant material will not arc-track under these conditions. However, since the high electric field and the corona exist regardless of material, removal of the PVC will not prevent corona, arcing, and the deterioration of the polyethylene cable. It would appear, however, that replacement of the PVC with some highly track resistant material will prevent the well from permanent failure by arc-tracking.

# CHAPTER V

# DISCUSSION OF RESULTS

While the hypothesis appears to have a clearly defined cause and effect relationship between the failed wells and the applicable variables, there is always a possibility that there are other factors not discovered by the experiments. This is particularly true when there is no solid theoretical basis for the failure mechanisms. Therefore, several areas were investigated in an effort to put the well failure hypothesis on a more theoretical footing.

First, since much of the degradation of the cable and the well has a thermal cause, there may be an effect from heating due to the normal insulation leakage current. This leakage current, caused by the DC electric field, would be due primarily to conduction through the dielectrics, or along the interfaces or surfaces between the dielectrics.

The total field can be examined by studying the axial and radial components, separately. Clearly, the highest field is the radial component at the grounded, threaded cable adapter at the open end of the well. During the experiments this region invariably showed a yellowing of the polyethylene of the cable due to corona caused by this high, local field. In the case of a DC voltage on a dielectric, the initial field is determined by the dielectric constants of the insulations. Then, in the steady state, the field becomes a function of the conductivities of the insulations.

Standard equations for the initial electric field are given by Kraus and Carver:

$$E_r = q_l/2\pi\epsilon r \qquad (5)$$

$$V = q_l \ln(r_0/r_i)/2\pi\epsilon \qquad (6)$$

Where: $q_l$ = linear charge density (C/in)

$r_0$ = outside radius (in)

$r_i$ = inside radius (in)

Eliminating $q_l$ from the two equations produces:

$$E_r = V/(r\ln(r_0/r_i)) \qquad (7)$$

Thus the field is not constant throughout the radius, but decreases as the distance from the center increases.[31]

Extending this equation to the case of two series, cylindrical dielectrics, produces:

$$E_{PE} = V/r(\ln r_0/r_i+l_n r_0/r) \qquad (8)$$

$$E_{air} = (\epsilon_{PE}/\epsilon_{air})E_{PE} \qquad (9)$$

Where: = electric field intensity in the polyethylene

$E_{air}$ = electric field intensity in the air

$\epsilon_{PE}$ = relative dielectric constant in the polyethylene

$\epsilon_{air}$ = relative dielectric constant of the air

$r_i$ = inside radius (i.e. radius of conductor)

$r_0$ = outside radius of the polyethylene

$r_0$ = outside radius of the air

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[31] John D. Kraus and Keith R. Carver, *Electromagnetics*, (New York: McGraw-Hill Book Company, 1973), pp. 79-81

The cable outside diameter is .375" and the air outside diameter is .40625". Using $\epsilon_{PE} = 2.2$ and $\epsilon_{air} = 1$, $E_{PE} = (76/r)$KV/inch. For $r = .045$, $E_{PE} = 1.70$ MV/inch, and for $r = .1875$, $E_{PE} = .41$MV/inch. According to Rogers, polyethylene has a mean breakdown strength of approximately 1.27 MV/inch, which makes the initial field at the center a bit too high.[32] However, the bulk of the cable is not over-stressed.

For the air, $E_{air} = 2.2(76/r)$KV/inch. At the cable/air boundary, $E_{air} = 892$KV/inch. This value is well above the mean breakdown strength of the air. Even at the interface of the air with the ground electrode, $E_{air} = 823$KV/inch. This means that the air cannot sustain this electric field intensity, so it doesn't supply any insulating properties and in effect, the field intensity in the polyethylene is marginally higher.

To calculate the leakage current, the resistivity of the polyethylene must be taken into account. According to Rogers, polyethylene has a conductivity ($\sigma$) of $3.67\text{x}10^{-16}$ ℧/m or a resistivity ($\rho$) of $2.72\text{x}10^{15}$ $\Omega$-m or $107.28\text{x}10^{15}$ $\Omega$-inch.[33] Calculating the current density in the radial direction,

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[32] E.C. Rogers and D.J. Skipper, "Gaseous Discharge Phenomena in High Voltage D.C. Cable Dielectrics, "<u>The Proceedings of the IEE</u>, June, 1960, 243.

[33] Rogers and Skipper, "D.C. Cable Dielectrics," 248.

$$J_r = E_r/\rho = (76/r\text{KV/inch})/(107.28\text{x}10^{15}\Omega\text{-inch})$$
$$= (708.43\text{x}10^{15}/r)\text{A/inch}^2 \qquad (10)$$

Then the current per unit axial length is

$$I = \int_s J_r ds = 2\pi r J_r = 2\pi(708.43\text{x}10^{-15})\text{A/inch}$$
$$= 4.45\text{x}10^{-12}\text{A/inch} \qquad (11)$$

The cable is under this high field intensity for an axial distance of 1 inch, so the total leakage current is 4.45 pA. The heating effect of this current is negligible.

In the steady state, when the field is determined by the resistivity of the dielectric, the field intensity is given by

$$E_r = J_r\rho^{34} \qquad (12)$$

As before, the total current per unit length is

$$I_e = \int_s J_r ds = 2\pi rJr \qquad (13)$$

$$E_r = I_1\rho/2\pi r \qquad (14)$$

$$V = \int E_r dr = I,\rho\ln(r_0/r_i)/2\pi \qquad (15)$$

Solving for I  and using the values for the cable produces

$$I, = 2\pi V/\rho\ln(r_0/r_i) = 4.71\text{pA}, \qquad (16)$$

which is very close to the initial leakage current and is likewise negligible.

The axial field component is easier to calculate with the help of some simplifying assumptions. Assume that the only ground point is the grounded, threaded cable adapter. Thus the entire 115KV is stressed across the length of the

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[34] Branko D. Popovic, <u>Introductory Engineering Electromagnetics</u> (Reading, Massachusetts: Addison-Wesley Publishing Company, 1971), pp. 209-211.

well. The average field strength then is

$$E = 115KV/8inch = 14.4KV/inch \quad (17)$$

Again, using the resistivity of polyethylene ($107.28\times10^{15}\Omega$-inch), the leakage current density is

$$J = (14.4KV/inch)/(107.28x10^{15}\Omega\text{-inch})$$
$$= 134.23x10^{-15}A/inch^2 \quad (18)$$

The cross sectional area of the polyethylene is $.110inch^2$. Therefore the leakage current $I = 14.77x10^{-15}A$, which is negligible.

The conclusion is that leakage current alone could not be heating the polyethylene or the PVC sufficiently to cause the degradation seen in the failed wells.

Another area to consider is charge injection from the metal electrodes onto the surfaces of the polyethylene and the PVC. Charge emission from electrodes typically occurs under either very high local field strengths or at elevated electrode temperatures. Two types of emission will be studied: Shottky injection and tunneling.

Shottky injection is a type of thermionic injection. The potential barrier is lowered due to the combined applied and imaged field: The resulting injection current is

$$i(E) = i_T\exp(\Delta\phi/kT) \quad (19)$$

where: $i_T$ = Thermionic current with no applied field

$\phi$ = work function (eV)

k = Boltzmann's constant = $8.63x10^{-5}eV/k$

T = temperature (K)

For $\phi = 4\text{eV}$, $i_T$ is very small at room temperature:

$$i_T = (273)^2 \exp(-4/(8.63\text{x}10^{-5})(273)) = (273)^2 \exp(-170)$$
$$= (273)^2 (18.43\text{x}10^{-75})\text{A} \qquad (20)$$

This brief analysis shows that Shottky emission is not a factor in the failure mode of the well.[35]

Tunnel injection occurs when the wavelength of the probability wave of an electron is larger than the thickness of the potential barrier. This emission produces a current density given by

$$J = 1.54\text{x}10^{-10}(E^2/\phi)\exp(-6.83\text{x}10^9 \phi^{3/2}/E) \qquad (21)$$

where: $J$ = current density ($\text{A/m}^2$)

$E$ = electric field intensity (V/m)

$\phi$ = work function (eV)

For any field less than $10^8$V/m, J is essentially zero.[36]

These alternative mechanisms were investigated in an attempt to see if the well failure mechanism could be other than arc-tracking. Instead, these alternatives were shown not to be a factor in the well failures. Even though arc-tracking cannot be theoretically developed and proven, it is the only mechanism that agrees with all the evidence.

The hypothesis is therefore proven by the experiments and by the evidence from field failures. Considering the operating voltage and the electrode configuration at

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[35] Roland Coelho, Physics of Dielectrics for the Engineer (New York: Elsevier Scientific Publishing Company, 1979), pp. 116-117.

[36] Coelho, Physics of Dielectrics, pp. 119-122.

both the high voltage end and at the ground end of the well, the design is at the borderline of corona occurrence. With the slightest bit of contamination, moisture, or a sharper than normal edge on an electrode, corona will be present.

Both Toriyama and Wolter have shown that polyethylene is degraded by corona and the by-products of corona in air. These by-products included ozone and activated radicals. As the polyethylene degrades, it releases $H_2$, $H_2O$, and carbolic acid. The acid further oxides the polyethylene.[37] Both the ozone and the carbolic acid also attack the steel contact spring and the brass tack. The acid also produces the sharp, acidic odor.

If there is a good supply of moisture to begin with, the reaction noted above is further catalyzed. The amount of water generated by the degradation of the polyethylene is very small in comparison to the moisture that starts the reaction. The initial supply of moisture also serves to carry the carbolic acid and the activated radicals to the surface of the PVC. This solution allows surface currents to begin flowing along the surfaces of the PVC and the polyethylene, much as in ASTM D2303 "Liquid Contaminant, Inclined Plane Tracking and Erosion Test." As the current moves through the solution, the field becomes concentrated across the areas that are still dry. This causes higher energy discharges.

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[37] Toriyama, et al, "Degradation of Polyethylene," 90.

The moisture tends to collect where the cable end is thrust laterally against the wall of the well by the spring force. This usually occurs somewhere between the two ends of the well. Therefore, the concentration of the field results at each electrode. This concentration produces more and stronger corona.

Eventually, the corona grows into more energetic discharges. These discharges begin the deterioration of the PVC. The PVC degrades thermally as the arcs heat the surface. Initially it gives off plasticizers and other volatiles and probably becomes somewhat brittle. As the arc temperature increases, carbon tracks begin to form.

If the reaction is stopped at this point by removing the cable, the well will show the visible and audible signs of arcing. Furthermore, the cable's contact tack will be tarnished and there will be an acidic odor. The polyethylene of the cable will show yellowed areas indicating oxidation. This is especially true opposite the ground electrode. The surface may also be eroded in an alligator-skin fashion by arcing and surface currents.

If the reaction is allowed to continue, the carbon tracks further intensify the field across the areas of the well that are still insulating. This causes a further increase in the arc intensity. From this point on, the reaction progresses quickly to failure.

Rapidly the rest of the insulating areas will be bridged by arc-tracks. At first the tracks will be thin, but as the full current available begins to flow through the carbon, the tracks will widen. Once the current can flow easily, the arcing will cease. Only the high effective resistance of the power supply and multiplier limit the current and prevent the tracks from burning through the PVC.

Once the initial tracking occurs, the process is irreversible. Prior to the tracking, removal of the cable and cleaning the well with a suitable solvent, such as Freon TF, will prevent further degradation. This is probably a result of the solvent drying the moisture. However, once carbon tracks form, they cannot be removed.

# CHAPTER VI

## SOLUTIONS

Based on the experimental evidence and on the literature researched, there are several possible solutions to pursue. However, the successful solution will not only prevent the arc-tracking, but it will also satisfy the practical considerations. These considerations include the size limitations and the available manufacturing methods.

Since the corona is the start of the degradation process, one possible solution would be to eliminate the corona by better electrode design. Both the high voltage contact spring and the threaded adapter that is the ground electrode have sharp features that have high field concentrations.

However, at the full voltage of the power supply, the necessary radiuses would cause a two to three times increase in the diameter of the well. This would make the well larger than the entire multiplier housing. Also, there is no good way to shield the helix of the spring without adding other sharp corners.

Another possibility would be to lengthen the well to reduce the stress on the surface. However, the well is already the longest part of the multiplier. The multiplier is also at the maximum size for the current power supply enclosure, Another approach is to replace the PVC well with a more track-resistant tubing. This new material could then withstand the corona without allowing the degradation process to occur. Two materials were looked at in this regard.

The first material was a fiberglass reinforced melamine resin tubing with a NEMA grade of G-9. NEMA ranks both tubes and sheets of various organic materials by different classifications. A rating of G-9 indicates that the material has superior arc resistance and thermal stability. Materials with a G-9 rating are used extensively in high voltage power frequency applications.

There were two problems encountered with the G-9 tubes. First, while the G-9 material performed better in the tests than the PVC, the G-9 material did show some deterioration under the more extreme arcing conditions. With 1.0 cc of water in the G-9 wells, the arcing caused the surface to become rutted. It appeared that the glass fibers had become exposed.

The second problem with the G-9 tubes was a manufacturing concern. The PVC well is easily assembled with PVC cement. The cemented joints are both strong and oil-tight, Obtaining an easily-cemented and a reliable joint was much harder with the G-9 tube. Also, the tubing is not easily machined for a threaded joint.

For these two reasons, the G-9 material was judged to be an unsuitable solution to the arc-tracking problem.

Another material investigated was acrylic. Acrylic, which is also known as plexiglass, is superior to the G-9 glass-melamine in that it is easily glued with conventional glues and techniques and it can be machined. Acrylic also is superior to PVC in its performance under arcing. Under tests run according to ASTM D495, PVC shows an arc resistance of 60-80 seconds while acrylics are listed as "no track."

As mentioned previously, ASTM D495 "Standardized Test for High Voltage, Low Current, Dry Arc Resistance of Solid Electrical Insulation" tests for arc resistance with an intermediate power density from a high voltage, low current arc under clean and dry conditions. Since the arcing in the well occurs under moist and contaminated conditions, good performance in the D495 test may not be sufficient for similar service as the high voltage well. Therefore, the acrylic wells were thoroughly tested under moist and contaminated conditions.

A test similar to the one used to create arc-tracking in the PVC wells was set up. Five-gallon buckets were filled with transformer oil and several inverted wells were placed in each bucket. All the wells in a given bucket were connected in parallel. One well received the cable from the high voltage power supply. The other wells had short cables installed to simulate actual conditions. Half of the buckets were sprayed with water, while the other half were dry.

None of the wells failed due to the arcing. However, the testing did show up a serious mechanical deficiency.

The acrylic material is very notch sensitive and is prone to stress cracking. The machined threads were the cause of a stress concentration that resulted in over 40% of the wells failing mechanically. The acrylic was also very sensitive to surface crazing caused by degreasing solvents.

The acrylic well was not used as a solution to the arcing well problem because of these mechanical shortcomings.

Finally, attention was turned to improving the well and cable surface conditions by eliminating the moisture and contamination. During the early stages of the problem, some methods of improving these conditions were implemented, but with only marginal success. These methods included shipping the power supply with a silica gel dessicant inside the well. Also, various O-rings and seals were added where the threaded adapter screwed into the well. None of these methods produced a major improvement in the problem.

The final method to improve the surface was to replace the air in the well with something with a higher dielectric strength. Various dielectric greases and gases were considered, but the solution that was implemented involved inverting the entire multiplier well assembly and filling the well with transformer oil.

Transformer oil has been used successfully for many years in HVDC cables and has several times the dielectric strength of air. The oil drastically decreases the amount of corona generated by the electrodes. Also, the oil displaces all the air in the well and increases the surface dielectric strength. Finally, the oil is compatible with both the PVC and the polyethylene, The power supplies have been operating in this way for four years without a single arc-tracking failure.

# APPENDIX A

## Experimental Procedures

## EXPERIMENTAL PROCEDURES

### Experiment 1

Procedure:

Four complete systems consisting of an electrostatic power supply, a high voltage cable, and a electrostatic spray gun, were set up and operated in an effort to cause well failures. Normal corona current from the gun electrode is 40-50 A. The current being supplied by the power supply was periodically recorded.

Data:

CURRENT ( A)

| SYSTEM | OHRS | 48HRS | 72HRS | 144HRS | 216HRS | 600HRS |
|---|---|---|---|---|---|---|
| 1 | 50 | 50 | 52 | 50 | 50 | 60 |
| 2 | 40 | 45 | 45 | 35 | 40 | 58 |
| 3 | 65 | 65 | 65 | 60 | 65 | 70 |
| 4 | 50 | Fail* | 60* | 40 | 50 | 50 |

*Cable had failed, was replaced.

### Experiment 2

Purpose:

To evaluate moisture and contamination as a cause of the arc-tracking.

For set up, see Figure 10, and see Table 3 for cable end contamination. The following notes are excerpts from the lab notebook.

Test began on 3/2/81 at 2:20 pm. Each power supply was reading 110 A.

3/3/81

Current down to 100 A.

But at 9:10 am, current jumped to 150 A and well 2B began arcing. Cable end has black carbon smudges on the tack end and a yellow stain near the swivel fitting. There was a distinct smell of acid. The well itself had visible arcs when energized without the cable.

Well 3D was worse off. The cable end had swollen from heat and was hard to remove.

Well 3D was replaced with a new well and a cable end with a Teflon heat shrink tubing over the polyethylene. Well 2B was replaced with a new well and a standard cable end. Both wells received 1.0cc of water.

· The test was resumed at 2:50 pm. Current on both units was 105 A.

Subsequent borescope examinations of the failed wells showed a single heavy track on 3D, but only hair-line tracks on well 2B.

3/5/81

Current has dropped to 90 A.

But at 1:00 pm, the current was at 110 A. By 1:10, one unit was at 150 A and the other was at 165 A.

Bucket 2 appeared to be drawing the high current, so it was taken apart and examined.

2A -- Incoming power-no degradation.

2B -- Water doped-was unable to remove cable from well because of swelling.

2C -- Solvent doped-showed faint signs of tracking and showed a carbon near the cable adapter.

Bucket 3 was than examined.

3A & 3B -- clean end to other wells and input power cable-both OK.

3C -- Solvent doped-looked OK.

3D -- Teflon heat shrink-still wet, but no degradation.

Continuing to Bucket 1-all wells OK.

Restarted the test, without well 2B, at 1:50 pm. Current was 100 A.

3/6/81

Set current limiters at 150 A for operation over the weekend. Examined the wells:

3D -- Teflon treeing apparent on surface of the polyethylene underneath the Teflon heat shrink. One spot of heat distortion on the Teflon and yellowing near the cable adapter. The well arcs without the cable in it.

2C -- Polyethylene showed some alligator-skin.

1B -- Cable has failed dielectrically.

All other wells OK.

Removed well 1B and resumed test. 3D arcing violently and rippling oil.

3/9/81

Terminated test. Current limiters had tripped.

3D had swollen so that it could not be removed (Teflon).

<u>Experiment 3</u>

Excerpts from lab notebook:

3/31/81

Reconfigured the test set up so that #3 bucket is driven by #1 power supply and the input power goes into well 3A. The cable end formerly in 3A, now goes into 3B and a new one goes into 3D. 3B & D are now the glass-melamine wells. 3C is empty. For now, 3D will be the control (no water) and 3B will have 1.0cc of water.

Test was started at 8:30 am, current at 128 A. By 4:35 pm, current was 118 A with no signs of arcing.

4/1/81

At 11:30, the wells were examined. 3D was OK, but 3B showed some signs of yellowing on the polyethylene near the cable adapter. The test was resumed with current at 180 A.

By noon, the current was up to 200 A. The cables were removed and the empty wells were energized. Arcing occurred in 3B. The cable end showed alligator-skin and was melted down to the inner conductor near the cable adapter.

3B was removed. 4cc of water were added to 3D and the test was resumed. By 3:30 3D had failed by arc-tracking on the PVC coupling.

4/30/81

A brass machining was used to replace the PVC coupling and another glass-melamine well was tested. The well failed by drawing excessive current within 2 hours. Inspection of the cable and well showed no carbonization on the well and only one spot of alligator-skin on the cable.

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