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CASE STUDIES OF FAILURE OF POLYMERIC ELECTRICAL INSULATION

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1.0 Abstract

Polymeric electrical insulation failures are due primarily to material composition, design, processing, service conditions or combinations thereof. Time to failure may be immediate, i.e., as manufactured, if specifications are not met. Others may not develop until after many years of service. Since life expectancy of electrical insulation is of the order of 40 years, failure in less time is considered unacceptable. Examples are given of many types of failure and their prevention for power distribution cable and for lower voltage applications.

2.0 Introduction

Polymeric electrical insulation is subject to failures of types other than electrical failure, as well as due to effects of electrical energy [1,2]. In general, all failures are due to the material, design, processing, service conditions, or combinations thereof. Time to failure may be immediate, i.e., as manufactured, if specifications are not met. Others may develop within months, up to about a year or less, unrelated to service conditions. Failures that occur in service may be of an electrical nature, or other factors such as thermal degradation or fracture due to mechanical stress. Failures due to processing often result from the high heat history required to form and crosslink polymer. The failure may be within a part of the overall construction other than the polymeric insulation. For example, appearance of the conductor surface [3] or fracture of a secondary polymer such as a mylar polyester wrap around the conductor beneath the insulation [4]. Examples of some of these failures are given in this paper.

3.0 Failures During Manufacture

Two broad categories are (1) failure to meet mechanical or electrical property specifications, such as insulation resistance or dielectric strength, and (2) appearance, such as dulling of the conductor surface [3], or discoloration of pigmented insulation or jacket. Appearance may not affect electrical or mechanical performance, but could be the cause of rejection. Halogen-containing polymers, such as fluorine or chlorine, or halogen-containing flame retardants, such as brominated hydrocarbons, may degrade during processing, releasing HF, HCl or HBr. Such byproducts of processing, even at very low concentration, may react with copper conductor. Dulling of the usual shiny copper surface has caused rejection of the product [3]. The effect of hydrogen halide on appearance or to degrade a component of the cable is enhanced if water is present, such as in steam curing under pressure. Water converts nonionic HX or other acids to the ionic form (H^+, X^-). In this form, corrosion of metal and hydrolysis of condensation polymer, such as mylar polyester, may occur readily. If lower temperature is used in processing to minimize problems of metal corrosion or polymer hydrolysis, the insulation may not be well fused or adequately crosslinked. Less than ideal fusion may cause the extrusion weld line to be a vulnerable locus of failure either electrically or mechanically. Balancing composition, design and processing to meet initial specifications and cost and to survive in service is a virtual "tightrope walk" for all the people involved in design, material selection and processing. Compromises are made to control cost and/or properties, often resulting in certain properties being diminished.

3.1 Examples of Failures During Manufacture

3.1.1 Examination of the conductor surface of low voltage fluoropolymer insulation revealed a dull appearance due to reaction with HF released from the polymer during extrusion. Surface analysis confirmed the presence of fluorine. The customer would not accept the lot even though no effect was expected on performance in service [3]. Control of processing conditions so that polymer does not degrade is critical in all plastics processing, especially so with halogen-containing polymers and flame retardants.

3.1.2 Mylar polyester film wrap over twisted insulated wires, below flame retardant insulation, was embrittled and cracked into many pieces as made [4]. Steam curing under pressure caused the polyester to hydrolyze in the presence of very low level of hydrogen halide formed in processing. See 3.1.1 last sentence.

3.1.3 Power distribution cable crosslinked with peroxide did not meet electrical properties as made. Heating of the whole cable reel for several hours in an oven was needed to reduce the volatile content so that electrical properties could be met. Cost and manufacturing time were affected. Possibly a different formulation would not require the additional heating step.

3.1.4 Colored jacket of cable was badly discolored as made in a very thin band of dark color at the outside surface. The cable was crosslinked with peroxide following extrusion under steam pressure in a continuous vulcanization (CV) line. Discoloration occurred only if the CV line was also used for other cables which were sulfur cured. Hydrogen sulfide (H_2S) is a byproduct of sulfur curing. If the same recycled water for steam curing was used for cables with both types of cure, unacceptable discoloration of colored cable occurred. While H_2S was the likely cause of discoloration, manufacturing engineers had to be convinced because it meant either using separate CV lines or not using recycled water to prevent discoloration. In either case, manufacturing cost or scheduling was affected.

The thickness of the discoloration was of the order of a small fraction of a micron. Analysis to detect sulfur in the discolored surface by scanning electron microscopy/energy dispersive x-ray spectroscopy (SEM/EDX) [5] was not positive. The method analyzes 1-2 microns, so that sulfur content was below the detectability limit. In addition, lead and sulfur overlap in the spectrum, and a colorless lead compound was present in the jacket formulation. Another method of analysis was needed if proof of the presence of sulfur as the cause of discoloration was to be confirmed.

X-ray photoelectron spectroscopy (XPS) [6] was performed on discolored surface and on undiscolored material below the surface. XPS analyzes thicknesses up to about 50-100 angstroms (5-10 nanometers or 0.005-0.01 micron). Sulfur was detected at the surface and not below the surface. Because the discolored samples analyzed had been handled without protective gloves, it was possible that the sulfur was from body chemicals, or sulfur compound dried on the surface from the water used in steam curing. To eliminate such extraneous sources of sulfur, the surface was washed with soap and distilled water and rinsed thoroughly with distilled water. Sulfur was still detected at the surface, confirming its role in discoloration. The color change is believed to have been caused by reaction with the colorless lead compound to form lead sulfide, a black compound. Figure 1 is the XPS spectrum showing the sulfur 2p peak at 168.75 electron volts (ev) binding energy [7]. The two largest peaks are lead and the medium size peak at 153.12 ev is silicon.

A change in formulation might prevent discoloration. If that is not possible, then either a separate CV line is needed or scheduling so that the colored cable is not exposed to H_2S during steam curing.

3.1.5 Crosslinked EPR type power cable had low dielectric breakdown strength as manufactured that could not be raised, so that whole lots of cable were unacceptable. Failures occurred in the weld line. Adjustment of extrusion conditions to improve fusion at the weld line gave acceptable product.

4.0 Failures That Developed After Manufacture in Service

4. Water treeing of polyethylene (PE) and crosslinked PE power distribution cable has caused failure in approximately 10-15 years of underground service [8]. Forty year life was expected. The cause is the synergistic effect of water and electrical energy together with traces of oxygen in the insulation. Significant improvement has been made by using polymer free of impurities and by incorporating tree retardants into the formulation. The term treeing is used because the degraded pattern that forms gradually with time and eventually causes electrical breakdown of the insulation has the appearance of trees when stained and examined microscopically.

4.2 In power distribution cable oxidative degradation and fracture occurred in PE jacket in direct contact with a copper wrap on the jacket bottom [9]. Failure occurred where the cable was wet for a long time, causing copper metal to form copper ion, which is a catalyst for oxidative degradation of PE. A metal deactivator and adequate antioxidant would help prevent embrittlement and fracture.

4.3 Neoprene jacket over a bundle of wires lying on the ground in a field to a radar antenna developed blisters on the outside of the neoprene [10]. The field was a corn field and agricultural chemicals sprayed on the crop caused neoprene to blister. Because the jacket was not required to be resistant to agricultural chemicals, this should not be considered a failure because the system was not designed for such service.

4.4 Failure due to corrosion of brass contacts occurred in an extension cord with a three pronged plug at one end. One inch thick clear thermoplastic insulation was over the set of three plugs. In service the brass contacts turned green, readily seen through the clear plastic, which was a copolymer of vinyl chloride and vinyl acetate. Analysis of the green corrosion by thermal desorption gas chromatography/mass spectroscopy (TD/GC/MS) [11,12] gave acetic acid and formic acid. The concentration of the acids was much less in the plastic away from the contacts. Figure 2 shows the plastic over the set of three plugs. Figure 3 is a sketch of a closeup of one contact with the green corroded area outlined dark. The acids probably formed in molding the thick copolymer over the contacts. High temperature would be needed to thoroughly fuse such a thick part. Copolymers with vinyl acetate split out acetic acid quantitatively at about 300 °C, and slowly at lower temperatures [13]. Organic acid formed during molding will react with brass to give green copper salt. Performance may not be affected adversely but the corroded appearance is undesirable. It may be possible to prevent such problems caused by acid with acid scavenger type stabilizers.

4.5 Low insulation resistance (IR) developed in service with low voltage single conductor cable, approximate thickness 3-5 mm. The cable consisted of plasticized PVC insulation and a different formulation PVC jacket. Insulation resistance fell to an unacceptable level in service. Analysis by TD/GC/MS showed that substantial transfer of additives occurred from jacket into insulation, causing insulation resistance to fall. The jacket formulation was not designed for high insulation resistance, so that migration of additives into insulation caused resistance to fall. Figure 4 gives the chromatograms of (a) unmolded insulation pellets, (b) insulation with low IR, and (c) jacket. In the b and c chromatograms, arrows point to peaks in the insulation that transferred from jacket. Formulation changes or a barrier layer are needed to prevent this problem.

4.6 Failure of unjacketed shielded underground polyethylene power distribution cable occurred in cold northern climate [14] with mineral rich soil. The failed cables have shield wires with heavy mineral encrustment of high calcium carbonate content (Figure 5). With the cable and shield wires dry, the resistance between the shield wires and the semiconductor layer over the insulation can be very high, approximately 50,000 ohms. The semicon layer itself had low resistance, as it should, so that the high resistance was not due to the semicon but to the fact that the shield wires lost their conductive connection to the semicon.

The first failures occurred 5-10 years after installation. Most of the failures occur in the spring, with 45% of the failures in May and 75% of the failures between May and August. This period corresponds to thawing and drying of the soil, along with lightning. The mechanism of failure appears to be that encrustment of the neutral wires causes separation and insulation of the neutral wires from the ground semicon over an appreciable distance. Lightning strikes or switching surges can cause a large potential difference between the conductor below the insulation and shield wires. Normally, the shield wires and ground semicon would be in contact and at the same potential. The earth conductivity is normally quite high and would act to ground the shield semicon with or without the shield wires. However, when the ground is frozen and the shield wires are separated from the ground semicon by encrustment, both the earth and the encrustment have low electrical conductivity.

Switching or lightning induced overvoltages would cause the potential difference between the ground strand and the ground semicon to rise to the point that the gap between the ground strand and the cable semicon breaks down, resulting occasionally in sufficient energy to puncture the insulation and more often in enough energy to puncture the semicon but not entirely puncture the insulation. When the ground thaws in the spring, failures occur as the insulation becomes saturated with liquid water and the insulation breakdown voltage drops in punctured locations. This accounts for the rash of May failures. The late summer failures are probably the result of lightning activity in conjunction with partly punctured cable. Thus the damage occurs mainly during the winter as high soil electrical resistivity is required, but the failures occur predominantly during the spring thaw. This failure mechanism requires two conditions: (1) encrustment of the ground shield wires and electrical separation of those wires from the semicon over a significant distance; (2) a very high soil electrical resistivity so that the ground semicon is not effectively grounded by the soil electrical conductivity or the ground shield wires. This occurs in frozen soil. The combination of high moisture, high calcium carbonate environment in a very cold climate provides the conditions for the failure mechanism.

The obvious lesson to be derived from these failures is to use jacketed cable so that the conditions that develop in the absence of a jacket do not occur. The use of unjacketed cable was mainly to lower cost, which turned out to be counter productive in the very cold climate with high calcium carbonate soil.

References

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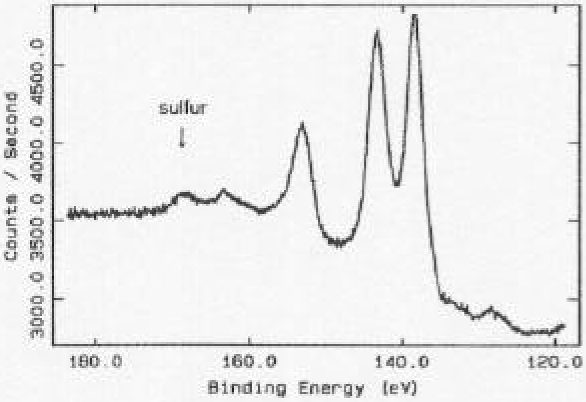

Figure 1. X-ray photoelectron spectrum of discolored surface of cable jacket. The peak with the arrow is the sulfur 2p peak, which is absent below the surface.

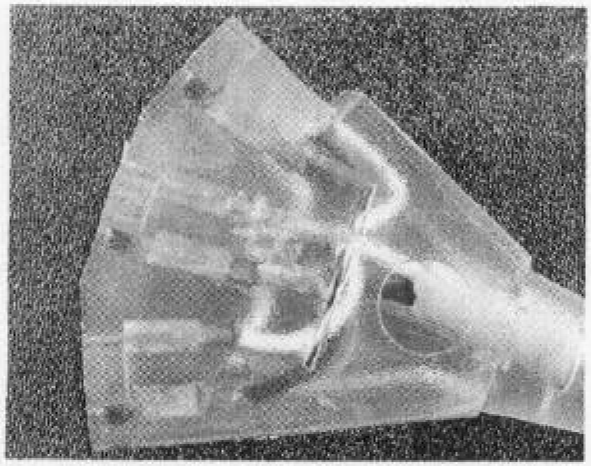

Figure 2. Transparent encapsulant on a three plug extension cord. Brass contacts have green corrosion (not visible in the figure).

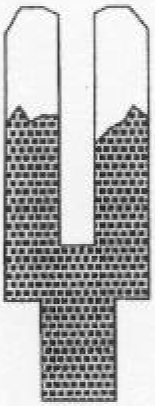

Figure 3. Sketch of a single brass contact of figure 2 with green corrosion indicated in dark area.

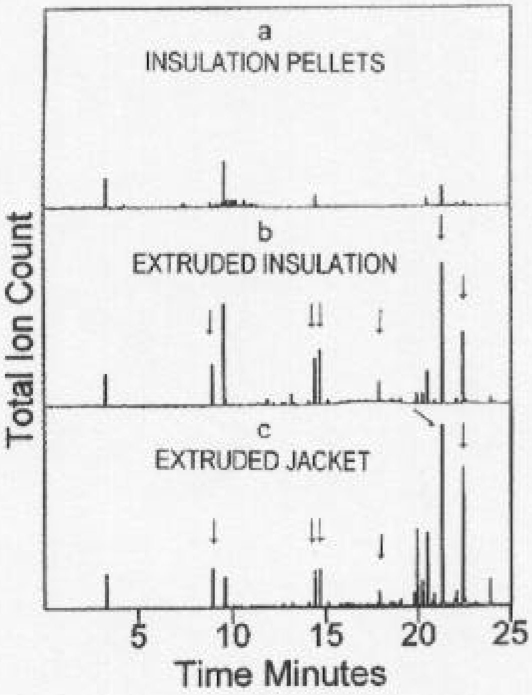

Figure 4. Thermal desorption gas chromatography/mass spectroscopy of cable that developed low insulation resistance in service; (a) insulation pellets before extrusion, (b) extruded insulation following some time in service, (c) extruded jacket; arrows indicate the compounds that migrated from jacket to insulation.

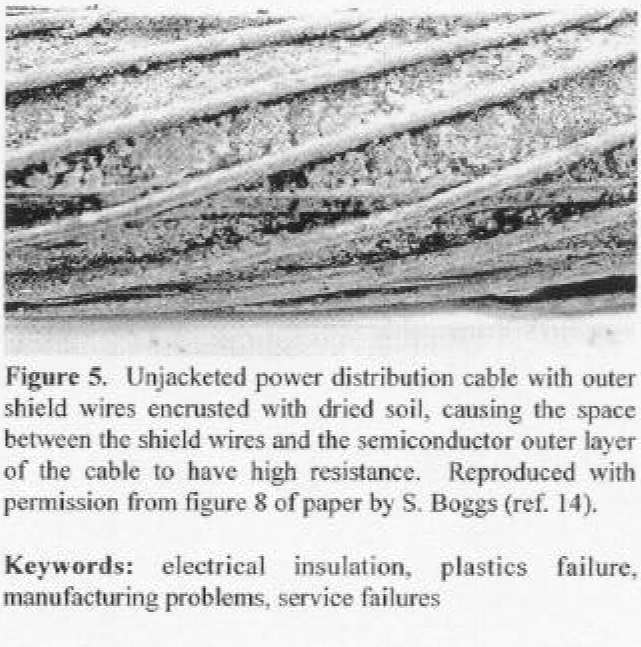

Figure 5. Unjacketed power distribution cable with outer shield wires encrusted with dried soil, causing the space between the shield wires and the semiconductor outer layer of the cable to have high resistance. Reproduced with permission from figure 8 of paper by S. Boggs (ref. 14).

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