The Effects of Fungi on the Direct Current Surface Conductance of Electrical Insulating Materials

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Received for publication October 14, 1954

The extent of visible fungus growth on pressure-sensitive electrical insulating tapes, as well as the effects of fungi on the mechanical strength of the tapes, was reported previously (Berk and Teitell, 1951). Fungi seriously decreased the tensile strength of tapes with cellulosic backings but had no more than slight effects on the tensile strength of tapes with elastomeric backings.

This report deals with the second phase of the investigation, the effects of fungi on the electrical properties of the pressure-sensitive insulating tapes and, particularly, the effects on surface conductance.

The literature is somewhat controversial concerning the relative importance of moisture and fungus growth on the failure of electrical equipment in service (Leutritz and Hermann, 1946; Leutritz, 1948). The Summary Technical Report of the National Defense Research Council (1946) on “Tropical Deterioration of Electric and Electronic Equipment” states, “Fungi are also important agents of deterioration in electric and electronic equipment. Hyphal strands of surface-growing fungi can introduce leakage paths which reduce insulation resistance and establish couples which promote electrolytic corrosion.” Titus (1945) considered fungi to be secondary causes of operational failures but stated that fungus filaments, when bridging terminals, might cause flash-overs. Proskauer and Smith (1945) stated that microorganisms contribute to the retention of moisture on surfaces that would normally dry out quickly, and the presence of these microorganisms might produce paths of low electrical resistance.

Leutritz and Hermann (1946) searched the literature from 1820, the year the galvanometer was invented, to 1945 and found no experiments that showed the effects of fungi on insulation resistance. They then studied the effects of humidity and fungus on unfilled and variously filled plastics and concluded that the decrease in insulation resistance was due to water absorption or adsorption and not due to fungi. There have been several additional investigations of the problem since 1945.

Witt, Chapman, and Raskin (1952) tested various plastics exposed to fungus and humidity; they used nitrogen atmospheres to prevent fungus growth where only humidity was desired; and they reported that the presence of moisture overshadowed any effects that fungi might have produced.

Luce and Mathes (1951) and Gauvey (1951) worked with plastic hook-up wire insulation and, using a technique of fumigation to prevent fungus growth, were able to separate the effects of humidity and fungi. They found that for many good plastic insulating materials there was a definite decrease in the direct current surface resistance caused by fungi and separate from any lowering caused by moisture. This decrease in resistance was detected electrically before any visual growth of fungi took place.

Leonard and Patouillet (1951) reported on a laboratory method that compared creepage resistance results from sterilized and viable inocula, and they were able to show that viable fungi lowered the resistance.

Dubois and Herou (1952) investigated the effects of mold on various plastic materials. They used as criteria the time required for travel of high voltage sparks and the number of drops of water or ammonium chloride solution required for a short circuit. They found that with some materials there is a degrading effect from the molds, which they attributed to the secretion of an electrolytic solution capable of penetrating the material.

In studying a slightly different aspect of the problem, Blake, Kitchin, and Pratt (1950) and Blake and Kitchin (1949) reported that soil microorganisms can cause failure of rubber insulation. The decreases in volume resistance were so great that sensitive measuring methods were not necessary.

MATERIALS AND METHODS

Method of Measuring Conductances

The insulating materials used in this study were:

- Vinyl pressure-sensitive tapes, black, Nos. 1, 2, 22 and 33
- Vinyl pressure-sensitive tapes, white, No. 20
- Nylon pressure-sensitive tape
- Polyethylene pressure-sensitive tape
- Saran pressure-sensitive tape
- Polyester pressure-sensitive tape
- Polytetrafluoroethylene sheet
- Methyl methacrylate sheet
- Polyvinyl chloride wire insulation
- Ethylcellulose wire insulation
- Micocryalline wax block
An effort was made to include the important types of electrical insulating tapes with elastomeric backings.

The method used for measuring the electrical values is a modification of that used by Luce and Mathes (Gauvey, 1951) for hook-up wires. The tapes, in strips 2 x 1 inches, were wrapped around stainless steel rods 2½ inches in length and ½ inch in diameter in order to leave ½ inch of rod bare at one end. Electrodes consisted of No. 30 aluminum wire wrapped in a tight coil, 1/16 inch wide, around the tape so that the electrodes were 1 inch apart. A third aluminum wire electrode was similarly wrapped around the bare rod to serve as a guard.

The same type of aluminum wrap-around electrodes were used on the plastic insulation of the two wires used in this study.

Electrodes were attached to the flat sheet samples as described in the American Society for Testing Materials (1949) D-257-49T method for attaching binding post electrodes to flat solid specimens. The specimens were 1 ½ x 1 inches and ½ inch thick. Stainless steel screws and nuts were used for the electrodes.

The incubation chambers for all samples were 32-ounce wide-mouth jars with plastic screw caps (figures 1A and 1B). The 3½-inch diameter plastic caps were modified by cutting out a circle 2¾ inches in diameter and filling this cutout with wax. The wax was a mixture of 25 per cent plastic wax and 75 per cent paraffin wax (mp 60 to 62 C). The surface conductance of the wax was less than could be measured with the instruments used (less than one micromicromho). Holes were drilled in the wax portion of the tops for the insertion of cork and rubber stoppers as shown in figure 1. Inlet and outlet glass tubes were added, and these tubes were used for inoculation and fumigation. Distilled water was placed in the bottoms of the jars to provide the humid atmosphere. Chromel A wires that were attached to the electrodes on the flat samples or the aluminum wires used as electrodes for the tape and wire samples protruded through the wax tops and served both as supports for the specimens and for continuing the circuit to the leads of the General Radio 544B Megohm Bridge\(^1\) used to measure the current flow. Readings were taken with the bridge 30 seconds after applying 100 volts across the electrodes. Measurements were taken over a period of 15 days for each specimen. The samples in the jars were incubated, and the measurements were made in a room maintained at 29 ± 1 C.

All of the samples were fairly clean and free from surface debris as received. The samples were handled with clean cellulose acetate gloves in order not to soil the surfaces.

**Separation of Effects of Humidity and Fungi**

Since fungi will grow only under conditions of fairly high humidity, and high humidity is known to increase the surface conductance of materials, it was necessary to distinguish between the effects produced by the moisture alone and the combination of moisture and fungi.

In order to make this distinction, the samples were exposed to the four conditions listed below before incubation at a nominal 100 per cent relative humidity.

**Condition F.** The sample was fumigated with ethylene oxide and then flushed with sterile air. This experimental condition would indicate the effects of moisture on the insulating materials free from microorganisms and added surface contaminants. Any effects produced by the 48-hour exposure to the fumigant would also appear.

**Condition I.** The sample was fumigated, flushed with sterile air, and then inoculated. This procedure would show the combined effects of moisture, fungus growth, and the surface contamination caused by the inoculum.

**Condition IF.** The sample was fumigated, flushed, inoculated, refumigated, and flushed. This condition would show the effects of moisture and surface contamination from the nonviable spores and bran dust.

**Condition N.** The sample was incubated as received. This method would show the effects of moisture and the flora normally present on the insulating material. This condition was also used to help determine whether fumigation had any effect on the material.

**Inoculation Method**

A large amount of inoculum was prepared by growing four species of fungi; *Aspergillus niger*, *A. flavus*, *Penicillium luteum*, and *Trichoderma sp.*, on moist bran powder in 32 ounce jars. After a 5-week incubation period, the bran culture was allowed to dry at room

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\(^1\) General Radio Co., Cambridge, Mass.
temperature. The resulting inoculum consisted of a mixture of dry bran powder fungus spores, and mycelial fragments.

For inoculation, the plastic samples, attached to a jar top with the wax insert by means of the chromel or aluminum wires, were lowered into the jar containing the inoculum. The cap was screwed down. By means of a rubber bulb attached to the glass inlet tube, an air blast was introduced into the jar. The fungus spores, along with some bran, deposited fairly uniformly on the surfaces of the specimens. After a 5-minute period for the inoculum dust to settle, the samples still attached to the cap were placed in the jar that served as the incubation chamber. Sterile distilled water was added to the jar through the glass inlet tube just before incubation. When the glass tubes were not in use, a sterile cotton plug was placed in the outlet tube, and a sterile glass rod attached to the inlet tube.

Fumigation Method

The fumigant that was selected to kill the fungus spores on the samples was ethylene oxide. It was found that many fumigants act as solvents or react with the elastomeric materials used. Ethyl mercuric phosphate was an excellent fumigant but was difficult to remove from polyvinyl materials by aeration. Propylene oxide was also a good volatile fungicide but had deleterious effects on the polyvinyl tapes.

Sterilization was accomplished by passing ethylene oxide through the dry jar containing the samples at a rate of 500 ml per minute for 30 minutes. The gas in the jars was allowed to act on the samples for 48 hours. The fumigant was then removed from the jar by flushing with a stream of sterile air for one hour.

Results

Figure 2 shows the surface conductance values of eight insulating materials during the 15-day incubation period. The values are the averages of 8 to 10 specimens. The samples that were sterilized by the fumigant did not show any significant increase in conductance. All the samples that had viable spores showed a pronounced increase in surface conductance going from one micromicromho or less to between 10,000 and 100,000 micromicromhos.

The only untreated (condition N) sample that showed

![Graph showing surface conductance over time for different materials.](http://aem.asm.org/)

Fig. 2. Effect of molds (and bran dust) on the DC surface conductance of electrical insulating materials. Code: △, Condition I, viable inoculum. ○, Condition IF, dead inoculum. X, Condition F, sterile but not inoculated. □, Condition N, incubated as received.
an appreciable increase in conductance was the ethyl cellulose covered wire, and this may be attributed to the microorganisms that happened to be present on the material. If allowed to incubate long enough (up to 57 days), some samples of other materials of condition N also showed an increase in conductance. This is also attributable to the natural flora present on the samples. The effects of moisture and small amounts of nonviable surface contaminants were negligible, whereas the presence of viable fungus spores under moist conditions definitely increased the surface conductance.

Fungus growth was visible after two days' incubation on all the samples of condition I, except for vinyl tape No. 20. However, vinyl tape No. 20 did have fungus growth visible when examined under the microscope. None of the samples of conditions F and IF had visible growth.

**Effects of Added Nutrients**

*No Added Nutrients.* The negative results of condition IF proved that bran without viable spores does not produce an increase in surface conductance. However, in order to determine the extent to which bran aided the viable spores in producing the increase in conductance, a number of experiments were conducted in which spor dust alone, without any added nutrient such as bran, was used as the inoculum for comparison with an inoculum containing bran. The experimental procedure was similar to the one described above. In order to obtain spores without added nutrients, the molds were grown on cellophane, and the spores were shaken loose from the culture by an air blast. A heavy load of spore dust was used as the inoculum. The samples were not fumigated in this experiment.

It was found that a longer time was required for an increase in conductance when bran was not present (figure 3). The increase is, however, faster than in condition N of figure 2 because of the large number of spores present on the samples.

![Graph](image-url)

**Fig. 3.** Effects of molds, with and without added bran dust, on the DC surface conductance of a vinyl electrical insulating tape.

*Inorganic Nutrients.* The conductance of insulating materials was measured after inoculating the samples in the following four ways.

**Condition DI.** Inoculated with a spore suspension made up in distilled water.

**Condition MI.** Inoculated with a spore suspension made up in a dilute solution of inorganic salts.

**Condition M.** The inorganic salts solution only, without spores, was applied to the samples.

**Condition N.** Incubated as received.

Triple washed spore suspensions of the four species of fungi grown on potato dextrose agar slants were used as inoculum. The spore load was adjusted to 2,000,000 spores of each organism per ml of distilled water or inorganic salts solution. The insulating materials were inoculated by spraying with the spore suspensions by using an atomizer at 16 lb air pressure. However, vinyl tape FA No. 1 and the nylon tape were inoculated by placing individual drops of the mixed spore suspensions on the samples. Spraying these samples produced an immediate increase in surface conductance, but inoculation with individual drops did not produce this effect. Fumigation was not used in these experiments. Figure 4 shows the effect of the four conditions of inoculation and incubation on the average DC surface conductance of seven insulating materials. In all cases, the viable fungus spores plus mineral salts (condition MI) increased the average surface conductance to values ranging from 7000 to 200,000 micromicromhos.

The results from the vinyl tapes and the polyester tape indicate that for the 15-day period studied minerals are required for the fungi to have an effect. Viable fungi in distilled water had only a negligible effect during this period, as did mineral salts without any added spores. The same is true of the polyethylene tape, except that there appeared to be sufficient naturally occurring organisms on the samples to produce a delayed conductivity increase under condition M.

Nylon undergoes an increase in surface conductance that could be measured and which is due to moisture absorption. The presence of viable spores appeared to increase this conductivity.

The results showed that Saran tape must have contained at least some of the required minerals, since there was an increase in conductance when inoculated with spores in distilled water.

The insulating materials inoculated with mineral salts plus viable fungus spores showed similar results to the specimens inoculated with bran plus viable spores. Microscopic fungus growth appeared after 5 to 7 days' incubation on the nylon tape and vinyl tapes Nos. 1, 2, and 22. No growth was visible on the Saran and polyethylene tapes. However, microscopic examination at

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2. KH2PO4, 0.7 g; K2HPO4, 0.7 g; MgSO4-7H2O, 0.7 g; NH4NO3, 1.0 g; NaCl, 0.005 g; FeSO4-7H2O, 0.002 g; ZnSO4-7H2O, 0.002 g; MnSO4-7H2O, 0.001 g; water, 1.0 liter.
450X showed a sparse continuous mycelial network between the two electrodes on the latter materials.

Relation of Microscopic Fungus Growth to DC Surface Conductance

Some of the previous observations indicated that a large increase in surface conductance occurred when a continuous mycelial network or bridge occurred between the two electrodes. An experiment was designed to correlate the extent of microscopic fungus growth with changes in DC surface conductance.

Methyl methacrylate sheets, 1/8 inch thick, were cut into strips 1 x 1½ inches and inoculated with the four spore suspensions made up in distilled water and in mineral salt solution as described above, except that the spore load was reduced to 400,000 of each organism per ml.

Surface conductance measurements were made and the plastic blocks then examined at 450X for extent of fungus growth. It was found that no increase in conductance occurred until a mycelial bridge formed between the two electrodes. Figure 5 illustrates the extent of mycelial growth on the plastic blocks and the corresponding surface conductance values in micro-micromhos obtained when the spore suspensions were made up in distilled water and in mineral salt solution. The surface conductance increased as the mycelial network became more and more extensive. In some samples a mycelial bridge of connecting hyphal strands did not form on the methyl methacrylate blocks. In the latter case no increase in surface conductance occurred. In a few samples, a mycelial bridge formed even on the specimens inoculated with the spores made up in distilled water and an increase in the surface conductance was recorded in these specimens.

Figure 5 shows that only a small percentage of the spores used in the inoculum germinated. The methyl methacrylate blocks were not sterilized. Some of the growth on the plastic may therefore be due to contaminating molds normally present on the surface.

Discussion

It has been reported (Leutritz and Hermann, 1946; Leutritz, 1948; Witt et al., 1952) that the effects of moisture on the insulation resistance of plastic insulating materials overshadow any effects caused by fungi.
With certain insulating materials, such as paper or wood-filled laminates, this is probably true. But the insulation resistance of these materials is substantially affected by moisture. During the course of the present study, it was found that the surface conductances of paper and cloth electrical insulating tapes were markedly increased by exposure in humid atmospheres. Any effects produced by a combination of moisture and fungi on paper and cloth insulating materials were not found to be significantly different from those produced by moisture alone.

The results of this report do show that fungus growth is of prime importance in increasing the DC surface conductance of insulating materials that are almost unaffected by moisture. These moisture-resistant insulating materials are chosen for use in equipment, because it is expected that their insulation resistance will not be affected by highly humid conditions.

The presence of surface contaminants, such as carbo-naceous materials and dust, have been reported (Mathes et al., 1949) to affect adversely the electrical properties of insulating materials. In this study the presence of small amounts of dead inoculum and bran dust did not change the surface conductance of the electrical insulating materials.

Viable mold spores on moisture-resistant insulating materials are able to increase the surface conductance under humid conditions because they are able to grow. It is characteristic of their growth that the hyphae formed from germinating spores connect in order to form a mycelial network. This occurs soon after germination and at first is visible only by using a microscope. If the amount of available nutrients is limited, mold growth visible to the naked eye may never occur but the conducting mycelial network may still be present.

Unless the materials are sterile, there are usually sufficient mold spores naturally present on insulating materials to produce eventually this conducting mycelial network. Intentional inoculation with numerous mold spores accelerates the rate of conductivity increase.

Most good electrical insulating materials are fairly free of the inorganic nutrients required for mold growth. For this reason, the mycelial network may not form on clean materials. Only small amounts of these nutrient materials are required to form a microscopic conducting mycelial network. In service, small amounts of dust and debris that may be present on the material would be sufficient to provide the required nutrients.

Even though molds were found to produce a 10^4-fold increase in surface conductance, the highest value measured was less than one micromho. It is probable

Fig. 5. Comparison of mold growth and conductance values with methyl methacrylate blocks. The mold spore suspension was made up in mineral salts solution for specimens A, B, and C, and was made up in distilled water for specimen D. The conductance values are shown in the lower left hand corner of each photograph.
that this increase in conductance on insulating surfaces will be serious only in very high impedance circuits.

ACKNOWLEDGMENT

Appreciation is expressed to C. C. Fawcett and E. R. Rechel of Pitman-Dunn Laboratories and to the Ordnance Corps for permission to publish this paper.

SUMMARY

The effects of fungus growth, as separated from the effects of moisture on the direct current surface conductance of a number of moisture-resistant electrical insulating materials, were determined. Several pressure-sensitive insulating tapes with elastomeric backings were included in the study.

The surface conductance of the materials was increased to $10^4$ to $10^5$ micromicromhos in the presence of viable fungi and 100 per cent relative humidity. When the fungus spores were present but killed by a fumigant, the surface conductances remained at less than one micromicromho. The rates of increase in surface conductance caused by the fungi were accelerated by small amounts of such accessory nutritive materials as could be present in dirt and debris. Correlation studies of the extent of microscopic fungus growth with surface conductance showed that the increase in conductance is due to the formation of a continuous mycelial bridge or network between the two electrodes.

REFERENCES


