

**POLYMER MATERIALS
FOR INSULATOR WEATHERSHEDS**

**THE OHIO BRASS COMPANY
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OHIO BRASS

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POLYMER MATERIALS FOR INSULATOR WEATHERSHEDS

Evolution of Polymers for HV Insulation

As we approach the broad field of today's polymer materials for insulator housings, it is appropriate to review briefly the origins of some of the polymers in use.

Butyls and Acrylics

The earliest polymer insulators were made of butyl and acrylic materials. While they enjoyed some commercial success, they quickly became obsolete because of high cost, limited manufacturing versatility and - most importantly - inadequate performance for high voltage applications in outdoor environments.

Epoxies

A significant advance was made with epoxy compounds introduced in insulator designs in the mid 1960's. Typical construction of suspension type insulators included casting of epoxy onto a fiberglass rod, while post-type insulators were solidly cast. Some early generations had limited service life due to problems associated with material compatibility at rod-housing interfaces and with poor electrical tracking performance. Some compounds, modified to address these concerns, exhibited other problems such as depolymerization over time, eventually resulting in electrical failure.

Bis-A (Bisphenol) epoxy is among the most common of epoxies, and is commonly used in coatings, adhesives, and insulators for indoor applications. In the late 1960's, outdoor insulators using Bis-A epoxy became available. Having some of the basic drawbacks as other epoxy materials, these insulators have typically only been used for low voltage applications (for example, A. B. Chance "Epoxilator").

In mid-1965, Ohio Brass patented a line post insulator based on a cast cycloaliphatic epoxy polymer. This compound was found to be far superior to other epoxies used for insulators at that time. A large number of 35 kV insulators were installed on utility systems, with the only damage ever reported being from gunfire. One post was recently returned after 24 years of service in the El Paso, Texas sun and altitude. The insulator was in excellent condition, physically and electrically.

The original Ohio Brass epoxy technology was transferred to S & C Electric Company, and introduced by them as "Cypoxy". The material was also used in SF₆ breaker bushing housings.

Ohio Brass did not continue using cycloaliphatic epoxies in outdoor insulators, but the longevity of these early insulators testifies to Ohio Brass' research skills. Test techniques and parameters derived from Ohio Brass' early polymer programs established benchmarks vital to evaluate advanced polymers for tomorrow's insulators.

Ohio Brass Dirigo 7345

The original housing material for Hi*Lite insulators, Dirigo 7345, was an EPM based compound. Prototypes using the material were installed in operating utility lines as early as 1971. This EPM polymer, commercially introduced in 1976, was chosen for use in a high-pressure injection molding process designed to eliminate voids in the material. Its prime qualities were excellent resistance to tracking, corona and ultra violet degradation. Dirigo 7345 was Ohio Brass' standard housing material through 1985.

Rosenthal Silicone

Introduced in the USA in 1977, this material had been on test since 1971. The material had good behavior in contaminated areas. However, the inherent mechanical weakness of the silicone material led to some cases of field damage.

EPDM Polymers

The first use of EPDM rubber was in the Sediver Armourlite product, introduced approximately 1977. Later, Lapp Polypace insulators were introduced with sheds of EPDM. While some other early EPDM formulations would not survive the electrical duty, later compoundings have produced a very versatile rubber for outdoor insulators. Ohio Brass chose to use the ethylene propylene co-polymer for its original polymer insulators. This was based on EPM's saturated chemical structure (no double bonds). It was theorized and subsequently verified by chemical evidence, that EPM should be more chemically and physically stable than EPDM.

It was through efforts to improve molding characteristics of EPM compounds that Ohio Brass discovered an EPDM based on dicyclopentadiene (ter-polymer). This ter-polymer in Ohio Brass' insulator compound turned out to have better

weathering, aging, physical and electrical characteristics than Ohio Brass' previous EPM based compound.

Alloy Polymers

The first successful rubber alloying of silicone (dimethylsiloxane) into an EP base was Ohio Brass' OBalloy, introduced into the Hi*Lite product in 1985.

As the Ohio Brass research continued and the alloying process improved, later formulations with improved properties and higher silicone contents were incorporated into the product.

Today's formulation is identified as ESP™, and has been in use for insulator weathersheds and arrester housings since 1988. Current Ohio Brass products with ESP weathersheds and housings include: Hi*Lite II, Hi*Lite XL and Hi*Lite XL-HP transmission insulators; Veri*Lite distribution insulators; PDV-65 and PDV-100 distribution arresters; PVR riser pole arresters; PVI intermediate arresters; Protecta*Lite transmission and distribution line protectors; and Optic*Lite fiber-optic link insulators.

Material Characterization

Polymer insulating materials are typically formulated to provide performance characteristics equivalent to or better than that of porcelain. Because of the different physical properties of porcelain and polymers, a comparison is usually made only on short term electrical characteristics of complete insulators - e.g. wet and dry 60 Hz flashover, critical impulse flashover.

However, there are many physical properties of a polymer material that must be understood and properly controlled to give the materials the characteristics necessary to serve a long life as a high voltage insulating polymer.

Physical properties are evaluated by a variety of tests. These are performed to ensure that the basic formulation exhibits the required characteristics for use in high voltage insulators (design tests) and that properties are properly controlled on a batch to batch basis (quality assurance tests).

Design Tests

A polymer compound's suitability for long term use in high voltage insulators is assessed by means of design tests. By necessity, given that an insulator's lifetime is measured in decades, design tests involve accelerated aging or conditioning.

Compounds should be tested for the ability to resist tracking, corona and ultra-violet (UV) radiation exposure. Performance is judged in terms of crazing, cracking, chalking, erosion, treeing, and hydrophobicity. Although of a short duration, the dielectric strength and tear strength of a compound are also important design tests.

The tracking resistance of a compound is a measure of its ability to withstand intense leakage currents combined with dry band arcing. The dry band arcing generates ozone, high temperature and UV radiation exposure on the polymer surface. Test conditions vary among laboratories, but typically samples of the compound are wetted with a conducting solution and then energized in a circuit with a controlled low current. Samples are then evaluated in terms of the number of cycles or time to failure. Acceptable performance is dependent upon materials and test methods. Good compounds will survive for thousands of cycles.

Polymer insulating compounds are exposed to UV radiation not only from dry band arcing, but also from corona and sunlight. UV stabilizers are added to the polymer during compounding to impart resistance to the degrading effects. Under accelerated testing methods, like ASTM G53 (QUV), a polymer compound should be capable of sustaining 10,000 hours of exposure without crazing, cracking, or displaying any loss of hydrophobicity.

The presence of corona combines UV and heat energy with a high level of ozone. The combination of these, with mechanical stress, accelerates degradation of a polymer. Under a combination of 30% strain and continuous surface corona, a polymer should be capable of surviving for at least 2,000 hours without cracking, splitting, cutting or electrical failure.

Anti-oxidants are incorporated into a polymer compound to inhibit the attack of oxygen and ozone on the compound's chemical composition. An oxidative stability test measures the time to deplete the anti-oxidants within a material under controlled conditions (extremely high temperatures). These anti-oxidants inhibit the attack on the compound by oxygen and ozone. Good compounds typically exhibit oxidation in times greater than 400 minutes in air at 200°C.

A polymer's ability to withstand high voltage stresses without puncturing is measured by its dielectric strength. A typical value would be 2,000 V/mil.

Tear strength is the force required to start or continue a tear in a fabric under specified conditions. An acceptable value would be 150 lb/in or more.

Ohio Brass first developed test techniques in the mid 1960's for evaluating these characteristics of polymer insulating compounds, and over the intervening years has continued to improve upon the methods. Details of the various tests are contained in a section devoted for testing. Twenty-five years of experience have indicated that materials which perform well in these tests will offer decades of satisfactory service in field use.

Quality Assurance Tests

Quality assurance tests provide the most frequently and readily measurable characteristics of a polymer compound. These tests ensure batch to batch compound consistency. Measurements include the ODR, modulus, tensile strength, hardness and specific gravity.

The Oscillating Disk Rheometer (ODR), also called a curemeter, measures the complete curing characteristics of a single polymer specimen, heated and maintained under continuous pressure during vulcanization. Torque is measured as a function of the cure state. In the uncured condition, torque ranges from 6 - 12 in-lb. A fully cured sample will exhibit a torque of 100 - 130 in-lb.

The modulus is the ratio of stress to strain for the compound. It is usually expressed in terms of 100% strain or 200% strain. The value expresses the compound's stiffness, or its resistance to extension (elongation). Typical minimum values for 100% strain would be in the order of 600 psi. At 200% strain, the maximum stress would normally be in the order of 850 psi.

Tensile strength is defined as the force per unit area of the original cross-sectional area which is applied at the time of rupture of the sample. It is expressed in pounds per square inch (psi). This is a measure of the physical strength of a compound. Values exceeding 850 psi should provide acceptable service.

The hardness of the polymer is an indication of the base compound and the cure state. It is also a good measure of the consistency from batch to batch of a compound. For elastomeric polymers, hardness is usually measured on the Shore A scale. Typical values are in the range 60-80.

Specific gravity is the ratio between the weight of a unit volume of a polymer compound and the weight of an equivalent volume of water at a given temperature. It is an important control test for checking the precision of the compounding. Values for Ohio Brass' ESP compound are typically $1.37 \pm .02$, while silicone compounds average $1.50 \pm .05$ at 25° C.

Comparison of Polymers In Use Today

There are four basic polymer types in use today for high voltage insulators.

1. Epoxy
2. EPR (EPM and EPDM)
3. Silicone Rubber
4. EPDM/Silicone alloy

Epoxy

Cycloaliphatic epoxy polymers can be cast to produce post type insulators. It's inherently low tensile strength prevents it from being used for suspension insulators, and limits its use in cantilever applications. Attempts have been made to produce epoxy suspension insulators with fiberglass as the tension member, but these were not successful due to the difference of thermal expansion coefficients between the mineral-filled epoxy and the glass-filled epoxy. The epoxy is improved, both electrically and mechanically, by the use of fillers. Alumina trihydrate (ATH) is a non-reinforcing filler, used to impart track resistance to the final compound. Silica is used as a reinforcing filler which enhances mechanical characteristics such as abrasion and erosion resistance.

Carboxylated rubber (CTBN) can be added to the formula as a flexibilizer. During curing, this material forms into nodules in the epoxy matrix and toughens the compound. The CTBN introduces 'give' into the cured resin to reduce the probability of fracture when cast around large inserts.

EPR

EPR, ethylene/propylene rubber, is the designation used to identify both EPM (ethylene propylene monomer) and EPDM (ethylene propylene diene monomer). EPM and EPDM polymers are often compounded with other materials to provide desired physical and/or electrical properties for specific applications (see under compounding section).

There are many different EPM and EPDM polymers available today, each offering different combinations of characteristics. The selection of a particular polymer has to be made on the basis of a thorough evaluation of the characteristics and their significance for the intended application. EPRs are among the best weathering resistant synthetic elastomers. With the exception of applications requiring resistance to hydrocarbon oils, there is scarcely

an application of either natural or other synthetic rubbers where EPRs have not challenged the incumbent elastomer. EPDMs, in general, have outstanding resistance to heat, light, oxygen and ozone. EPDMs, depending on the particular diene monomer used, can provide improved electrical and mechanical properties and superior aging and color stability.

The EPDM used in Ohio Brass insulating compounds was selected only after extensive analysis and testing of a large number of available polymers. Ohio Brass, through such testing, continually strives to develop compounds with improved performance characteristics.

Silicone Rubber

Silicone rubber is technically classified as an inorganic material. It is often mistakenly believed that this means that the material contains no carbon atoms. However, the base polymer used in silicone rubber compounds for high voltage insulation applications is invariably dimethylsiloxane having an organic content of about 45%.

The molecular chains of silicone rubber have a combination of organic-inorganic properties. Compared to organic rubber polymer chains, they have a large molar volume and very low intermolecular attractive forces. The molecules are unusually flexible and mobile, and can coil and uncoil freely over a relatively wide temperature range.

Many types of wire and cable are insulated with silicone rubber mainly because its electrical properties are maintained at elevated temperatures.

As is the case for EPRs, there are several different silicone base polymers (gum) available, few of which are suitable for outdoor high voltage insulation applications. Extensive evaluation, analysis and testing is required to ensure an appropriate match of material characteristics with application needs.

Perhaps the most discussed characteristic of silicone rubber when used for outdoor high voltage insulators is hydrophobicity. Hydrophobicity is a measure of the material's ability to repel water. Several studies have indicated that silicone rubber is able to recover its hydrophobicity after a temporary loss and this phenomenon is due to the surface migration of low molecular weight (LMW) silicone oil(s) normally found in the silicone compound.

While the hydrophobic property of silicone rubber is beneficial, there are some drawbacks to the use of silicone rubber for outdoor insulator applications:

- compared to EPR, silicone rubber has poor mechanical characteristics, increasing the susceptibility to damage from mishandling, vandalism, and high pressure washing
- lower tear strength
- higher moisture transmission

EPDM/Silicone Alloy

Recognizing the one primary beneficial characteristic of silicone rubber -good hydrophobicity- but desiring a compound which had the excellent electrical and mechanical properties that EPDM can provide, Ohio Brass developed an alloy of EPDM and silicone which combines the best properties of these two materials. This proprietary compound, ESP, was developed over a period of four years and has been used in Hi*Lite insulators since 1988.

Compounding

In the field of polymer technology, rubber compounding is one of the most difficult and complex subjects to master. Compounding is part art, part science. The compounder's knowledge and experience of selecting and combining elastomers and additives are required to obtain a mixture that will develop the necessary physical and chemical properties of a finished compound.

To be successful in compounding, one must not only understand the properties and functions of hundreds of elastomers and rubber chemicals, but must also have detailed knowledge of the equipment used for mixing, molding and vulcanization. Only with this knowledge can a compounder successfully secure certain properties of the finished product to satisfy requirements and attain processing characteristics necessary for efficient utilization of available equipment.

Knowledge + Experience + Time = Success

A practical compound formulation typically consists of 10 or more ingredients. Each ingredient has a specific function and each has an impact on properties and processibility. Knowledge of the function and effectiveness of compounding ingredients is essential in the development of a compound for high voltage insulation.

The remainder of this section will be dedicated to brief descriptions of the ingredients and their functions.

Elastomers

The most important, and usually the first, step in compounding is the selection of a base polymer or elastomer. Elastomers, as a class of engineering materials, possess some common basic characteristics. All elastomers are elastic, flexible, tough and relatively impermeable to water and air. Beyond these common characteristics, each elastomer has its own unique properties. The selection of an elastomer should be based on the properties desired and processibility of that elastomer. The elastomers/polymers currently used in outdoor high-voltage applications were discussed in the previous section.

Vulcanizing Agents

Vulcanizing agents are ingredients used to cause a chemical reaction, resulting in the cross-linking of elastomer

molecules. Through chemical cross-linking, an elastomeric compound is converted from a soft, tacky thermoplastic to a strong, temperature stable thermoset. The proper selection of a vulcanizing agent is extremely important. Unless a suitable vulcanizing agent in the proper concentration is used, a compound will not develop its optimum properties and adequate processibility. There are two major types of vulcanizing or curing agents used: sulfur and peroxide. Sulfur tends to stiffen the stock, making it very difficult to mold as well as making the final product too hard for assembly purposes. As a result, Ohio Brass uses peroxide in its compound.

Coagents

By inhibiting bond degradation during cross-linking, coagents provide for rapid cross-linking at the point of free radical generation. In other words, a coagent protects the already cross-linked bonds between the polymer and vulcanizing agent from being torn apart while at the same time making new bonds. This assures that bonds are not broken as fast as new bonds are generated.

Some coagents work better than others. For example, sulfur can be used as a coagent for EPDM based compounds. It imparts high tensile strength but is not desirable for insulators because it provides a low state of cure which lowers electrical stability.

Antidegradants

Antidegradants are used to retard the deterioration of a rubber compound initiated by oxygen, ozone, heat, light, metal catalysis and mechanical flexing. These antidegradants are also known as antioxidants, antiozonants and inhibitors. The antioxidant used by Ohio Brass also acts as a pH adjuster for the compound. In a peroxide cure system it is important for the compound to remain on the alkaline side, otherwise acid cleavage of the peroxide occurs, drastically reducing its crosslinking efficiency.

In the selection of antidegradants the following factors must be considered:

1. type of protection desired
2. chemical activity
3. persistence (volatility and extractability)
4. discoloration and staining

Processing Aids

Processing aids are added to a rubber compound to help mold flow and release. Some processing aids are also used as a lubricant, desiccant or homogenizing agent. The elastomer type and processing operation (such as mixing, calenderizing, extruding or molding) will determine what kind of processing aids are needed.

Fillers

Fillers are used to reinforce physical properties or to impart certain processing characteristics. There are two types of fillers: reinforcing and extending. The reinforcing type improves hardness, tensile strength, modulus, tear strength and abrasion resistance of a compound. There are two kinds of reinforcing fillers, carbon black and fine-particle mineral pigment, such as silica. Ohio Brass uses a small amount of this non-black filler not only for physical and mechanical improvement, but also to resist erosion that comes from the electrical stress to which the compound is subjected in the field.

An extending filler is a loading or non-reinforcing material. It may be used to reduce cost or to impart other desirable properties. In Ohio Brass' ESP, alumina trihydrate (ATH) is used to impart a high resistance to electrical tracking and to fire (ESP will not support its own combustion).

Coupling Agents

A coupling agent provides a chemical bond between the filler and the elastomer. The coupling agent used in ESP is specifically designed for use in mineral-reinforced, peroxide cured EPR insulation compounds. The coupling agent treats the ATH and is effective in providing stable wet electrical properties. It also provides improved modulus and tensile strength.

Plasticizers and Softeners

Plasticizers and softeners are used to either aid mixing, modify viscosity or provide flexibility at low temperatures without substantial loss in physical properties. Many ingredients in this group may also be considered as processing aids or extending fillers.

The important criteria in selection of plasticizers are elastomer compatibility, efficiency, stain resistance and

cost. If the plasticizer selected is not compatible with the base elastomer(s), the material will also influence the hardness of the cured compound.

Special Purpose Materials

Special purpose materials are used for a specific purpose which is not normally required in the majority of rubber compounds. Ohio Brass' proprietary silicone compound falls into this category. Its purpose is to enhance the hydrophobic characteristic of the ESP compound. The hydrophobic characteristic of a compound in an outdoor high voltage application helps prevent an insulator surface from forming a continuous film of moisture during fog, mist or rain. This is particularly important in areas of high natural or industrial contamination.

In R & D, once a compound has been formulated to meet the desired criteria, various types of tests are run. The different types of testing are chemical, mechanical/physical, electrical and thermal. When a change in formulation has occurred, only certain specific tests need to be initially run. This is to determine if the formulation change achieved the intended goal. If all looks well, an engineering trial batch is ordered to evaluate the molding of the insulator products. It is important to note that when one property has been improved due to a formulation change, other properties may have been affected.

Depending on the change made, past experience indicates what characteristics to examine. An example of this is if a new antioxidant is used, an oxidation stability test should be performed to see how the new compound compared to the current. If the results are favorable, tests would be performed to look at the effect on the cure system and the stability of the color. These two properties can be affected by a change in antioxidant.

Ohio Brass has over 30 years of experience in material selection, compound formulation and design of high voltage polymeric insulators. Ohio Brass pioneered the use of EPRs in outdoor high voltage applications, and has continued to develop compounds with improved performance and processing characteristics. Out of several hundred compounds developed, analyzed and tested, today's ESP marks the third generation of EPR used in Ohio Brass products.

Testing

While there are several standardized (e.g. ASTM, IEC) tests to evaluate insulating materials, few of these are particularly suited to proper assessment of the characteristics required for outdoor high voltage insulation. As a consequence, Ohio Brass has developed a number of specialized tests for evaluating materials for its polymer insulator products.

Ultra Violet

Resistance to degradation resulting from ultra violet (UV) exposure is an important factor in determining the service life of a polymer. The UV spectrum constitutes about 5% of the energy in sunlight. Wavelengths of UV rays range from 250 to 400 nanometers.

The photochemical effect of this low wavelength radiation is responsible for most of the damaging effects of sunlight. The absorption of UV radiation results in mechanical and chemical degradation of a polymer structure which can affect the dielectric and weathering properties of that polymer. The rate at which the degradation occurs is dependent upon the intensity and wavelength of the radiation. These factors vary with season, time of day, elevation and latitude. Acceleration of the effects occurs in the presence of moisture on the polymer's surface.

The effects of UV radiation for a polymer include:

1. crazing, checking or cracking of the surface
2. breakdown of molecular structure
3. loss of hydrophobicity
4. discoloration

In the presence of UV radiation, water containing dissolved oxygen on the surface of the polymer accelerates the rate of degradation. The effects include:

1. oxidation of the surface
2. acceleration of the photochemical reaction
3. depolymerization of polymer bonding matrix
4. reduction of the arc resistance and mechanical strength

Polymer compounds for use in outdoor environments should, therefore, be evaluated in the combined presence of UV radiation and high humidity. An accelerated evaluation can be performed in a Weatherometer or QUV tester. Ohio Brass

has adopted the QUV test as being the most meaningful for outdoor insulation. Through comparisons with tests performed at the Desert Sunshine Exposure Test (DSET) site in Arizona, the aging acceleration of the QUV test has been assessed at 8:1; that is one hour of QUV test is equivalent to eight hours of exposure in the Arizona desert, considered the most severe natural UV environment in North America. Test results obtained from the QUV test provide a means of comparatively ranking the UV resistance of materials

QUV Tester

The QUV test is an accelerated weathering test performed in conformance with ASTM G53. The QUV test alternates UV radiation exposure and condensation during each cycle. A cycle consists of 8 hours of condensation and 16 hours of UV exposure.

The QUV test simulates the effects of sunlight by means of fluorescent UV lamps positioned within inches of the test specimen. A water reservoir at the bottom of the test chamber is heated to produce vapor. The hot vapor keeps the chamber at 100% relative humidity. The water vapor condenses on the cooler surfaces of the test specimens. The combination of condensation with high intensity UV radiation results in an accelerated exposure test.

Typically, samples are exposed to several thousand hours. Evaluation of a material is based on loss of hydrophobicity, checking, chalking, crazing and erosion. Figure 1 shows the QUV tester used by Ohio Brass. Table 1 summarizes the QUV test results for some compounds.

Corona

Corona discharges form at the surface of an insulator when the electric field intensity on the surface exceeds the breakdown strength of air, which is about 15 kV/cm. Corona generation is dependent on atmospheric conditions such as air density, humidity, wind, surface roughness, geometry of the insulator, and several other factors. The effects of corona are radio interference, TV interference, noise generation, ozone production, and energy loss.

Corona accelerates the aging of polymers. The electric discharge subjects the insulator to severe electrical strain and chemical degradation. The degradation results in the form of corrosive or conductive products. Continued degradation may render the polymer unusable.

Material	Time, Hrs	Comments
Dirigo 7345	8000	Loss of hydrophobicity
ESP	24000+	Still hydrophobic
EPDM1	1000	Checking of surface
EPDM2	4000	Loss of hydrophobicity
Silicone rubber	60000	Still hydrophobic

Table 1. QUV test results

Note: Each 10,000 hours of QUV testing is equivalent to 9.1 years of exposure in the Arizona desert.

+ indicates ongoing tests

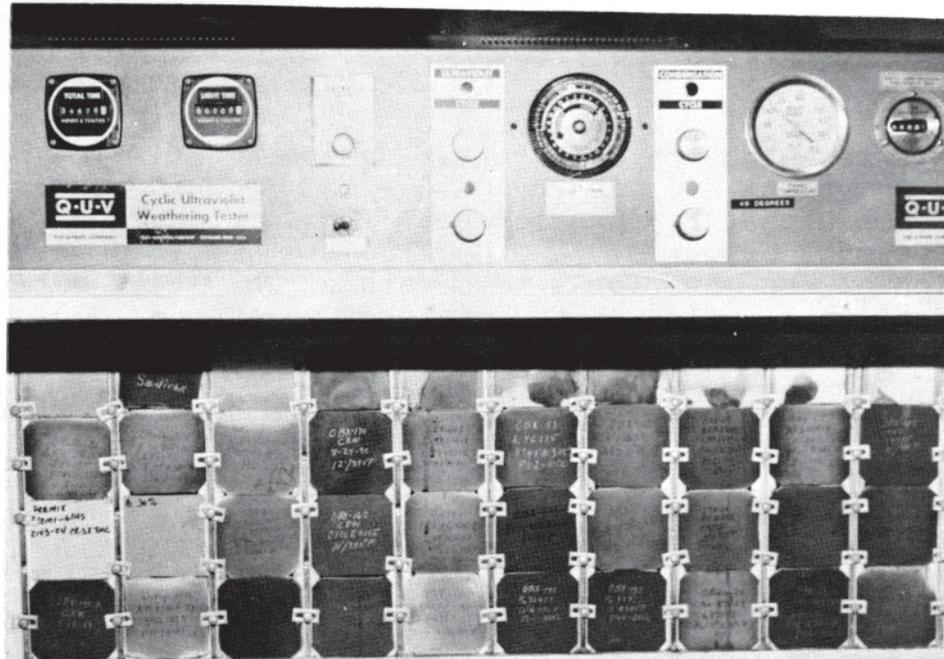


Figure 1. QUV Tester

A polymer must be able to withstand this chemical degradation throughout its service lifetime. At Ohio Brass, all compounds are evaluated in a corona cutting chamber. Electrical insulation that may be subject to corona must be made from a properly compounded EPR elastomer or silicone gum.

Corona Cutting Chamber

Accelerated aging of samples under corona is studied in a corona cutting chamber. Samples, 5 cm by 7 cm, are subject to a mechanical stress of approximately 30,000 microstrain by bending the sample over a grounded electrode. Corona is continuously generated by applying 12 kV to a needle-like electrode placed 1 mm above the surface of the sample as shown in figure 2. The mechanical strain accelerates any degradation of the polymer in the presence of corona.

The chamber accommodates 30 samples. The test can be conducted under dry air or with controlled humidity. The test is either run for a set time (500/1000 hours) or until failure of the sample. In the latter case, the cumulative time to failure is recorded. Samples fail by splitting or cutting under corona. This test is used for relative comparison. Results of some of the tests conducted at Ohio Brass are listed in table 2.

Oxidative Stability

Oxidative stability is measured by using the thermal analysis technique of differential scanning calorimetry (DSC). A typical DSC used by Ohio Brass is shown in figure 3. DSC measures the amount of heat flowing into (endothermic) or out of (exothermic) the sample as a function of the material's temperature. This test determines the reaction kinetics or the state of cure (i.e. degree of vulcanization) in a polymer compound.

Antioxidants are added to polymers to protect them from oxidation-reduction reactions. The effectiveness of an antioxidant is very important in electrical insulation applications. The oxidative stability test is run at an elevated temperature. (This is because heat is generated from corona activity on the surfaces of insulators, and high temperature accelerates the oxidizing process.)

Oxidation is a highly exothermic process and is readily studied by DSC techniques. The sample is rapidly heated in a nitrogen atmosphere to the test temperature of 200° C. The

Material	Hours/failure	Comments
Dirigo 7345	404	Failure
ESP	3250+	No failure
EPDM	2780+	No failure
Silicone rubber 1	348	Failure
Silicone rubber 2	1650+	No failure

Table 2. Corona Cutting Results

Note: + indicates ongoing tests

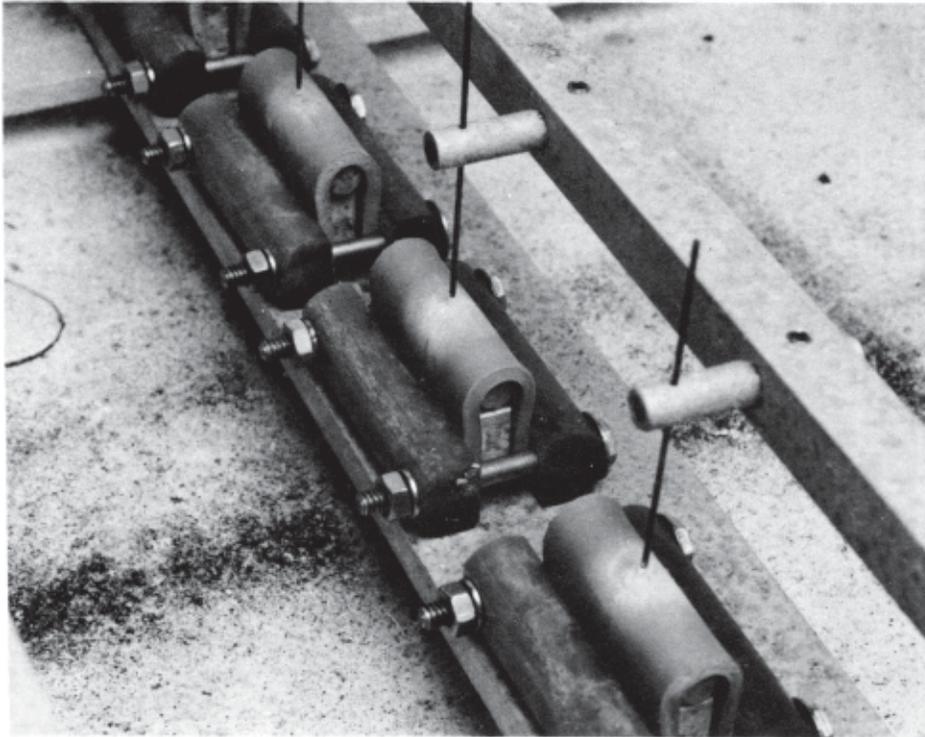


Figure 2. Corona Cutting

Material	Time, minutes
Dirigo 7345	20-26
ESP	440+
EPDM1	20
EPDM2	400+
Silicone rubber	400+

Table 3. Oxidative Stability Test Results

Note: + indicates ongoing tests

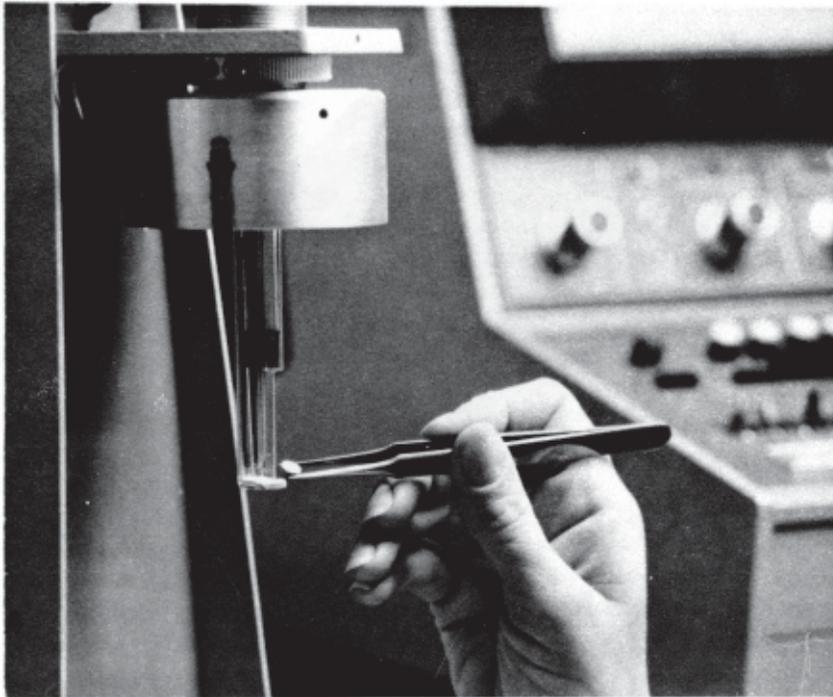


Figure 3. Oxidative Stability Test

atmosphere is then changed to oxygen and the temperature is maintained until the sample begins to oxidize. When the sample oxidizes or decomposes, an exothermic reaction is registered. This indicates that all of the antioxidant has been consumed and that the rubber sample is no longer protected. Table 3 lists the results of some of the tests performed at Ohio Brass.

Tracking Test

It is essential that a polymer exhibit excellent resistance to tracking and erosion. Polymers degrade by erosion and tracking due to the heat generated by leakage currents and dry band arcing. Since each polymer differs in terms of tracking resistance, one of the ways to differentiate various compounds is to subject them to a tracking test.

The Ohio Brass tracking test was designed to evaluate the tracking and erosion resistance for outdoor electrical insulating materials by use of a conductive liquid and electrical stress. This test evaluates the relative ability of an insulating material to withstand the action of electrical discharges on the surface which are similar to those that may occur in service under the influence of dirt, moisture and conducting salts condensed from the atmosphere.

Samples are mounted on a 30 degree incline with electrodes attached on either side. The electrodes are positioned 35 mm apart (see figure 4.). The samples are cyclically sprayed with a conductive solution and then energized. Each cycle is 90 seconds. The conductive liquid has a resistivity of about 400 ohm-cm and is formulated to leave no residue on the sample's surface. A voltage of 10 kV is applied with a controlled current of 20 mA. The leakage current and subsequent dry band arcing dry the surface of the sample.

Failure is judged by one of three criteria:

1. carbonization of tracking of the sample's surface
2. the sample remains conductive at the end of the 90 second cycle
3. Erosion creates a hole in the sample

Silicone compounds typically fail before completing 20,000 cycles due to the combination of tracking, erosion and moisture absorption. EPM/EPDM compounds typically survive 10,000 to 50,000+ cycles. The test is terminated if no failure occurs at 50,000 cycles. Table 4 summarizes results of some of the compounds tested at Ohio Brass.

Material	Cycles	Comments
Dirigo 7345	50,000+	No failure
ESP	50,000+	No failure
Silicone rubber	16,000	Failure
EPDM	1,800	Failure

Table 4. Tracking Test Results

Note: + indicates ongoing tests

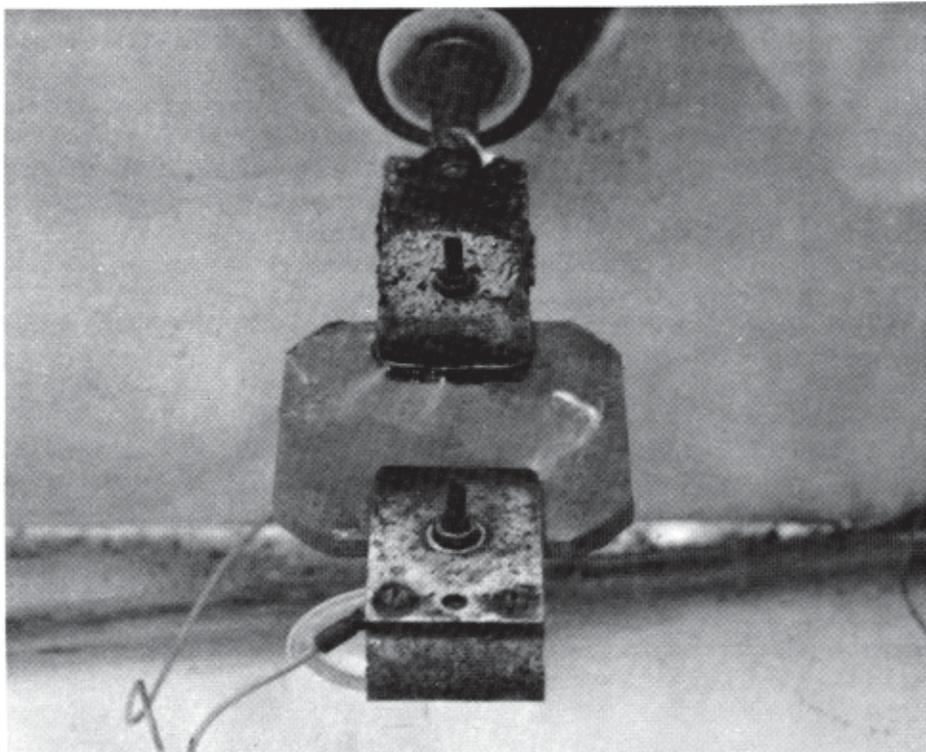


Figure 4. Tracking Test

Surface Dynamics/Hydrophobicity

Polymer surface dynamics reveal that the molecular reorientation of a polymer surface depends upon the environment and is most significant in the presence of air and water. This alters certain properties of the polymer which could influence performance in terms of leakage current suppression and material degradation.

A polymeric surface changes with continued exposure to atmosphere, especially when the surface is in contact with water, humidity, or fog. Contaminants, surface roughness, sunlight, ultra violet radiation, dry band arcing, corona and several other factors cause the surface to behave differently.

An often discussed surface property of polymeric insulating materials is hydrophobicity.

A polymer's hydrophobicity is defined as the ability to resist the formation of a thin water film along the surface.

Loss and Recovery of Hydrophobicity

Prolonged exposure to moisture changes the surface properties of a polymer. With dry band arcing and discharge activity, there is a temporary loss of hydrophobicity. This is due to the formation of free radicals, specifically hydroxyl groups, formed by the interaction between the polymeric surface and moisture. Hydroxyl groups have higher surface energies and an affinity to water and moisture. Water more easily wets along the surface and a thin water film may be formed. The ability to suppress leakage current is reduced and the polymer may begin to degrade. This condition increases the probability of flashovers.

Certain polymers regain their hydrophobic surface over a period of time when there is little or no dry band activity. The time required to recover or regain a hydrophobic surface is dependent upon physical changes, polymer composition, periods of intense dry band activity and many other factors. Recovery is basically due to the diffusion of low molecular weight (LMW) polymer chains from the bulk to the surface of the polymer.

For a long service life, it is necessary that a polymer surface maintains a high degree of hydrophobicity, and has the capability of recovering hydrophobicity after temporary loss. Early in the development process, the hydrophobicity

of a polymer's surface should be tested and comparatively judged. Contact Angle measurement is a simple, but effective, means of assessing hydrophobic properties of a polymer.

The contact angle is the angle of contact between the water drop and polymer surface as illustrated in the figure 5. The greater the contact angle, the more hydrophobic the polymer surface. Thus, the contact angle can be used as an indicator of hydrophobicity.

At Ohio Brass, the contact angle is measured by magnifying a sessile drop of 10 μ l on the surface of the polymer and measuring the angle on a graduated screen. Typically, the water drop is magnified 20 to 30 times, which makes it possible to get a more accurate measurement of the contact angle.

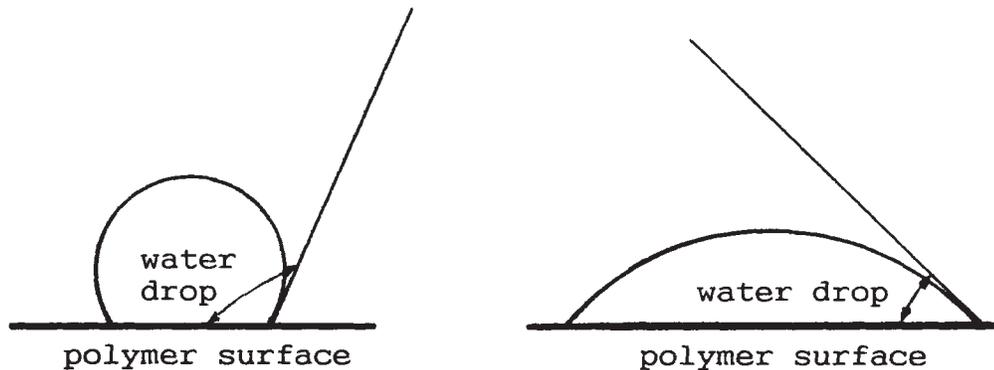


Figure 5. Contact Angle

The contact angles can change a few degrees in less than a minute, so it is essential that the readings be taken very quickly. At Ohio Brass, the device used to measure the contact angle requires less than 30 seconds for one measurement, with a reading error of 2%.

Measurement of Loss and Recovery of Hydrophobicity after Aging

An important factor in extending the life of polymer compound is the ability to recover its hydrophobicity following an electrical event (i.e. corona or dry band arcing). The level of electrical activity on an insulator is usually cyclic and related to daily temperature excursions.

As a result, polymer compounds must be able to repeatedly regain their hydrophobicity within about 12 hours.

To examine this characteristic, small rectangular samples of polymer materials are prepared (0.5 cm by 6 cm by 4 cm). An initial contact angle is measured for the unaged material. Table 5 lists the initial angles for silicone rubber and ESP. The samples are then placed inside the corona cutting chamber (described earlier). These samples are removed at regular intervals of 100 hours. The contact angle is measured immediately following removal from the chamber, and then monitored over a period of several hours to determine the rate of recovery of its hydrophobicity.

The results obtained are plotted for detailed analysis. The recovery pattern throws light on the behavior of the polymer under service conditions. Figures 6 and 7 show the typical recovery pattern of some of the polymers evaluated at Ohio Brass. The results are comparative and offer feedback to our researchers in their development of improved compound.

Material	Contact angle in degrees
Silicone rubber	99
ESP	89

Table 5 Initial Contact Angle of Polymer Materials

HYDROPHOBICITY - RECOVERY
AVG OVER 1000 HOURS OF CORONA AGING

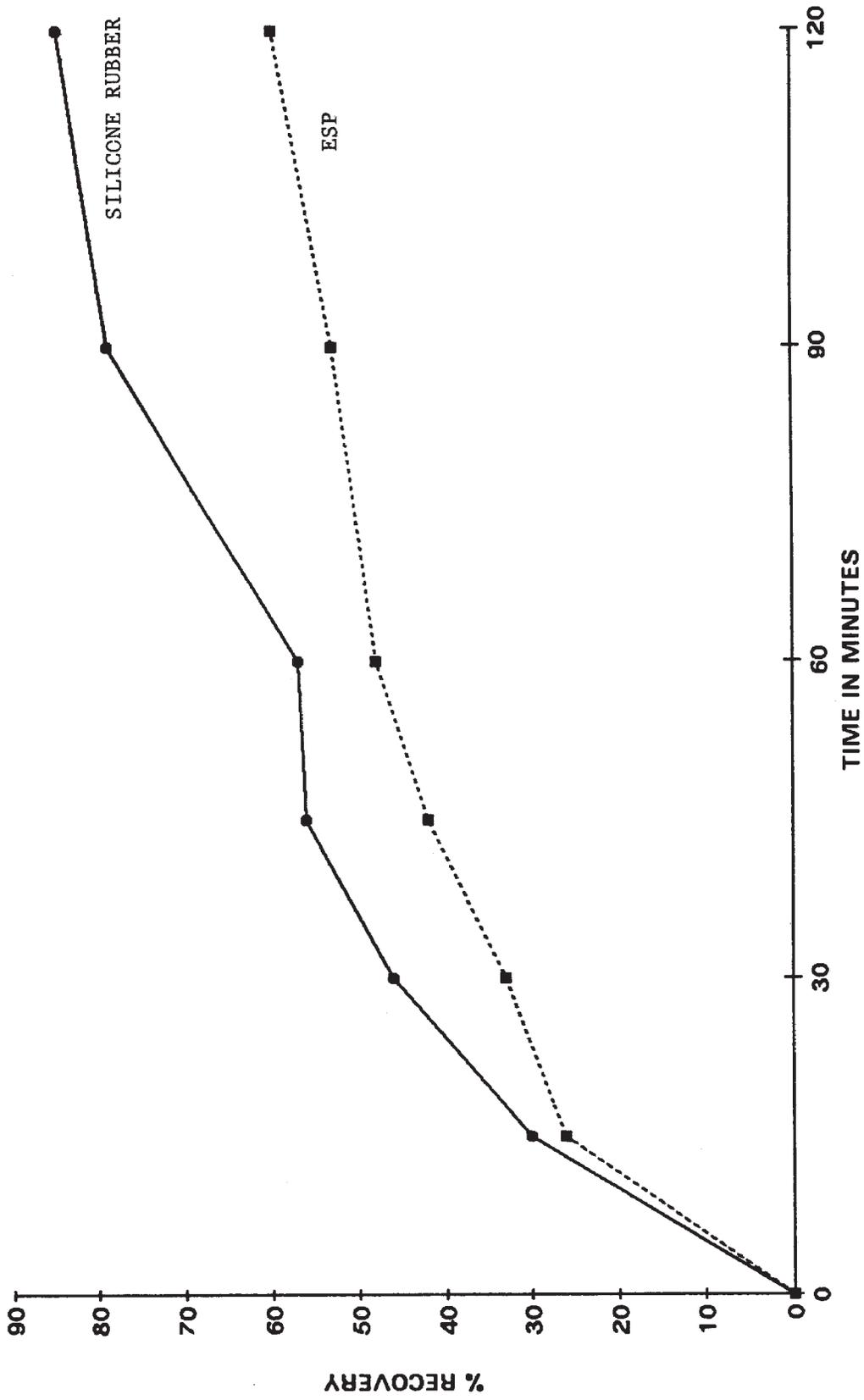


FIGURE 6

HYDROPHOBICITY - AFTER CORONA AGING
CYCLE-TO-CYCLE RECOVERY

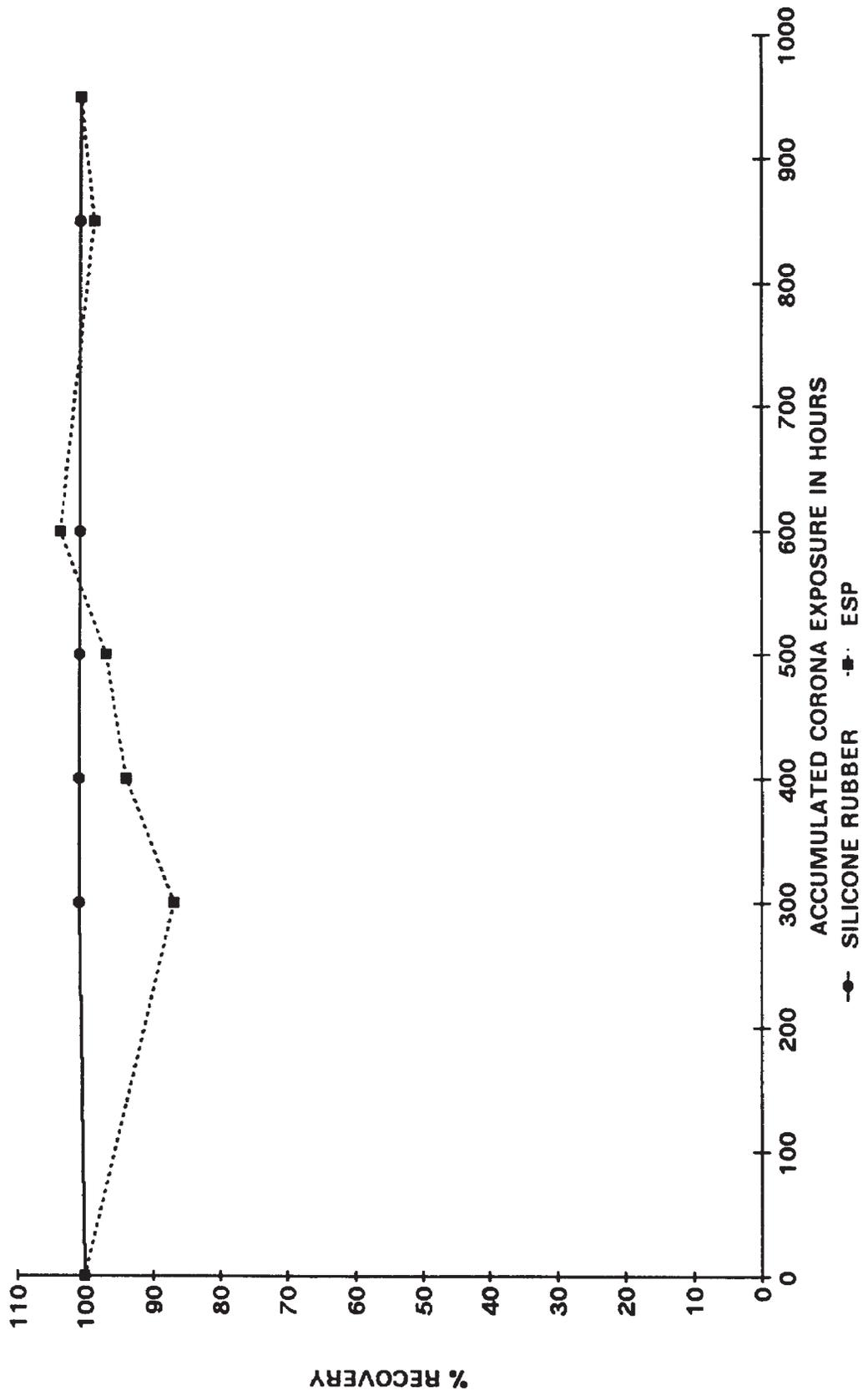


FIGURE 7



POWER SYSTEMS, INC.



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