

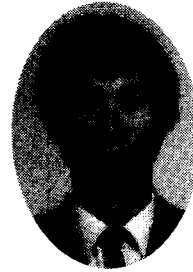
Characteristics of EPDM Compounds for Electrical Insulation and Factors Affecting Performance of Outdoor Insulation



Chul Ho Lee
Fine Polymer Inc.



Sang Wook Kim
Dept. of Chem. Eng., The Univ. of Seoul



Kwang S. Suh
Dept. of Mat. Sci., Korea Univ.

1. EPDM Rubber

1.1 General Review of EPDM Rubber

The ethylene propylene rubbers originated from the work of Ziegler and Natta on the development of stereo-specific catalysts for the polymerization of alkenes. About 1954 high-density polyethylene was introduced using Ziegler catalysts whilst a modified catalyst system developed by Natta led to the introduction of polypropylene in 1957 [1]. Ethylene propylene copolymers can be obtained by copolymerizing ethylene and propylene. The resulting, so-called EPDMs are amorphous and rubbery, but since they do not contain unsaturation, they can only be crosslinked with peroxides. If, during the polymerization of ethylene and propylene, a third monomer, a diene, is added the resulting rubber will have unsaturation, they can be crosslinked with peroxides [2].

Ethylene propylene copolymers are denoted EPM and ethylene propylene diene terpolymers are labeled EPDM by ASTM nomenclature. In EPDM, the "E" stands for ethylene, the "P" for propylene, the "D" for diene, and the "M" for the repeating CH_2 units of the saturated polymer backbone. The term EPR is used in the electrical industry to refer to all ethylene propylene rubbers whether or not they contain a diene monomer. The term EP rubber is used likewise [3].

Of the many third monomers tested, those which are currently used in commercial production are ethylidene norbornene (ENB), 1,4-hexadiene (HD) and dicyclopentadiene (DCPD). Their formulae are given in Fig. 1.

The most commonly used monomer at the moment is ENB because it is the one which best meets the requirements. Compared to ENB, HD gives the polymer a slightly slower cure rate. Among the advantages of DCPD are low cost and a good copolymerization

rate, but its polymers are slow in crosslinking and are very branched [4].

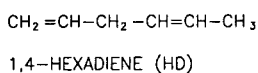
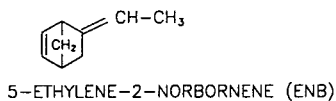


Fig. 1. Third monomers for EPDMs

1.2 EPDM Polymer Properties and Variables

EPDM has outstanding resistance to ozone and oxygen, excellent weathering and heating resistance, low temperature flexibility, and excellent electrical properties. The saturated polymer backbone of EPDM is the key to its superb oxidative stability and excellent weathering resistance. Thus, oxidative attack by oxygen or ozone on the olefinic site in EPDM does not result in cleavage of backbone. Its low density (0.865 specific gravity) combined with its ability to accept high levels of extender oils and filler loadings provide the opportunity to make

Table 1. Polymer variables in EPDM compounds [7]

Properties	Benefits	At the Expense of :
Increasing molecular weight	<ul style="list-style-type: none"> • Tensile and shear strength increase • Filler and plasticizer can be increased for lower cost • Distortion or "sag resistance" during curing improves 	<ul style="list-style-type: none"> • Difficult mixing and dispersion • More difficult to extrude • Higher filler/plasticizer reduces electrical properties
Increasing ethylene content	<ul style="list-style-type: none"> • Tensile strength increases • Accepts higher filler/plasticizer • Easier to pelletize polymer and compounds • More efficient peroxide cures 	<ul style="list-style-type: none"> • Higher hardness • Poorer permanent set • Poorer elastic recovery • Poorer low temperature flexibility
Increasing diene content	<ul style="list-style-type: none"> • More efficient peroxide cures • Improved crosslink density ("cure state") 	<ul style="list-style-type: none"> • Lower heat resistance • Elongation decreases • Compound cost increases
Narrow MWD	<ul style="list-style-type: none"> • Lower die swell • Improved cure rate and state • Better physical properties • Accepts higher filler/plasticizer 	<ul style="list-style-type: none"> • Generally more difficult to mix • Lower critical shear rate makes thin wall difficult to smooth
Broad MWD	<ul style="list-style-type: none"> • Easier to process • Best for injection molding 	<ul style="list-style-type: none"> • Higher die swell • Slower cure rate and state due to low MW components

competitive compounds for a wide variety of applications and can result in reduced costs for finished products [5]. Inherent characteristics of EPDM include resistance to polar fluids, such as alcohols, ketones, certain esters and acetates ; resistance to water and a variety of aqueous solutions; good low temperature flexibility ; high resilience over a fairly broad temperature range ; excellent electrical properties and radiation resistance. However, EPDM compounds do not possess resistance to hydrocarbon oils and solvents [6].

The most important and most significant parameters which are a characteristics of the EPDM elastomers available on the market are molecular weight, molecular weight distribution, propylene content, type and amount of third monomer. These considerations of polymer variables are summarized in Table 1 [7].

· Molecular weight

Low viscosity polymers are preferable for good quality compounds with moderate filler content. The high molecular weight polymers, which relates to mooney viscosity, contribute improved physical properties, such as increased tensile and tear strength, and are more extendable, but tend to extrude more slowly and generally process with more difficulty. Lower molecular weight polymers are generally easier processing and are particularly useful in lightly loaded compounds, needed in some high performance parts. Polymer hot green strength increases with increasing molecular weight or viscosity.

· Molecular weight distribution (MWD)

Since the chains are not all the same length, each polymer molecule is not exactly the same molecular weight. Broader MWD is more desirable for good mill and calender processing. Some narrower MWD is more desirable for extrusion processing. In general, broader MWD polymers have better processing but poorer cure characteristics than

their narrow MWD counterparts [8].

· Ethylene to propylene ratio

The ratio may vary from 45:55 to 75:25 in commercially available types. Propylene groups are not stereo-regular enough or of sufficient block length to make them a factor in EPDM crystallinity [9]. The higher ethylene polymers are, as a rule, more extendable. Higher propylene polymers are more suitable for mill processing, provide better calendaring and have somewhat improved low temperature properties.

· Type and amount of third monomer

Current practice is tending to increasing use of ENB although the other two dienes are still used commercially. The greater degree of unsaturation permits compounds with faster cure rates. The usual amount is somewhere between 2 and 5% of the total monomer although up to 10% may be used in fast-curing grades.

2. Electrical Applications of EPDM Compounds

The inherent properties of EPDM polymers have led to their usage in a considerable variety of applications. The major market for EPDMs are as Table 2 [10].

Table 2. Application fields of EPDM [10]

Field of application	%
Automotive	42
Electrical insulation	15
Building	10
Appliance	10
Industrial	9
Blends with plastics	9
Other	5
	100

Because of its combinations of superior electrical properties, its flexibility over a

wide temperature range and its resistance to moisture and weather, EPDM is used in a diverse range of electrical applications [11] :

- Power cables
- Flexible cords
- Control and instrument wire
- Automotive ignition wire
- Appliance wire
- Motor lead wire
- Mining cable
- Molded electrical accessories

EPDM has performance characteristics that permit power cables to be used successfully under conditions of electrical stress, heat, and moisture, which have produced increasingly higher rates of failure in cables with other insulating polymers [12]. Moreover, most joints, splices, elbow for switchgear, terminations and polymer insulators are made of EPDM.

The non-polar hydrocarbon nature of EPDM results in its excellent electrical properties, which approach those for XLPE. Excellent electrical properties and water resistance are keys to making EPDM so useful in electrical applications [3].

EPDM has been used for insulation since its commercial introduction 40 years ago. EPDM insulation has several attractive features :

- Corona resistance
- Wet electrical stability
- Water tree resistance
- High temperature performance
- Flexibility

EPDM retains its integrity as an insulation at the emergency overload temperature of 130°C by maintaining acceptable physical strength [13]. Low temperature flexibility is excellent with glass transition temperatures approaching -60°C. Ease of installation is another important consideration in choosing electrical insulation. EPDM is much more flexible than ceramic and plastic

materials over a wide range of temperatures.

Polymeric insulations are increasingly being used in both the distribution and the transmission voltage ranges and are steadily capturing a wider share of the market. It has been reported that polymeric insulators have captured about 20% of the US transmission line insulator market. Currently, in the United States, polymer insulators have a market share between 60 to 70% of all new installations of high voltage insulators [14] and their share of the market continues to grow. Polymeric line post insulators command about 33% of the total line post market, whereas polymeric suspension insulators have only about 15% of the total suspension insulator market [15].

A variety of polymer insulating materials have been developed for overhead electrical insulation. However, only the elastomeric materials have shown success in outdoor electrical insulation, i.e. EPDM and silicone elastomers. Today's EPDMs are suitable for distribution and transmission class insulation up to 765 kV [16].

Due to the hydrophobic surface [17], the EPDM materials offer an additional advantage of better contamination performance over porcelain and glass [18]. This makes their virgin surface hydrophobic or water repellent. These advantages have been possible, chiefly because polymers can be formulated suitably to make them more resistant to damage from the numerous elements in nature, such as temperature extremes, UV radiation in sunlight, chemicals, corona and electrical arc discharge activity. For surge arrester housings, EPDMs visco-elastic nature has made it possible to contain violent explosions that can occur with porcelain within the housing, thereby minimizing injury to personnel during arrester failure.

During outdoor service, the surface of the insulating devices is frequently subjected to moisture and contamination which lead to

dry band arcing, causing material degradation in the form of tracking and erosion. Under certain conditions, the dry band arcs cause flashover across the surface of the insulating device, thus resulting in a power outage.

3. Compounding of EPDM for Electrical Applications

Compounding is the technology of converting the raw rubber resin into useful materials through the addition of fillers, reinforcers, stabilizers, process aids, curatives, flame retardants, pigments, etc. The resulting composition is called a compound.

Material technology is forever changing. Improved EPDM formulations are being continuously developed.

3.1 Curing System

The pendant unsaturation allows sulfur vulcanization in EPDM compounds. Previous investigations have demonstrated that sulfur-cured EPDM insulations are electrically less stable in hot-wet environments than peroxide cured EPDM, so the latter are generally used in insulating compounds [19, 20].

Peroxide systems are generally quite expensive in terms of compounding ingredients and in the high temperature and pressures. They are also inhibited by oxygen in the mold and acidic components in the mixture, because of hydrolytic scission of peroxide, without creation of radicals, due to the presence of oxygen and acids [21].

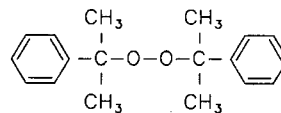
A comparison of sulfur and peroxide cures is summarized in Table 3 [7]. The most commonly-used peroxide is dicumyl peroxide (DCP). It can be used in all cures above 150 °C, and produces a characteristic odor in the product due to a byproduct of its thermal decomposition, acetophenone [22]. Another commonly-used peroxide is 1,4-bis(t-

butylperoxy-isopropyl)benzene. Fig. 2 shows chemical structure of these peroxides.

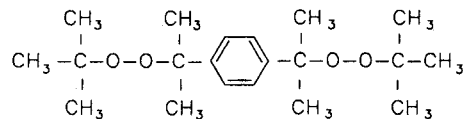
A so-called coagent, such as acrylates, methacrylates, vinyl ester and triallyl cyanurate (TAC), is often used with the peroxide to enhance some compound property or characteristic, such as compression set, heat resistance, and tear resistance.

Table 2. Application fields of EPDM [10]

Type of cure	Benefits	Disadvantages
Peroxide	<ul style="list-style-type: none"> Electrical stability Heat stability 	<ul style="list-style-type: none"> Requires higher temperatures and pressure vs. sulfur Inhibited by oxygen or acidic compounding ingredients
Sulfur	<ul style="list-style-type: none"> High tensile and tear strength Can be carried out at lower pressures and temperatures in air 	<ul style="list-style-type: none"> Wet electrical stability Heat stability Odors



DICUMYL PEROXIDE



1,4 BIS(T-BUTYLPEROXY-ISOPROPYL)BENZENE

Fig. 2. Peroxides for EPDM compound

3.2 Fillers

Because EPDM is non-crystallizing elastomer, the use of reinforcing filler is a necessity to achieve acceptable mechanical properties. However, the choice is substantially narrowed by various requirements of the electrical industry, including physical properties, electrical losses, electrical stability, breakdown strength and moisture absorption. The effects of a filler in a compound depend on particle size, particle shape, surface treatment, the degree of dispersion of the filler in the rubber and the tendency to form agglomerates or structure.

Calcined clays are particularly important in EPDMs and they are currently used in the production of insulating compounds for low, medium and high voltage cables [23]. ATH is used at 120~200 phr in compounds requiring track resistance or low smoke evolution when burned, which will be discussed in section 4.2. Although carbon black is the most useful fillers in rubber industry, carbon black has a negative effect on the electrical properties. Of particular interest with EPDMs are conductive compounds for semi-conductive sheaths of medium and high tension electric cables [24].

Small amount of special fillers can be incorporated into insulation compounds for special purposes. Zinc oxide at levels as 5 phr generally provides improved heat resistance [25]. Titanium dioxide provides a neutral color base for colored insulations and weatherability, but at some sacrifice of dielectric constant [26].

3.3 Plasticizers

Plasticizers are added to reduce the compound viscosity and improve the processing characteristics. Aromatic oils tend to give poorer properties and have an adverse influence on weathering and UV resistance. They must not be used in conjunction with peroxide curing systems. Naphthenic oils are highly compatible and generally used in

EPDMs, but they can vary widely in volatility and should be selected carefully if heat aging or weathering is involved [27]. So, extremely pure paraffinic oils are acceptable in electrical insulations.

Stearic acid, zinc stearate, paraffin waxes, low molecular weight polyethylenes, or other internal lubricants are often included in the compound to aid process, i.e. mill release, mold flow and release.

Because of the restriction of electrical losses, the use of plasticizers should be carefully considered, and avoided if possible.

3.4 Miscellaneous

EPDM polymers can be additionally stabilized by relatively small addition of anti-degradants. In combination with peroxide-cure systems, antioxidants, such as polydehydroquinolines, thiophosphates, parphenylene diamines, and modified triazines, are also reported to be suitable [28]. Silane coupling agents may be used to promote polymer/filler interaction to enhance mechanical properties. Various lead compounds, which offer wet stability, function as efficient anion scavengers. Because of the high toxicity of lead compounds the severe hazards presented by their dust, they are all available to the rubber compounder as pre-dispersed, dust-free concentrates in various carriers such as paraffin wax, petrolatum, mineral oil and EP rubber.

4. Factors Affecting to Outdoor Polymeric Insulation

Polymeric materials used for electrical insulations are subjected to a number of factors during service. The main components of the environmental stress which cause degradation are weather, pollution, and thermal effects.

4.1 Weathering and Pollutants

4.1.1 Sunlight

The sun is the primary cause of most climatic phenomena found on earth. It supplies heat to the earth's surface, transports water from the seas into the atmosphere and generates air movement and winds.

The spectrum of sunlight penetrating to the surface ranges from about 290 to 3000 nm [29]. The composition of the radiation reaching the earth's surface is approximately 5% ultraviolet, 45% visible and 55% infrared [30].

Light can only cause a chemical change if energy of the individual photons is at least equal to the lowest bond energy found in the polymer molecule. The energy of a photon is related to its wavelength by the equation [31].

$$E = hc/\lambda \quad (1)$$

where h is Planks constant (6.624×10^{-27} erg · s), c is velocity of light (2.998×10^{10} cm /s), λ is wavelength of photon, N is avogadro number (6.023×10^{23} /mole).

$$\begin{aligned} 1 \text{ einstein} &= Nhc/\lambda \quad (2) \\ &= 6.023 \times 10^{23} \text{ mole}^{-1} \times 6.624 \times 10^{-27} \\ &\quad \text{erg} \cdot \text{s} \cdot 2.998 \times 10^{10} \text{ cm} \cdot \text{sec}^{-1} / \lambda \\ &= 1.196 \times 10^5 / \lambda \text{ kJ/mole} \end{aligned}$$

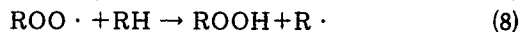
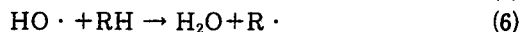
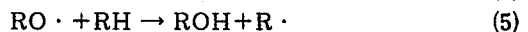
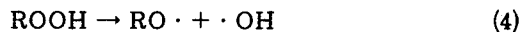
For example, energy with 290 nm, which is the most shortest and strongest wavelength reaching the earth's surface.

$$\begin{aligned} E &= 1.196 \times 10^5 / 290 \text{ kJ/mole} \quad (3) \\ &= 419 \text{ kJ/Einstein} \end{aligned}$$

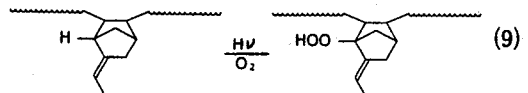
A comparison of the energy radiation at different various chemical bonds is shown in Table 4. It indicates that the energy level of photons from solar radiation is sufficiently high for breakage of bonds in polymeric materials.

4.1.2 Photo-degradation of EPDM

The initial photochemistry of EPDM is the formation of hydroperoxides, as in polyethylene and polypropylene. The radicals resulting from hydroperoxide decomposition initiate further oxidation [34]. This cycle rapidly propagates new hydroperoxides during the early stages photooxidation :



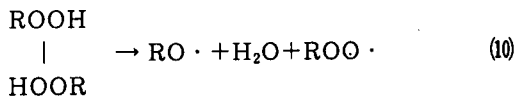
In EPDM containing ENB moieties, the bridgehead carbons of the norbornene ring were found to be oxidized in high yield [35].



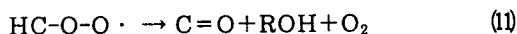
As photooxidation progresses and hydroperoxides accumulate, they begin to associate the decompose by a bimolecular mechanism [36].

Table 4. Energy of different wavelength, bond energy and dissociation of bonds in polymers [32, 33]

Wavelength nm	Energy kJ/Einstein	Bond Type	Bond energy kJ/mole	Dissociation energy kJ/mole
290	419	C - H	380~420	413
300	398	C - C	340~350	348
320	375	C - O	320~380	351
350	339	C - Cl	300~340	317
400	297	C - N	320~340	351



According to Geuskens and Kabamba [37], the key step regulating the rate of photooxidation of polyolefins is the competition for peroxy radicals between hydrogen abstraction [eq. (8)] and disproportionation of two peroxy radicals [eq. (11)]. The former reaction accelerates degradation and the latter retards it.



4.1.3 Moisture

Water appears in the outdoor environment in the form of airborne humidity, fog, dew, rain, snow, frost, or hail. The presence of liquid water, in particular the duration of surface wetness, is probably an important feature in determining the rate of breakdown of polymeric materials.

Moisture can attack and degrade different polymers in a number of ways [38] :

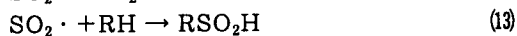
- chemical hydrolysis
- production of hydroxyl radicals in presence of sunlight which can further participate in radical reactions in the polymer leading to degradation.
- freezing of water in surface imperfections can cause cracks in which more water may lodge causing further cracking on freezing.
- pollutants dissolved in a surface moisture film can cause loss of electrical integrity e.g. by tracking or dielectric puncture.
- in certain polymers moisture may dissolve out plasticizers and stabilizers, resulting in embrittlement or reduction in ability to resist oxidation etc.
- adsorbed or absorbed water increases the electrical losses which may result in a redistribution of electrical stress and hence failure.

On the other hand, rain may be beneficial in certain cases e.g. by washing away pollution from exposed surfaces.

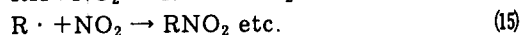
4.1.4 Pollutants

Atmospheric pollutants, such as nitrogen oxides, sulfur oxides, hydrocarbons, and other particulates provide an hostile chemical environment that degrades polymeric materials.

Nearly all fuels contain some sulfur and when these fuels are burnt sulfur dioxide is released into the air. Dainton and Ivin [39] have shown that in the presence of UV light, sulfur dioxide reacts with a hydrocarbon material to yield sulfinic acids which may be deleterious, since wetting will occur more readily and electrical properties may be impaired :



Nitrogen dioxide reacts with hydrocarbons to produce either a nitro or nitride side group along the polymer backbone, or scission and crosslinking [39] :



4.1.5 Thermal Effects

The actual temperature of the insulation depends, of course, upon the temperature rise due to internally generated heat, which is added to the ambient. The environment is such that cable terminations may experience both high and low temperatures and sudden changes in temperature.

High temperature alone may cause chemical changes in the material through thermal activation of reactions. These changes may be divided as [40] :

- depolymerization reactions which lead to breaking of the main chain

- crosslinking reactions between the chains
- reactions of the chain substituents

4.2 Tracking and erosion phenomena of outdoor insulation

According to ASTM [41], the terminology related to tracking can be defined as :

- track : "partially conducting path of localized deterioration on the surface of an insulating material"
- tracking : "the process that produces tracks as a result of the action of electric discharges on or close to the insulation surfaces"
- erosion : "the progressive wearing away of electrical insulation by the action of electrical discharges"

4.2.1 Failure Mechanism

Many kinds of electrical equipment includes an insulation surface under electrical stress. These solid/air interfaces may be at bushings, terminations, polymer insulators, lightning arresters housing, and on support structures. As time goes on, and dust and other contaminants collect on these surfaces, the integrity and the reliability may be jeopardized under humid conditions by a form of surface failure called "tracking" [42].

A moisture film on a surface, whether formed by condensation or precipitation, will conduct leakage current with a magnitude determined by the type and extent of pollution. As the leakage current flows between live parts, or from a live part to ground, the conductive film will heat non-uniformly and begin to evaporate non-uniformly, distorting the stress distribution over the surface. In particular, "dry-band" will form, resulting in regions of very high resistivity between the edges of the remaining wet film. Nearly the total surface voltage will appear across this dry-band, causing

flashover of the gap. The arcing will continue until the gap widens sufficiently by the further evaporation to the point where the arc can be longer be maintained.

When this occurs on the surface of an organic material, the temperature of the arc may be sufficient to decompose the material locally, releasing free carbon. Dry-banding, arcing, and the formation of free conducting carbon will proceed in a relatively random manner (the location of the arc may tend to prefer previously carbonized spots) until a continuous conducting path forms between the live parts, or at least bridges a sufficient proportion of the surface, that flashover occurs.

This failure mechanism is summarized in Fig. 3.

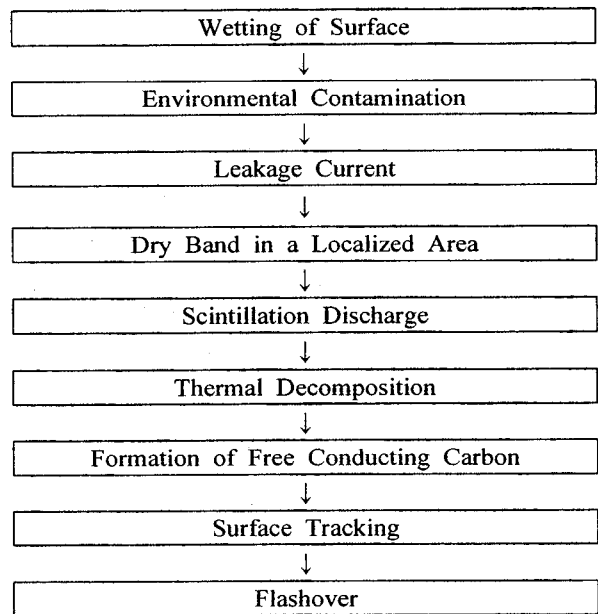


Fig. 3. Tracking mechanism on the surface of polymeric materials

Nunes et al. [43] have shown that pyrolysis was the major event leading to gaseous product formation in tracking degradation of

EPDM. In their work, gases which were released during pyrolysis of EPDM tracking degradation were identified by infrared spectroscopy and gas chromatography. They also detected the surface of EPDM sample reached 488°C just before final breakdown as a result of tracking.

They summarized pyrolytic events in tracking degradation of EPDM as shown in Fig. 4.

4.2.2 Prevention of Tracking

The most common surface pollution responsible for tracking is a combination of dust and water where the soluble content of the dust increases the conductivity of the water and the insoluble part provides for easier wetting of the insulation [44].

Significant degradation of the insulation occurs after the interruption of the liquid film during boiling off, when small arcs are formed between receding films that decom-

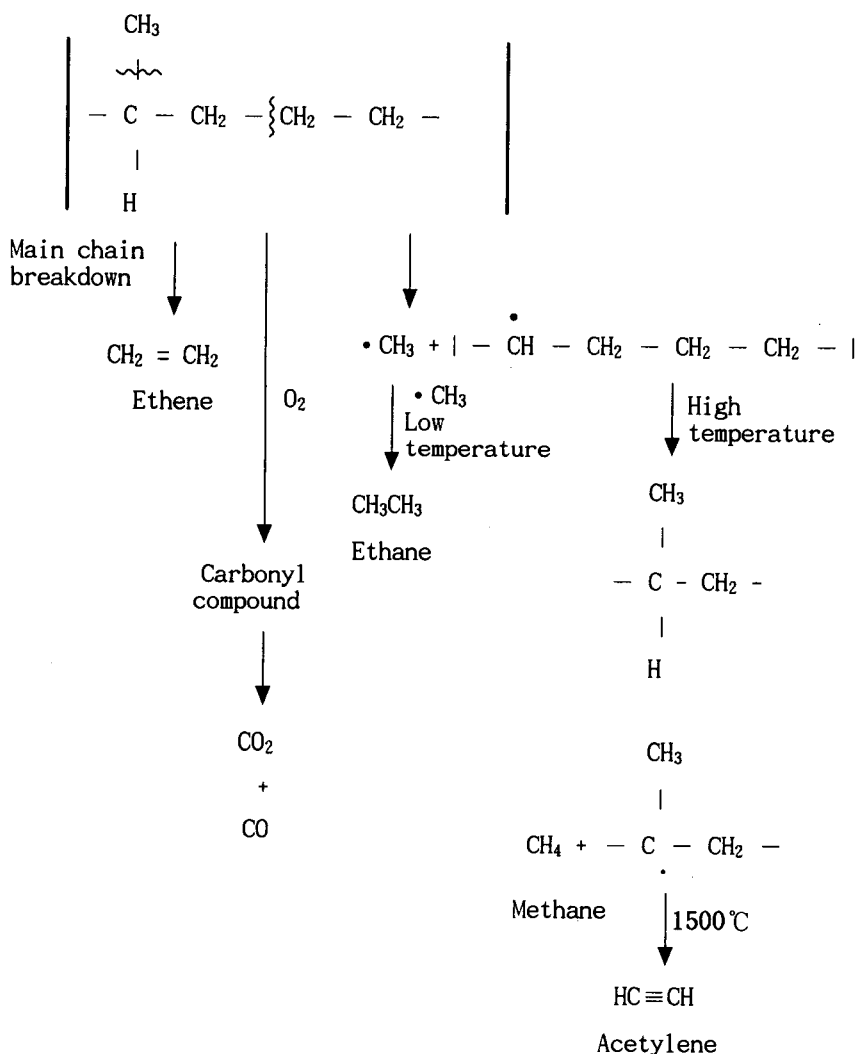


Fig. 4. Pyrolytic events in tracking degradation of EPDM [43]

pose the adjacent insulation. The power available to these small surface arcs depends on the source of supply, particularly the maximum voltage and the resistance of the water films, the latter being determined by the conductivity of the solution, the leakage path length and film thickness. At the higher voltages the track is completed by flashover, so that when dry again the insulation resistance may appear satisfactory, especially if the power to the short circuit has been restricted before disconnection [45].

Insulator flashover, tracking and erosion are all related to leakage current [46]. The good performance of the polymeric materials such as silicone and EPDM originates from the fact that polymer surfaces are difficult to wet because of their low surface energy, weak boundary layers, etc [47]. When a water droplet is in contact with a solid surface, the angle formed between them is named the "contact angle" (Fig. 5) [48]. The high energy surface is wetted readily and allows water to spread over it in a continuous film. On the other hand, the low energy surface repels water such that the droplets stand separately. In the latter case, the contact angle is large ($>90^\circ$) and the surface is said to be hydrophobic or water repellent. Water droplets tend to run off a low energy surface [49].

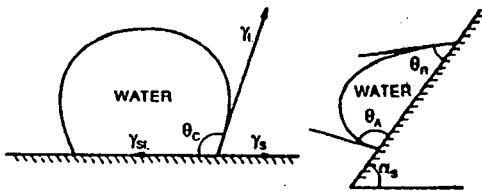


Fig. 5. Contact angle of water drop on polymer surface

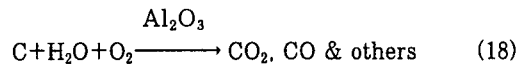
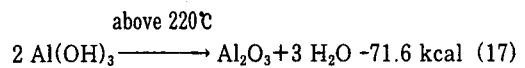
The contact angle is dependent on the free energy of the solid surface and wettability of

the solid surface is related to the contact angle. The free energies are interrelated via Young's equation [50].

$$\gamma_s = \gamma_{sl} + \gamma_l \cos \theta_c \quad (16)$$

where γ_s , γ_l , and γ_{sl} are the surface tensions or sometimes called the surface free energies per unit area of the solid, liquid interfacial surfaces, respectively, and θ_c is the contact angle on a horizontal surface.

Polymeric insulators for outdoor use were made feasible by the discovery in the 1950s that ATH filler increase the tracking and erosion resistance of the polymeric materials [51]. ATH is now universally used and form between 40 to 55% of the total component [52]. At higher temperatures above 220°C , the water from the hydration of ATH filler and O_2 in air combine with carbon trace formed as a result of polymer degradation to form gaseous products such as CO or CO_2 which escapes from the surface [53]. During dry band arcing, surface temperature between 260 to 400°C were measured [53], and the water of hydration is released as a vapour which then cools the surface. Thus, formation of free carbon on the surface is prevented.



In the process of the chemical reaction (18), Al_2O_3 acts as a catalyst [54]. Due to the process described above, the increase of ATH filler is of great help to improve the tracking resistance of EPDM.

4.3 Dielectric Loss

One effect of very high dielectric losses is to cause further temperature increase and even higher power losses. The effect on

temperature is given as

$$\Delta T = \pi V^2 f \epsilon_0 \epsilon_r \rho \tan \delta \quad (19)$$

where V is the rms phase to ground voltage in volts, f is the frequency in Hz, $\epsilon_0 = 8.854 \times 10^{-12}$ F/m is the permittivity of free space, ϵ_r is the relative permittivity or dielectric constant of the insulating material, and ρ is the thermal resistance in m°C/W. The temperature obviously is independent of conductor geometry but only small temperature increases can be generated at power frequency [55].

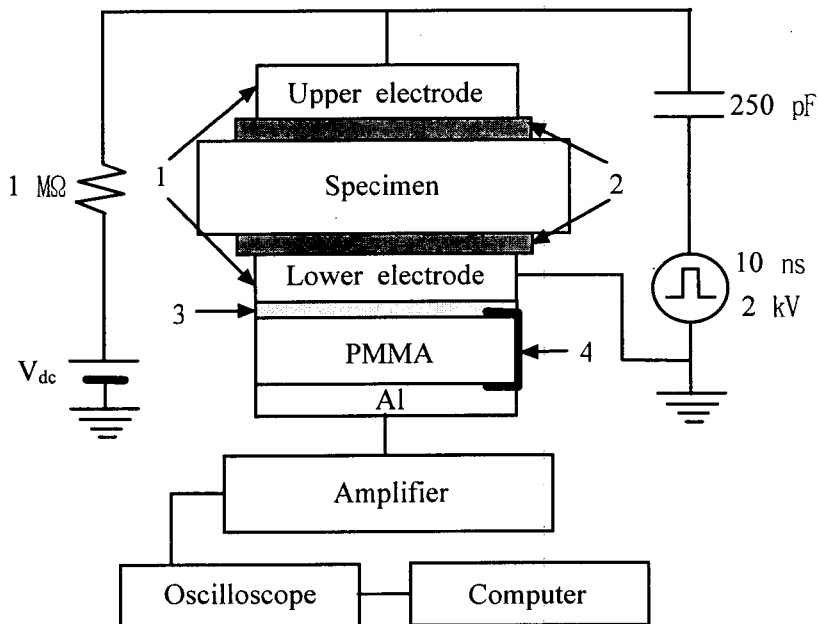
The power losses which are suffered in the dielectric can be calculated by the use of the relation [56].

$$W = 2\pi V^2 f \epsilon_0 \epsilon_r \tan \delta \rho (A/t) \quad (20)$$

where A is cross-sectional area of insulation which has thickness t .

4.4 Space Charges in Polymeric Insulating Materials

Accumulation of space charge in polymeric insulation such as XLPE or EPDM can have a significant, often detrimental effect on its performance [57]. Space charges have been recognized as harmful for dc applications ; they are also play a leading role in long term electrical degradation of polymers under ac stress [58]. Many research results show that the space charge formation and accumulation in insulation may distort the electrical stress distribution, initiate electrical tree, cause insulation aging, and even lead to the breakdown of local insulation in some severe conditions of polarity reversal



- 1: Al electrode, 2: Semiconductive electrode
3: PVDF film, 4: Tin film

Fig. 6. PEA system for space charge measurement

and short-circuit [59].

Generally, space charge in polymer materials mainly consists of two parts. One is the mobile carriers injected from electrodes, which is dominant under higher electrical stress, and is referred to as homocharge. The other is the activation of intrinsic charges, caused by the dissociation of bulk charges, which is major under the lower electrical stress, and is referred to as heterocharge [60]. The effect of space charge changes with location, polarity, and so on. For example, under dc voltage application, a heterocharge near the electrode is expected to reduce the breakdown voltage, whereas a homocharge will increase it. However, after polarity reversal under ac conditions or particularly in dc transmission lines, the homocharge is converted to hetero space charge and is expected to reduce the breakdown voltage [61].

Charge transfer may also occur at the interfaces. The local increase of the internal electric field which results from this non-homogeneous charge distributions reduce the effective electric strength of the dielectric and may lead to disruptive phenomena [62].

Among the various measuring techniques, pulsed electro-acoustic (PEA) method is widely used due to some advantages in the quantitative and qualitative measurement of space charge in various geometries of samples [60, 63]. Fig. 6 shows the PEA system for space charge measurement. The pressure wave in the sample is generated by an electric pulse and transformed to a voltage signal by a polyvinylidene fluoride (PVDF) transducer. Generally, the electric pulse has an amplitude of 2 kV and a width of 10 ns, and measurements are made within 2 min after short-circuiting at the end of the application of voltage for 30 min.

References

- [1] J. A. Brydson, "Rubbery Materials and Their Compounds", Elsevier Applied Science, London, 147, 1988.
- [2] W. Hofmann, "Rubber Technology Handbook", Hanser Publishers, New York, 93, 1989.
- [3] R. J. Arhart, IEEE Electr. Insul. Magazine, 9, 32, 1993.
- [4] L. Corbelli, "Developments in Rubber Technology and Rubber Composites", Applied Science Publishers, London, 2, 89, 1985.
- [5] E. L. Borg, "Rubber Technology", Van Nostrand Reinhold Co., 220, 1973.
- [6] R. D. Allen, J. Elastomers and Plastics, 15, 19, 1983.
- [7] M. Brown, IEEE Electr. Insul. Magazine, 10, 18, 1994.
- [8] N. P. Chermisnoff, Polym. Plast. Technol. Eng., 31, 713, 1992.
- [9] H. Starkweather et al., Macromolecules, 15, 1600, 1982
- [10] L. Corbelli, "Developments in Rubber Technology and Rubber Composites", Applied Science Publishers, London, 2, 120, 1985.
- [11] M. Brown, IEEE Electr. Insul. Magazine, 10, 16, 1994.
- [12] M. Brown, IEEE Electr. Insul. Magazine, 4, 20, 1988.
- [13] R. J. Arhart, IEEE Electr. Insul. Magazine, 9, 13, 1993.
- [14] T. Zhao and R. A. Bernstorff, IEEE Trans. Insul. Magazine, 14, 26, 1998.
- [15] H. M. Schneider et al., IEEE Trans. Power Delivery, 4, 2214, 1989.
- [16] E. A. Cherney, IEEE Electr. Insul. Magazine, 12, 7, 1996.
- [17] A. W. Adamson, "Physical Chemistry of Surfaces", 3rd Edition, Jhon Wiley and Sons, 1976.
- [18] R. S. Gorur et al., IEEE Trans. Power Delivery, 5, 1923, 1990.
- [19] M. Brown, Electrical Elastomers, EE-340.1 ; DuPont Company.
- [20] C. H. Lee et al., KIEE Summer Conference, 1697, 1996.

- [21] W. C. Endstra and T. J. Wreesmann, "Elastomer Technology Handbook", Ed. N. P. Cheremisinoff, CRC Press, London, 496, 1993.
- [22] D. McAllister, "Electric Cables Handbook", Granada, London, 51, 1982.
- [23] J. C. Chan et al., IEEE Electr. Insul. Magazine, **9**, 9, 1993.
- [24] L. Corbelli, "Developments in Rubber Technology and Rubber Composites", Applied Science Publishers, London, **2**, 111, 1985.
- [25] R. D. Allen, J. Elastomers and Plastics, **15**, 25, 1983.
- [26] M. Brown, IEEE Electr. Insul. Magazine, **10**, 19, 1994.
- [27] J. A. Riedel and R. V. Laan, "The Vanderbilt Rubber Handbook", 3rd Ed. R. T. Vanderbilt Co., 136, 1990.
- [28] A. P. Tuesehev et al., Int. Polymer. Sci. Technol., **7**, 27, 1980.
- [29] W. Schnabel, "Polymer Degradation", Hanser International, New York, 96, 1981.
- [30] A. Davis and D. Sims, "Weathering of Polymers", Applied Science Publishers, London, 4, 1983.
- [31] 大澤善次郎, "高分子の劣化と安定化", 武蔵野クリエイト, 東京, 32, 1992.
- [32] F. Gugumus, "Plastics Additives Handbook", Hanser Publishers, Munich, 97, 1985.
- [33] Encyclopedia of Polymer Science & Engineering, 2nd Ed., Wiley Interscience, New York, **17**, 542, 1986.
- [34] J. MacCallum, Developments in Polymer Degradation, **6**, 191, 1985.
- [35] J. Lemaire and R. Airnaud, Polymer Photochemistry, **5**, 243, 1984.
- [36] G. Geuskens et al., Polymer Photochemistry, **5**, 313, 1984.
- [37] G. Geuskens and M. Kabamba, Polymer Degradation and Stability, **4**, 69, 1982.
- [38] R. J. T. Clabburn, Proc. IEEE Trans. PAS, 1834, 1973.
- [39] H. H. G. Jellinek, J. App. Poly. Sci., **13**, 107, 1969.
- [40] P. Paloniemi, IEEE Trans. Electr. Insul., **EI-16**, 1, 1981.
- [41] ASTM D 2303, "Standard Test Method for Liquid-Contaminant, Inclined-Plane Tracking and Erosion of Insulating Materials".
- [42] M. Kurtz, IEEE Electr. Insul. Magazine, **3**, 12, 1987.
- [43] S. P. Nunes et al., IEEE Trans. Electr. Insul., **EI-24**, 99, 1989.
- [44] M. J. Billings et al., IEEE Trans. Electr. Insul., **EI-2**, 131, 1967.
- [45] M. G. Weller, Mining Technology, February, **84**, 1980.
- [46] R. S. Gorur et al., IEEE Trans. Power Delivery, **3**, 1167, 1988.
- [47] A. E. Vlastos and S. M. Gubanski, IEEE Trans. Power Delivery, **6**, 888, 1988.
- [48] S. H. Kim et al., IEEE Trans. Electr. Insul., **27**, 610, 1992.
- [49] J. D. Andraded, "Polymer Surface and Interface Dynamics", Plenum Press, 8, 1988.
- [50] D. K. Owens and R. C. Wendt, J. Appl. Polym. Sci., **13**, 1741, 1969.
- [51] J. F. Hall, IEEE Trans. Power Delivery, **8**, 376, 1993.
- [52] T. Zhao and R. A. Bernstorff, IEEE Electr. Insul. Magazine, **14**, 26, 1998.
- [53] R. S. Gorur et al., IEEE Trans. Power Delivery, **2**, 486, 1987.
- [54] N. Yoshimura et al., IEEE Electr. Insul. Magazine, **13**, 16, 1997.
- [55] R. Bartnikas et al., IEEE Trans. Power App. Systems, **PAS-99**, 1575, 1980.
- [56] R. M. Eichhorn, IEEE Trans. Electr. Insul. **EI-16**, 478, 1981.
- [57] M. A. Dakka et al., Proc. IEEE-CEIDP, 136, 1998.
- [58] C. Laurent et al., IEEE Trans. Dielectrics EI, **4**, 585, 1997.
- [59] M. Ieda, IEEE Trans. Electr. Insul., **19**, 162, 1984.
- [60] X. Wang et al., J. Appl. Phys. **84**, 1546, 1998.
- [61] M. Ieda and Y. Suzuoki, IEEE Electr. Insul. Magazine, **13**, 10, 1997.
- [62] T. Ditchi et al., IEEE Trans. Electr. Insul., **24**, 403, 1989.
- [63] A. Vazquez et al., J. European Ceramic Society, **19**, 1219, 1999.