

# Microstructure Assessments for Determining Electric Cable Insulation Remaining Life

D. A. Horvath and R. L. Steinman  
*Advent Engineering Services, Inc.*  
*Ann Arbor, Michigan*

## Abstract

The concern of electrical insulation aging covers the gamut of industry, military, government, and private arenas with an existing short-term focus on nuclear power plants, aircraft, electrical transmission and distributions systems, fossil power plants, and aging industrial facilities. Both the nuclear and aircraft industries have an immediate need for an acceptable electrical insulation monitoring technique. Ideally, this technique would be non-destructive and capable of predicting the remaining life of installed insulation. Many techniques currently exist for electrical and mechanical testing of insulation to confirm the present integrity of the insulation, but none of the current methods are both non-destructive *and* predictive of acceptable future life. This paper reports on a promising technique for assessing remaining cable insulation life based on microvoid content.

The mode for insulation failure differs as a function of the operating voltage regime. At higher voltages, the failures are dominated by partial discharge effects. At lower voltages, the failure mode is related to loss of integrity (breaks or cracks in the insulation material), which could then cause a circuit failure problem in high moisture or high humidity environments. Our research indicates that both failure modes can be shown to be related to microvoid content growth.

New (and good) insulation has been found to have voids of 2 to 20 microns in diameter and densities of 100 to 1000 per cubic millimeter. More research is needed to determine growth rates and levels at which the various failure modes occur. This paper will report on techniques available to image or otherwise assess void content and correlate to remaining life.

## 1. Introduction

Nuclear power plants in the US were initially designed and licensed for forty years of operation. Because no new nuclear plants have been ordered and built in recent years and consistent with our continually growing power needs, efforts are now underway to extend the license of many of these plants an additional 20 years. This process requires that the effects of aging on electric cable insulation be evaluated and resolved for the license renewal term. In many ways the aging of electric cable insulation in nuclear power plants is similar to what occurs in other facilities such as commercial and military aircraft, fossil power plants, and industrial facilities.

During a research project undertaken in the early 1990s, staff members at Advent Engineering, Ann Arbor, Michigan explored the microstructure of several electric insulation materials using optical, acoustic, and electron microscopy. We examined unaged, naturally aged, and artificially aged samples. In all cases evidence of microvoid formation was found. We also found the microvoid content to be notably higher in the naturally aged samples compared to the more newly manufactured cable insulation samples [1]. Both the size of the voids and their number were noted to be higher for the aged sample cases. One explanation considered was that manufacturing processes had improved during the time frame of the insulation's original

development. Another explanation was that the microvoid content had increased as a result of aging. Although both explanations are likely, it was this second postulate that offered itself as a potentially valuable property to consider for assessing electric cable insulation aging.

This paper will report on our efforts to date to evaluate this promising approach for developing a portable, non-destructive method of determining remaining life in electric wire insulation. This approach will be applicable for all polymer insulation materials commonly used in low to high voltage applications and will be based on monitoring and correlating changes occurring due to aging at the micro-structural level. Although this concept has not yet been fully explored and verified, some evidence exists demonstrating these micro-structural changes to be manifesting themselves as increasing microvoid content.

## **2. Existence of Microvoids**

What are microvoids? Microvoids are microscopic cavities within a solid dielectric insulation, often as small as 1 to 10 microns. In general terms, the bulk of a polyolefin polymer, such as polyethylene, has a crystalline texture determined by the rate at which the polymer material was cooled when originally formed. During the initial cooling process some non-crystallized material is left trapped between the spherulites formed during primary crystallization. At temperatures below the primary crystallization temperature, this initially non-crystallized material begins to slowly revert from its amorphous form to create a new crystalline state, such as a folded or extended chain. As this secondary crystallization occurs, the newly crystallized polymer material occupies less volume, resulting in microvoids or discontinuities forming between the rigid bulk polymer material.

The secondary crystallization process may occur over a number of years at ambient temperature. Thus, microvoid content has been found to change with age in response to environmental and operational stress factors. These microvoids have the potential to become sites of ionization and eventual tree growth when exposed to an electric field. For this reason, microvoids are thought to be the precursors for eventual mechanical failure in high voltage insulation and may also play a role in medium and low voltage cable integrity failures.

A paper by Kageyama [2] found that steam cured cross-linked polyethylene cable insulation contained microvoids several microns in size at densities of one million per cubic millimeter. If a heating medium other than steam was used, the number of microvoids was reduced to 10,000 per cubic millimeter, but it was concluded to be extremely difficult to bring this concentration down to 0. Another paper by Namiki [3] reported densities of 100 to 1000 per cubic millimeter for dry cured XLPE. Other recent papers (primarily based on work being performed in France, Great Britain, and Japan) continue to report on microvoid content in electric polymer insulation.

## **3. Polymer Structure and Electric Insulation Acceptance Criteria**

In order to explore the potential value of assessing aging through evaluation of the insulation's microstructure it is first necessary to consider a brief description of a polymer material's internal structure and then to define some acceptance criteria for end of life.

The internal structure of polymers consists of molecules of high relative molecular mass. Each molecule is comprised of multiple repetitions of smaller units (monomers). After formation and during cooling, islands of crystals are formed separated by amorphous layers of polymer chains.

The various interfaces between crystalline and amorphous layers of polymers are of primary interest and represent potential sites for microvoid formation and growth.

In general, the advanced polymer insulation materials developed over the last couple decades and now commonly used in most industrial applications have been found to have very long lives and indeed almost indefinite lifetimes for some environmental conditions and applications. However, in all cases, there will exist at least three acceptance criteria for defining end of useful life:

- For all electric insulation, even instrument and control cable in low and medium voltage applications, a loss of cable structural integrity occurs.
- For instrument cable (and to a lesser extreme control cable), unacceptable leakage current occurs.
- For the power cable in medium and high voltage applications, excessive partial discharge takes place.

#### **4. Evidence for Microvoid Content Growth During Aging**

Three mechanisms for polymer aging exist: physical, chemical, and electrical. Physical aging occurs due to residual and applied mechanical stresses. Chemical aging occurs in response to exposure to oxygen and other reactants. Electrical aging takes place when voltage-induced stresses are high, typically above 3kV. All three mechanisms account for polymer aging in most applications.

It is well accepted that microvoids become sites for partial discharge and eventual tree initiation and growth in high voltage regimes. Growth during normal service conditions is expected, but evidence is less direct; however, such growth has not been disproved. In addition to our studies others have reported on evidence for microvoid content growth in response to aging.

Dissado and Fothergill in their often referenced textbook *Electrical Degradation and Breakdown in Polymers* [4] provide an excellent introduction to polymer science and aging effects. Of particular note, Chapter 3 provides an overview of low level degradation in polymers. Three major relevant points are made in support of the contentions in this paper.

1. The effect of mechanical stresses of a sufficiently high level is to increase the microvoid density and size [within polymer materials].
2. Microvoid production in polyethylene was observed in cable samples that had been unused and exposed only to a service environment.
3. Local density increases due to secondary crystallization is compensated by a generation of microvoids and discontinuities. [Thus density increases can occur in concert with microvoid production.]

Dissado and Fothergill derived these conclusions from two published works reporting on research projects conducted separately in the US and the UK.

In the first paper, Barlow, Hill, and Marino [5] describe their research conducted for US Industrial Chemicals of Columbus, Ohio. The purpose of their work was to investigate an alternative cause of void formation based on an inherent property of polyolefins. They report as a result of

their testing and analyses that microvoid formation continues with time as a result of secondary crystallization with such polymers.

The second paper by Stevens, Perkins, and Champion [6] discusses a joint project of the Central Electricity Research Laboratories and City of London Polytechnic both in the UK. The authors experimentally tested for and found evidence for microvoid growth as a result of aging from the separate and independent effects of mechanical and electrical stressing.

Many other papers report on the high voltage regime relationship of microvoid growth in electrical insulation and consequential tree growth effects.

Thus it is considered reasonable to explore use of this material property for assessing aging effects.

## 5. Using Microvoid Content to Assess Aging

Based on the research and observations discussed above, it is surmised that determining microvoid content has high potential value for age assessments. To perform such assessment, Advent is proposing imaging and capacitive measurements as two viable candidate options. The following discussion extracted from [7] explains how acoustic microscopy can be applied. Use of capacitive measurements is presented in a separate paper.

Figure 1 outlines how such a system would work. The transducer (A) converts electrical signal to acoustic signal and converts return (reflected) acoustic signal to electrical signal. The signal transmitter (B) sends an electrical signal of the required frequency and pulse shape / width to satisfy the control setting. The control setting (C) inputs the desired insulation depth window to be viewed / analyzed. The control setting can be adjusted to ignore any reflections from the cable jacket or electrical conductors. The amplifier / discriminator (D) boosts the received signal and screens to minimize noise and optimize the desired signal characteristics. (For example, discriminate to view only the reflections indicative of the control setting depth range, which corresponds to a window of reflected time for each transmitted pulse.) An output signal is also available for display of an image representative of actual void sizes and dispersion within the insulation medium.

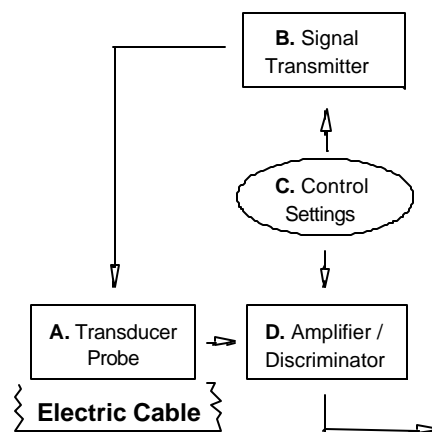


Figure 1 Void Detection and Processing

The principle of acoustic microscopy is that sound waves reflect at interfaces of material density decreases such as from solid polymer to a gaseous void site. The sharper the discontinuity in density, the stronger the reflected wave. Sonoscan, Inc. volunteered use of its C-Mode Scanning Acoustic Microscope (C-SAM) Series D6000 for this research. This C-SAM operates at 10 to 100 MHz, which was found to provide the desired resolution. Through adjustment of the observed time interval of the reflected wave, the C-SAM was found to be capable of filtering out reflections from the cable's jacket material. Therefore, images of the electric insulation's internal void characteristics were readily apparent. Figures 2 and 3 provide two sample views of electric insulation using acoustic microscopy. Figure 2 is a view of a jacketed cable as it would appear if monitored in the field (in situ). Figure 3 is a prepared (cut) sample view.

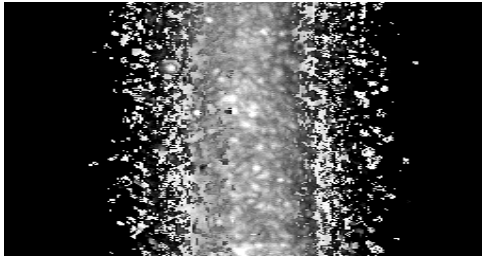


Figure 2 Aged Ethylene Propylene Viewed with C SAM at 15 MHz. The bright spots are reflected void formations.

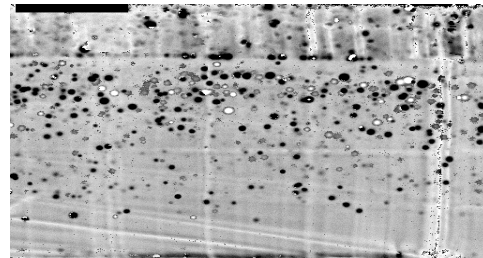


Figure 3 Aged Polyethylene Viewed with C SAM at 50 MHz. In this inverted image the voids are dark spots.

Void size and density are indicative of remaining life through comparison to end of life criteria values. Such a correlation can be performed as shown in Figure 4 and described below. Note that this technique requires no baseline or trending. It is not necessary to know past void history. Only the present level of proximity or margin to limiting void parameters is required to establish remaining life.

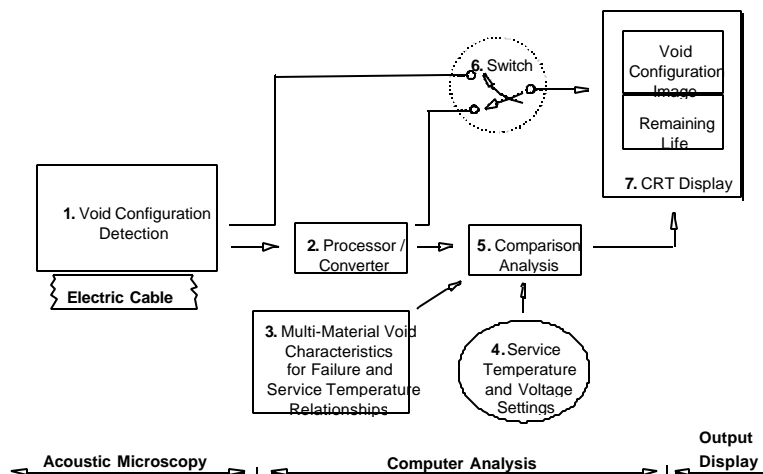


Figure 4 Electrical Insulation Life Determination Using Acoustic Microscopy and Void Analysis

Void information is detected (1) using a system similar to that shown in Figure 1 and sent to a Switch (6) as well as to a Processor / Converter (2). The Processor / Converter allows a

conversion to a digital signal which is analyzed and converted to an equivalent insulation medium of uniform void size and density (homogeneous dispersion throughout the insulation medium). Equivalent is defined as the same (or somewhat more limiting in terms of) susceptibility for production of an electrical partial discharge path across the electrical insulation medium under design potential conditions. This equivalent void size and density configuration is provided as one input to the comparison analysis device (5). An analog output signal representative of this “equivalent configuration” could also be made available for display (7) via switch (6).

Using void characteristics and partial discharge failure prediction techniques, relationships for service temperature and limiting void size and density corresponding to the appropriate failure criterion are available for various insulation materials [from data base (3)] as the second input to the comparison analysis performed by device (5).

Desired future service temperature and design voltage conditions are set in via setting (4). Inputs from (2), (3), and (4) are used to determine remaining life in device (5) by first determining the margin between actual equivalent void configuration and the limiting (impending failure) configuration and then calculating void growth rate, which is a function of temperature and material type. The output is a numerical or temperature dependent signal, which is sent to the display monitor (7) such that either remaining life for a given temperature or a graph of remaining life vs. temperature can be displayed.

The Display Switch (6) allows monitoring on device (7) of either a “raw” (unprocessed) reflected signal representative of the actual void configuration within the insulation medium or the equivalent void configuration.

This display device (7) is envisioned to be a CRT such as that typically used by a personal computer. The upper portion of the display will show an image of the insulation medium’s void configuration (processed or unprocessed). The lower portion will provide the remaining life result (for a specified temperature or as a function of temperature).

## **6. Work to Go**

Much research and development work remains to assure feasibility and to establish the required material data bases for predicting remaining life. The following five phase program has been established:

1. Refine acoustic microscopy technology and/or investigate other imaging and assessment techniques (currently available) to better investigate and evaluate small void sizes.
2. Develop database of limiting void parameters for commonly used electrical insulation materials.
3. Establish void content growth rates as a function of the following exposures: temperature, radiation, voltage, and harsh environment effects.
4. Develop software to convert 3D void images to a numeric void content value.
5. Develop software to perform comparison analyses and to generate any necessary displays.

## 7. Conclusions

It is concluded that something is continuously happening at the microstructural level (as a result of aging), which later when some threshold level for external property observation is exceeded, insulation failure becomes visible. As reported by others, we also believe that this “something” is related to microvoid formation and growth especially in the anomalous areas of the polymer. Microvoids represent “weak” areas in the structure of the polymer. These weak areas increase in size and are the likely sources of integrity failure of the polymer insulation. More research is needed to prove that microvoids are indeed the mechanism to failure. Even if microvoid growth is not the all conclusive answer, research in this area will identify the correct mechanism or combination of mechanisms causing aging degradation and failure.

Thus evaluating microstructure effects has high potential value for performing age assessments. Also, we believe that Imaging and capacitive measurements hold high promise for performing such investigations and evaluations.

## 8. References

1. Avila, S.M. and D.A. Horvath, "Microscopic Void Detection as a Prelude to Predicting Remaining Life in Electric Cable Insulation", *Proceedings of the ANS International Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human Machine Interface Technologies* (November 2000).
2. Kageyama, S., M. Ono, and S. Chabata, "Microvoids in Crosslinked Polyethylene insulated cables," *IEEE Power Apparatus Systems*, 94 (4), pp 1258-1263 (1975).
3. Namiki, Y., H. Shimanuki, F. Aida, and M. Morita, "A Study on Microvoids and Their Filling in Crosslinked Polyethylene Insulated Cables," *IEEE Transactions on Electrical Insulation*, Vol. EI-15 No. 6 (December 1980).
4. Dissado, L.A. and J.C. Fothergill, *Electrical Degradation and Breakdown in Polymers*, Chapter 3, Peter Peregrinus Press, London, UK (1992).
5. Barlow, A., L.A. Hill, and M.F. Marino, "Possible Mechanism of Microvoid Formation in Polyethylene Insulated High Voltage Cables," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-102, No. 7, pp. 1921-1926 (July 1983)
6. Stevens, G.C., E. Perkins, and J.V. Champion, "Microvoid Formation and Growth in Epoxy Resins Under Mechanical and Electrical Stress By Laser Light Scattering," *IEE Conference on Dielectric Materials, Measurements, & Applications*, IEE Conf Pub 289, pp. 234-237 (1988).
7. Horvath, D.A., D.C. Wood, and M.J. Wylie, "Microscopic Void Characterization for Assessing Aging of Electric Cable Insulation Used in Nuclear Power Stations," *IEEE Conference on Electrical Insulation and Dielectric Phenomena* (October 2000).