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Use Of Micro-Void Content Growth Rates To Validate And Add Value To Electrical Insulation Tan-Delta Aging Testing

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ABSTRACT

Our research as well as others has shown that micro-void content in electric insulation polymers grows in a way that can be correlated to the degree of aging. Specific results of our experiments combined with research by others have led us to conclude that a promising technique for predicting remaining life in electric cable insulation, based on micro-void content and proximity to void limiting parameters, can be developed.

This approach involves use of acoustic or optical microscopy to establish an estimate of void content in polymers by determining micro-void sizes and density. Separate research is used to establish limiting values for percent void content correlating to material failure. The mode of failure varies depending on the applied voltage regime. For example, at medium and high voltage levels, partial discharge detection can be considered indicative of pending end of life. Whereas for low voltage regimes, brittleness to the point of cracking susceptibility would allow the potential for moisture ingress and shorting and can be considered end of life. It has been separately shown that void growth rate is a function of temperature and radiation dose rate both during normal and nuclear accident conditions and is predictable based on the known polymer chemical degradation equations, which produce gaseous products in the form of oxygen, water vapor, carbon dioxide, and carbon monoxide.

Thus if end of life void content is known, the degree of void content growth occurring during a design basis accident is properly accounted for, and void content growth rates during normal temperature and radiation conditions are considered, then remaining life in electrical insulation can be accurately predicted. In recent years, several techniques have been proposed to assess electrical insulation aging. One of the more promising approaches for use with medium voltage cable is the tan-delta technique. This paper will demonstrate how the mirco-void content approach can be used to validate other techniques such as tan-delta and add additional meaning and value not otherwise available from tan-delta alone.

1 INTRODUCTION

Electric cable is an important component of nuclear power plants because of its unique ability and need to convey power as well as signals for instrumentation and control. If a nuclear power plant is intended to function beyond its license term of typically 40 years, it becomes necessary for critical components to be assessed or monitored for deleterious aging effects. Such critical components include electric cable used in safety-related and other essential applications such as power generation, fire protection, accident monitoring, and plant security. With regard to aging of electric cable, nuclear power stations have many unique considerations such as:

- tens of thousands of installed cable making complete replacement impractical,
- many areas inaccessible for inspection or testing for periods of time of 18 months or more,

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- multiple cable manufacturers representing diverse insulation system jacket and dielectric material combinations, and
- concurrent temperature and radiation aging during the plant's normal life license term.

In addition, for a limited number of essential equipment cables, continued operability is required during a harsh environment assumed to occur at the end of the plant's license term. This harsh environment (an accelerated aging period) is postulated to be caused by a design basis event such as a major steam system pipe break and can produce elevated levels of temperature, pressure, radiation dose, humidity, and possibly even chemical spray.

The weak limiting subcomponent of electric cable is its dielectric insulation. Thus it is desirable to be able to monitor aging degradation of electrical insulation while allowing margin (remaining life) for some accelerated aging to occur during a postulated design basis event.

In this paper we will describe how electric cable insulation health may be characterized in terms of micro-void content and consider how such micro-voids may be detected based on an update of our earlier research. [1, 2, 3, and 4] Then the micro-void content approach is used to validate or supplement how tan-delta assesses cable insulation aging and can assist in a theoretical way to predict remaining life of electrical insulation.

2 ELECTRICAL INSULATION “HEALTH” AND REMAINING LIFE AS A FUNCTION OF MICRO-VOID CONTENT

2.1 What is End of Life for Electrical Insulation?

As with most industrial facilities, nuclear stations contain power, instrumentation, and control cables. The end of life for a power cable (normally energized at or near rated voltage and at an appreciable amount of electric current) would typically be based on preventing significant partial discharge to the point where reliable current carrying functionality is affected.

End of life for instrument and control cable is based on preventing excessive leakage current such that instrument accuracy or controlled equipment operation is detrimentally affected. Such conditions can occur when the insulation becomes hard or brittle and subject to cracking and moisture ingress during a postulated design basis event.

In both cases, margin to end of life must be confirmed for the license term (40 years in the US but shorter and/or longer time frames exist in some other countries). This paper will focus on medium voltage power cable assessments but similar approaches can be used to assess proximity to embrittlement in ways similar to how margin to prevent unacceptable partial discharge is outlined below.

2.2 Void Content as an Indicator of Insulation “Health”

Discharges within cavities (voids) in solid insulating systems has long been associated with gradual degradation and eventual dielectric failure. Studies by the C. Laurent and C. Mayoux of Laboratoire de Genie Electrique [5] have shown that gas-filled cavities (or voids) can originate in a wide range of solid dielectric systems through many mechanisms including differential thermal expansion, incomplete impregnation or excessive mechanical stress, or improper process control. Such cavities can originate during the manufacturing process or over a lifetime of operation as a result of environmental and operational stresses. Progressive deterioration caused by discharges in gas filled cavities has long been known to be a major factor limiting the life of cables. [6]

Voids will grow in size and the void density will increase as a function of energy absorption (heat, radiation dose, electrical field induced stress, etc.). The insulation's polymer structure consists of long, intertwined molecular combinations of carbon, hydrogen, and oxygen atoms. When the polymer absorbs energy while in the proximity of oxygen or ozone, radicals and various gases are produced. The resulting chemical reaction products include carbon dioxide, carbon monoxide, water vapor, and other volatile gaseous molecules. Some or many of these gaseous reaction products will create new void sites or accumulate in nearby voids contributing to an increase in density and size in a manner which will, therefore, be a function of the cable's insulation aging degradation rate.

It is also possible that voids would additionally be formed from physical rearrangements of the molecules due to crystallization from aging. The voids distributed throughout the insulation structure will increase in size and the polymer structure of the material will weaken. The result is that the net or equivalent amount of insulation between the separated conductors decreases. A point will be reached at which partial discharge and/or voltage breakdown between nearby conductors of high potential can occur.

As the void content increases with age, the equivalent remaining thickness of the insulation reduces to a point where a breakdown (discharge) can occur. The limiting equivalent remaining insulation thickness that is just large enough to prevent breakdown can then be determined. By modeling the void growth from service condition factors (including post-nuclear accident harsh environment effects), the remaining life can be accurately predicted. It will be necessary to determine by experimental test at what void content (for a given insulation material) end of life occurs.

For a given temperature, the production rate for each single gas molecule product should be approximately constant. Using the ideal gas law, the rate of increase in the volume occupied by that gas (assumed to accumulate in the voids) will be directly proportional to the gas molecule production rate, which is a constant for a given temperature. Therefore:

$$^{dV}/_{dt} = K \tag{1}$$

$$dV = \ Kdt \tag{2}$$

$$V(t) = Vo + Kt \tag{3}$$

Where:

V = Volume occupied by voids
t = Time
K = experimentally determined constant
Vo = Volume at t = 0

If the voids are modeled as approximately spherical and the void size increase effect dominates over the density increase effect as expected then:

$$V(t) = \frac{4}{3}\,\pi r^3 n \text{, then} \tag{4}$$

$$Vo + Kt = \frac{4}{3}\,\pi r^3 n \tag{5}$$

$$r = [3(vo + Kt)/4\pi n]^{1/3} \tag{6}$$

Where:

n = number of voids
r = equivalent radius of each void.

Therefore, the size of the voids will approximately follow the cubic root of the elapsed time which perhaps explains the long life, in general, of electric insulation. This relationship assumes no pressure build-up in the voids and no leakage of gases from the insulation medium. These two considerations would further reduce the void size increase rate but allows the above relationship to be conservatively high for modeling purposes. This approximation is also simplistic in that it does not account for the accelerated growth, which occurs near end of life from space charge build-up and self- heating effects. [7]

As a first-order approximation, it is expected that the gaseous production rate will be a linear function of temperature, which allows a determination of void size growth rate for different elevated temperatures. It is expected that early in life, void density will increase and then level off as a sufficient number of gas collection sites are created. After a certain point, long before the onset of any degradation of concern, the dominant factor will be void size growth.

More accurate computer modeling can be accomplished by considering multiple gaseous production reactions and gaseous loss rates and by calibrating via use of experimental test results.

Research by C. Dang et al [8] and A.C. Gjaerde [9] summarize advantages and disadvantages of current aging models including theories, multifactor effects and validating data. Relationships deduced from these aging models include a decrease in insulation life when:

- applied electric field goes up,
- applied electric field frequency goes up,
- increased exposure time to moisture,
- increased residual stresses (thermal, electric, mechanical),

Also, for increased exposure to moisture, the applied voltage to cause breakdown decreases. Each of these relationships can be correlated with increasing void content and computer modeled with the aid of experimental calibration.

3 VOID CONTENT MONITORING AND CORRELATION TO REMAINING LIFE

3.1 Void Detection

Previous research results [1] have confirmed successful void detection and imaging of electric insulation void size and density using dissected samples and imaged using either an optical or electron microscope. Figures 1 and 2 provide two views of micro-voids of various sizes (0.3 to 12 microns) within aged polyethylene electric cable insulation.

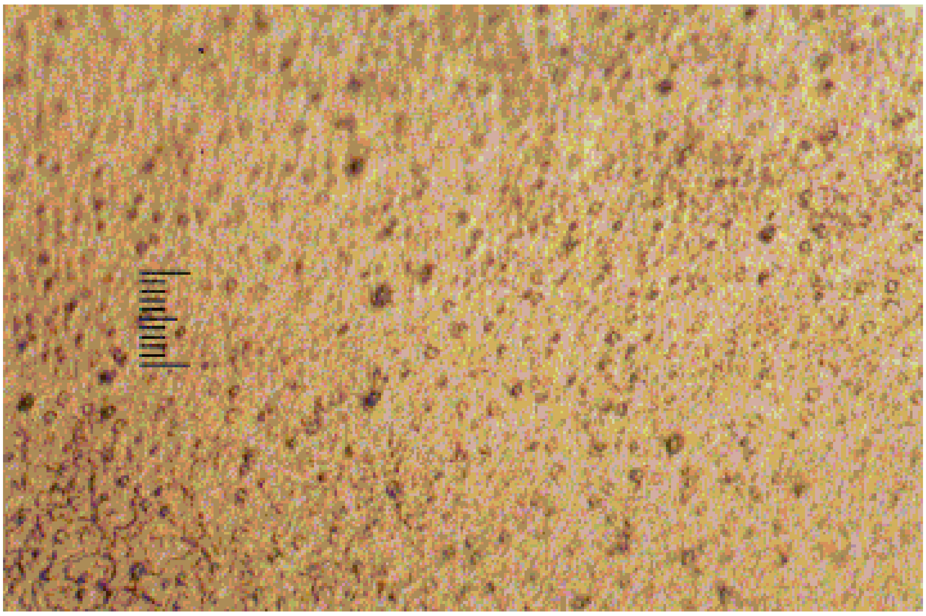

Figure 1: Sample 1 (Aged Polyethylene) Using an Optical Microscope at 500X

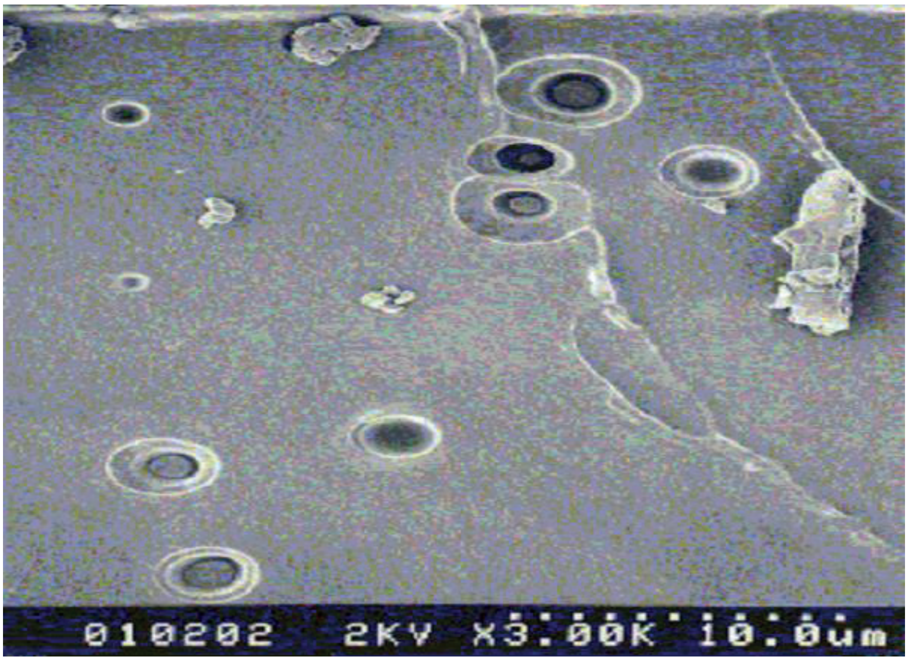

Figure 2: Sample 1 (Aged Polyethylene) Using a Scanning Electron Microscope at 3000X

Use of acoustic microscopy was also investigated and found to be another valuable tool although it would require prior calibration by other means such as by comparison to a sample dissected and viewed using an optical or electron microscope.

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. of Chicago, Illinois, USA 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. The C-SAM through adjustment of the observed time interval of the reflected wave 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 3 and 4 provide two sample views of electric insulation using acoustic microscopy. Figure 3 is a prepared (dissected) sample view. Figure 4 is a view of a jacketed cable as it would appear if monitored in the field (in situ).

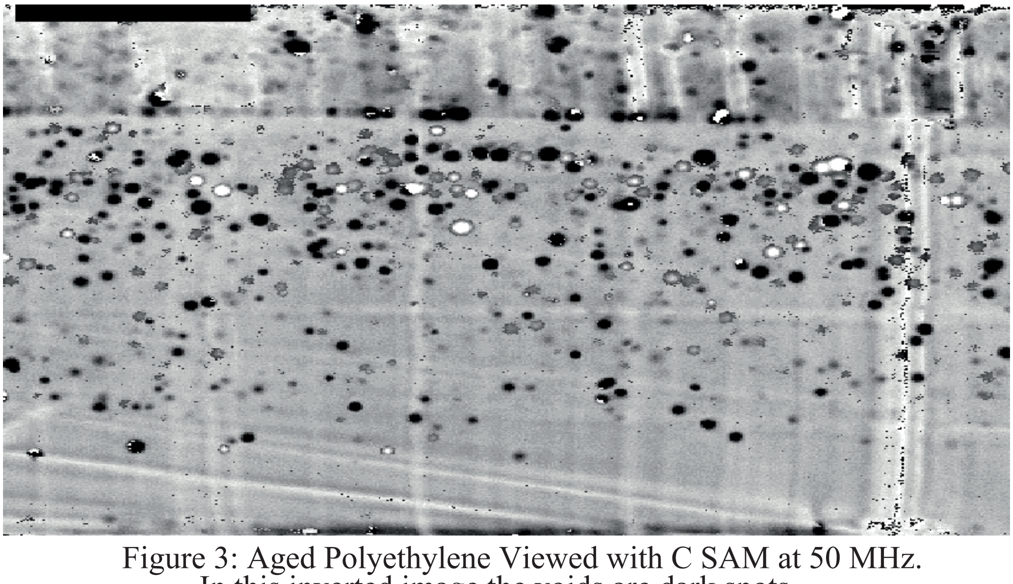

Figure 3: Aged Polyethylene Viewed with C SAM at 50 MHz.
In this inverted image the voids are dark spots.

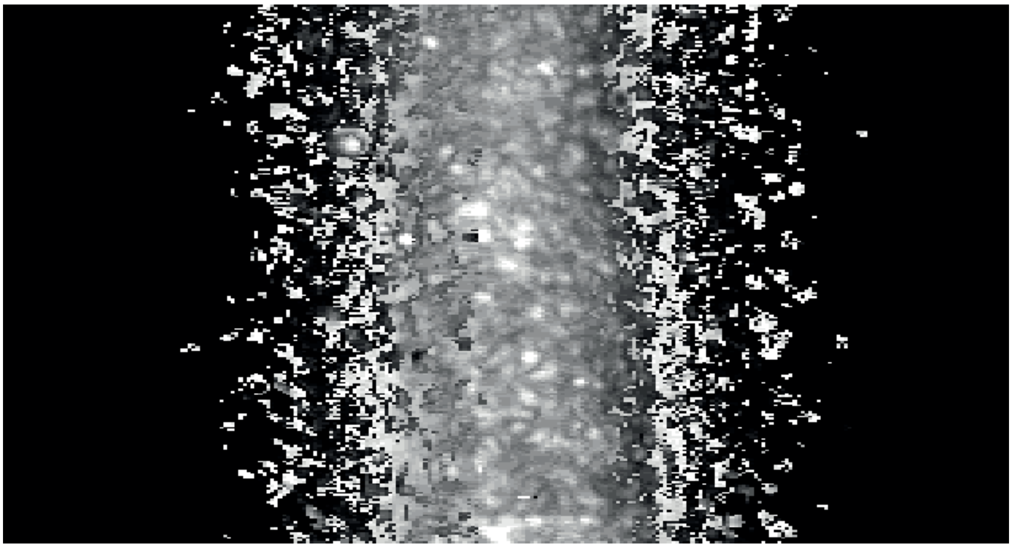

Figure 4: Aged Ethylene Propylene Viewed with C SAM at 15 MHz. The bright spots are reflected void formations

3.2 Void Correlation to Remaining Life

As stated earlier, 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 5 and described below.

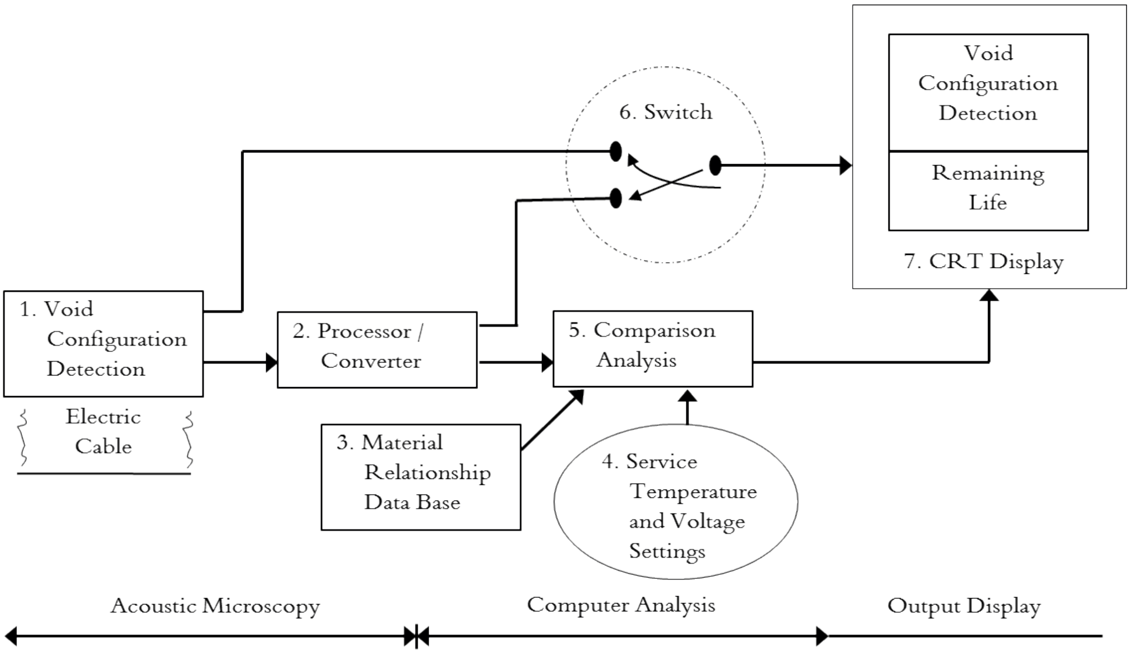

Figure 5: Electrical Insulation Life Determination Using Acoustic Microscopy and Computer Aided Void Content Analysis

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.

Void content information is detected (1) using an Acoustic Transducer (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 the display screen on a laptop 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).

4 COMPARISON TO TAN-DELTA METHOD

4.1 Tan-Delta Testing Approach

Tan-delta testing [10] has proven promising in recent years for assessing the integrity of medium voltage cables even when such cables are buried or otherwise inaccessible. The process does, however, require that the cable be de-energized and, except for a ground connection, the remaining conductors are disconnected. Tan-delta testing consists of applying a test voltage at a very low frequency (VLF) near or above the rated voltage to a pair of conductors, one of which is grounded and then measuring the dissipation factor. The VLF is typically between 0.01 to 1 Hz.

The dissipation factor is the ratio of the resistive component of the insulation impedance between the conductors being tested and the capacitive resonance portion. The capacitive resonance portion is inversely proportional to the test frequency and equivalent capacitance. This quantity is also the tangent of the angle (delta) between the tested insulation leakage current and an ideal leakage current where the cable conductors act like a perfect capacitor with infinite resistance. When a cable is new with no defects, it behaves almost like a perfect capacitor and tan-delta is almost zero.

As the cable insulation ages, the resistive component of impedance decreases and the corresponding resistive current through the insulation is lower. It has also been found that for a given sample cable age and test frequency, the resistive component decreases with applied voltage (whereas the capacitive resonance component remains relatively constant). Therefore, for an aged cable as applied voltage is increased, a decrease in tan-delta (the ratio of resistance to capacitive resonance) will be detected and can be monitored or trended.

It follows that the lower the VLF used for testing, the more sensitive the test and more accurate and useful will be the resulting tan-delta value.

4.2 Comparison, Validation, and Remaining Life

The results of tan-delta testing of aged medium voltage cable can be explained and validated when considering the role of micro-void content. As discussed earlier, as polymers age, micro-void content increases. The micro-void content increase results in an increase in measurable insulation leakage current.

Previously [4] we had predicted that the existence of micro-voids in insulation increases the energy storage ability of the electric field created between adjacent conductors subjected to a test voltage at or near rated conditions. Since capacitance is a measure of the ability to store energy in an electric field, the size and density of the voids would affect the equivalent capacitance of the dielectric and, therefore, also affect insulation leakage current.

High void content would cause high equivalent capacitive effects resulting in increased leakage current. However, results of extensive tan-delta testing in recent years has demonstrated that this increased capacitance effect is minor when compared to the reduced equivalent resistance paths created between the conductors by the micro-voids.

The micro-voids contain gases, which are easily ionized when subjected to an electric potential. This ionization reduces the effective thickness of the insulation correspondingly and raises the resistive component of the leakage current.

At the present time, many nuclear utility plant owners are baseline testing and monitoring trends resulting from data collected by tan-delta testing. Depending on the number of cables, this amount of testing can be both time consuming and costly with no end in sight. However, as demonstrated above, the results of a one-time tan-delta test is, in theory, correlatable to micro-void content. If the insulation material and environmental stressors are known as discussed in Sections 2.2 and 3.2, a slight variation of the Figure 5 process can be used to predict remaining life. The one drawback is the need to create the material data base for the various insulation types. At the present time an extensive number of cable insulation samples exist from throughout the industry representing various degrees of aging and can be tested to establish the needed parameters for the future benefit of all nuclear plant owners and possibly also other industries.

5 FUTURE WORK

It is desirable that future research efforts should include and prioritize the development of a comprehensive material data-base, which would characterize both micro-void growth rates for various environmental stressors and micro-void content representative of end of life for low, medium, and high voltage cable insulation. This work should be done for the most widely used polymer materials (PE, EPR, and SiR) to start with and can be expanded at a future time if needed. It may even be possible to show that material content and formulations are secondary effects to aging processes for most materials when compared to the more dominating effect of void content.

Over the last decade, research funding in the US for techniques to monitor and assess electric cable insulation aging has been limited to a small number of approaches such as the indenter, oxidation induction time, and tan-delta all of which have their limitations. Now that a better understanding exists of the way in which polymers age through void content increases, it is considered prudent to expand future research in directions more universally useful and adaptable.

6 CONCLUSIONS

Micro-void content within electric cable insulation is an important precursor to deleterious aging effects. Such micro-void content is theoretically correlatable to results of tan-delta testing and to a prediction of remaining life as a function of environmental stressors (such as temperature, radiation dose, and applied voltage) and insulation material. Future research efforts will demonstrate the necessary relationships and help to develop the parameters needed for a predictive lifetime polymer material data base.

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