Wire Inspection Technologies Under Development at NASA Langley Research Center

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Abstract

Wiring integrity and safety issues have recently emerged as a major area of concern for the aerospace community. A number of commercial aircraft incidents have been linked to electrical system faults. The space shuttle, which itself is an aging aerospace vehicle, has likewise experienced launch delays and in-flight failures due to wire related problems. In aerospace vehicles wire related problems have been known to cause anomalous signals, loss of signal, system shutdown, smoke, fire and catastrophic failure. Modern civilian and military aircraft contain hundreds of miles of wire. For example each orbiter contains approximately 161 miles of permanent wiring. Therefore, the diagnosis, location and repair of wiring faults is a time consuming and expensive task.

This paper will discuss wire insulation characterization methods under development at NASA Langley Research Center (LaRC). These methods are aimed at nondestructively assessing degradation of wire insulation to provide useful tools to detect insulation flaws and help predict remaining wire life. Lock-in thermography, ultrasonics, and chemical sensing of combustion by-products are all being investigated as potential techniques for the characterization of various wire insulation types. An overview of each of these technologies and a discussion of their usefulness and limitations will be presented.

Introduction

The safety of aging wiring has become both a high interest and a high cost item for the aerospace community. During the past several years a number of highly visible incidents have been linked to the degradation of electrical systems including wiring. For example about 5 seconds after liftoff of STS-93, flight controllers noted a voltage drop on one of the shuttle's electrical buses. Because of this voltage drop, one of two redundant main engine controllers on two of the three engines shut down. The redundant controllers on those two engines – center and right main engines – functioned normally, allowing them to fully support Columbia's climb to orbit. After the return of STS-93 it was determined that the cause of the voltage drop and subsequent failure of the main engine controller was an arcing event caused by a chafed wire. The Shuttle Independent Assessment Team, formed following this incident, indicated in their report that "the reliability of the wire visual inspection process should be quantified (success rate in locating wiring defects may be below 70% under ideal conditions).[1]"

This example highlights the inadequacy of visual inspection for the detection of flaws in wiring systems. The time maintenance personnel spend diagnosing and repairing faulty wiring is becoming a leading cause of aircraft downtime. Visual inspection of individual wires in a bundle or connector is not practical because as wire ages it becomes stiff, and dismantling the bundle or connector may introduce collateral damage resulting in safety hazards. Without providing maintenance personnel improved diagnostic equipment, the costs associated with wiring failures will continue to increase. Therefore improved nondestructive, nonintrusive inspection methods are required to ensure the safety of aging wiring.

This paper will discuss three approaches to wiring inspection that are being developed at NASA's Langley Research Center. Ultrasonic inspection has historically proved reliable in the inspection of both metallic and composite structures. Current efforts described in this paper will show the extension of this technology to the inspection of wire insulation materials for both defects and aging. A second technique being explored for wiring inspection is infrared thermography. Like ultrasonics, thermography has been used extensively for the inspection of metals and composites. Here the authors will describe a technique that utilizes the internal temperature change in a wire caused by a modulated alternating current as a heat source for performing infrared thermographic inspections. Finally an inspection approach is presented using coupling gas chromatography with recent advances in microelectromechanical systems (MEMS). In recent years MEMS sensors with the ability to detect the presence and concentration of specific chemical species have become available. Using devices similar to these to detect both the instantaneous (arcing) and long-term (aging) degradation of wire insulation could provide another enhancement to current visual inspections.

Ultrasonics

For testing purposes, the geometry of insulated wire suggests treating wire as a cylindrical clad wave-guide, where the wire conductor is the core and the wire insulation is the cladding. A number of researchers have examined acoustic guided wave propagation in a cylindrical geometry[2-6] and for detailed analysis the reader is referred to these papers. Some applications of ultrasonic guided waves include material testing or characterization of wire[7,8] or fibers, and for use as ultrasonic delay lines. In general many acoustic wave modes will propagate in an isotropic cylinder and in part be a function of material property, geometry, and frequency.

This work demonstrates the generation of ultrasonic axisymmetric and flexural guided waves in a plastic coated solid aluminum rod and in insulated wire samples using a simple clip-on piezoelectric transducer for ultrasound generation. Guided wave measurements on the bare aluminum rod are used to distinguish between the axisymmetric and flexural wave modes. Even though the flexural wave mode is larger in amplitude than the axisymmetric mode, the axisymmetric mode's faster phase velocity, and low dispersion, makes it easier to isolate and measure. Thus, the axisymmetric mode wave was used for these measurements.

Two ultrasonic transducers are used in a pitch catch configuration to generate and receive an ultrasonic guided wave in the wire. Part of the wave will travel in the wire and part in the wire insulation. The condition of the wire insulation, its stiffness, will affect the wave speed and amplitude of the guided wave. Thus, a measurement of wave speed will, in part, be a measurement of material stiffness or wire insulation condition.

The experimental system is schematically shown in Figure 1. This system consists of two piezoelectric transducers, ultrasonic pulse generator, ultrasonic pre-amp, and oscilloscope. The transducers were low frequency, broadband acoustic emission transducers with a bandwidth of 50 kHz to 1.5 MHz. The signal from the ultrasonic receiver is first fed through a pre-amplifier with a 20 kHz to 2 MHz bandwidth and a 40 or 60 dB gain and then through another amplifier with a maximum gain of 42 dB and a bandwidth set at 10 kHz to 300 kHz. The output of the amplifier was recorded by an 8-bit/500 MHz digitizing oscilloscope. The signal was averaged 1000 times to improve signal to noise and then recorded for later analysis. The transducers were mechanically clipped to the rod or wire in a manner that held the wire along the center of the transducer surface. The wires were nominally 60 cm long and the ends of the wires were clamped to hold the samples straight while measurements were taken.

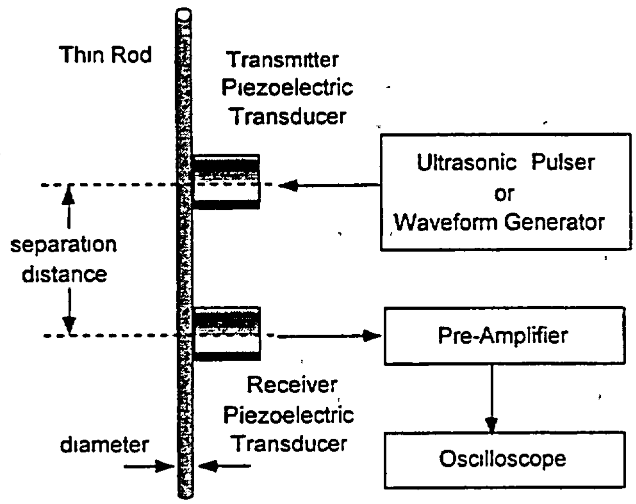

Figure 1 – Schematic of ultrasonic experimental setup.

The phase velocity was determined by taking a series of measurements of a constant phase point as a function of transducer separation. The separation distance varied from 30 mm to 290 mm over which 10 to 12 measurements were taken. The location of a constant phase point was plotted against the transducer separation and a linear curve fit was applied to the data. The slope of the linear fit was the measure of the phase velocity and the standard deviation of the fit was the error for the measurement.

Initial measurements were carried out on a simple model of an insulated wire to identify the axisymmetric and flexural wave modes. This model consisted of a solid aluminum rod with a polymer coating. The aluminum rod, simulating the wire, had a 3.23 mm diameter. The polymer coating, simulating the wire insulation had a thickness of 0.57 mm. The coating was a thermoplastic heat-shrink material of Polyolefin. The final diameter of the model was 4.37 mm. It was assumed that there was a perfect bond at the interface of the aluminum and polymer coating. The measured phase velocity of the axisymmetric mode wave in the bare rod and the polymer coated aluminum rod, were 5128 m/s and 4663 m/s, respectively. The bare aluminum rod phase velocity measurement is consistent with a calculated bar velocity of 5119 m/s. The aluminum properties used here were 70.76 GPa and 2.7 gm/cm^3 for Young's Modulus and density, respectively. The measured changes in phase velocity between the bare and coated aluminum rod demonstrate the effect of the coating. It indicates that some of the ultrasonic energy is traveling in the insulation and, therefore, should be sensitive to stiffness changes in the wire insulation.

To test this theory, some mil-spec wire samples were heat-damaged to change the condition in the insulation. It was assumed the heating did not change the insulation geometry or the boundary conditions between the insulation and the wire conductor because the temperature was not high enough to melt the insulation. The samples were 12, 16, and 20 gauge MIL-W-81381, MIL-W-22759/34, and MIL-W-22759/87 wires and were cut to a length of approximately 60-cm. The MIL-W-81381 wire has a polyimide insulation, the MIL-W-22759/34 has a ethylene-tetraflouroethylene insulation, and the MIL-W-22759/87 has a combination of polyimide and flouroethylene polymer insulation.

One sample of each gauge was used for the baseline measurements, one of each gauge was heated in an oven for a short exposure and one of each gauge was heated for a long exposure. Oven exposure temperatures were either 349^{0}C or 399^{0}C, and times were arbitrarily chosen to induce heat-damage in the insulation. In the case of MIL-W-22759/34 wire, the insulation on baseline samples was smooth, flexible, and off-white in color. For the short exposure samples the insulation remained smooth and flexible, but its color changed to gray, while the insulation for the long exposure samples became brittle, cracked, and black in color. The phase velocity in these samples was measured following the same procedures described earlier. In each gauge family the baseline samples showed the lowest phase velocity. For the short exposure condition, the phase velocity increased about 400 to 500 m/s and the long exposure phase velocity increased an additional 100 to 200 m/s. Overall, this result shows that the axisymmetric phase velocity measurement is able to distinguish between the baseline and heat-damage conditions.

To examine the effect of heat damage in more detail, MIL-W-22759/34 wire samples of each gauge were oven aged at 270^{0}C for up to 200 hours. Wire samples of each gauge were removed from the oven about every three hours up to fifteen hours and then about every twenty hours. The samples were then ultrasonically examined as in previous measurements. Results in Figure 2 show the individual data points with an average phase velocity error for each gauge set and a Weighted Least Squared curve fit to highlight the trend of the data. The data for each gauge shows a high rate of change in phase velocity at short oven exposure times and a lower rate of change in phase velocity at longer oven exposure times. It appears as if the condition of the insulation is approaching a limiting phase velocity value. In general the phase velocity increase, as a function of oven exposure, is consistent with the earlier results at a few temperatures and times.

The axisymmetric wave mode measurements in the aluminum rod and polymer coated aluminum rod illustrated that the coating not only attenuated the wave amplitude, but decreased the phase velocity. Thus ultrasonic energy propagated in both the polymer coating and aluminum rod and the concept of using guided waves to interrogate the wire insulation was shown to have potential. The mil-spec wires measurements, in general, showed the axisymmetric wave velocity increase for increasing heat damage or oven exposure. Thus, measurements of the axisymmetric mode phase velocity may be sensitive to stiffness changes in the wire insulation. Although the heat-damage conditions are not the same as aging conditions, with further development and refinements, the small clip on transducers may be used to inspect wire insulation for detrimental aging conditions. Future plans include conducting oven-aging experiments on the other mil-spec wire types and measuring the stiffness of the insulation at the different aging conditions in a testing machine. Correlating the testing machine measurements to the phase velocity measurements will illustrate that the material stiffness of the insulation can be measured by axisymmetric phase velocity.

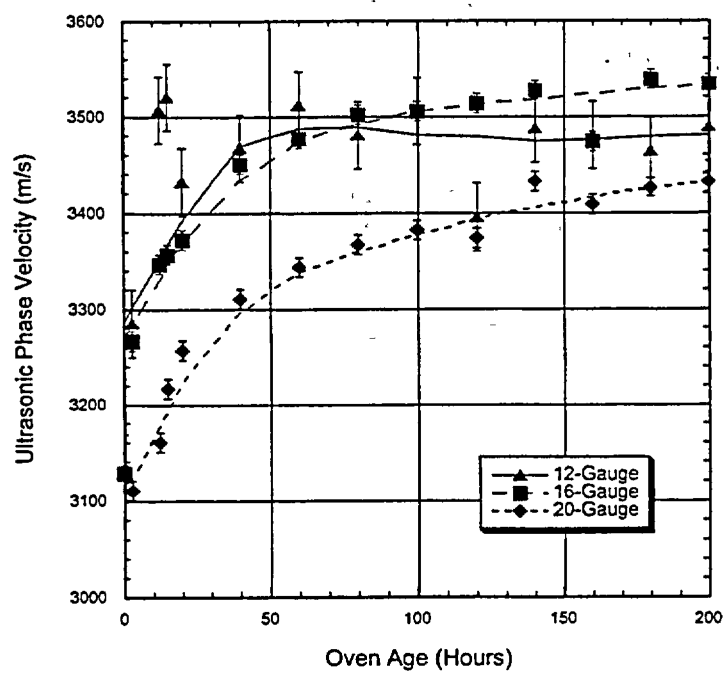

Figure 2 – MIL-W-22759/34 phase velocity as a function of oven age.

Lock-in Thermography

Lock-in thermography is a frequency domain technique that has been used extensively as an inspection tool[9-15]. Typical implementation of this technique involves the modulation of the surface temperature of a specimen by use of a time varying heat source, either externally by optical excitation or internally by Joule heating. The surface temperature is then monitored synchronously by means of an infrared (IR) camera, the output of which is stored digitally using an image processor. By multiplying the IR images collected with the sine and/or cosine of the modulation frequency of the temperature source, and averaging the results for each heating period, one can obtain amplitude and phase images of the specimen's surface temperature.

In the present application, passing an alternating current through the wire under inspection internally generates a time varying thermal source. The alternating current drives the wire through repeated heating cycles at two times the modulation frequency (since heating occurs regardless of the direction of current flow). The time varying surface temperature of the wire is monitored synchronously by means of a commercially available lock-in thermography system, the DeltaTherm 1000 manufactured by Stress Photonics, Inc.

The DeltaTherm 1000 uses a 128 x 128 element Indium Antimonide (InSb) infrared array cooled by liquid nitrogen to produce IR images in the 3-5μm wavelength range. The synchronous lock-in technique is performed automatically in the system electronics at a frame rate of 464 frames per second. Because of the high frame rate of this system it is possible to operate over a wide modulation frequency range (typically 0.25 Hz to 116 Hz) without aliasing. The DeltaTherm system electronics produce amplitude and phase images for a given inspection period. These images are then transferred from the system electronics to the host computer via a parallel interface. The DeltaTherm control software allows the user to control the gain of the IR detectors, the accumulation time (how long the DeltaTherm averages to produce a single sine and cosine image) and the integration time (how many subsequent sine and cosine images are averaged together to produce a final amplitude and phase images).

To achieve good spatial resolution (0.1mm per pixel), the magnification of the IR camera was enhanced by increasing the distance between the external optics (a 50mm Germanium lens) and the detector by 2.54 cm. Figure 3 shows a block diagram of the experimental configuration used with lock-in thermography. Figure 4 shows the results of inspecting a wire insulated with poly-tetraflouroethylene (PTFE) containing an area of thinned insulation using a modulation frequency of 0.25 Hz for the 5 ampere driving current.

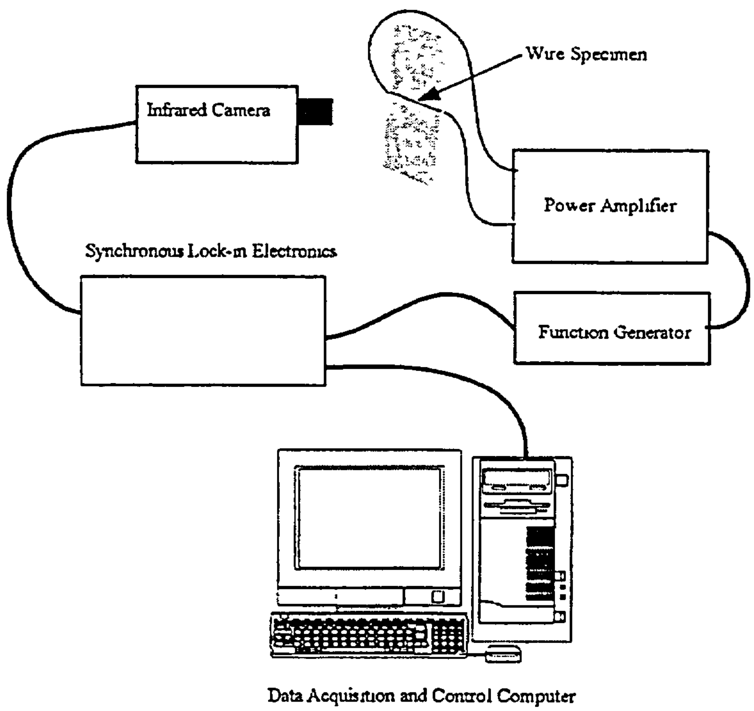

Figure 3 – Block diagram of the experimental setup for performing lock-in thermography on wire specimens.

As can be seen from these images, lock-in thermography has the potential to serve as a nondestructive insulation inspection tool, but a number of further refinements are necessary. For example, quantification of changes in material thickness or composition is essential if lock-in thermography is to provide information regarding remaining life of wiring. Therefore, further research is being performed to enhance the inspection capabilities of this technology. Because lock-in thermography is a frequency-based technique, both phase and amplitude information is available. Thus far, only amplitude information has been considered. Variations in the phase angle of the surface temperature change relative to the frequency of the driving current should contain information that is directly related to both the thickness of the insulation and the heat transfer properties of the insulating material. Therefore, experiments are now being formulated to investigate these relationships in an effort to further quantify this technique. Additionally, it should be possible to create temperature changes in the wire more efficiently by using amplitude modulated radio frequency current to produce standing waves in the wire. This approach would allow much lower current levels while still resulting in measurable temperature changes in the wire. Future work will investigate this method of heating to enhance the technique.

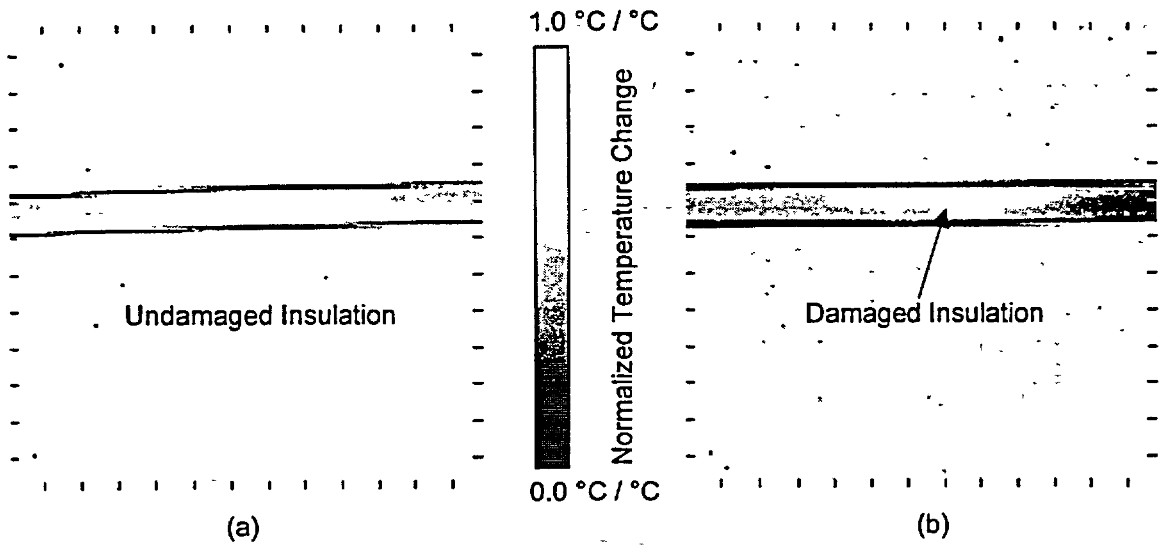

Figure 4 – Results of lock-in thermography inspection of a wire showing (a) an undamaged and (b) a damaged region of insulation.

Chemical Sensing of Combustion By-products

The degradation of electrical wire insulation can occur due to a number of factors. General aging from exposure to temperature, moisture and stress can cause deterioration in the insulation. Additionally, current overloading in a wire can seriously degrade both the metallic conductor and the insulation material. Finally, catastrophic insulation damage can occur under arcing conditions. A proposed means of detecting and locating degraded insulation consists of measuring the concentration of combustion by-products given off by the insulation either during arcing or current overloading. The advent, in recent years, of MEMS sensors for the detection and characterization of specific chemical species[16] has shown the potential to create a distributed network to remotely monitor the condition of wiring insulation.

This proposed methodology was tested using a portable fast gas chromatography system. The zNose™ is an electronic nose system which uses an uncoated 500 MHz surface acoustic wave (SAW) detector to measure molecular concentration. Input vapors enter the system through a temperature-controlled inlet and are preconcentrated for a specific time. These vapors are then injected as a short pulse into a temperature controlled capillary column for dispersion by molecular weight. The dispersed column effluent is then deposited onto the SAW detector, which records the time and amount of each chemical as a shift in the resonant frequency[17,18].

Two identical wire specimens were prepared using poly-tetraflouroethylene (PTFE) insulated 20-gauge wire (M22759-11-20). A 128.3 cm length of wire was cut, cleaned with methanol and inserted into a 40 ml glass vial. The ends of the wire were passed through a septum at the end of the vial and connected to a computer controlled DC power supply. The current flowing in the wire was increased from zero to nine amps and back to zero in 0.5 amp increments every four minutes. Air was preconcentrated for 20 seconds, analyzed using the zNose™, and then stored to the control computer's hard disk every two minutes. Figure 5 shows the gas chromatograph produced by the zNose™ comparing readings at zero amps (baseline) and at nine amps. The number of counts contained in the peak at a retention time of 3.66 seconds (labeled "Wire Peak #1") was subsequently plotted as function of applied current as shown in Figure 6.

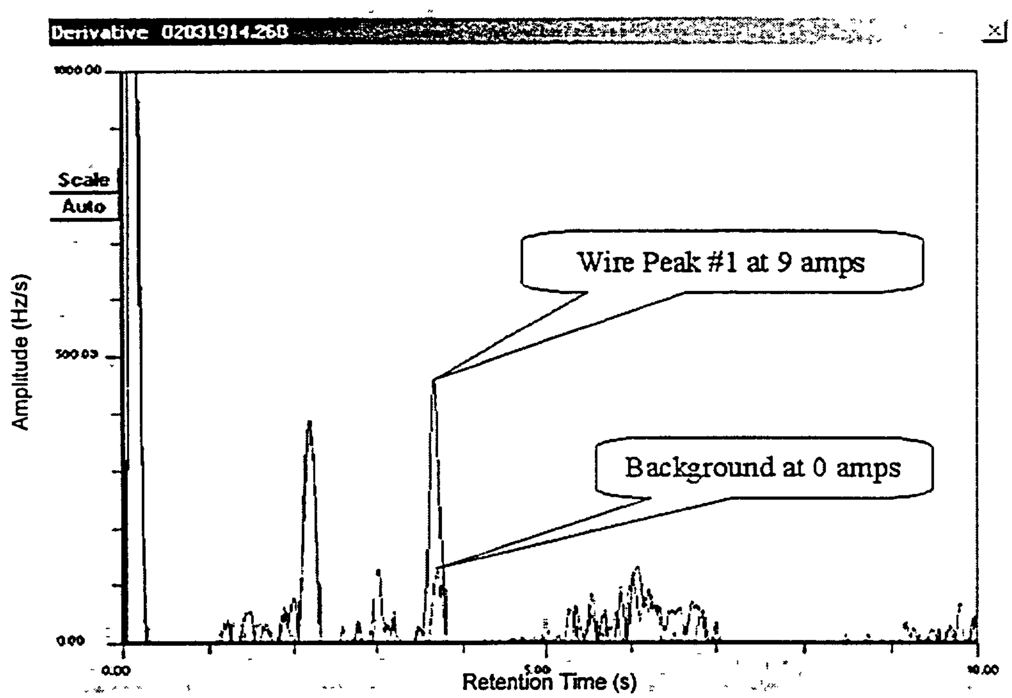

Figure 5 – Sample gas chromatograph produced by the zNose™ comparing the outgassing that occurred in PTFE insulated wire at zero and nine amps.

This experiment was repeated six times using the initial wire specimen and then four more time using the second specimen. The maximum value for counts in "Wire Peak #1" is plotted for each of the 10 experiments conducted in Figure 7. These results indicate that repeated heating of these wire specimens has resulted in a decrease in the concentration of "Wire Peak #1" likely due to changes in the insulation chemistry with "age."

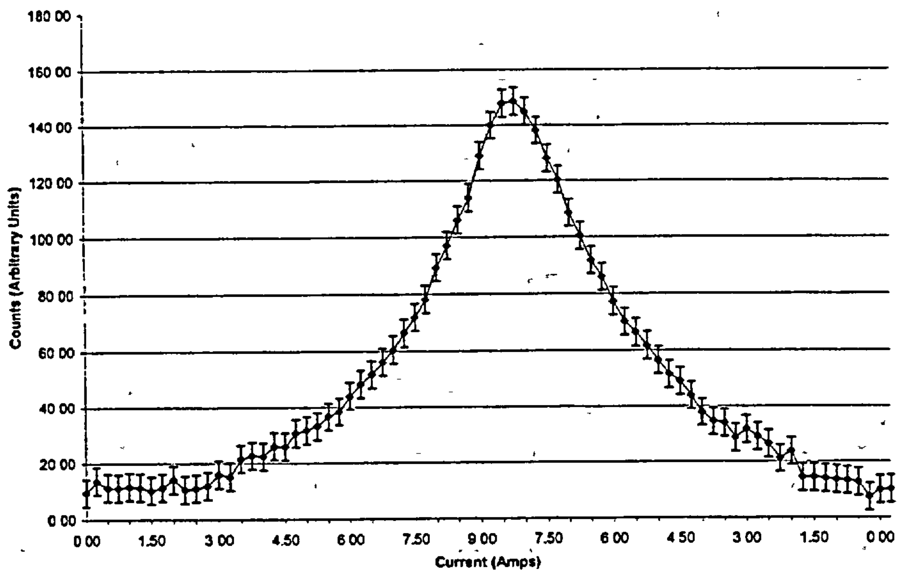

Figure 6 – Average number of counts contained in "Wire Peak #1" as a function of current for PTFE insulated wiring.

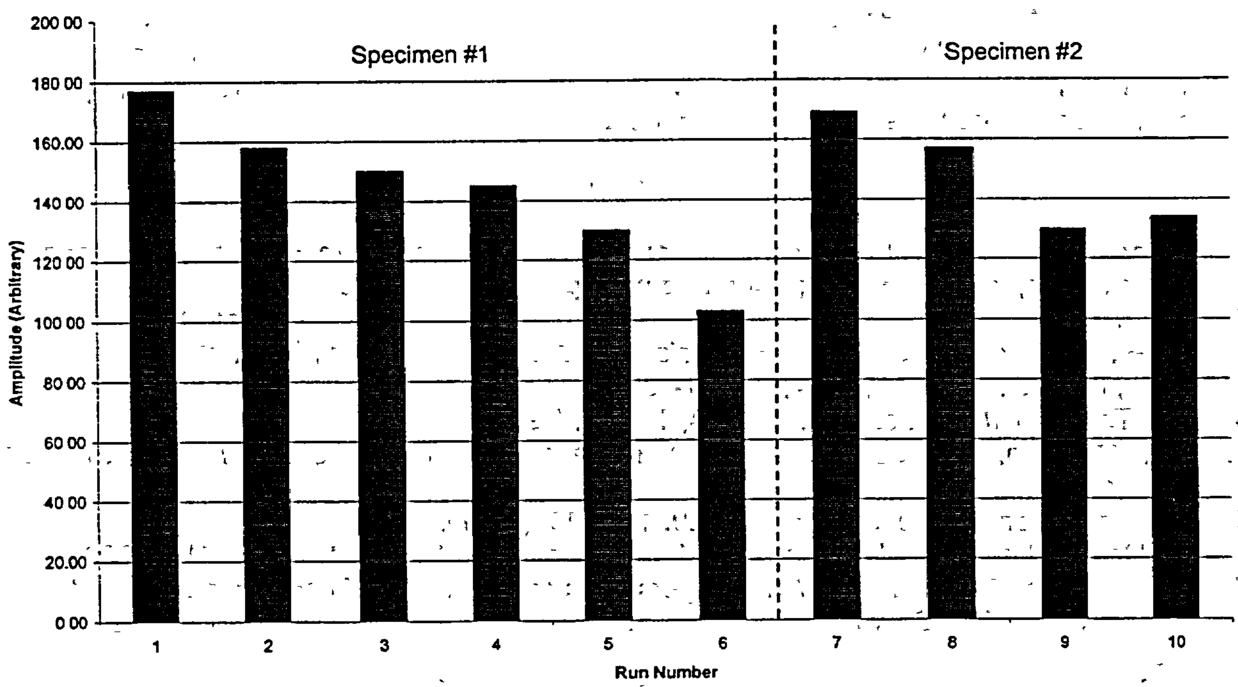

Figure 7 – Maximum number of counts contained in "Wire Peak #1" for each of 10 experiments on two PTFE insulated wire specimens.

This work has demonstrated the potential of measuring changes in the chemical composition of wire insulation as an indication of wire aging. Initial results have shown promise both as a diagnostic and prognostic tool for evaluation of wiring. Future work will include expanding the specimen set to additional insulation types commonly used in the aerospace industry and statistically determining the resolution of the gas chromatography system. Additionally, it may be possible to use this technology to evaluate the by-products produced during an arcing event and thus provide information regarding the location and extent of the damage that has occurred. Work will be performed using a specially constructed specimen chamber to analyze the volatiles produced during wire arcing.

Conclusion

Three separate techniques are currently being investigated at NASA LaRC for the characterization of wire insulation. Ultrasonic measurements of the velocity of sound in various insulation types show significant changes with insulation degradation. The measurements of the axisymmetric mode phase velocity that have been performed to date show sensitivity to stiffness changes in the wire insulation, thus indicating the potential for this technique to be used to characterize insulation aging. Lock-in thermography measurements have been shown to successfully detect changes in the thickness of wire insulation using alternating current. Further work is necessary to relate the amplitude and phase measurements made with lock-in thermography with other material properties of interest such as density and specific heat. Finally, the amount of chemical by-products produced by wire insulation during current heating has been shown to decrease with repeated heating of the wire system. This demonstrates the potential of this technology as a diagnostic tool for assessing the age of wire insulation for a particular insulation type (PTFE). Further work is being pursued to extend this work to other insulation materials and to investigate the response of the technique to other aging mechanisms beyond current heating. Also, future work will investigate the detection of wire arcing by means of the chemical by-products produce during the arcing event.

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New Methods for Monitoring the Condition of Aged Cable Jackets

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ABSTRACT

An ideal probe of the condition of cable jacketing and insulation materials would be fast, simple to execute, require minute amounts of sample and be sensitive to low levels of aging. Two methods that offer considerable promise are the modulus profiler and Nuclear Magnetic Resonance (NMR) relaxation times. A modulus profiler measures the indentation of a small tip into the surface of a polymer sample. The degree of indentation at a constant load can be related to the modulus of the material. NMR relaxation times of a polymer are a measure of the molecular dynamics of the backbone chain. When a polymer is swollen in a suitable solvent, the relaxation time responds to the degree of crosslinking. The experiment requires only minutes to complete and has been performed on samples as small as 0.1 mg. The response of NMR relaxation times to aging is comparable to that of classical mechanical measurements. Examples of both techniques applied to various commercial cable jacket formulations will be presented and compared to classical measurements.

INTRODUCTION

We are being funded by the Nuclear Energy Plant Optimization program to develop and evaluate innovative condition monitoring (CM) tools for assessing the condition of aged cable materials used in nuclear power plants. An ideal CM technique would be responsive to aging in a wide variety of materials and would require minimal amounts of sample. We have developed two methods that offer considerable promise of meeting these objectives. A modulus profiler measures the indentation of a small tip into the surface of a polymer sample. The degree of indentation at a constant load can be related to the modulus of the material. Nuclear Magnetic Resonance (NMR) relaxation times of a polymer are a measure of the molecular dynamics of the backbone chain. When swollen in a suitable solvent, the relaxation time of the cable material responds to the degree of crosslinking. The response of NMR relaxation times to aging is comparable to that of classical mechanical measurements.

The utility of candidate techniques is being evaluated by comparing these CM measurements to tensile elongation measurements performed on materials that have been aged to various extents. Samples available from previous Sandia accelerated aging studies as well as samples currently being aged offer a broad cross-section of materials and environments for correlation studies. Examples of both techniques applied to various commercial cable jacket formulations will be presented.

MODULUS PROFILING

We have developed a unique modulus profiling apparatus [1,2] that allows quantitative, highly reproducible modulus measurements to be made across the cross-section of a material with ~50 micrometers (2 mil) resolution. Such measurements have proven invaluable for following the aging of materials and determining whether heterogeneous aging effects [e.g., diffusion limited oxidation (DLO) or enhanced degradation near cable conductors caused by ohmic heating] occur [3-8]. In addition, the ability of the technique to make measurements on small material samples could lead to a CM approach capable of measurements on thin surface slices weighing less than 1 mg. Earlier screening studies with this instrument indicate that changes in modulus of cable materials often correlate with deterioration of mechanical properties [2,3,8,9]. The basic measurement underlying modulus profiling is similar in concept to the principle underlying the Indenter that has been shown to be a very promising CM technique for cable materials [10]. Modulus profiling provides 1) the opportunity to make more quantitative measurements, 2) the ability to assess diffusion-limited oxidation and other heterogeneous effects and 3) the ability to make measurements on very thin sacrificial slices.

Average tensile elongation results versus aging time for Rockbestos chloroprene cable jacket are shown at three aging temperatures (80°C, 95°C and 110°C) in Fig. 1. Fig. 2 shows the modulus profile results for samples that were aged at the lowest and highest aging temperatures for the times indicated on the figures. Although eventual application of modulus measurements as a CM technique may require measurements to be made on thin samples removed from the outside surface of cables, complete modulus profiles across aged sample cross-sections were emphasized for these studies. The results at all three temperatures show that oven-aging leads to modulus increases (hardening) of the material with aging time. Except for the longer aging times at 110°C, the increases with aging time are relatively uniform throughout the cross-section, indicative of the absence of significant DLO effects.

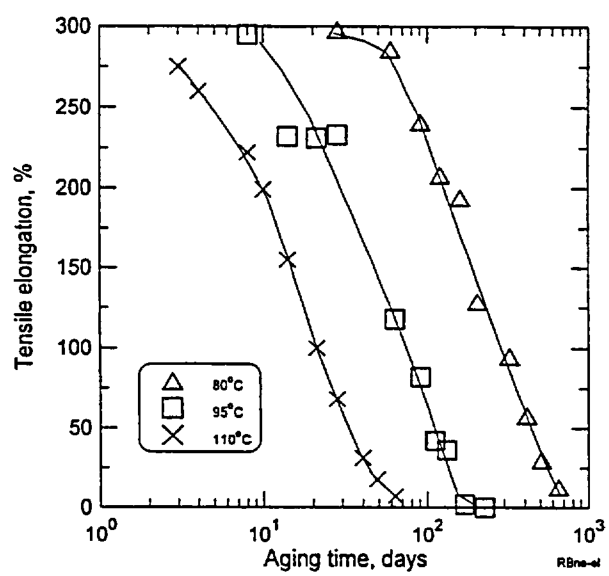

Figure 1. The tensile elongation as a function of time for Rockbestos chloroprene cable jacket aged at 80, 95 and 110 °C.

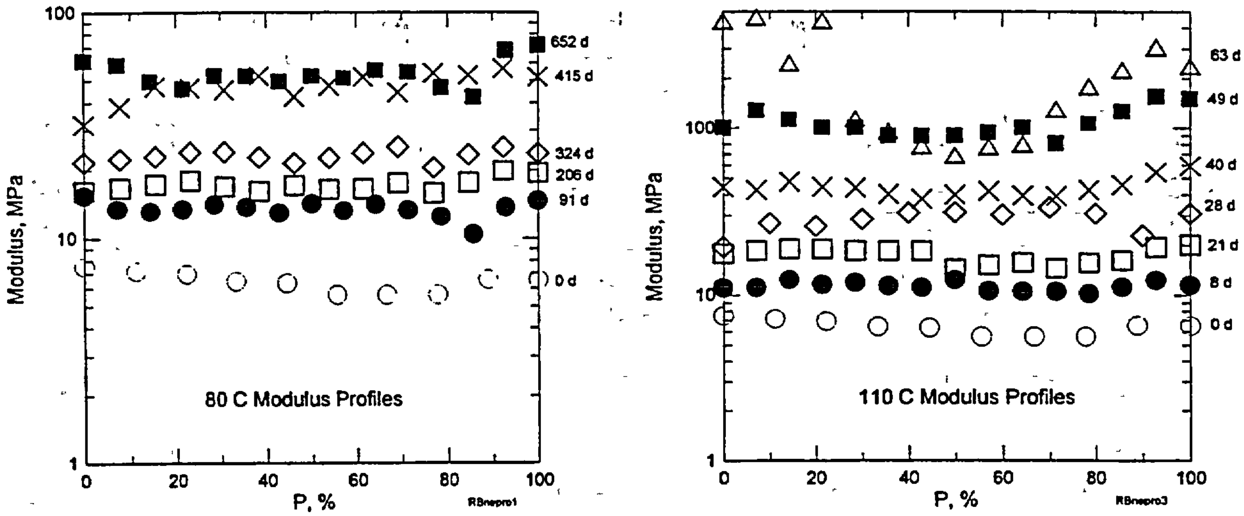

Figure 2. Modulus profiles as a function of aging time for Rockbestos chloroprene cable jacket at 80 and 110 °C.

To determine the correlation of the modulus profiling results with conventional elongation measurements, the outside surface moduli were plotted versus average elongation for the three temperatures. The results, Fig. 3, provide an excellent correlation between surface modulus and elongation. The correlation is independent of aging temperature, even for the samples that showed evidence of DLO effects. This latter observation is not surprising given our earlier studies that indicated such correlations are often observed even in the presence of very significant DLO effects [2,3,6,9]. When hardening (modulus increases) dominates oxidative degradation and hardening is maximum at the surface, one would expect cracks to initiate at the hardened surface during tensile testing. If these cracks rapidly propagate through the remainder of the sample, then the surface condition will determine the tensile elongation value.

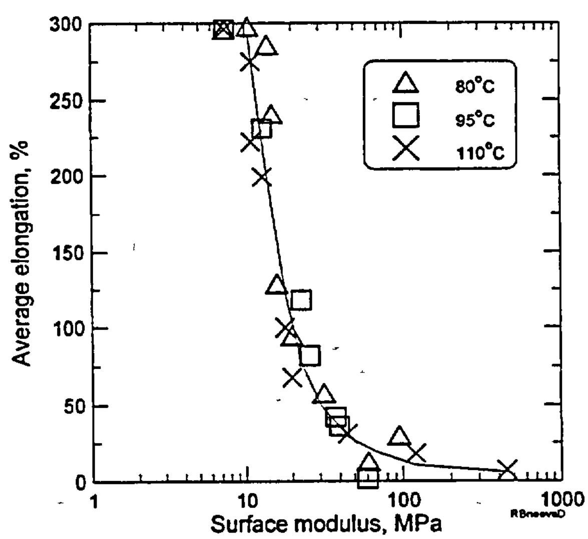

Figure 3. The correlation between elongation and surface modulus for Rockbestos chloroprene cable jacket aged at 80, 95 and 110°C.

Thus, a rational basis underlies the correlation of surface modulus with elongation and it not surprising that the correlation appears to be independent of aging temperature. If, as we believe, a similar correlation is valid at temperatures outside the experimental range, then a modulus measurement on a small surface slice taken from an ambiently aged cable can be used to estimate the elongation value for the material. It has been suggested that an absolute elongation of 50% represents sufficient margin to withstand accident radiation and to function electrically during design basis events [11]. If 50% absolute elongation is tentatively selected as the "failure" criterion for aging, the results of Fig. 5 imply that surface modulus values above ~30 to 40 MPa correspond to failure. Similar values for the surface modulus at 50% absolute elongation have been observed for several materials.

NMR RELAXATION TIME MEASUREMENTS OF SWOLLEN SAMPLES

Modulus measurements are sensitive to the overall crosslink density in the material and changes in modulus often determine changes in mechanical properties (e.g., elongation). Unfortunately the moduli of some semi-crystalline materials are dominated by the presence of the rigid crystalline phase, leading to a relative insensitivity of modulus to the changing crosslink density occurring in the amorphous phase. An important class of materials that often show such effects consists of the cross-linked polyolefin (XLPO) insulation materials. These materials are also commonly found to have sensitivity problems for other CM techniques, including the Indenter, density and OIT/OITemp. We had previously performed some preliminary experiments using a relatively simple and quick NMR [13-15] technique that we felt could be applicable to many important nuclear power plant cable materials as a CM approach. The measurements are easily performed, extremely reproducible and require only 1 to 10 minutes for sample preparation, data accumulation and data analysis. The approach is based on the fact that NMR relaxation times are sensitive to the crosslink density in the amorphous phase so that the confounding effects of the crystallites on mechanical properties are eliminated. Although similar measurements have been employed for some time to measure the condition of bulk polymers, we found that their sensitivity to the aging of crosslinked polymers can be increased significantly by swelling the polymer in a suitable solvent at elevated temperatures [13-15]. This method requires less than 1 mg of sample and can be implemented on powdered samples or sample slivers collected from cables in the field. Although our measurements were performed on a state-of-the-art NMR spectrometer, affordable commercial bench-top spectrometers are available and appear capable of duplicating our measurements.

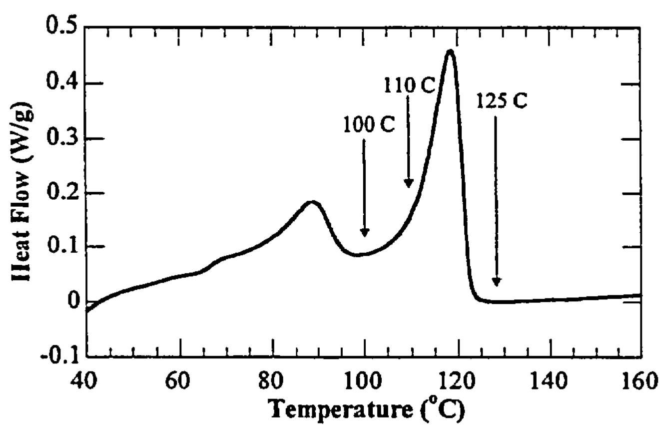

Figure 4. The DSC trace of Brandrex XLPO cable showing the three aging temperatures and the primary melting point at 118°C.

We first examined a Brandrex XLPO cable insulation that was thermally aged at 100, 110 and 125°C. Fig. 4 shows a DSC trace of this material. The two lower aging temperatures are below the primary crystalline melting point of 118°C, while the highest aging temperature was above the crystalline melting point. Modulus measurements were not sensitive to the age-induced changes in elongation of this material. The ^{1}H NMR T_2 relaxation curves from four unaged samples and two samples aged at 110°C are shown in Fig. 5. It is evident that the four experiments on unaged material show excellent reproducibility and that the decay rate increases significantly when the material is subjected to thermal oxidation. To provide a convenient number to quantify the results, we chose the point where the signal intensity has decayed to 1/e of its initial value and define this time as the spin-spin relaxation time, T_2.

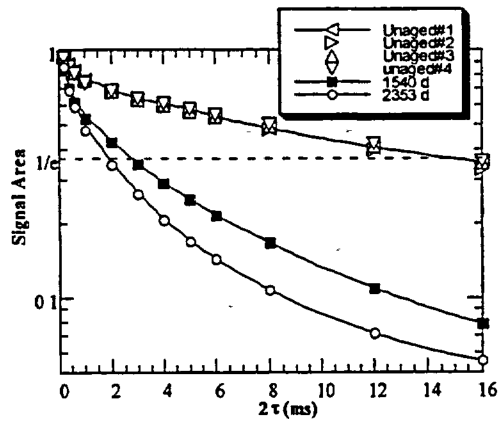

Figure 5. The ^{1}H NMR T_2 relaxation curves of Brandrex XLPO cable. The four unaged samples exhibit excellent reproducibility while the aged samples show the response of relaxation times to thermal aging.

The correlation between ultimate elongation and $1/T_2$ is shown in Figure 6. The inverse of T_2 was plotted since it increases with crosslink density, thus providing curves similar to those describing the correlation between elongation and modulus. Samples aged at 100 and 110°C (below the principal melting transition) lie on the same curve. Samples aged at 125°C appear to obey a different relationship, this difference is not surprising since the material was completely molten and therefore amorphous while being aged at this temperature.

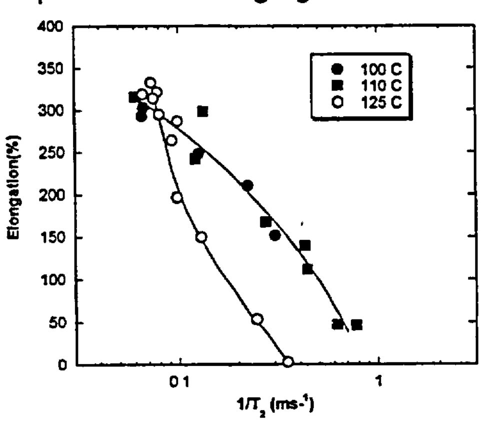

Figure 6. The correlation between ultimate elongation and $1/T_2$ for Brandrex XLPO cable.

The NMR technique was also been applied to an Anaconda chlorosulfonated polyethylene (CSPE) cable jacket. The NMR relaxation results at five aging temperatures (100°C, 120°C, 130°C, 140°C, and 150°C) are shown in Fig. 7. The data show excellent correlation between T_2 and ultimate elongation as seen in Fig. 8. A time-temperature analysis can be performed on the relaxation data in order to derive multiplicative shift factors. An Arrhenius plot of these factors exhibits excellent linearity over the aging temperature range. The activation energy obtained from the slope is 103 kJ/mol (24.6 kcal/mol), which is consistent with the Arrhenius activation energies found for the elongation of this and other CSPE materials. Thus the NMR approach appears to be promising for CSPE as well as XLPO materials.

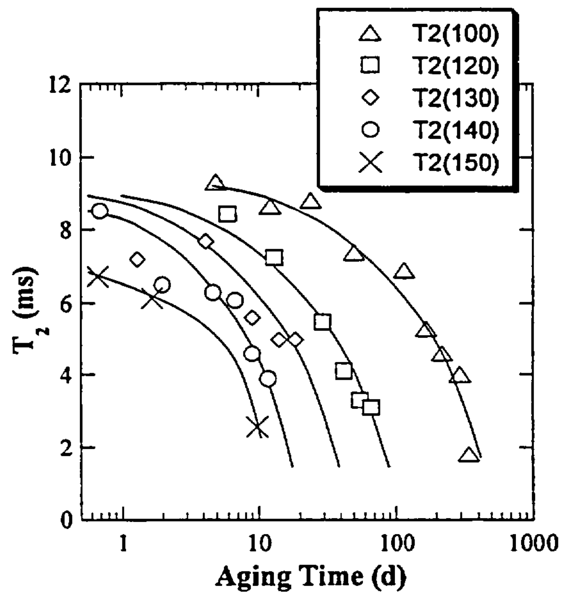

Figure 7. The time temperature curves for the T_2 of Anaconda CSPE jacket for the aging temperatures shown.

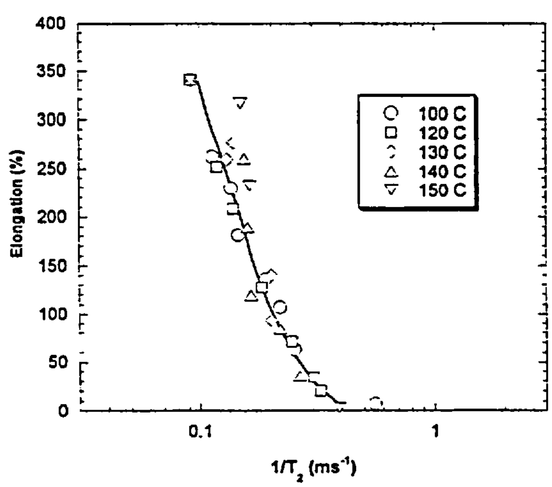

Figure 8. The correlation between ultimate elongation and $1/T_2$ for Anaconda CSPE jacket for the aging temperatures shown.

CONCLUSIONS

Innovative CM approaches will lead to more confident assessments of the condition of aged cable materials. Modulus profiling measurements appear to be applicable to a wide variety of cable materials and environments. Perhaps most remarkable are the similarities observed for the modulus values (~30 to 40 MPa) when the elongation approaches ~50%. If such a generic conclusion turns out to be valid, then the condition of any material in the field can be judged on an absolute scale.

Because modulus measurements appear to be insensitive to the aging of highly crystalline XLPO insulations, some limited screening measurements were completed using NMR relaxation techniques. The NMR approach provided excellent response to changes in elongation for a XLPO cable insulation. NMR results were also extremely encouraging for a CSPE cable jacket aged at 5 different temperatures. The NMR approach is particularly attractive because of the ease of performing the measurements, the availability of low-cost commercial NMR spectrometers, and the ability to perform measurements on very small samples (1 mg or less).

ACKNOWLEDGEMENT

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

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Application of Optical Diagnosis to aged Low-voltage Cable Insulation

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ABSTRACT

A novel non-destructive optical diagnosis for low-voltage cable insulations used in nuclear power plants has been developed. The key feature of this diagnosis is the use of light sources of two wavelengths to measure the change in reflective absorbance (ΔA_R) between the two wavelengths. Then, chemical kinetics is used to predict the lifetimes of the cable insulations. When cable insulations darken with age, the ΔA_R increases. This means that the cross-linking density in the cable insulations increases due to deterioration reaction, so that conjugation in the insulation expands, and the electronic transition absorption (equivalent to reflective absorbance A_R) increases. When the cross-linking density of an insulation increases, its elasticity corresponding to the material's life increases.

The elongation property of insulation is one of the most important parameters which can be used to evaluate material lifetimes, because it relates to elasticity. The ΔA_R correlated with the elongation property, and the correlation coefficient of an accelerated experiment using model pieces was over 0.8.

Thus, we concluded that this optical diagnosis could be applied to evaluate the degradation of cable insulations used in nuclear power plants.

1 INTRODUCTION

The method of low-voltage cable qualification is tendency of elongation of cable insulation with naturally aged cables in nuclear plant in long time. In recent years, there are several non-destructive methods which use for physical characteristic, and some of them are evaluated as potential method for use as condition monitoring technique in future.

This optical diagnosis makes use of the characteristic of changing color from oxidation degradation in insulation, and is able to detect the microscopic change on crosslinking of the polymer materials. This diagnosis method is also very easy for only irradiation and perfectly non-destructive. We expect that this non-destroying diagnostic technique is applicable to the future cable diagnostic technique.

2 THEORY

2.1 DIAGNOSIS OF THERMAL DETERIONATION FOR CABLE INSULATION

Diagnosis of thermal aging for cable insulation is based on reported procedures [2,3]. Electrical, mechanical and environmental stresses are important causes of cable aging, but to use chemical kinetics, the basic cause of deterioration of insulation is assumed to be thermal stress, and all characterization changes of insulation are caused by structural changes of materials, that is

$$P = f(x) \tag{1}$$

Where is P is an arbitrary characterization, and x the amount of structure change. According to the chemical kinetics

$$\frac{dx}{d\tau} = k\,g(x) \tag{2}$$

where k is a chemical kinetics constant, and $g(x)$ is a function of structure change due to the thermal deterioration reaction, k is defined by Equation (3) using Arrhenius's law

$$k = a \exp\left[-\frac{\Delta E}{RT}\right] \tag{3}$$

where a, ΔE, R, and T are the frequency factor, the apparent activation energy, the gas constant, and the absolute temperature, respectively. Integrating Equation (2) gives

$$\int_0^x \frac{1}{g(x)}\,dx = a\int_0^t \exp\left[-\frac{\Delta E}{RT}\right] d\tau \tag{4}$$

where x is the value at the time $\tau = t$. Here, as the integral on the right side of Equation (4) has the dimensions of time, it is called "reduced time θ".

$$\theta = \int_0^t \exp\left[-\frac{\Delta E}{RT}\right] d\tau = t \exp\left[-\frac{\Delta E}{RT}\right] \quad (5)$$

θ means the aging degree when the structural change of a material equals x.
Replacing the left side of Equation (4) by $G(x)$ gives

$$G(x) = a\,\theta \quad (6)$$

As θ is a function of x,

$$\theta = h(x) \quad (7)$$

Rearranging Equation (7) using Equation (1) gives

$$\theta = h\left[\int^{-1}(P)\right] \quad (8)$$

For equivalent values of θ, P values of the materials would be equal even if the materials were subject to different thermal histories. Then, letting θ_0 be the value of the reduced time at breakdown $\tau = t_0$, the difference $\Delta\theta$ between θ_0 and θ is given by Equation (9).

$$\Delta\theta = \theta_0 - \theta = \int_t^{t_0} \exp\left[-\frac{\Delta E}{RT}\right] d\tau \quad (9)$$

When the thermal condition is known after $\tau = t$, the lifetime $\Delta t(=t_0-t)$ until breakdown can be evaluated using this Equation.

3 MEASUTEMENT OF REFLECTIVE ABSORBANCE

This diagnosis uses the reflective absorbance A_R at the wavelength λ (nm) as an evaluating parameter. The two wavelengths is obtained by a spectrophotometer or carried type diagnostic equipment with optical fiber sensor. The A_R value obtained with the optical fiber sensor is calculated from Equation (10)

$$A_R = -\log(I / I_0) \quad (10)$$

where I and I_0 are the reflective light intensities on the sample and on a white block of standard AL_2O_3 material. The A_R spectrum was measured using a spectrophotometer with 150 mm ϕ integrated sphere in the 400 to 1500 nm wavelength region.

In optical reflective analysis, the angle displacement of incident rays and any small stains or dust particles on the surface affect the value of the reflective absorbance. This is not a severe problem for laboratory measurements, but may affect the measurement data for equipment used in the field. Thus, rather than an absolute value at an arbitrary wavelength, we used the difference of the reflective absorbance at the two wavelengths in order to reduce the surface effect. The difference of reflective absorbance ΔA_R

between the two wavelengths is given by Equation (11)

$$A_R = A_{R,\lambda_1} - A_{R,\lambda_2} \quad (11)$$

where $\lambda_1 < \lambda_2$. When a material becomes darker with aging, the value of ΔA_R increases. This means that the crosslinking density in the insulation increases due to thermal oxidation, so that conjugation in the insulation expands, and the α_e (equivalent to A_R) increases: When the crosslinking density of a insulation increases, its elasticity, which corresponds to the material's life, increases, and then cracks are produced by vibration or heat cycling. This diagnosis detects the extent of aging of insulation as a chemical structure change, non-destructively, before any cracks are formed.

4 EXAMINATION

4.1 CABLE

We examined the cable following cable material used in BWR Nuclear Plant in Japan.

(1) Cross-linked polyethylene (XLPE) insulation polyvinyl chloride jacket (PVC) cable
(2) Flame retardant Cross-linked polyethylene (FR-XLPE) insulation flame retardant polyvinyl chloride (FR-PVC) jacket cable
(3) Flame retardant Ethylene Propylene Rubber (FR-EPR) insulation Neoprene® jacket cable

4.2 DETERIORATION

This examination was performed on unused cables accelerated at high temperature using oven. Three or more different temperature conditions were set up, and cables were accelerated in those conditions so that a master curve has finally been created.

It measured also naturally aged cables sampled from nuclear power plant which have been laid for over 20 years.

5 EXAMINATION RESULT

5.1 THE MEASUREMENT RESULT BY OPTICAL DIAGNOSIS

(1) FR-XLPE (Flame retardant Cross-linked polyethylene)

Figure.1 shows the reflective absorbance A_R spectral change of XLPE insulation. Curves shown are acceleration for 120h, 240h 960h, 1920h, 4320h, 6000h at 120℃ heating.

With heating times, the A_R at shorter wavelengths is larger than that above 1200nm. The main contributor to the increase in the A_R spectrum is the electronic transition absorption α_e in the visible wavelength range, which is caused by specific chemical double bonds. Typically, there are two kinds of α_e, the carbon-carbon double bond(>C=C<), and the carbonyl group (>C=O<). It has been theorized that for thermal deteriorated insulation, as the crosslinking densities increase due to thermal oxidation reactions, the extent of conjugation in the insulation expands is also increased, and that α_e thus increases exponentially. The absorption peak at 1400 and 1200 nm are due to higher harmonic C-H molecular vibration, and with heating time, the A_R seldom changes.

Figure 2. shows the difference of reflective absorbance ΔA_R between the two wavelengths (420-1310 nm). It turns out that difference of reflective absorbance ΔA_R is rising with heating time (equivalent to insulation aging).

Next using the data in Figure 2, we rescaled the aging time t to reduced time θ, using Equation (5). An apparent activation energy ΔE for the ΔA_R change of the insulation was estimated using the Arrhenius method, and that value is 1.1×10^5J/mol. The four curves in Figure 2 were shifted and overlapped as shown in Figure 3, and the diagnostic master curve for ΔA_R was obtained.

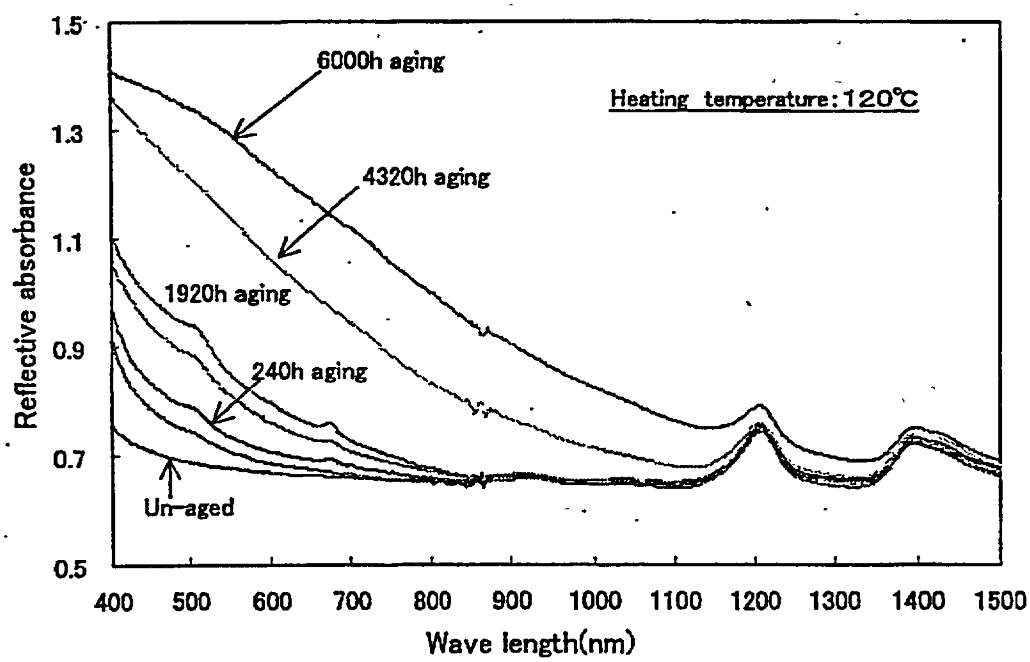

Figure 1. Reflective absorbance spectral change of aging FR-XLPE insulation as measured with a spectrophotometer

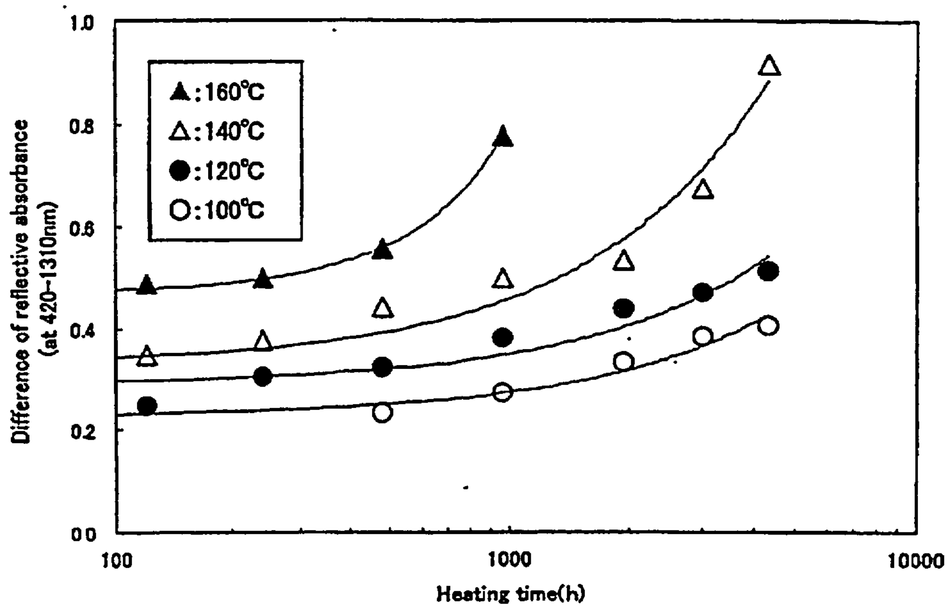

Figure 2. Time dependence of the difference of reflective absorbance ΔA_R between the two wavelengths at 420-1310 nm of the thermal deteriorated FR-XLPE insulation

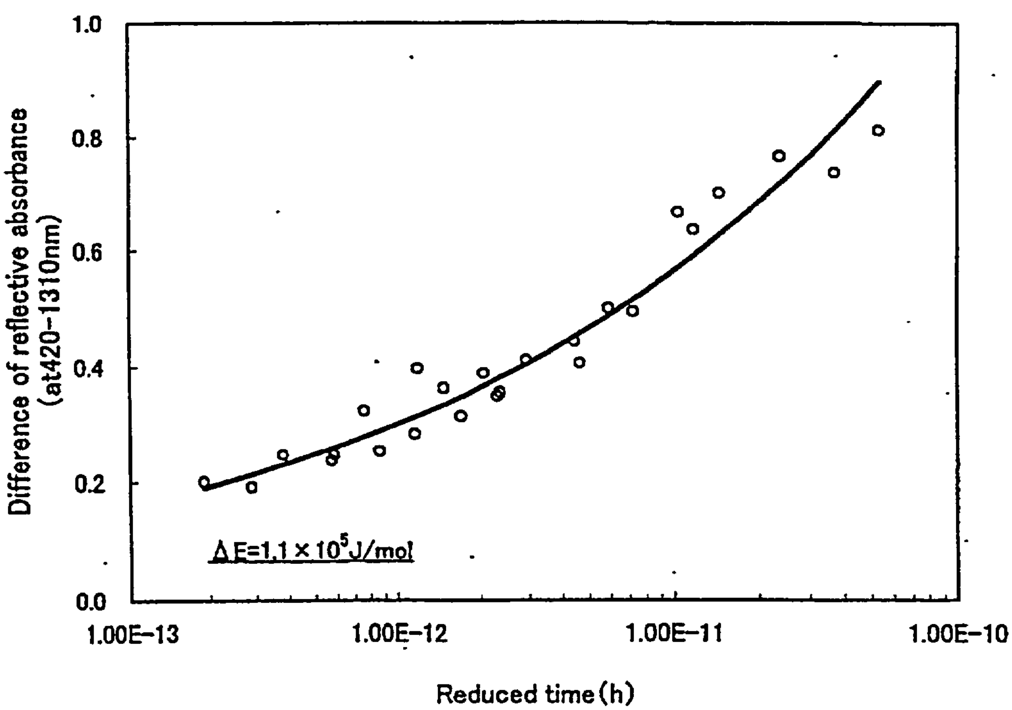

Figure 3. Diagnostic master curve using a difference of reflective absorbance ΔA_R of the FR-XLPE insulation

(2) EPR(Ethylene Propylene Rubber)

It examined like XLPE also to EPR. An examination result is shown Figure4, 5.

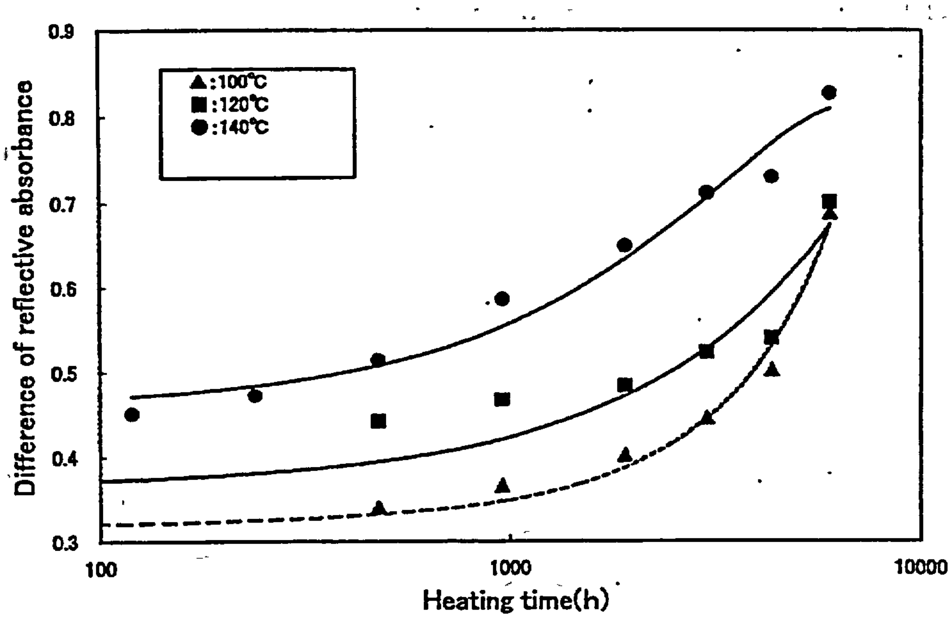

Figure 4. Time dependence of the difference of reflective absorbance ΔA_R between the two wavelengths at 420-1310 nm of the thermal deteriorated FR-EPR insulation

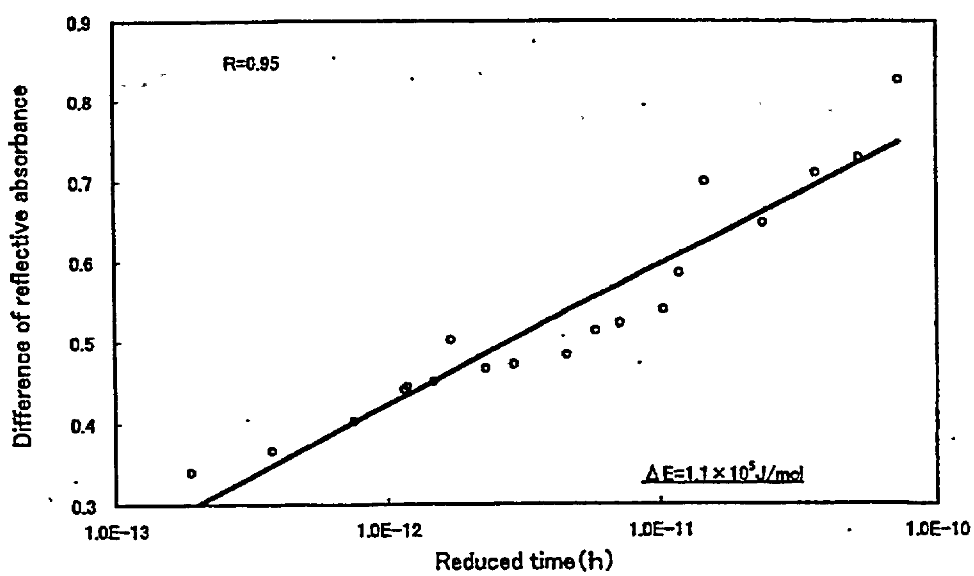

Figure 5. Diagnostic master curve using a difference of reflective absorbance ΔA_R of the FR-EPR insulation

(3) Naturally aged cables (XLPE)

Figure.6 shows the reflective absorbance A_R spectral change of XLPE insulation. Curves shown are unused cable and naturally aged cable. From this characteristic, the increase in the difference of reflective absorbance can be seen also in naturally aged cables, and it can evaluate that this technique can be applied.

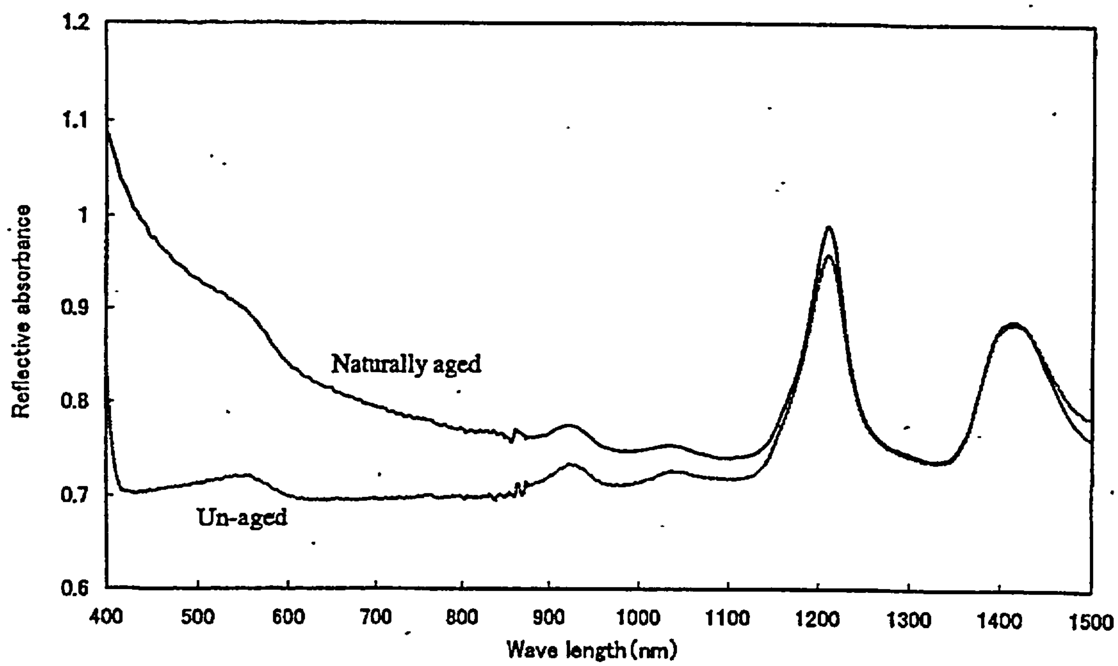

Figure 6. Reflective absorbance spectral change of naturally aging XLPE insulation as measured with a spectrophotometer

5.2 CORRELATION WITH ELONGATION AT BREAK

The elongation property of insulation is one of the most important parameters which can be used to evaluate cable lifetimes, because it relates to elasticity.

So it was examined correlation of optical diagnosis and elongation.

Figure 7. shows the elongation of FR-EPR insulation under the different aging condition. Correlation with the ΔA_R from Figure. 4 to the elongation characteristic is shown in Figure 8, 9. The ΔA_R correlated with the elongation property, and the correlation coefficient was over 0.8.

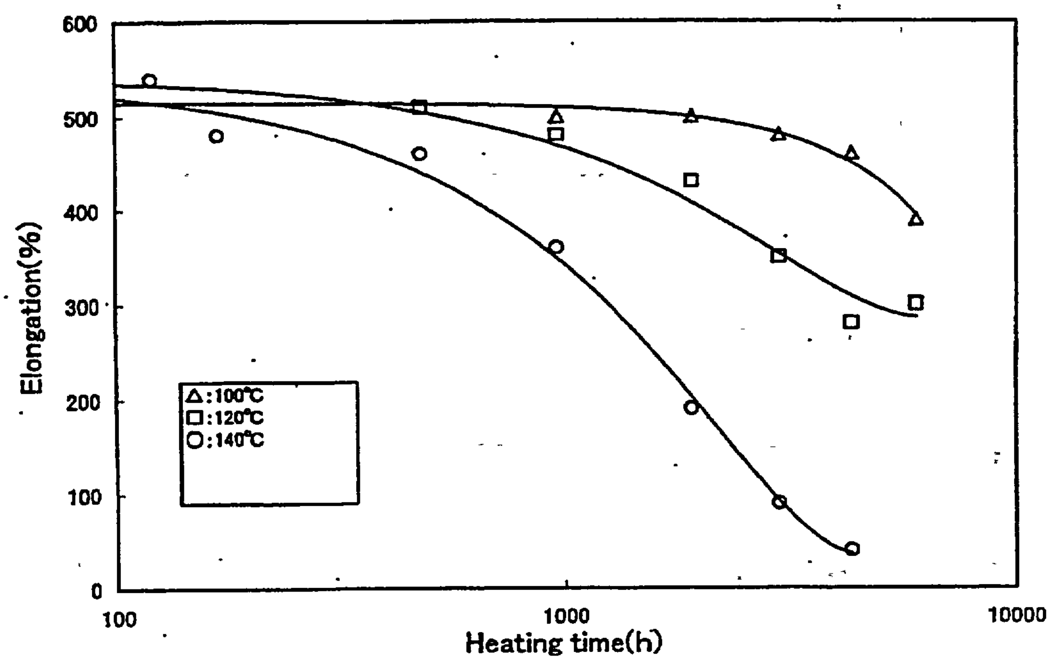

Figure 7. Time dependence of the difference of reflective absorbance ΔA_R between the two wavelengths at 420-1310 nm of the thermal deteriorated FR-EPR insulation

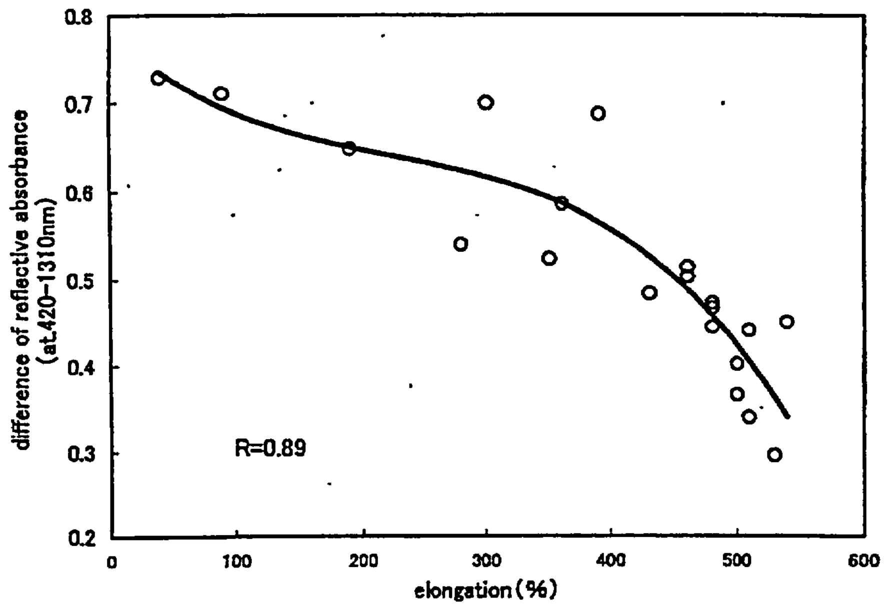

Figure 8. Relation between breaking elongation and optical transmission losses in FR-EPR insulation

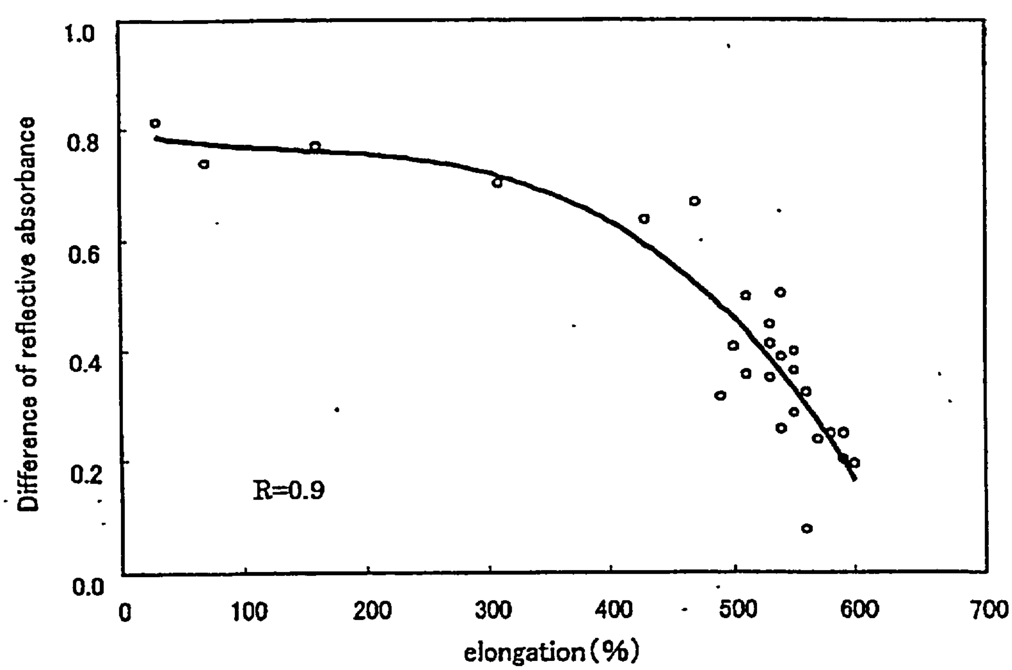

Figure 9. Relation between breaking elongation and optical transmission losses in FR-XLPE insulation

5 CONCLUSIONS

Optical diagnosis for accelerated cable and naturally aged cable has studied. We measured the change of ΔA_R of cable insulation, and obtained the following things;

(1) The ΔA_R increased with cable aging.

(2) The. ΔA_R correlated with the elongation property, and the correlation coefficient was over 0.8.

(3) The master curve of cable insulation that is used to evaluate cable lifetimes was obtained.

Thus, we concluded that this optical diagnosis could be applied to evaluate the degradation of cable insulations used in nuclear power plants.

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Nuclear Plant Cable Evaluation via Visual/Tactile and Indenter Techniques

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Abstract

Visual/tactile inspection of cables may be used as a screening technique for evaluation of cables in worst-case environments to determine if significant degradation is occurring in nuclear power plant applications. Most of the cables in currently operating power plants have jackets that harden or change color when degraded such that aging can be identified by using visual/tactile assessment techniques. If a large number of cables are identified by visual/tactile means as having aged significantly, more sophisticated techniques can be employed to precisely determine the degree of aging to allow replacement schedules to be developed and, thereby, reduce the impact of replacement activities.

Introduction

Most U.S. nuclear power plants are 20 or more years old. Concern exists that the insulation on portions of the electrical cabling systems may be deteriorating, which could result in safety concerns for cables that could subjected to accident environments and to operational concerns should cables fail that affect plant output. Cost effective techniques for assessing cable systems for determining if significant aging has occurred are described here.

Aging of Nuclear Plant Cable

In nuclear power plant applications, the dominant cause of insulation deterioration from aging is thermal stress. For safety cables, the thermal stress is from environment surrounding the cable. For operationally important cables, ohmic heating from conductor currents may also be a factor in aging. Radiation aging is possible for both types of cables but is generally limited and is not significant for most cables. Normal radiation levels are low for nearly all safety related cables. Some operationally important cables, such as those in close proximity to the reactor vessel, may be affected by normal radiation levels. However, even for these cables, only short segments nearest the reactor would be affected. Assessment for radiation damage need only be performed in the areas where high radiation levels exist under normal operation.

For most of the cable insulations used in the U.S., the aging of cable insulation and jacket materials leads to hardening of the polymers. Once severe hardening has occurred, manipulation of the cable during maintenance can lead to through cracking of the polymer or the cable crack spontaneously if exposed to a pressurized steam environment as would occur inside containment if a loss-of-coolant accident occurred.

For the field cables, conductor breakage and corrosion are minimal. Breakage, if it occurs at all, is confined to the terminations of the cables or to the local wiring associated with devices connected to the cable. Corrosion of conductors is rare and is limited to cable segments in wet locations such as the recirculating water intake structure. The deterioration of the conductor is most often limited to termination areas where short segments of conductors may be exposed to moisture depending on the type of termination.

The insulation systems for low voltage cable are not adversely affected by water. The insulation on low-voltage cable is very thick due to mechanical protection concerns that the electrical stresses are very low and do not cause deterioration of the polymer. Electrically induced deterioration does affect medium voltage cable (<4,160 Vac). Electrical deterioration proceeds very slowly in insulation systems having even potential stress gradients. Disruptions in stress gradients from pinching or other adverse mechanical stresses will accelerate electrical deterioration. Wetting of medium voltage cables will also accelerate electrical deterioration. However, the cables will generally have a life of at least 20 years and the failures will be random in nature. Wetting in the presence of operating voltage will lead to water treeing. The water trees cause localized distortions in the potential gradient through the insulation. When the tree gets large, a system voltage transient can cause the water tree to convert to an electrical tree. Thereafter, electrical deterioration is relatively rapid and breakdown can occur. The visual/tactile discussions described here are for low-voltage cable and are not applicable to medium voltage cables.

Constraints on Cable Aging Assessment

The cabling systems in nuclear power plants contain millions of feet of cable. Most cables are located in trays, conduits, or ducts. From time of installation, cables require little additional care and are rarely disturbed. Because cable related work is infrequent, cable trays are not located for easy access. Rather, they are placed in areas where they will not interfere with maintenance of equipment. Accordingly, the cables are often behind or above equipment making access more difficult. Sets of trays are generally stacked with a separate tray for different cable applications: I&C, low-voltage power, and medium voltage power. Individual trays often contain a large number of cables. Within the trays, cables are rarely marked with circuit numbers. Therefore, identifying a specific cable circuit within a tray is often difficult. In addition, the distance between trays may be limited leaving little room for application of test equipment and gaining visual access. For cables located within conduits, inspection and testing can only be performed at junction and termination boxes.

The types of cables used in nuclear plants have think insulation and jacket layers. Most of the cables are unshielded configurations. These characteristics make the cables difficult to assess for aging with electrical tests. Without a shield, there is no consistent ground plain to use in electrical testing. Because of the thick insulation layers, voltage withstand capability is 100s to 1,000s of times higher that the application voltage. Even identifying through wall cuts requires very high voltages unless water, an ionized gas or a contaminant is present to provide an electrical path for testing. More sophisticated electrical tests can be used in the laboratory to identify the subtle changes in electrical properties caused by thermal and radiation aging. Tan delta changes at very low frequencies (~0.1 hz) can be detected. However, the transition from the laboratory to the plant has not been possible to date. Accordingly, there are no effective end-to-end electrical tests for cables that will detect even severe thermal or radiation aging, whether localized or affecting the entire circuit. Electrical tests are important troubleshooting tools, even if they are not useful for aging assessment. Insulation resistance, capacitance, and time domain reflectometry are all important and useful troubleshooting tools and are highly important in maintaining the overall health of the cable system.

Favorable Attributes of Cable System with Regard to Assessment

Even though the cabling system of a nuclear plant is very large, major segments of the cable system are located in benign environments that will cause little or no significant aging within the aging. The environment for much of the plant is <35°C (<95°F) with no appreciable radiation dose rate and causes extremely low rates of cable polymer aging. In such areas, at 60 years, other than a dust layer on the surface of the benign environment cable, there will be little detectible difference between a new cable and that installed in the plant. In addition, humidity is low and there is no significant vibration present. In these benign areas, chemical or oil contamination does not occur. Accordingly, there is no concern for cable aging in large segments of the plant.

With respect to working in trays, the trays often contain numerous cables produced by the same manufacturer with the same materials and configurations. Most of the cables within the tray were installed at the same time. Cables generally have the manufacturer's name and cable type marked on the surface. Accordingly, the need to identify a specific cable within a tray is not critical. Evaluation of a few of the cables within the tray provides the insights needed to understanding of the degree of aging of all of the cables occurring at that location in the length of the tray.

Proximity of process piping to cables and trays is easy to observe allowing identification of potential hotspots by walkdown. Infrared temperature assessment can be used to determine the temperature at the tray or conduit without having to physically access the cables. Accordingly, eliminating hotspot concerns and focusing on actual adverse conditions are possible without having to erect scaffolding or ladders for direct access. For most circuits, the adverse environment is often at the end device because that is where the circuit links to a device connected to or near process piping, or where the cable connects to a device with significant ohmic heating (e.g., a large motor). Fortunately, periodic maintenance activities on the end device allow assessment of the local wiring and the end of the field cable where is could be adversely affected.

Visual/Tactile Cable Assessment

Most of the cables in use at nuclear plants have jackets with neoprene or Hypalon™ jackets. These materials harden when subjected to elevated thermal and/or radiation environments. They are more sensitive to thermal and radiation aging than the insulations they protect. Accordingly, the hardening of neoprene and Hypalon™ jackets can be used as a leading indicator of aging of the overall cable.

Environmental qualification research tests have indicated that as long as some elasticity and resilience remains in cable polymers used in nuclear safety applications, they will successfully with stand accident environments and function properly. Hypalon™ and neoprene initially have 240 to 400 % elongation at break. EQ research indicates that along some residual elongation before break, somewhere between 15 and 50%,[1] remains, the cables will not crack under accident steam and radiation conditions associated with a loss-of-coolant accident. For Hypalon™ and neoprene age to the

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[1] *Investigation of Bonded Jacket Cable Insulation Failure Mechanisms*, EPRI, Palo Alto, CA, May 2002, 1001002.

point where only 15 to 50% elongation before break remains, they have hardened enough that the degradation can be identified easily by light manipulation of the cable or by pressing against the surface of the cable.

Given that aged cables can be detected by visual/tactile assessment and that localized adverse environment areas can be identified, inspection of segments of a limited number of cables in the worst environments can provide an indication of the degree of aging of the overall cable system. When these cables are assessed at a plant, there is a range of possible outcomes. There may be no or very few cables detected with appreciable aging or there could be a large number of circuits having deterioration. If very few cables have appreciable aging, replacement of the affected cables probably would be the most cost effective means to resolve aging. Assuming the plant is 20 or more years old, future assessments would not have to be frequent and could continue to use visual/tactile testing.

If the inspection identified a large number of cables with significant aging, a more sophisticated approach would be desirable. First, the assessment may have to be expanded to larger segments of the plant having less severe environments to verify the extent of significant aging. Secondly, more sophisticated condition monitoring techniques will be necessary to more closely understand the rate and degree of aging to allow informed replacement schedules to be developed. While visual/tactile inspection can identify significant aging, discriminating between degrees of aging is difficult and subjective. Accordingly, in-situ and/or laboratory condition monitoring techniques would be needed to separate those cables that are the most degraded from those which are least degraded. The data from such assessments will allow schedules to be developed that allow the most cost effective scheduling of replacements.

If a large number of circuits are identified as having significant aging, more frequent cable system assessments will be necessary and if severe aging is identified, changes to cable types and/or relocation of the cables may be necessary to reduce the effects of aging.

Skills Required for Visual/Tactile Assessment

To allow use of visual/tactile assessment, evaluators must be familiar with unaged as well as aged cables. They must also understand the configurations and types of cables in use even if they have the same polymers and construction materials. In the unaged state, different polymers have different initial physical characteristics. Rubbers, such as neoprene, Hypalon™, ethylene propylene rubber, and silicone rubber[2], are relatively soft and pliable, and generally harden as they age. Thermo-plastics, such as crosslinked polyethylene and chlorinated polyethylene, are relatively hard, stiff materials that do not change in a physically detectible manner as they age.

In addition to understanding the basic nature of the polymers, the evaluators must understand how the construction of cable may change its apparent physical characteristics. Cables with large conductors will be much stiffer than cables with small conductors. Accordingly, the feel of the insulation rather than the stiffness of the overall

[2] Ethylene propylene and silicone rubbers age very slowly by comparison to neoprene and Hypalon™. Hardening, if it occurs, would only be experienced in extremely severe thermal environments.

cable must be assessed for large conductor cables. Also, the evaluator must be familiar with the changes to visual aspects of the cable.

Training Aids

Cable aging assessment training aids contain unaged and incrementally aged cable specimens that are used to train evaluators. The aids contain both single insulated conductors and cabled configurations. The commonly used insulations in a plant should be included in a plant specific kit. Common configurations should also be included (e.g., multi-conductor unshielded and shielded versions). Figures 1 and 2 show training aid specimens.[3]

Evaluation and manipulation of the single conductor specimens provide insights into the basic insulation types used in nuclear plants, which are crosslinked polyethylene (XLPE) and ethylene propylene rubber (EPR). Frequently, EPR insulation is directly covered with a Hypalon™ layer. Some of these EPR/Hypalon systems are bonded together in manufacture and form a composite. The evaluation of the XLPE insulated specimens indicates that there is no discernable difference in hardness or flexibility through most levels of expected aging. In addition, XLPE is seen to be a relatively hard plastic. Manipulation does not detect aging of XLPE and the material will be relatively hard whenever evaluated. The EPR/Hypalon™ insulated specimens are highly flexible when new and the Hypalon™ layer hardens significantly during aging and, at later stages of aging, cracks when bent. Aging of the Hypalon™ layer can be identified by gentle manipulation without having to cause failure of the insulation system. With the EPR/Hypalon™ system, the Hypalon™ layer can become a controlling factor in the potential for cracking of the insulation after significant aging. Manipulation can cause the Hypalon™ to crack and further manipulation will cause the crack to propagate through EPR insulation. Severely aged EPR/Hypalon™ insulation can experience a through crack when exposed to a pressurized steam accident environment.

Evaluation and manipulation of the multi-conductor specimens provide insights on the over aging of the cable. Nearly all safety cables used in the U.S. have neoprene or Hypalon™ overall jackets. These materials harden when exposed to significant thermal and radiation stresses for an extended duration. Accordingly, the jackets on the cables can be used as an indicator of the overall aging of the cable. Neoprene and Hypalon™ age more rapidly than the insulation systems they cover. Therefore, if the thermal and radiation stresses are from the environment, the jacket will be an early indicator of the overall aging of the cable. Significant aging can be detected by light flexure of the cable or by pressing thumbnail into surface of the jacket. In addition to hardness changes, rapid aging under severe environments often cause visually detectable changes to color and surface texture.

Visual/Tactile Assessment versus More Sophisticated Techniques

Visual/tactile assessment of cables is relatively inexpensive to implement. Training is not difficult and many cables can be assessed quickly. The cost of the inspection essentially is the cost for staff to get to the cable, which may take an appreciable effort.

[3] These training aids were prepared under the Nuclear Energy Plant Optimization Program, a cooperative program between EPRI and the U. S. Department of Energy.

Finding the tray or conduit may be time consuming and ladders or scaffolds may be necessary to gain access. The actual evaluation of any individual cable takes a few minutes. To keep costs in control, evaluation of cables should be coordinated with work in the vicinity of the cable. When work is required on the device connected to the cables, scaffolds and ladders are put in place. Evaluating the cable at the same time eliminates the cost required to gain access. The cable inspection activity can be scheduled for lulls in activity on the connected device.

Visual/tactile assessment can be used as a screening tool to identify aging or a lack of aging of cables, especially in the areas with the most adverse environments. Identification of significant aging is easy. However, differentiating between degrees of significant aging is more difficult and is subjective. If large numbers of degraded cables are identified, immediate replacement could take an extended period and may be unnecessary. A means of differentiating between degrees of degradation will be desirable to allow phased scheduling of replacements. A number of techniques are available that allow differentiating between those cables needing immediate replacement and those that can be used for an additional period without affecting safety and operations. The more sophisticated assessments include in-situ testing (Indenter modulus) and micro-physical laboratory tests (e.g., oxidation induction time (OIT), oxidation induction temperature (OITemp), density, and nuclear magnetic resonance (NMR))[4]. Use of Indenter in-situ test is described below. Numerous reports exist on OIT, OITemp, and density. NMR is under development at Sandia National Laboratories.

Indenter

The Indenter measures compressive modulus of an insulation or jacket wall. The compressive modulus is directly related to hardness and correlates inversely with elongation-at-break for most materials. The test was developed for power plant cables, is non-destructive, and is performed in place. The measurement is made by pressing an instrumented anvil against the cable surface at a constant velocity. The slope of the plot of force versus position during compression of the cable wall is the Indenter modulus. As the cable materials harden with age, the slope (modulus) increases. The compressive modulus increases significantly for Hypalon™, neoprene, and PVC (thermal aging only) as they age. Figure 3 shows the Indenter concept. Figure 4 shows a typical plot of Indenter modulus versus degree of thermal aging.

Figure 5 shows measurements that were made in the room under the turbine of a BWR to assess the severity of thermal aging. Severe aging of some cables had been detected during maintenance of motor operated valve actuators (MOV). The maintenance crew for the MOV noted that the insulation materials of the control and power cables were hard and crystalline rather than rubber like through visual/tactile assessment during normal maintenance of the actuator. They raised a concern that resulted in an indenter assessment of the overall cable system in the room.

The cables were all non-safety related but were procured to nuclear safety requirements. Many of the cables in the room had been exposed to extreme thermal conditions for their first eight years of service. The room was normally hot and, in addition, the thermal

[4] *Diagnostic Matric for Evaluation of Low-Voltage Electrical Cables*, EPRI, Palo Alto, CA, November 1997, may be used as a starting point to understand the use of some of these techniques.

insulation on a 500°F bypass header had been damaged on the side facing the adjacent cable trays.

New cables of the type used in the plant have an Indenter modulus of approximately 10-12 N/mm. The measured moduli ranged from 10 through 200 N/mm or from essentially new to extremely hard and severely over aged. While the some of the cables were very severely hardened, the electrical insulation properties had not deteriorated. Spontaneous cracking had not occurred. The concerns for these cables are that they could not be manipulated without cracking, and if a steam leak occurred, they may crack in the vicinity of the impingement. As previously stated, these cables were for operationally important circuits not safety circuits and immediate replacement was not necessary.

For this assessment, the cables with 10 to 20 N/mm would not need to be replaced. Those with measurements that are 40 N/mm and higher would be candidates for near-term replacement with those having 60 to 200 N/mm measurements needing replacement soonest. Values of 60 N/mm and above indicate cables that will crack when bent. Indenter values above 60 N/mm are progressively more delicate and take less effort to cause a cracking.

Conclusions

The discussion indicates that immediate implementation of sophisticated cable aging assessment techniques is not warranted. Instead, the worst-case environments with respect to insulation/jacket systems should be identified and limited assessments of worst-case applications should be performed. The scope of any additional efforts will depend on the condition of these cables. If the condition of the worst-case cable applications is acceptable, then the next assessment of these cables could be scheduled another three to five refueling outages into future. If these worst case cables are found to be in deteriorated condition, the scope of the assessment should be expanded to the next to worst case level of cables to determine the extent of degradation. If large numbers of cable circuits are identified as having significant degradation, more sophisticated assessment techniques should be used to more precisely determine the degree of degradation such that replacements can be scheduled and reduce impact on outage length.

Figure 1. Training Aids – Individual Insulated Conductors

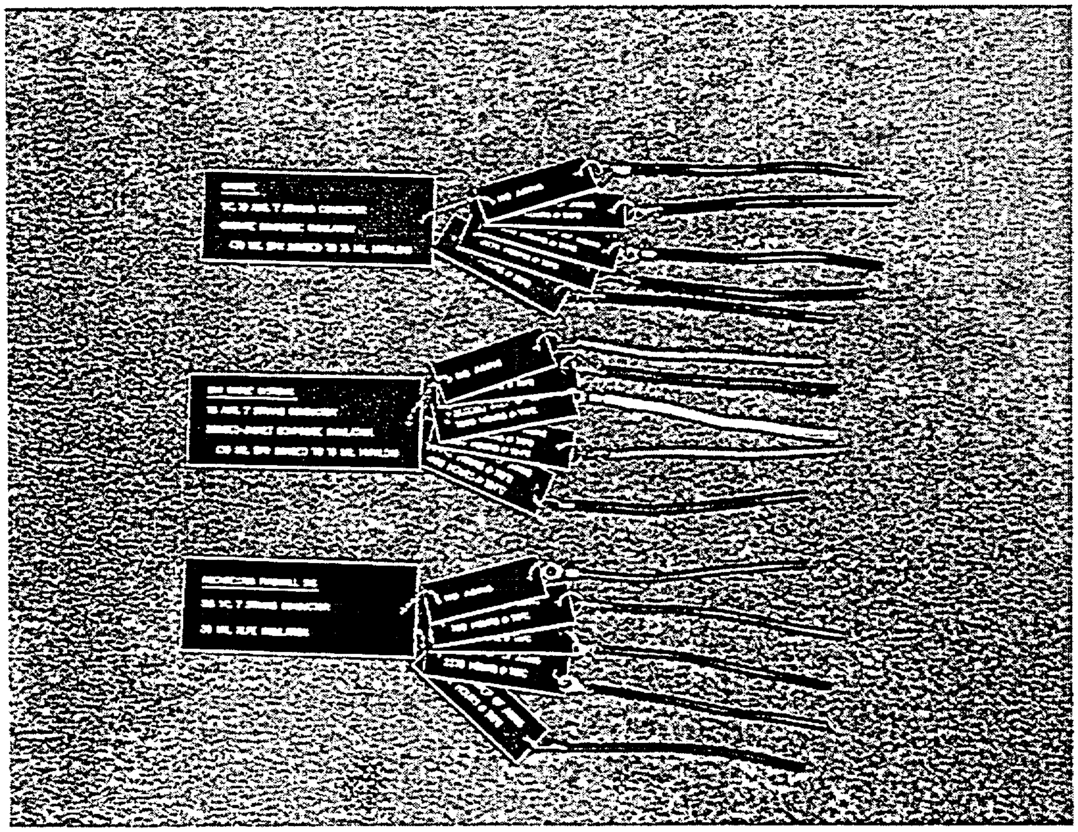


Figure 2. Training Aids – Three Conductor Cable

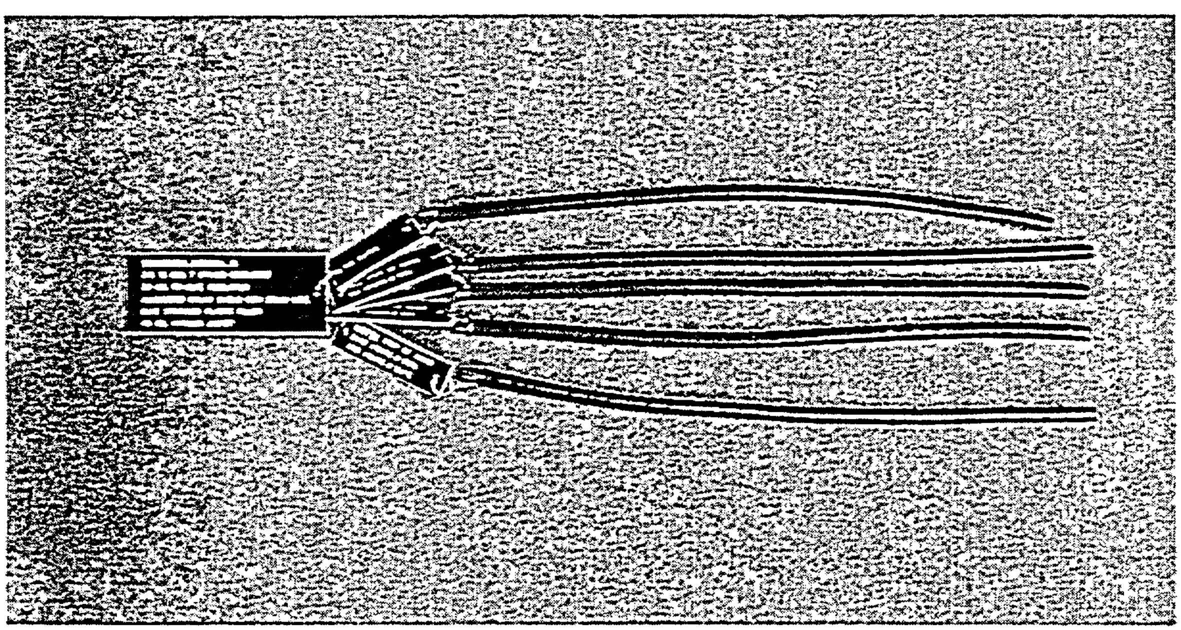


Figure 3. Indenter Concept

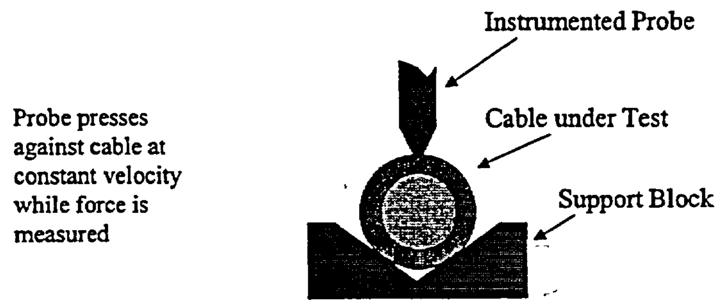


Figure 4. Typical Indenter Plot

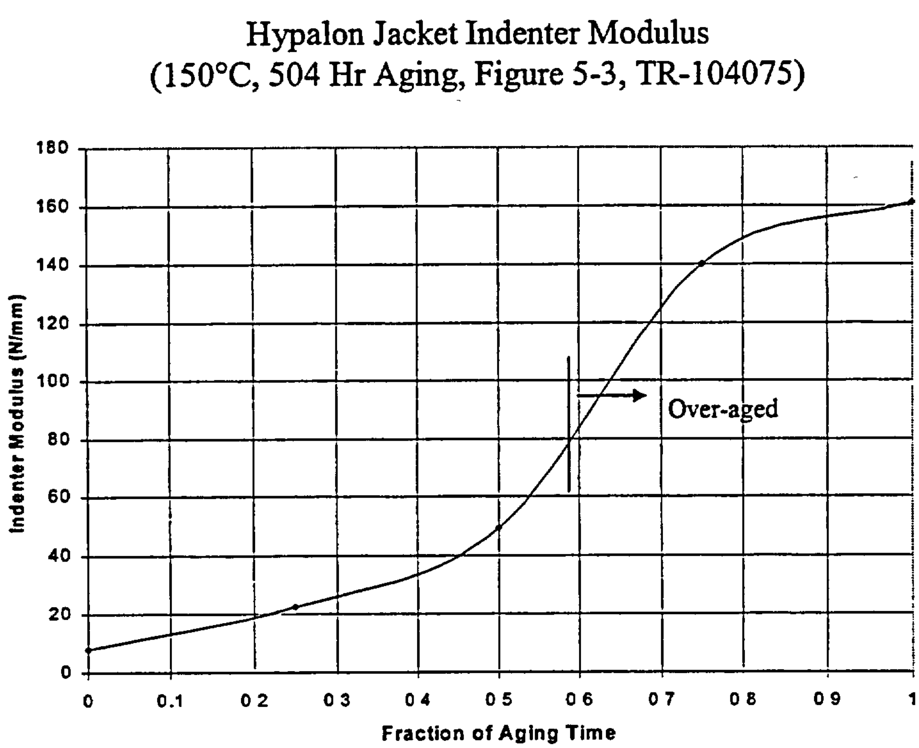
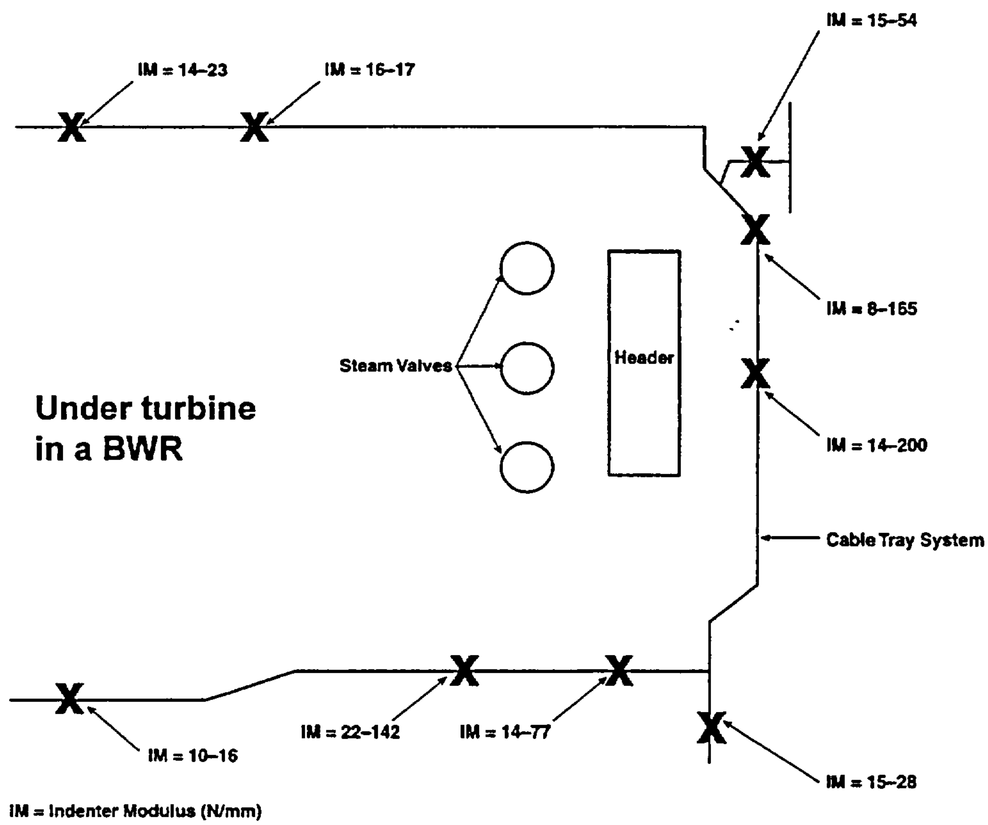


Figure 5. Indenter Results from Measurements in Cable Trays Located under a BWR Turbine



*Inspection and Testing of Wiring via Broad Band Impedance**

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Abstract

We demonstrate that the broad band impedance of a transmission line can be used for diagnostic/prognostics of the wiring health. We show that the broad band impedance is sensitive to changes in the physical and chemical state of typical aircraft wiring. For example, we measured the impedance response of three different types of wiring to exposure to Skydrol, at selected temperatures as well as to air of controlled humidity and temperature.

We present a phenomenological procedure that can be used to extract the wire's electrical parameters: resistance, inductance and dielectric function. These wire properties are important because they all depend on the frequency and therefore determine the wire's impedance spectrum. We find that the dielectric function is very sensitive to changes in the chemical and physical state of the wiring insulation, especially the imaginary component that increases by two to three orders of magnitude after the wire is exposed to the envirnoment. As a result of exposure the wiring insulation is far more lossy than before it was exposed. This implies that the wiring is more probable to fail when it is powered up.

We present wire models, both undamaged and after exposure to different environments. These models are based on a lossy, distributed transmission line and use a phenomenological representation of the wire's insulation dielectric function, $\varepsilon(\omega)$. Calculations of the model's broad band impedance spectra are compared with measured spectra of selected cables. Furthermore, this model can be uses to simulate other changes in the wiring, for example degradation of a small segment of the wire. In this way we show that the broad band impedance can be used to determine the amount of the wiring that has been degraded and the location of the damage before failure by a short.

* This work was supported by Boeing's IR&D and the FAA Aging Wire Program.

I. Introduction

The ultimate goal of this work is to develop an impedance-monitoring prototype device equipped with failure databases and appropriate rules based software that can be used as an inexpensive and convenient tool for electrical wiring maintenance in commercial aircraft. The resulting device is to be operated by a maintenance crew while the aircraft is on the ground to test the health of the wiring insulation. Impedance testing will enable the maintenance crew to not only diagnose the health-state of the insulation material, but also to predict it's remaining lifetime. Such prognostics are critical for preventing a short developing during flight leading to critical electrical equipment failure and arcing that could cause an in-flight event.

It is well-known that any short or open in a transmission line will give rise to oscillations in the wire's impedance. The frequency at which these oscillations occur has a minimum (or maximum) determined by the location of the fault. Thus, the wire's impedance can be used for diagnostics of wiring faults. However, good maintenance requires a more proactive approach. One of the goals of this project is to demonstrate that the broad band impedance is sensitive to changes in the wire's chemical and physical state. If true, the broad band impedance might be used for wire prognostics.

Here we show that the broad band impedance senses changes in aircraft wiring chemical and physical state. Specifically, we reports on the effect of

(1) Humidity

(2) Hydraulic fluid (Skydrol)

on the wire's properties. Furthermore, we show that the broad band impedance can be used to determine the amount of the wire that is degraded and the position of the damage. Note that the wire is not shorted.

In Section (II) we show that the wire's broad band impedance can be used to determine the frequency dependent resistance ($R(\omega)$), inductance ($L(\omega)$) and dielectric function ($\varepsilon(\omega)$). These quantities determine the transmission line's electrical properties and mirror the state of the wire's insulation and metal. We find that the skin effect manifests itself in the metal's resistance, but not in the wire's inductance. Furthermore, we find that the dielectric function, $\varepsilon(\omega)$, of the wiring insulation is dominated by two microscopic processes. One is a very slow ionic process that is nearly Debye and the other is a fast electronic process that is nearly independent of frequency.

In Section (III) we examine the effect of four envirnomental stresses on the wire's properties. We find that the wire's dielectric function, especially its imaginary part [$\varepsilon_2(\omega)$] is sensitive to changes in the insulation physical and chemical state. We find that the inductance, $L(\omega)$, is changed by these envirnomental stresses. In these experiments we measured the broad band impedance first when wire is not exposed, then when the wires were exposed and the finally after the wiring has been cleaned or dried. We extract the wiring properties and develop a model for the dielectric function. We find that changes in the wiring $\varepsilon(\omega)$ mirror new microscopic processes. One is a very fast ionic process, that is Debye in nature and the other one is a fast electronic process.

In these experiments the entire wire was exposed to the environment stresses. In Section (IV) we present a variety of simulations in which a segment of the wire is exposed. We show that the broad band impedance can determine the amount of the wiring that has been degraded and the location of this damage. Note that there are no shorts or opens in the wiring system.

Finally, we present our conclusions of broad band impedance as an approach for diagnostic/prognostic aircraft wiring.

II. Analysis Approach

II.1 Phenomenological Procedure

In this section we briefly give a phenomenological procedure that allows us to extract the wire's electrical properties from impedance measurements, specifically: (1) resistance, (2) inductance, (3) the real component of the dielectric function and (4) the imaginary component of the dielectric function. In addition, we can determine (5) the propagation velocity for electric signals. These parameters are important to diagnose degradation and predict lifetime of wiring insulation.

We can extract the wire properties from two independent impedance measurements. Specifically, when the wires are open and when they are shorted. The impedance for these two situations are given by Equations (2.1) and (2.2), below.

$$Z_{short}(\omega) = Z_0(\omega)\,\mathrm{Tanh}[g(\omega)\,\ell] \tag{2.1}$$

$$Z_{open}(\omega) = Z_0(\omega)\,\mathrm{Coth}[g(\omega)\,\ell] \tag{2.2}$$

Here ℓ is the length of the transmission line, $Z_0(\omega)$ and $g(\omega)$ are the characteristic impedance and the propagation function. These quantities are functions of the resistance/meter (($R(\omega)$), the inductance/meter ($L(\omega)$), $C(\omega)$ is the capacitance per length and $G(\omega)$ is the conductance per length via Equations (2.3) and (2.4).

$$Z_0(\omega) = \sqrt{\frac{(R(\omega) + i\,\omega\,L(\omega))}{G(\omega) + i\,\omega\,C(\omega)}} \tag{2.3}$$

$$g(\omega) = \sqrt{(R(\omega) + i\,\omega\,L(\omega))(G(\omega) + i\,\omega\,C(\omega))} \tag{2.4}$$

A is a frequency-independent parameter that is determined by the transmission line structure, e.g. twin pairs, coax etc and is given below, in Equation (2.10). Note that the inductance is linear dependence of A. Also, that

$$V(\omega) = \sqrt{L(\omega)C(\omega)} \tag{2.5}$$

Here $V(\omega)$ is the propagation velocity of electrical signal traveling on the wires.

Figure (2.1.1): Depicts two common transmission lines structures. The structure on the left is a coax and the right for a pair of twisted wires.

Using Equations (2.3) and (2.4) we have

$$Z_0(\omega)=\sqrt{Z_{open}(\omega)Z_{short}(\omega)} \tag{2.6}$$

$$g(\omega)=\frac{\operatorname{Tanh}^{-1}\left[\sqrt{\dfrac{Z_{short}(\omega)}{Z_{open}(\omega)}}\right]}{\ell} \tag{2.7}$$

In Equations (2.3) and (2.4) the conductance and the capacitance relate to the dielectric function, $\varepsilon(\omega)$ of the insulation via

$$C(\omega)=A\,\varepsilon(\omega) \tag{2.8}$$
$$G(\omega)=\omega\,A\,\varepsilon(\omega) \tag{2.9}$$

Here A is a geometric factor that depends on the transmission line's structure. Figure (2.1.1) depicts two structures.

The geometric factors for these two structures are

$$A_I=\frac{2\pi}{\ln\left(\dfrac{r_2}{r_1}\right)} \qquad A_{II}=\frac{\pi}{\operatorname{Cosh}^{-1}\left(\dfrac{s}{d}\right)} \tag{2.10}$$

For the aircraft wiring we have examined, we have found that A_{II} = 4.76, 5.22 and 5.71 for EFTE, Kynar and Poly (Table I). The ratio of the wire separation to the single wire diameter, averaged for the entire transmission line is 1.19, 1.19 and 1.16. These ratios are virtually the same.

Table (I): Wire Types used for this study

We can extract the wire properties from Equations (2.3)-(2.10) and have

$$R(\omega)=\mathrm{Re}[Z_0(\omega)g(\omega)]$$

$$L(\omega)=\frac{\mathrm{Im}[Z_0(\omega)g(\omega)]}{\omega}$$

$$C(\omega)=\mathrm{Re}\left[\frac{g(\omega)}{Z_0(\omega)}\right] \tag{2.11}$$

$$G(\omega)=\mathrm{Im}\left[\frac{g(\omega)}{Z_0(\omega)}\right]$$

$$v(\omega)=\frac{\omega}{\mathrm{Im}[g(\omega)]}$$

II.2 Baseline Wire Properties

In this section we apply this phenomenological procedure to the three types of wiring in Table (I) that form the base of this study and extract the dielectric function, resistance and inductance.

II.2.1 Dielectric Function

Most models of the dielectric function involve two distinct processes and involve what is known as the fraction law. The first is an ionic process that is very slow, on the order of tens of ms or longer. Its contribution to the dielectric function is of the form

$$\varepsilon(\omega)=\varepsilon_{ionic}(\omega)+\varepsilon_e(\omega) \tag{2.12}$$

Here $\varepsilon_{ionic}(\omega)$ and $\varepsilon_e(\omega)$ are the ionic and electronic contribution to the dielectric function.

$$\varepsilon_{ionic}(\omega)=\frac{A_S\,\varepsilon_0}{1+(i\,\omega\,\tau_{ionic})^{n_{ionic}}}. \tag{2.13}$$

Here A_S << 1, $n_{ionic} \approx 1$ and ε is dielectric constant of vacuum. The second process is electronic and is very fast, on the order of ns. Its contribution to $\varepsilon_0(\omega)$ is of the form

$$\varepsilon_e(\omega)=\frac{B_S\,\varepsilon_0}{1+(i\,\omega\,\tau_e)^{n_e}}. \tag{2.14}$$

Here $B_S \approx$ 3-10 and $n_e \leq 0.1$. Thus ionic processes manifest in the low frequency portion of the dielectric function's spectra and while the electronic process dominates the entire spectra in the sense that it is much larger. However, its spectrum is flat for frequencies in which $\omega\ \tau_e \leq 1$.

Figure (2.2.1) depicts the real component of POLY's dielectric function spectrum, $\varepsilon_1(\omega)$ from 100Hz to 1MHz at the temperatures: 25C, 35C, 90C and 150C. Note that the real component of the dielectric function is very sensitive to temperature from 25°C to 35°C. Beyond that range, $\varepsilon_1(\omega)$ is independent of temperature (35°C to 150°C). In particular, $\varepsilon_1(\omega) \approx 8.52\ 10^{-12}$ f/m at 25°C and grows to $3.17\ 10^{-11}$ f/m at 35°C, a factor of 3.8. However, at 150°C it increases only by 1% to $3.17\ 10^{-11}$ f/m. Note that $\varepsilon_1(\omega)$'s spectrum is flat.

Figure (2.2.2) depicts the imaginary component of POLY's dielectric function spectrum, $\varepsilon_2(\omega)$ from 100Hz to1MHz at the selected temperatures: 25C, 35C, 90C and 150C. The imaginary component of the dielectric function displays the same dependence on temperature as $\varepsilon_1(\omega)$. Note that $\varepsilon_2(\omega)$ exhibits two local maxima and a minimum. These features appear at $\omega = 4$kHz, 32kHz and 10kHz. Also $\varepsilon_2(\omega)$ is flat beyond 40kHz.

Figure (2.2.1): Depicts $\varepsilon_1(\omega)$ for selected temperature in the frequency range for 100Hz to 1MHz.

Figure (2.2.2): Depicts $\varepsilon_2(\omega)$ for selected temperature in the frequency range for 100Hz to 1MHz.

Modeling of POLY's $\varepsilon(\omega)$ follows from Equations (2.11)-(2.13) using the dielectric function parameters stated in Table (II).

Table (II): Model parameters used in fitting the dielectric function for selected temperatures.

Examination of Table (II) reveals that the time responses of both the ionic (τ_{ionic}) and electronic (τ_e) processes are faster as the temperature increases between the range of 25°C to 35°C. Beyond that are no changes in the time response. The strength of these processes also increase with temperature. Specifically, the electronic process increases by more than three times from 25°C to 35°C. The strength of the ionic process increases by 30% in the same temperature range.

The real and imaginary components for the three aircraft wiring samples that we have examined are compared in Figures (2.2.3) and (2.2.4). Note that the real part of the dielectric function is nearly constant. Furthermore the $\varepsilon_1(\omega)$ for the POLY wire is significantly smaller than for the two other types of wiring. But the imaginary component exhibits a local maximum near 8kHz and afterwards is either constant (POLY) or exhibits a $\omega^{0\ 5}$ frequency dependence (KYNAR or EFTE).

Figure (2.2.3): Compares $\varepsilon_1(\omega)$ for Kynar, ETFE and POLY.

Figure (2.2.4): Compares $\varepsilon_2(\omega)$ for Kynar, ETFE and POLY.

III.2.2 Resistance

Figure (2.2.5) depicts the resistance. Its frequency dependence is due to the skin effect. Note that the resistance of all three types of wires is nearly the same. Furthermore, the inset compares of the wire's resistance to a high frequency skin effect, $R(\omega) \to \omega^{1/2}$ for frequencies of 10^5Hz and above. In general, the transmission line's resistance becomes frequency dependent with the skin depth $\delta_s(\omega) = (2/\omega\,\sigma\,\mu)^{1/2} \le r_0$, where r_0 is the wire's radius, σ is the metal's conductivity, $\mu = 4\pi\ 10^{-7}$ (mks). Therefore, when the frequency satisfies the inequality

$$\omega \ge \frac{2}{\sigma\,\mu\,r_0^2}, \tag{2.15}$$

the resistance increases with frequency as $\omega^{1/2}$.

Examination of the wire under high magnification (Figure (2.2.6)) shows that the metal wire consists of nineteen strands. The radius of each strand is .075mm and the entire ensemble is 0.365mm. Further examination of the figure reveals that the strands themselves consist of a Cu core with a thin electrodeposited outer coating of silver. We can use the low frequency resistance to determine the conductivity of the metal via

$$\sigma_{dc} = \frac{1}{\pi\,R_{dc}\,r_0^2}\left(\frac{s/d_0}{\sqrt{(s/d_0)^2 - 1}}\right). \tag{2.16}$$

Here s is the wire separation, $d_0 = 2\ r_0$ is the wire diameter. Using Equation (2.16) to determine the dc conductivity with s/d = 1.19, d_0 = .73mm and the low frequency resistance $R_{dc} = 0.09\Omega/m$, we find the $\sigma_{dc} = 4.95\ 10^7$.

Figure (2.2.5): Depicts the frequency dependence of the wire resistance

Figure (2.2.6) EFTE, FLOUROPOLYMER TEFZEL (MIL-22759/43-22-9)

However, if we compare the normalized resistance predicted by the standard skin effect theory to the measured resistance (using the phenomenological procedure) we find they are in serious disagreement. However, if we assume that $\sigma_{dc} = 2.38 \times 10^8$ Ω/m, then the agreement is much better. This is depicted in Figure (2.2.4). Note that the measured resistance grows somewhat faster that the classical skin effect.

These disagreements imply that the wire acts as an ensemble and furthermore the strand's conductivity is more complex than that of a single strand of copper.

Figure (2.2.7) Skin depth of Cu wire.

Figure (2.2.8) Comparison of measured resistance to classical skin effect.

III.2.3 Inductance

The low frequency inductance for a pair of twisted wires is

$$L = \frac{\mu}{\pi} \mathrm{Cosh}^{-1}\left[\frac{s}{d}\right]. \tag{2.17}$$

Here μ is the magnetic permeability equal to $4\,\pi\,10^{-7}$, and s/d is the ratio of the wire separation to the wire diameter. From the discussion in Section (II) have for EFTE and KYNAR, $L = 2.42\ 10^{-7}$ H and for POLY $L = 2.23\ 10^{-7}$ H. From our measurements we find that the inductance is about eight times larger than Equation (2.17) requires.

Figure (2.3.1) depicts frequency dependence of the inductance, $L(\omega)$ for the three types of wiring that we have studied. Note that $L(\omega)$ decreases very slowly as a function of frequency. A fit of the data shows that the in the range from 100kHz to 1MHz, the inductance varies with frequency as

$$\begin{aligned} &L(\omega) = 3.61\ \mathrm{x}\,10^{-6}\left(\frac{\omega_s}{\omega}\right)^{0.05} \mathrm{H}. \\ &\omega_s = 200\mathrm{kHz} \end{aligned} \tag{2.18}$$

This behavior results from the fact that the inductance of the transmission line depends on the magnetic field between the two wires. As a result, the strands, not the ensemble determine the inductance. Using the classical skin effect we find that the inductance drops more rapidly with frequency that it should for a single strand. This disagreement is probably due to the fact that there is interface between the magnetic field from all of the separate nineteen strands.

Figure (2.3.1): Depicts the frequency dependence of the wire inductance

Figure (2.3.2): The comparison of the measured inductance (blue) with two predictions of the classical skin effect for a single strand (red) and the entire ensemble (green).

III. Results (I): Degradation of Wire

In this section we present our results on wire prognostics. Of interest is the response of the wire insulation's dielectric function to several environmental stresses. We also discuss the response of the metal resistance and inductance to these envirnoment stresses.

We report on types of environmental stresses:

(1) Humidity
(2) Skydrol

The analysis compares the wiring properties for

(1) baseline
(2) the environment
(3) after cleaning (or drying)

We find that the dielectric function is very sensitive to these environmental stresses, especially the imaginary component. For example, if the wiring is exposed to humidity (85°F/85%) for a week we find that the imaginary component of the dielectric function increases by more than two orders of magnitude over this range of frequencies. This implies that the insulation is more lossy.

III.1 Dielectric Function

III.1.1 Humidity

This section we present are analysis of the changes that the dielectric function undergoes due to stress of humidity (85°F/85%). The protocol for humidity testing of wires is below:

<u>Day 1</u>

Measure baseline open and short impedance spectra with wire in the oven
Heat the oven up to 85°F
Measure the open and short impedance spectra at 85°F
Add 85% RH
When system has re-equilibrated, measure the open and short impedance spectra
Allowed to stand at 85%/85°F overnight

<u>Day 2</u>

Measure the open and short spectra at 85%/85°F
Turn off oven and water
When system has equilibrated at ambient temperature, measure the open and short spectra
Re-equilibrate at 85%/85°F
Allow to stand overnight

Day 3 to Day 6

Repeat Day 2

Day 7

Measures the impedance spectra at 85%/85°F
Turn off system
Dry out oven when it has equilibrated at RT
Measure open and short impedances

Figure (3.1.1): Depicts POLY's dielectric function of the frequency range from 100Hz to 1 MHz.

Figure (3.1.1) depicts the response of POLY's dielectric function to heat and moisture in the frequency range from 100Hz to 1MHz. Note that the dielectric function does not return (blue) to its initial state (light green). Furthermore, the more time the wiring is exposed to this environment, the larger are both components of the dielectric function at any frequency. This reflects the fact water has penetrated in the wire insulation. Furthermore water's dielectric function is very lossy and its real part $\varepsilon_1(\omega) \approx 7\ 10^{-10}$ f/m. The real component of the wire's dielectric function increases by a factor of 4.45 and the loss (imaginary component) of the dielectric function) has increased by a factor of 1131 after two days of exposure. After drying, these ratios decrease to 2.94 (real) and 768 (imaginary).

Modeling of POLY's dielectric function reveals that there are three processes. One is a slow ion process ($\tau_1 = 45$ms), the second is a fast ion process ($\tau_2 = 0.35$ms) and the third is a fast electron process ($\tau_3 = 1.0$ns). We find that for POLY, the dielectric function is well fitted via

$$\varepsilon(\omega) = \frac{3\ 10^{-10}}{1+(i\,\omega\,\tau_1)} + \frac{.95\ 10^{-9}}{1+(i\,\omega\,\tau_2)^{45}} + \frac{.59\ 10^{-9}}{1+(i\,\omega\,\tau_3)^{05}} \ . \tag{3.1}$$

Modeling of EFTE's dielectric function reveals that there are three different processes. Specifically, there is a slow ion process ($\tau_1 = 100$ms), the second is an electronic process ($\tau_2 = 31$ns) and the third is a fast electron process ($\tau_3 = 1.0$ns). We find that for EFTE, the dielectric function is well fitted via

$$\varepsilon(\omega) = \frac{7.5 \times 10^{-11}}{1+(i\,\omega\,\tau_1)} + \frac{.2 \times 10^{-11}}{1+(i\,\omega\,\tau_2)^{35}} + \frac{2.25 \times 10^{-10}}{1+(i\,\omega\,\tau_3)^{01}} \tag{3.2}$$

Figure (3.1.2): Depicts EFTE Fluoropolymer, Tefzel's dielectric function of the frequency range from 100Hz to 1 MHz.

Figure (3.1.3): Depicts Polyalkene & polyvinylidene fluoride, KYNAR's dielectric function of the frequency range from 100Hz to 1 MHz.

Modeling of KYNAR's dielectric function reveals that there are three different processes. Specifically, there is a slow ion process ($\tau_1 = 1$ms), the second is a very fast ion process (τ_2= 0.79□s) and the third is a fast electron process (τ_3=1ns). We find that for KYNAR, the dielectric function is well fitted via

$$\varepsilon(\omega)=\frac{1.2\,\mathrm{x}\,10^{-11}}{1+(i\,\omega\,\tau_1)}+\frac{.6\,\mathrm{x}\,10^{-11}}{1+(i\,\omega\,\tau_2)^{9}}+\frac{1.9\,\mathrm{x}\,10^{-10}}{1+(i\,\omega\,\tau_3)^{.35}}. \tag{3.3}$$

III.1.2 Skydrol

This section we present the analysis of the changes that the dielectric function undergoes due to environmental stress of Skydrol. The test procedure is the following:

Measure baseline open and short impedance spectra with wire in the beaker
Fill beaker with Skydrol and heat the beaker to (25°C, 35°C, 90°C or 150°C)
Allowed to stand at (25°C, 35°C, 90°C or 150°C) 24hr.
Measure the open and short impedance spectra at (25°C, 35°C, 90°C or 150°C).
Clean the wires
Measure the open and short impedance spectra at 25°C, 35°C, 90°C and 150°C.

We first examine at the effects of Skydrol on the wiring dielectric function at different temperatures. We compare the wiring $\varepsilon(\omega)$ at three states: baseline, wire placed in Skydrol and after cleaning.

Figure (3.1.4) depicts EFTE's $\varepsilon(\omega$ forthe three states: (1) baseline, (2) placed in Skydrol and (3) after cleaning. The wire's temperature was 25°C.

Figure (3.1.4): Compares the response of EFTE dielectric function at T = 25°C for baseline, immersion in Skydrol and after cleaning.

The upper graphs compare the real and imaginary components of the dielectric function before immersed in Skydrol and then after cleaning. The lower graphs include the state in which the wire is immersed in Skydrol. Note that $\varepsilon(\omega)$ does not return to it initial state (baseline). Particular, $\varepsilon_2(\omega)$ increases from 1 10^{-13} f/m to 3 10^{-13} f/m at low frequencies (10kHz or lower). On the other hand, $\varepsilon_1(\omega)$ suffers little change. Examination of the lower graphs, reveal that immersed in Skydrol greatly changes both the real and imaginary components of the dielectric function. Specifically, the $\varepsilon_2(\omega)$ increases 200 times from 10^{-13} f/m to 2 10^{-11} f/m in the neighborhood of 50kHz and $\varepsilon_1(\omega)$ increases from 3.4 (lower frequencies) to 2.4 times (higher frequencies, 1MHz).

Figure (3.1.5) depicts KYNAR's $\varepsilon(\omega)$ for the three states: (1) baseline, (2) placed in Skydrol and (3) after cleaning. The wire's temperature was 25°C.

Figure (3.1.5): Compares the response of KYNAR's dielectric function at T = 25°C for baseline, immersion in Skydrol and after cleaning.

Again, the upper graphs compare the real and imaginary components of the dielectric function before immersed in Skydrol and then after cleaning. The lower graphs include the state in which the wire is immersion in Skydrol. Again $\varepsilon(\omega)$ does not return to the initial state. In particular, $\varepsilon_2(\omega)$ increases from 1 10^{-13} F/m to 5 10^{-13} F/m at low frequencies (10kHz or lower). Again $\varepsilon_1(\omega)$ suffers little change. Examination of the lower graphs, reveal that immersion in Skydrol greatly changes both the real and imaginary components of the dielectric function. Specifically, the $\varepsilon_2(\omega)$ increases 250 times from 10^{-13} f/m to 2.5 10^{-11} f/m in the neighborhood of 50kHz and $\varepsilon_1(\omega)$ increases from 4.5 (lower frequencies) to 2.75 times (higher frequencies, 1MHz). KYNAR's $\varepsilon(\omega)$ response is somewhat larger that EFTE's, is it very similar.

Figure (3.1.6) depicts POLY's $\varepsilon(\omega)$ for the three states: (1) baseline, (2) placed in Skydrol and (3) after cleaning. The wire's temperature was also 25°C.

Figure (3.1.6): Compares the response of POLY's dielectric function at T = 25°C for baseline, immersion in Skydrol and after cleaning.

The response of POLY's dielectric function is similar as the other wiring types.

The next three figures compare the dielectric function at selected temperatures, 25°C (blue), 35°C (green), 90°C (orange) and 150°C (red) when the wire is immersed in Skydrol. Figure (3.1.7) depicts EFTE's $\varepsilon(\omega)$ response.

Figure (3.1.7): Compares the response of ETFE's dielectric function.

Examination of Figure (3.1.7) reveals that the real component of the dielectric function has a weak dependence on temperature from 25°C to 35°C. For example, the spectrum is flat from 100Hz to about a few 15kHz. Beyond that it falls about 40% near 1MHz. At higher temperatures the spectra change somewhat. For example, at 150°C, spectrum is no longer flat. For example, $\varepsilon_1(\omega)$ possesses a local minimum at very low frequencies. It then increases to a maximum near 100kHz. With further increase in frequency it falls from 1.55 10^{-10} f/m to 10^{-11} f/m.

$\varepsilon_2(\omega)$'s spectrum is dominated by a peak in the same frequencies where $\varepsilon_1(\omega)$ falls, which is to be expects due to Kronig-Kramer rule. Note that as the temperature increases, the peak shifts to high frequencies, especially at 150°C. Furthermore, a new ionic process appears at higher temperatures at low frequencies. However, we have not be able to model this process in a convincing way.

This behavior reflects two processes. One is a new fast ionic process and the other is an electronic one. The dielectric function can be fitted by the following formula in the frequency range from 3.1kHz to 1MHz.

$$\varepsilon(\omega)=\varepsilon_0\,\frac{A_{ionic}}{\left(1+\left(i\,\omega\,\tau_{ionic}\right)^{n_{ionic}}\right)}+\frac{A_e}{\left(1+\left(i\,\omega\,\tau_e\right)^{n_e}\right)}. \tag{3.4}$$

The values of the dielectric parameters are given in the Table (II). We note that the electronic process can be fitted in a number ways because $\varepsilon(\omega)$ is only weakly dependent on the time response, τ_e. Specifically, the power law is n_e = 0.025. Thus a change in τ_e by three orders, say to 1ns from μs, changes the frequency-dependent part of the electronic contribution to the dielectric function by a factor of 1.19.

Table (III): Parameters for Models for EFTE's Dielectric Function

An examination of Table (III) reveals that as the temperature increases the ionic process becomes faster with changing from 25.12μs to 5.01μs, a five fold decrease in time response. Furthermore the strength of this process increases with an increase in temperature. However, the changes are relative small, 15%. Note that the ionic process is Debye in nature, with an exponent of 1. On the other hand the electronic process time response is unchanged with temperature changes, stays at 1 μs. The strength of the electronic process is unchanging from 25°C-90°C. However, it decreases five fold in the temperature range from 90°C-150°C.

Figure (3.1.8) depicts KYNAR's $\varepsilon(\omega)$ response. Examination of Figure (3.1.8) reveals that real component of the dielectric function weakly depends on temperature from 25°C to 35°C. For example, the spectrum is flat from 100Hz to about a few tens of kHz. Beyond that it falls about 40% near 1MHz. Thus KYNAR's behavior is the same as EFTE in this temperature range. However, its dielectric behavior is different than EFTE's at 90°C. For example, at very low frequencies, ε_1 for is for KYNAR shows a maximum, whereas ε_1 for EFTE is flat in this portion of the spectrum. KYNAR's spectrum is not flat anywhere in the frequency range from 100Hz to 1MHz. Thus, dominates by a new ionic process $\varepsilon_1(\omega)$ that does not appear for EFTE.

The $\varepsilon_2(\omega)$ spectrum for EFTE is dominated by at peak in the same frequency range where $\varepsilon_1(\omega)$ falls, which is to be expects due to Konig-Kramer rule. Note that at 90°C the peak shifts to higher frequencies. Furthermore, a new ionic process appears at higher temperatures as seen in the low frequency spectrum.

Table (IV) summarizes the model dielectric function parameter for KYNAR. Note that the fast ionic process is Debye and its time response is close to that of for that of EFTE. However, the electronic process differs in the sense that the exponent is twice as large as EFTE's, and its strength is significantly smaller.

Table (IV): Parameters for Models for Kynar's Dielectric Function

Figure (3.1.8a): Compares the response of KYNAR's dielectric function.

Figure (3.1.8b): Compares the response of POLY's dielectric function.

Figure (3.1.9) compares the dielectric response of POLY to exposure to Skydrol at the temperatures of 25°C, 35°C, 90°C and 150°C. In general, POLY's dielectric function is the same as for the other types of wire. Note that the wire's dielectric function is very sensitive in the temperature range from 25°C-35°C. Specifically, $\varepsilon_1(\omega)$ increases by over a factor of 3.9 $\varepsilon_2(\omega)$increases by factor of 4.5. However, $\varepsilon_1(\omega)$ is nearly independent of temperature from 35°C to 150°C. Table (IV) summarizes the key dielectric parameters uses in Equation (3.4).

Table (V): Parameters for Models for Kapton's Dielectric Function

Examination of Table (V) reveals that the electronic process attains its maximum at 35° and the ionic process, which is Debye, is almost at a maximum. Note that the time response follows the same pattern as the two types of wiring.

Figures (3.1.9) through (3.1.11) compares the dielectric response of these three wiring types at the selected temperatures. In line with the discussion above about Kapton's dielectric function, we found that its $\varepsilon(\omega)$ response is much larger that the two types at 35°C although is it significantly smaller than Kynar's response at 25°C.

Figure (3.1.9): Comparison of $\varepsilon(\omega)$ for EFTE (green), KYNAR (blue) and POLY (red) wiring immersed in Skydrol maintained at a temperature of 25°C

Figure (3.1.10): Comparison of $\varepsilon(\omega)$ for EFTE (green), KYNAR (blue) and POLY (red) wiring immersed in Skydrol maintained at a temperature of 35°C

Figure (3.1.11): Comparison of $\varepsilon(\omega)$ for EFTE (green), KYNAR (blue) and POLY (red) wiring immersed in Skydrol maintained at a temperature of 90°C.

Figure (3.1.12): Comparison of $\varepsilon(\omega)$ for EFTE (green) and POLY (red) wiring immersed in Skydrol maintained at a temperature of 150°C,

III.2 Resistance

We note that the resistance for a pair of twisted wires depends on the ratio of the wire resistance d, to the distance between the two wires, s via

$$R(\omega)=\frac{2\,R_s(\omega)}{\pi\,d}\left[\frac{s/d}{\sqrt{(s/d)^2-1}}\right]\equiv\Re(\omega)\left[\frac{s/d}{\sqrt{(s/d)^2-1}}\right]\equiv\Re(\omega)\,f(s/d). \qquad (3.6)$$

Here $\Re(\omega)$ is the resistance of the twisted pairs in the limit that $s/d \to \infty$. The factor f(s/d) is important when the wires swell, due to envirnoment changed.

III.2.1 Humidity

In this section we examine the effect of humidity on the wire resistance. We find that humidity increases the wire's resistance because of swelling in the wire insulation.

This happens in all three types of wiring. EFTE is most affected by humidity and POLY is the least influenced by humidity.

Figure (3.2.1) compares EFTE's resistance for (1) the baseline (2) the wiring as exposed to controlled humidity for seven days and (3) after the wiring is drying after exposure. Examination of the data reveals that the ratio of ($d_{humidity}/d_{baseline}$) is 5.8%. Specifically, in the low frequency limit, the resistance started at 0.0875 Ω /m, after seven days of controlled humidity it increased 18.5% to 0.1037 Ω /m and after dried decreased to 0.0889 Ω/m. Thus the wire insulation has swelled by 5.8% (we assume that the wire distance s is not affected). Furthermore, after drying out, the wire is diminished and the ratio of ($d_{dried}/d_{baseline}$) is 0.5%.

Figure (3.2.1): Compares the resistance of EFTE wiring exposures to controlled humidity. Here baseline (black), two days at 85°F/85% of humidity (green), same a week (red) and have dried out (blue).

Figure (3.2.2) depicts the same experiment but for KYNAR wiring. Examination of the data reveals that the ratio of wire diameter to the wire separation increased by 8.6%. Specifically, in the low frequency limit, the resistance started at 0.096 Ω /m, after seven days of controlled humidity it increased 19.5% to 0.116 Ω /m and after drying decreased to 0.098 Ω/m. Thus the wire insulation has swelled by 5.3% (we assume that the wire distance s is not affected). Furthermore, after drying out, the wire has nearly returned to it initial size.

Figure (3.2.2): Compares the resistance of KYNAR wiring exposures to controlled humidity. Here baseline (black), two days at 85°F/85% of humidity (green), same a week (red) and have dried out (blue).

Figure (3.2.3) compares POLY's resistance for (1) the baseline (2) exposed to controlled humidity for sevens days and (3) after the wiring has been dried. Examination of the data reveals that the ratio of the wire diameter to the wire separation as increased by 8.6%. Specifically, in the low frequency limit, the resistance started at 0.096 Ω /m, after seven days of controlled humidity it increased 19.5% to 0.115 Ω /m and after decreased to 0.098 Ω/m. Furthermore, after drying out, the wire returns nearly to it initial size.

Figure (3.2.3): Compares the resistance of POLY wiring exposures to controlled humidity. Here baseline (black), two days at 85°F/85% of humidity (green), same a week (red) and have dried out (blue).

III.2.2 Skydrol

In this section we review our results on the wiring resistance response to Skydrol. This data shows the importance of the temperature in wire insulation swelling. Specifically, at 25°C there are no changes in the resistance for all three types of wiring. However at 90°C the resistance displays significant increases at low frequency. Table (VI) depicts the changes in the wire resistance (at 977Hz) and the decrease in the ratio of the wire diameter (d) to their separation (s). Examination of this table reveals that the ratio of the diameter of the wire to the wire separation increases as a function temperature. For example, with EFTE, the ratio increases up to 10% at 150°C.

Table (VI): Response of wire size to Skydrol at a function of temperature.

III.3 Inductance

All of our measurements indicate that the standard theories of wiring inductance do not describe aircraft wiring. For example, the low frequency wiring inductance extracted from our measurements are over eight times larger than what the standard theories predict. Furthermore the standard skin effect completely failed to describe the frequency dependence of aircraft wiring.

From the work reported on the resistance, we know that the ratio of the wire diameter to the wire separation increases by humidity and Skydrol. For example, the EFTE response to a week of humidity is to increase the d/s by near 6%. Thus, we would expect that the inductance would decrease after the wiring has been exposed to humidity. Instead, the inductance increases, as can be seen in Figure (3.3.1) which depicts the changes of the inductance after exposure to high humidity (85°F/85%). Examination of this figure reveals that the inductance increases from 4.5% (EFTE) to 7.5% Kynar).

Figure (3.3.1): Depicts the response of the inductance to humidity (85°F/85). Here green is EFTE, blue is Kynar and red is Kapton.

Thus, a more detailed description of wiring aircraft is required. We will not examine this issue here and will only reports the results. Figures (3.3.2), (3.3.3) and (3.3.4) depict the response of the wire inductance to Skydrol. Again we find that the inductance increases although the ratio of the wire diameter to the wire separation has increased.

Figure (3.3.2): Depicts the response of the EFTE's inductance to Skydrol.

Figure (3.3.3): Depicts the response of the KYNAR's inductance to Skydrol.

Figure (3.3.4): Depicts the response of the POLY's inductance to Skydrol.

IV. Results (II): Degradation of a Segment

In this section we present numerous simulations of a transmission line in which only a part of the wiring as been degraded. We calculate the impedance for an EFTE transmission line that was damaged by (1) humidity and (2) Skydrol. In these simulations we used the data reported in Sections (II) and (III).

IV.1 Approach

In this section we derive the broad band spectrum for a pair of twisted wires in which only a segment has been degraded. We assume that both of the wires have been degraded the same way and that only one segment has been damaged. Let the wire length being L_T, and the system is open-circuited. The region in which the wire is degraded is from L_1 to L_2 (Figure (4.1.1). Let $Z_{01}(\omega)$ and $g_1(\omega)$ be the characteristic impedance and propagation function for the healthy wire, and $Z_{02}(\omega)$ and $g_2(\omega)$ be the same for the degraded wire.

Figure (4.1.1): Depicts the model for a degraded transmission line.

The impedance for this system is

$$Z(\omega)=\frac{Z_{01}(\omega)(Z_{01}(\omega)A_1(\omega)-Z_{01}(\omega)\mathrm{Coth}[g_1(\omega)(d+L_1-L_T)]A_2(\omega))}{Z_{02}(\omega)B_1(\omega)-Z_{01}(\omega)\mathrm{Coth}[g_1(\omega)(d+L_1-L_T)]B_2(\omega)}$$

$$A_1(\omega)=Z_{02}(\omega)\mathrm{Tanh}[g_1(\omega)d]+Z_{01}(\omega)\mathrm{Tanh}[g_1(\omega)L_1]$$

$$A_2(\omega)=Z_{02}(\omega)+Z_{01}(\omega)\mathrm{Tanh}[g_2(\omega)d]\mathrm{Tanh}[g_1(\omega)L_1] \tag{4.1}$$

$$B_1(\omega)=Z_{01}(\omega)+Z_{02}(\omega)\mathrm{Tanh}[g_2(\omega)d]\mathrm{Tanh}[g_1(\omega)L_1]$$

$$B_2(\omega)=Z_{01}(\omega)\mathrm{Tanh}[g_2(\omega)d]+Z_{02}(\omega)\mathrm{Tanh}[g_1(\omega)L_1]$$

Note that in the limit of no degradation, ($g_1(\omega) \to g_2(\omega) \equiv g(\omega)$ and $Z_{01}(\omega) \to Z_{02}(\omega) \equiv Z_0(\omega)$) Equation (4.1) reduces to that of a simple open-circuited transmission line of length of length L_T

$$Z(\omega)=Z_0(\omega)\mathrm{Coth}[g(\omega)L_T]. \tag{4.2}$$

Also, in the limit that $Z_{02}(\omega) \to \infty$, the impedance reduced to an open-circuited transmission line of length L_1.

IV.2 Amount of Degradation

Exposure to humidity or Skydrol increases the wiring dielectric function, especially the imaginary component. Figure (4.2.1) depicts the phase spectrum for POLY that has been exposed to humidity. Calculations reveal that the phase spectrum, $\Phi(\omega)$, is more sensitive to the physical and chemical state of the wire insulation than is $|Z(\omega)|$. Thus, we will restrict our simulations to $\Phi(\omega)$.

Figure (4.2.1) Simulations of the phase impedance spectrum of Kapton in which a different amount of the wiring has been degraded by humidity.

We examine the low frequency portion (100Hz-1MHz) of $\Phi(\omega)$ for the case in which a segment of a 10m POLY wire has been exposed to 85% humidity for seven days and then dried. Specifically, we compare the phase spectra in which the segment length varies from 0m (baseline) to 2m in steps of 0.5m. Here black is the baseline (no degradation), blue (0.5m), green (1m), violet (1.5m) and red (2m). Examination of Figure (4.2.1) reveals that the amount of the wiring that has been damaged is clear from the phase spectrum. In particular, $\Phi(\omega)$ is virtually flat at –90° in the baseline. However, structure appears near 1kHz where wire has been exposed to humidity. Furthermore as d (amount of the wiring that has been degraded) increases the peak near 1kHz increases. In particular, the deviation from –90° is linear with d.

Next, we examine the low frequency (100Hz-1MHz) spectrum of $\Phi(\omega)$ for the case in which a segment of a 10m POLY wire has been exposed to Skydrol for 24hours. Specifically, we compare the phase spectra in which the segment length varies from 0m (baseline) to 2m in steps of 0.5m. Examination Figure (4.2.3) reveals that the amount of the wiring that has been damaged is clear from the phase spectrum. In particular, $\Phi(\omega)$ is virtually flat at –90° in the baseline. However, structure appears near 32kHz when the wire has been exposed to Skydrol. Furthermore as d increases, the peak at 32kHz increases. In particular, the deviation from –90° is linear with d.

Figure (4.2.2): Simulations of the phase impedance spectrum of KYNAR in which different amount of the wiring has been degraded by Skydrol.

IV.3 Location of Degradation

In this section we present simulations of the effect of both humidity and Skydrol exposure on the high frequency spectrum of the impedance.

Figure (4.3.1) depicts a simulation of the high frequency spectrum of $|Z(\omega)|$, specifically in the region near the minimum of the first oscillation. Here a 0.5m segment of a 10m length POLY wire that has been stressed by humidity. The segment has been exposure to humidity (85%/85F) for seven days and then dried. Note that the location of the damage is closely correlated with the frequency of the minimum of $|Z(\omega)|$. The further away that the damage is from the point of measurement, the greater is the decrease of the frequency of the minimum from that of the baseline (no damage). The only exception is the case in which the damage is located from 0.0m to 0.5m, were the minimum is slightly increased in frequency. After that, the minimum is always decreased in frequency.

Figure (4.3.1): Simulations of a portion of the high frequency phase impedance spectra of Kapton in which a 0.5m segment of the wire has been degraded by humidity. The location of the damage effects the position of minimum of $|Z(\omega)|$.

Figure (4.3.2) depicts a simulation of the high frequency spectrum of $|Z(\omega)|$, specifically in the region near the minimum of the first oscillation. Here a 0.5m segment of a 10m length of POLY wire has been exposed to Skydrol for 24hr. Note that the location of the damage is closely correlates with the frequency of the minimum of $|Z(\omega)|$.The further away the damage is from the point of measurement, the larger is the downshift from the baseline (no damage).

Figure (4.3.2): Simulations of a portion of the high frequency $|Z(\omega)|$ spectra of POLY in which a 0.5m segment of the wire has been degraded by Skydrol. The location of the damage effects the position of minimum of $|Z(\omega)|$.

V. Discussion and Conclusions

In this paper we have reported our findings on using broad band impedance as a probe of the physical and chemical state of wire insulation. We have measured and analyzed the wire impedance in which the wire has been exposed to humidity and Skydrol. Using this data, we have determined the changes in the wire's resistance, inductance and the dielectric function due to the environmental stresses.

We found that these environmental stresses have (1) increased the dielectric loss by two to three order of magnitude and (2) have increased the real component of $\varepsilon(\omega)$ by a factor of two or three times. Furthermore, (3) the resistance increases because the wire's insulation enlarges by both humidity and Skydrol. Thus the wire impedance can be used to probe of wire's physical and chemical state. Furthermore, we have show in theory that the impedance mirrors the amount of the wiring that has been degraded and where the damage occurs.

Acknowledge

Research supported by the FAA's Aging Wiring program and Boeing's IR&D.

Tables

Abbrev.	Mil Spec	Generic/Chemical Name
EFTE	MIL-22759/43-22-9	EFTE Fluoropolymer, Tefzel
KYNAR	MIL-81044/13-22-9	Polyalkene & polyvinylidene fluoride, Kynar
POLY	MIL-81381/7-22-9	Aromatic polyimide (Kapton)

Table (I): Wire Types used for this study

T(°C)	A_S	n_{ionic}	τ_{ionic}(ms)	B_S	n_e	τ_e(ns)
25	.1	1	10.0	1.8	.003	1.00
35	.16	1	7.9	6.89	.003	.79
90	.16	1	7.9	7.12	.003	.79
150	.16	1	7.9	7.12	.003	.79

Table (II): Model parameters used in fitting the dielectric function for selected temperatures.

T(°C)	A_{ionic}	τ_{ionic}(μs)	n_{ionic}	A_e	τ_e(μs)	n_e
25	3.92	25.12	1	21.96	1	.025
35	4.04	19.95	1	21.96	1	.025
90	4.04	7.94	1	21.36	1	.025
150	1.19	5.01	1	4.51	1	.025

Table (III): Parameters for Models for EFTE's Dielectric Function

T(°C)	A_{ionic}	τ_{ionic}(μs)	n_{ionic}	A_e	τ_e(μs)	n_e
25	4.98	25.70	1	21.65	1	.05
35	5.41	23.44	1	21.86	1	.05
90	8.01	11.22	1	21.65	1	.04

Table (IV): Parameters for Models for Kynar's Dielectric Function

T(°C)	A_{ionic}	τ_{ionic}(μs)	n_{ionic}	A_e	τ_e(μs)	n_e
25	2.15	31.62	1	5.87	1	.05
35	9.01	25.12	1	22.52	1	.05
90	8.03	11.22	1	18.60	1	.05
150	9.40	5.82	1	19.29	1	.05

Table (V): Parameters for Models for Kapton's Dielectric Function

Wire Type	T(°C)	%R (977Hz)	% d/s
EFTE	25	0%	0%
EFTE	35	2%	.9%
EFTE	90	22%	6.6%
EFTE	150	42%	10%
KYNAR	25	0%	0%
KYNAR	35	2%	0.9%
KYNAR	90	12%	5.9%
POLY	25	0%	0%
POLY	35	2%	.6%
POLY	90	18%	5.8%
POLY	150	37%	9.3%

Table (VI): Response of wire size to Skydrol at a function of temperature.

Figures and Captions

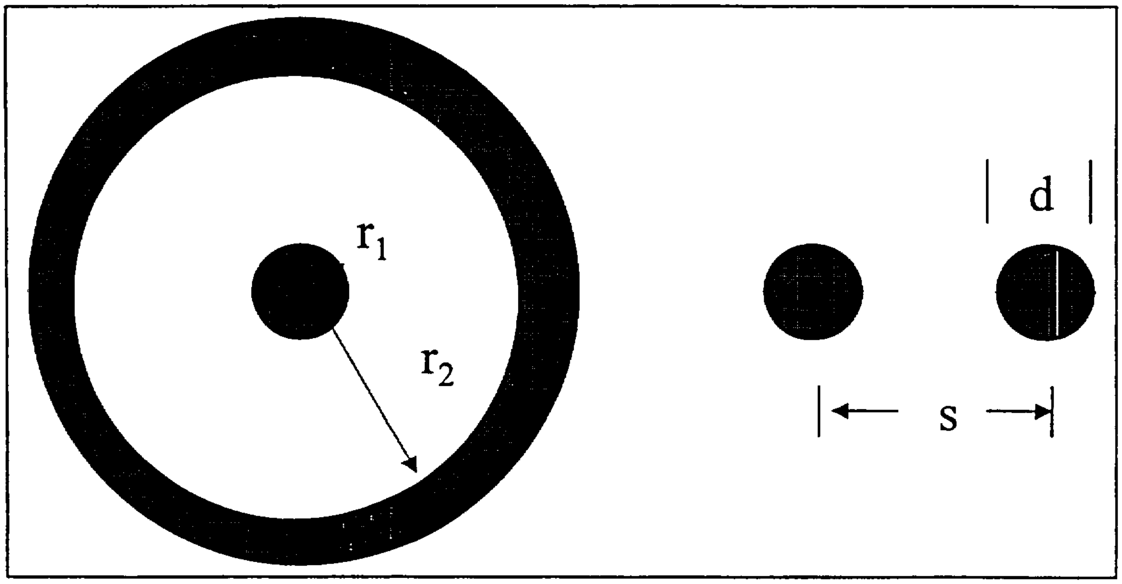


Figure (2.1.1): Depicts two common transmission lines structures. The structure on the left is a coax and the right for a pair of twisted wires.

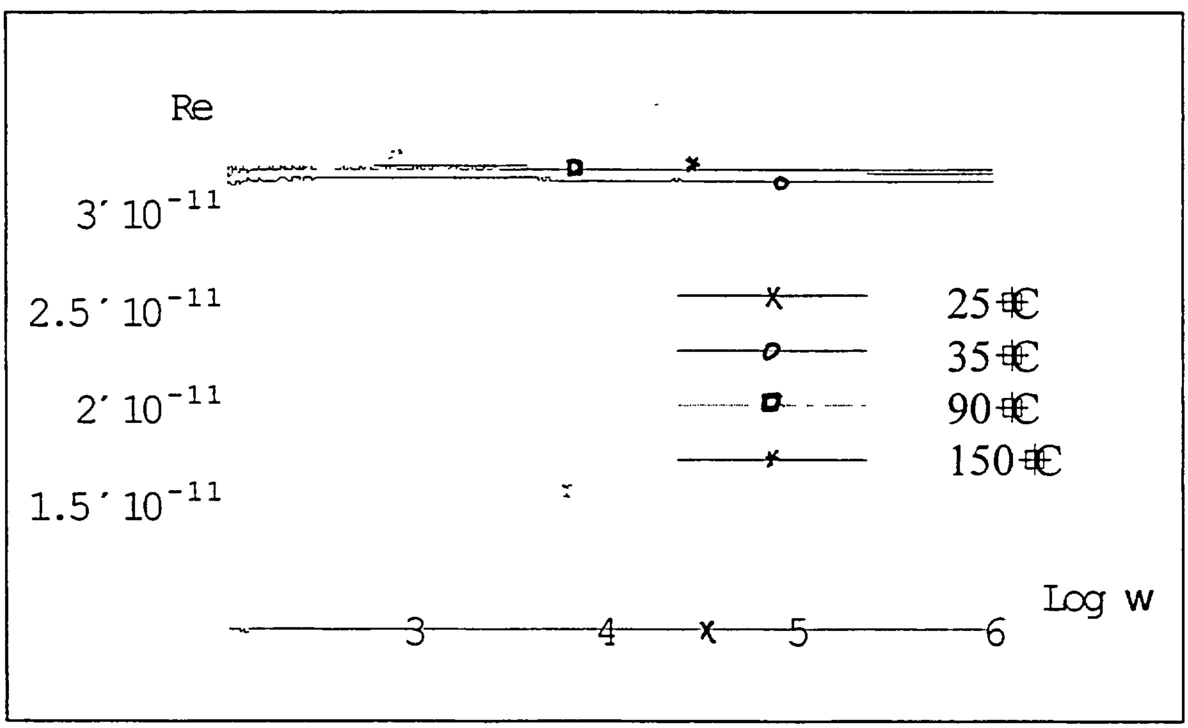


Figure (2.2.1): Depicts $\varepsilon_1(\omega)$ for selected temperature in the frequency range for 100Hz to 1MHz.

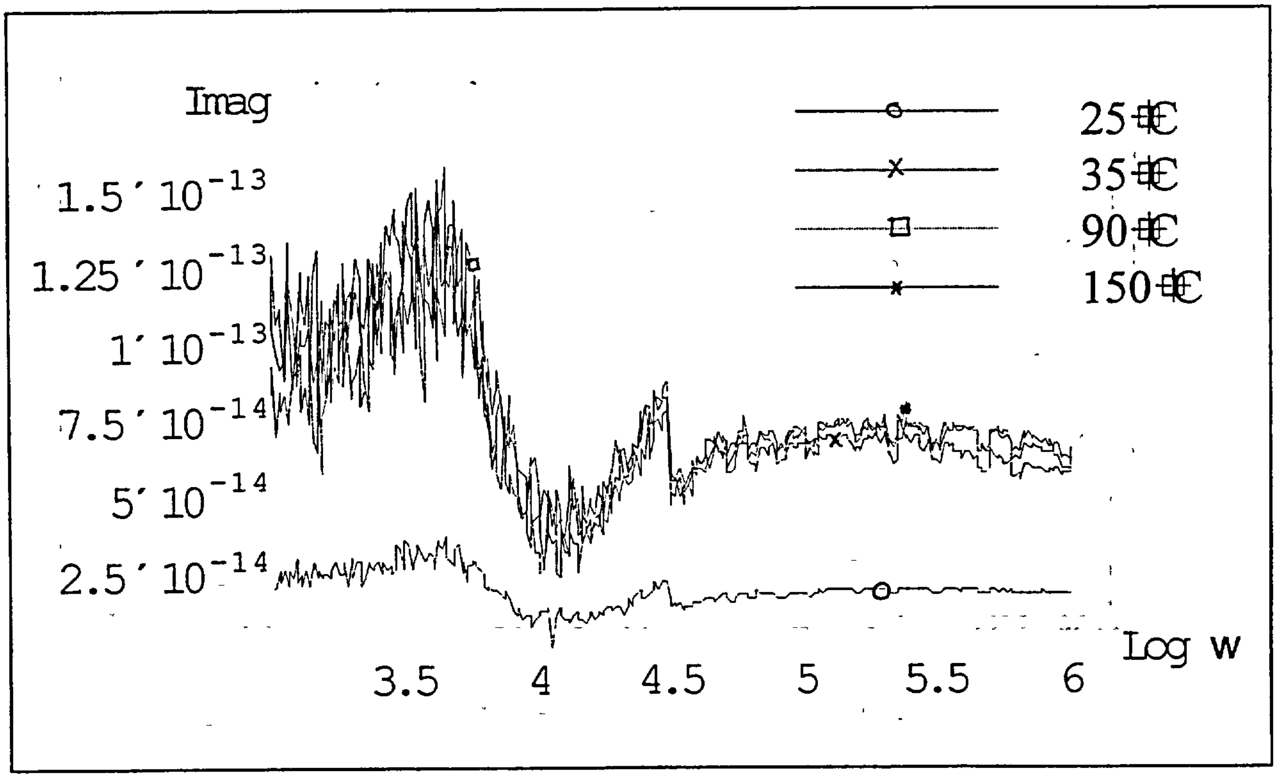


Figure (2.2.2): Depicts $\varepsilon_2(\omega)$ the selected temperature in the frequency range for 100Hz to 1MHz.

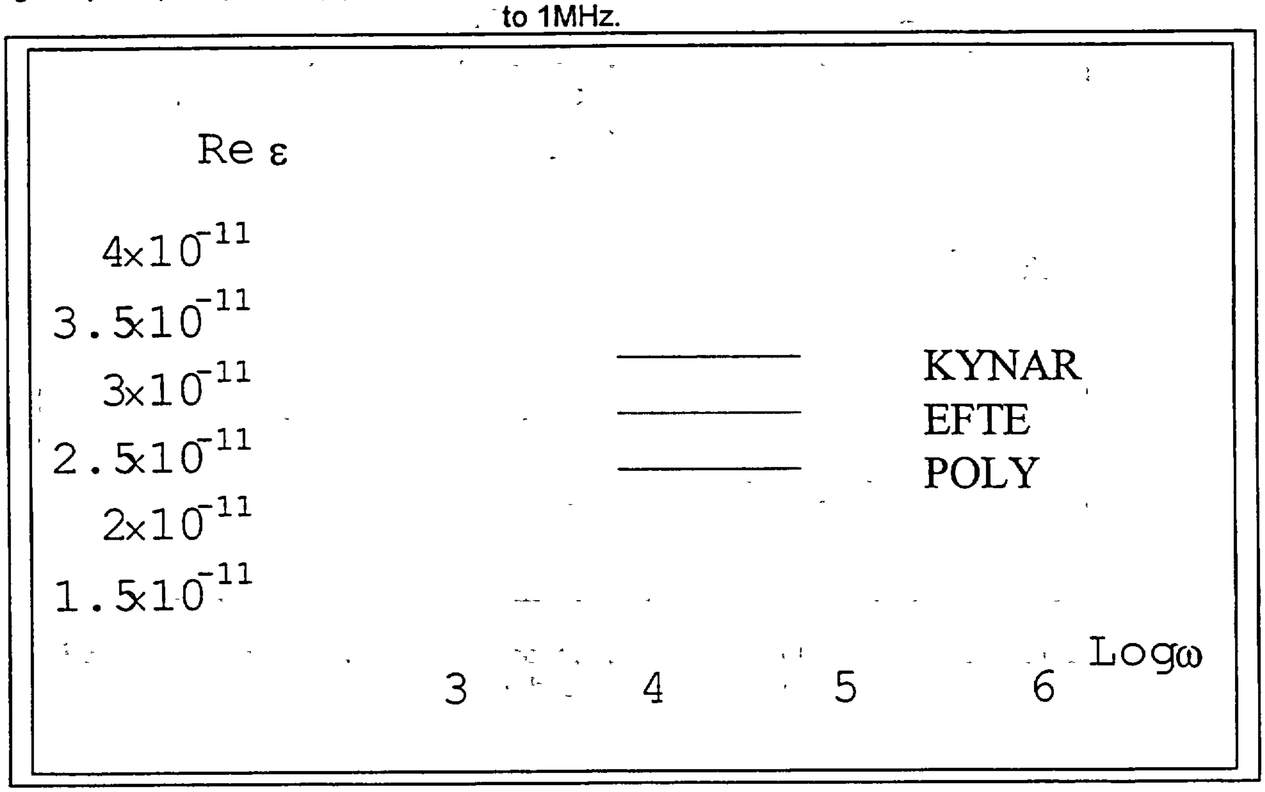


Figure (2.2.3): Compares $\varepsilon_1(\omega)$ for KYNAR, ETFE and POLY.

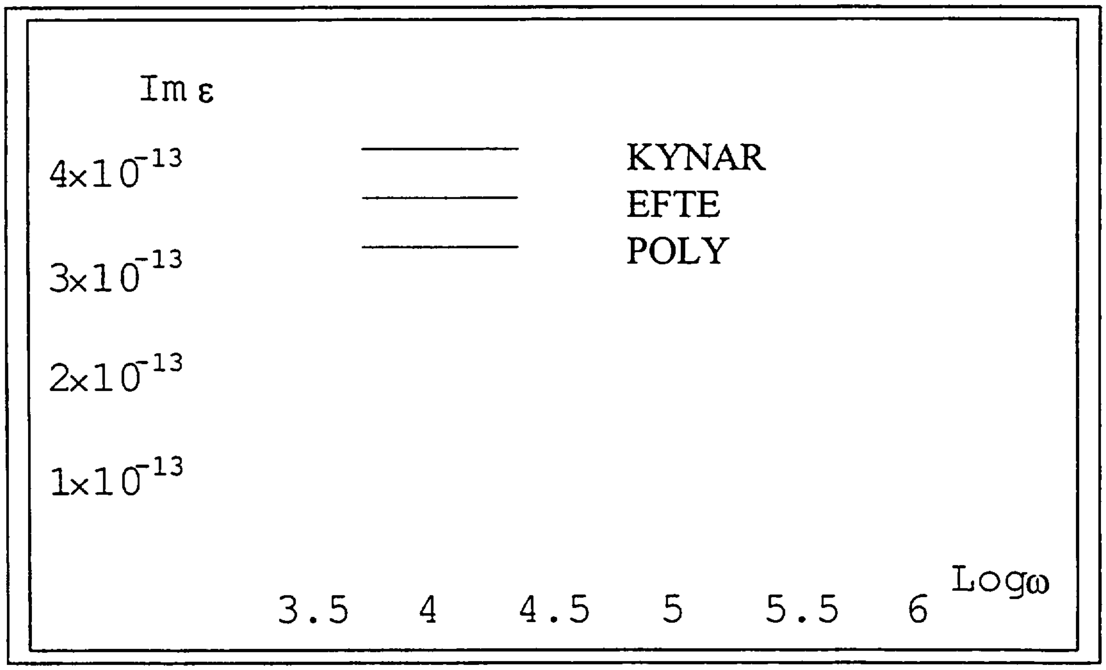


Figure (2.2.4): Compares $\varepsilon_2(\omega)$ for KYNAR, ETFE and POLY.

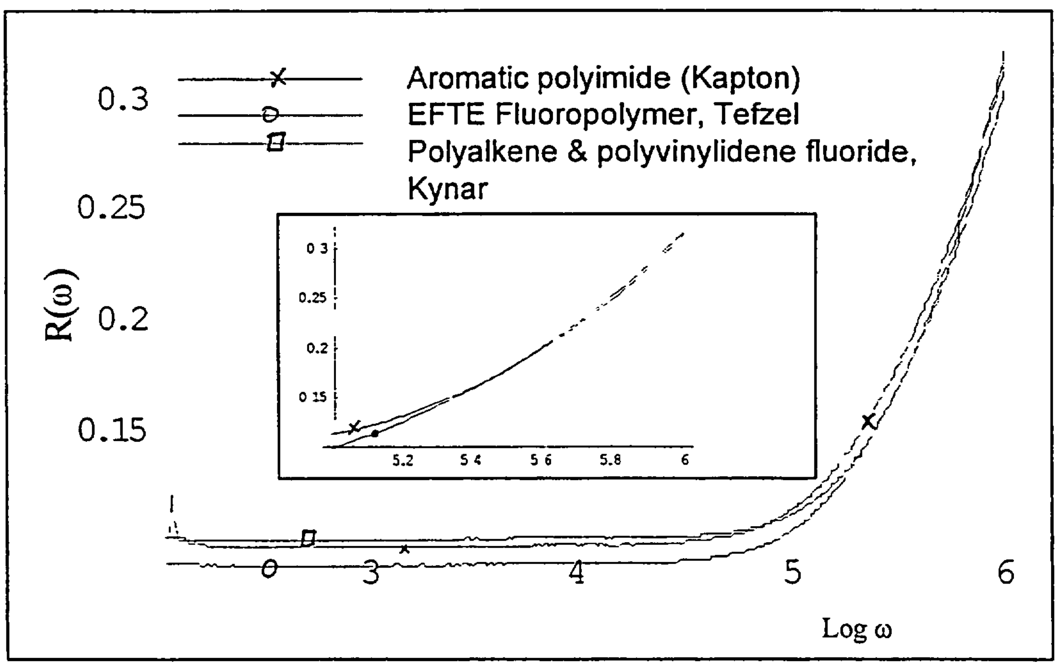


Figure (2.2.5): Depicts the frequency dependence of the wire resistance. Here POLY (blue), EFTE (red) and (KYNAR) (green).

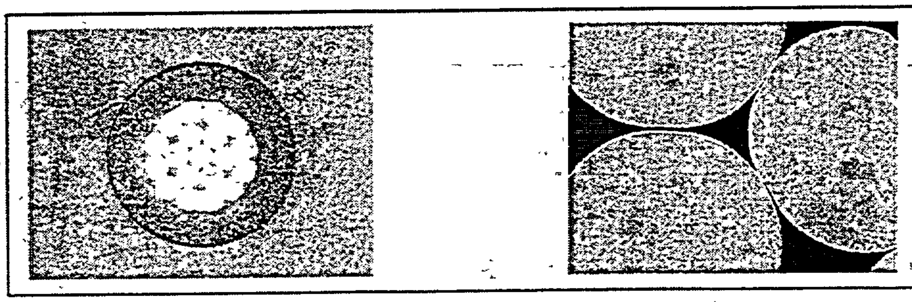


Figure (2.2.6) EFTE, FLOUROPOLYMER TEFZEL (MIL-22759/43-22-9)

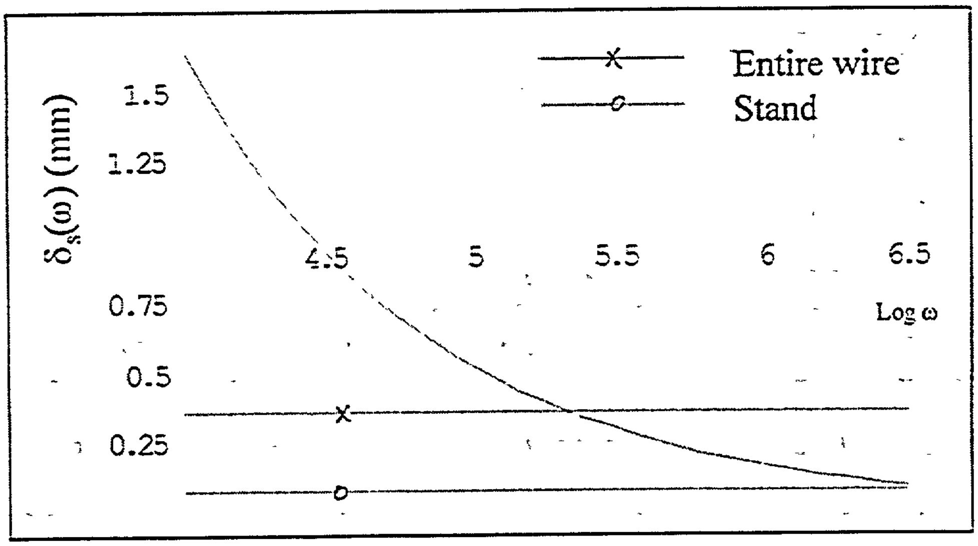


Figure (2.2.7) Skin depth of Cu wire.

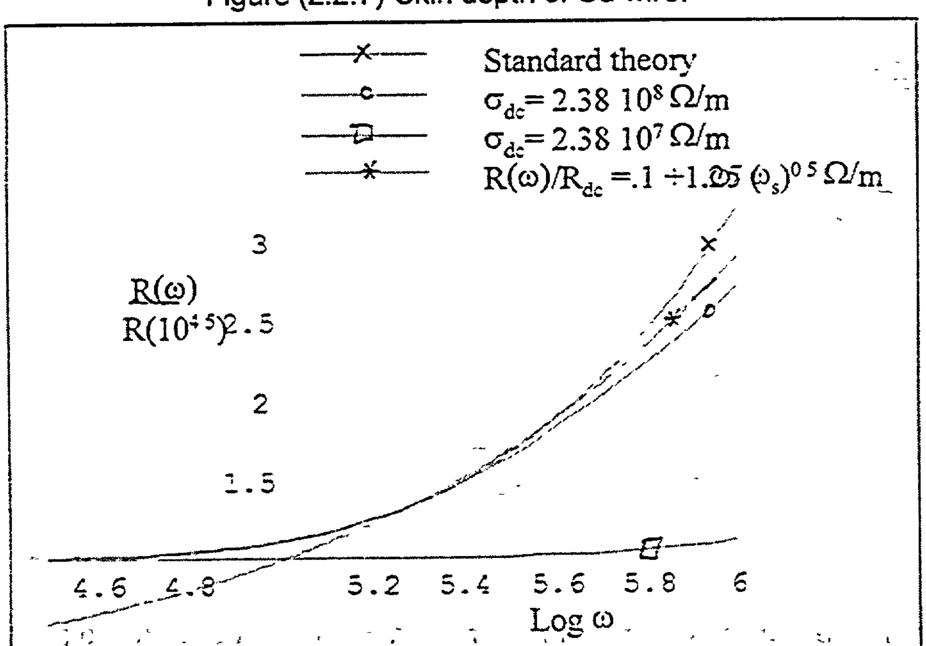


Figure (2.2.8) Comparison of measured resistance to classical skin effect.

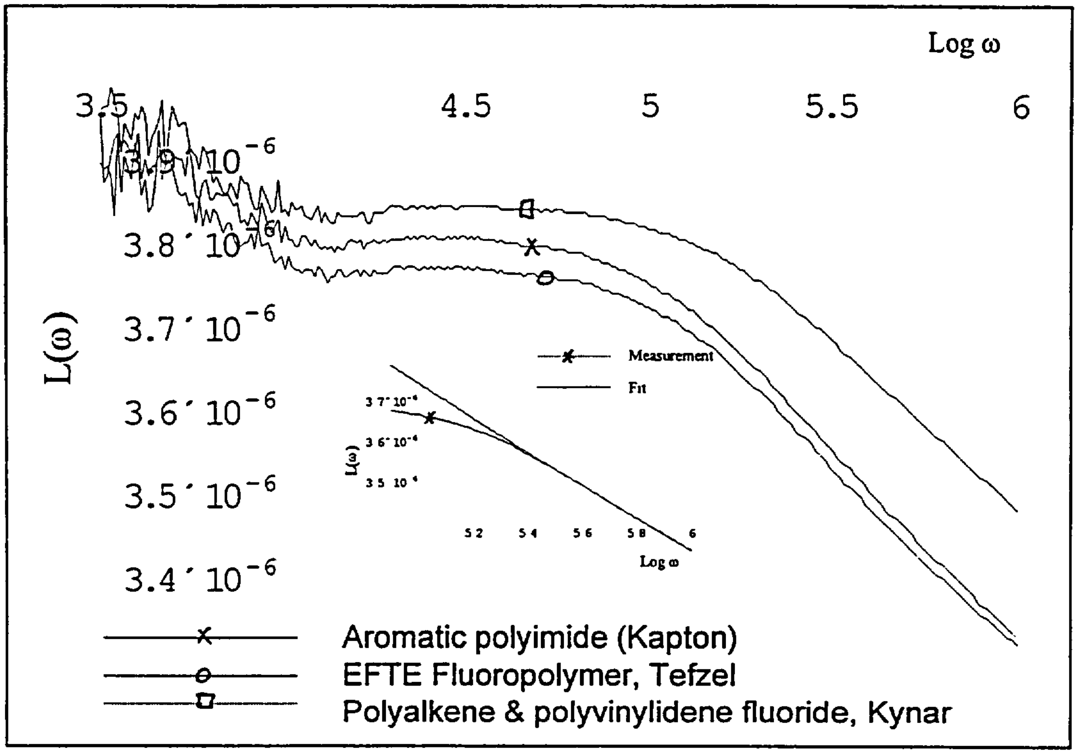


Figure (2.3.1): Depicts the frequency dependence of the wire inductance

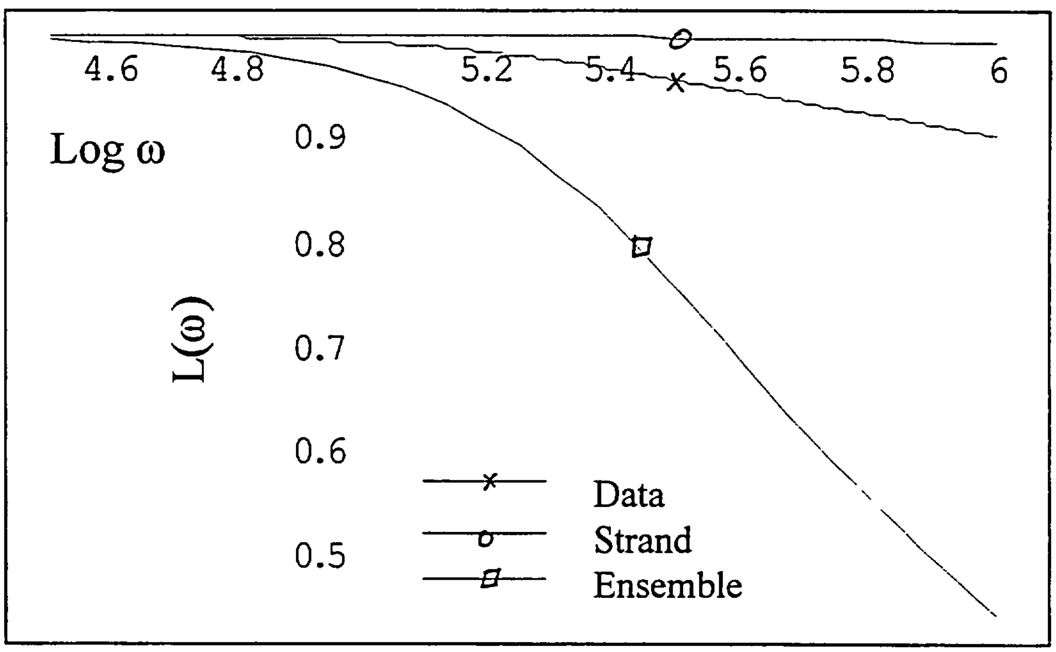


Figure (2.3.2): The comparison of the measured inductance (blue) with two predictions of the classical skin effect for a single strand (strand) and the entire ensemble (green).

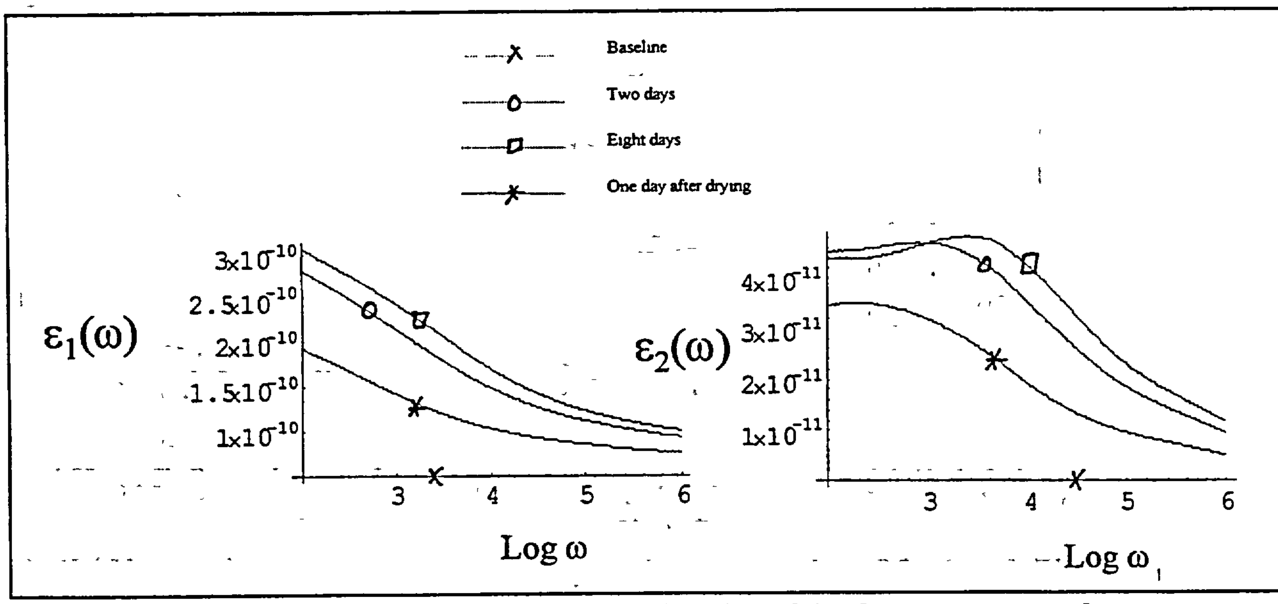


Figure (3.1.1): Depicts POLY's dielectric function of the frequency range from 100Hz to 1 MHz.

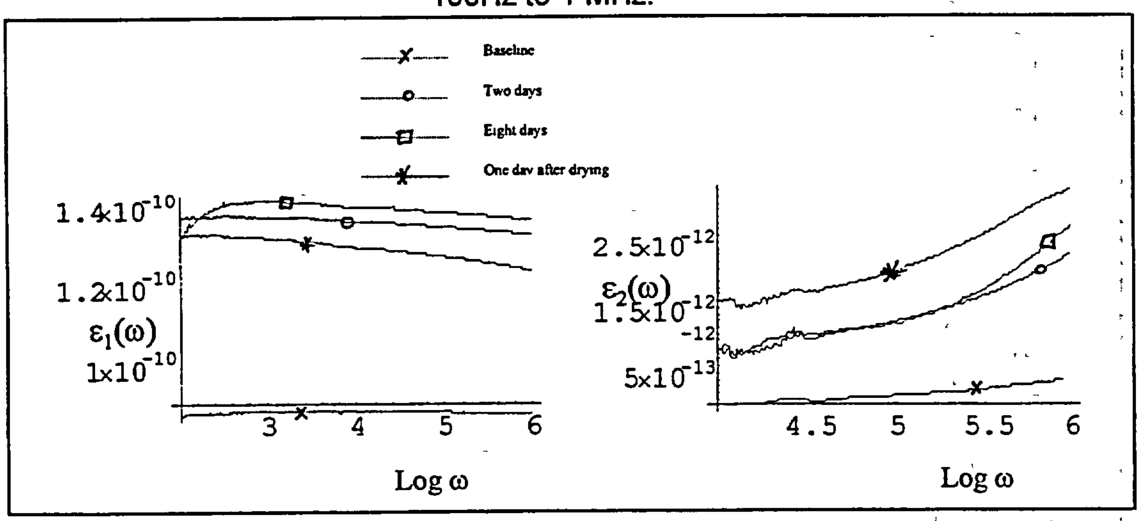


Figure (3.1.2): Depicts EFTE Fluoropolymer, EFTE's dielectric function of the frequency range from 100Hz to 1 MHz.

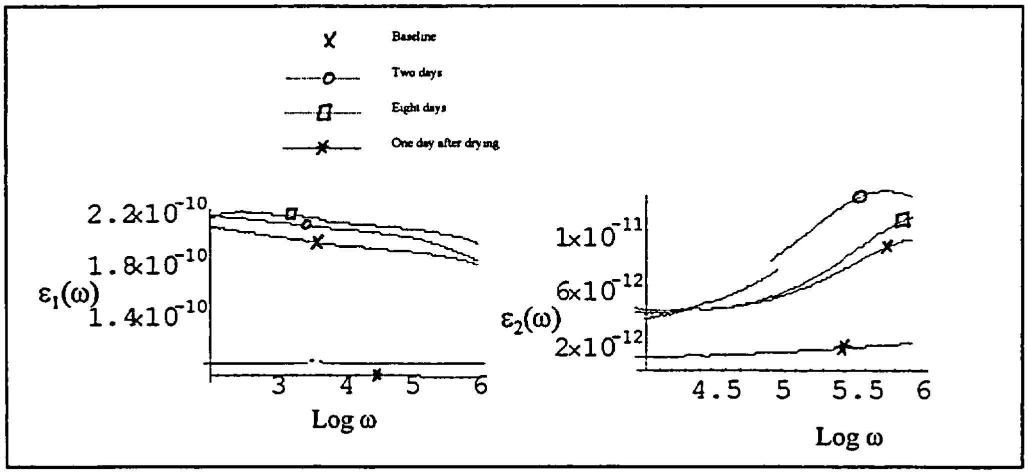


Figure (3.1.3): Depicts Polyalkene & polyvinylidene fluoride, KYNAR's dielectric function of the frequency range from 100Hz to 1 MHz.

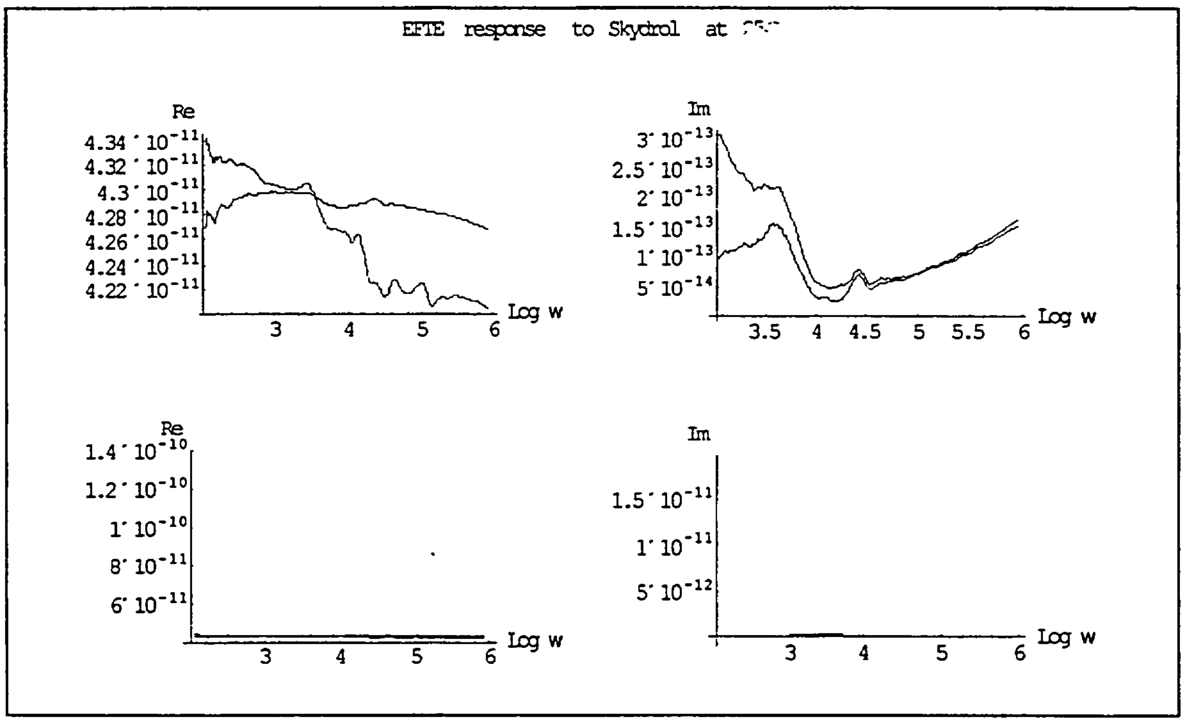


Figure (3.1.4): Compares the response of EFTE dielectric function at T = 25°C for baseline, immersion in Skydrol and after cleaning.

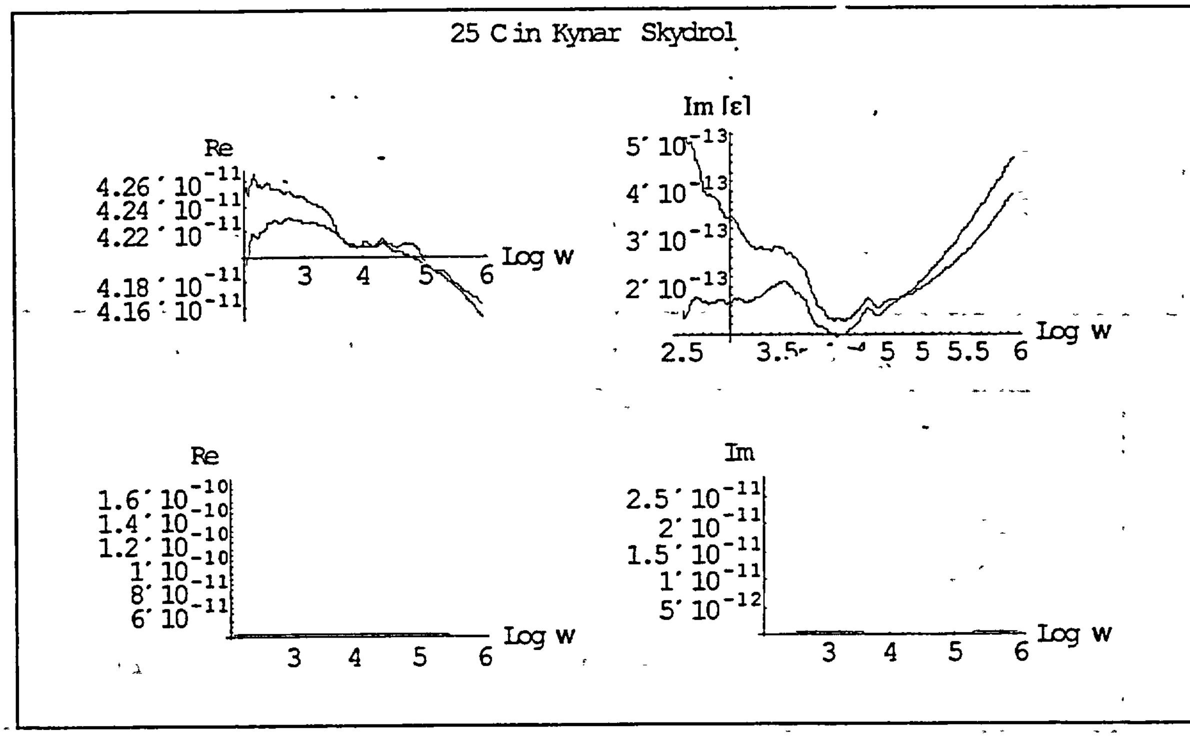


Figure (3.1.5): Compares the response of KYNAR's dielectric function at T = 25°C for baseline, immersion in Skydrol and after cleaning.

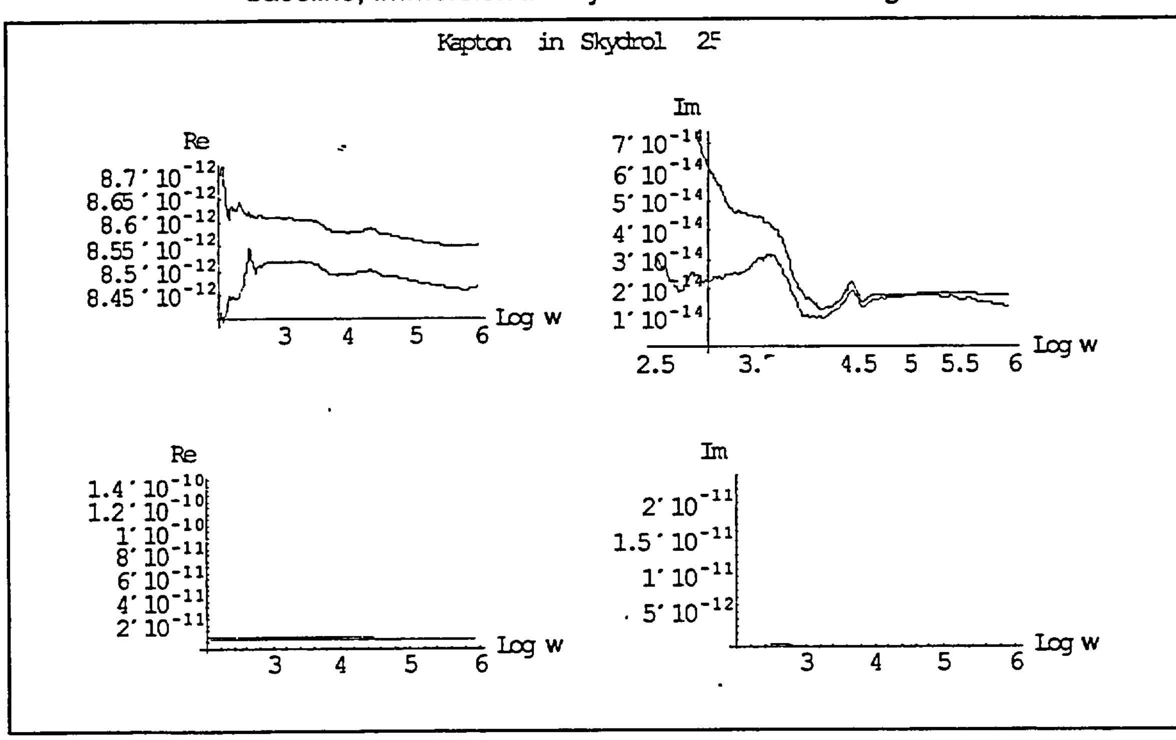


Figure (3.1.6): Compares the response of POLY's dielectric function at T = 25°C for baseline, immersion in Skydrol and after cleaning.

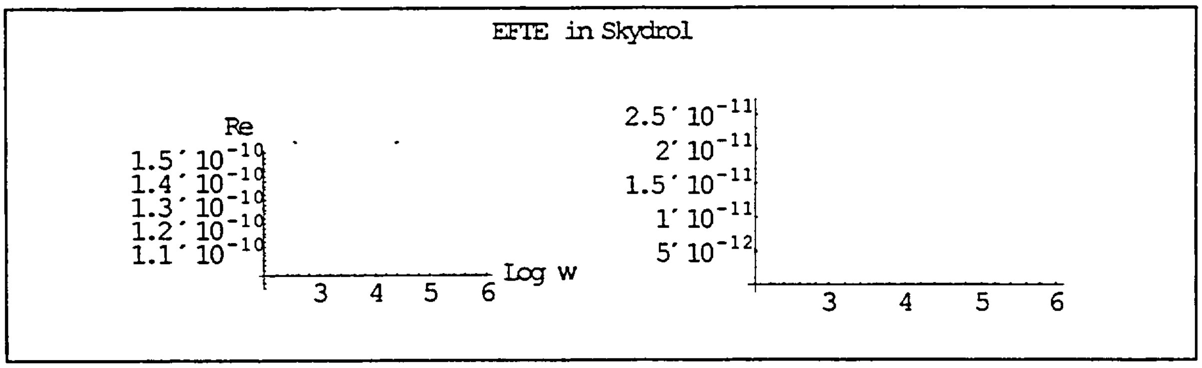


Figure (3.1.7): Compares the response of EFTE's dielectric function.

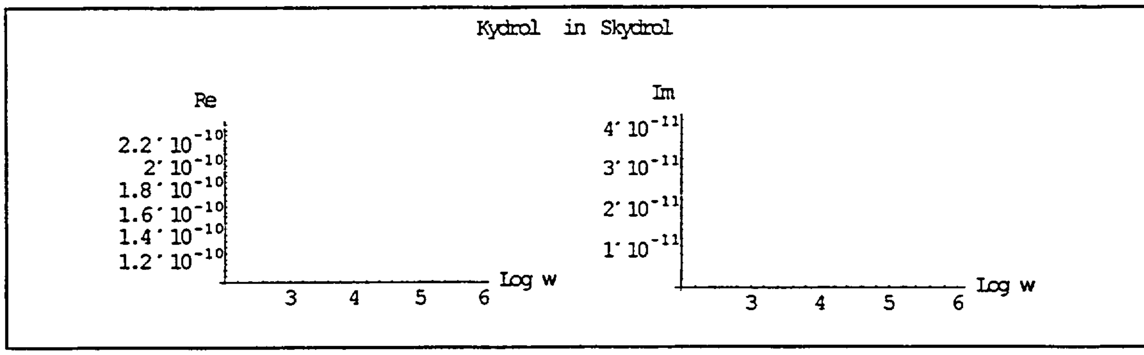


Figure (3.1.8a): Compares the response of KYNAR's dielectric function.

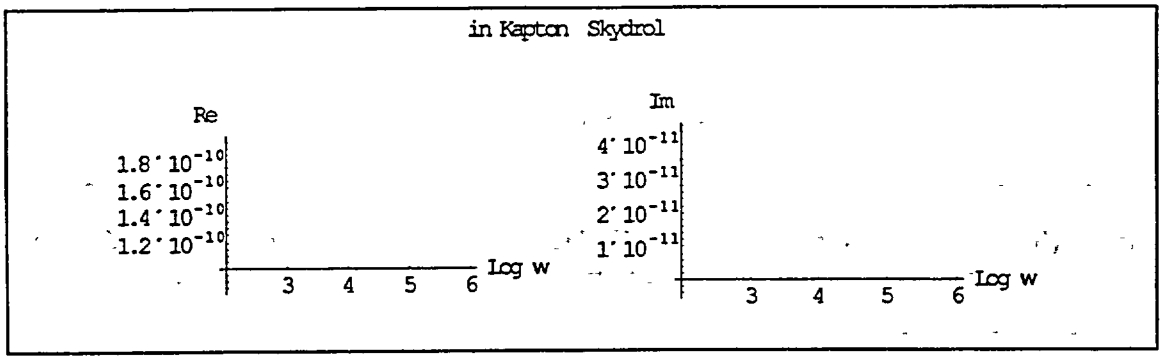


Figure (3.1.8b): Compares the response of POLY's dielectric function.

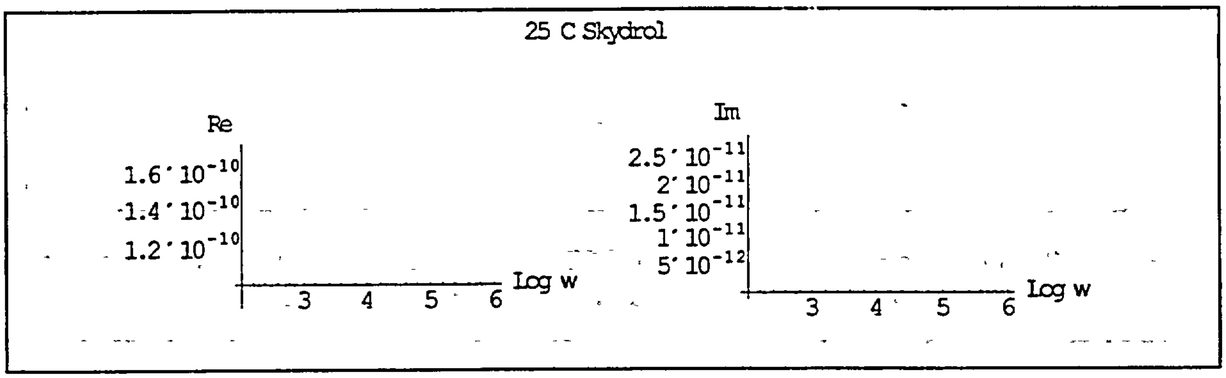


Figure (3.1.9): Comparison of $\varepsilon(\omega)$ for EFTE (green), KYNAR (blue) and POLY (red) wiring immersed in Skydrol maintained at a temperature of 25°C

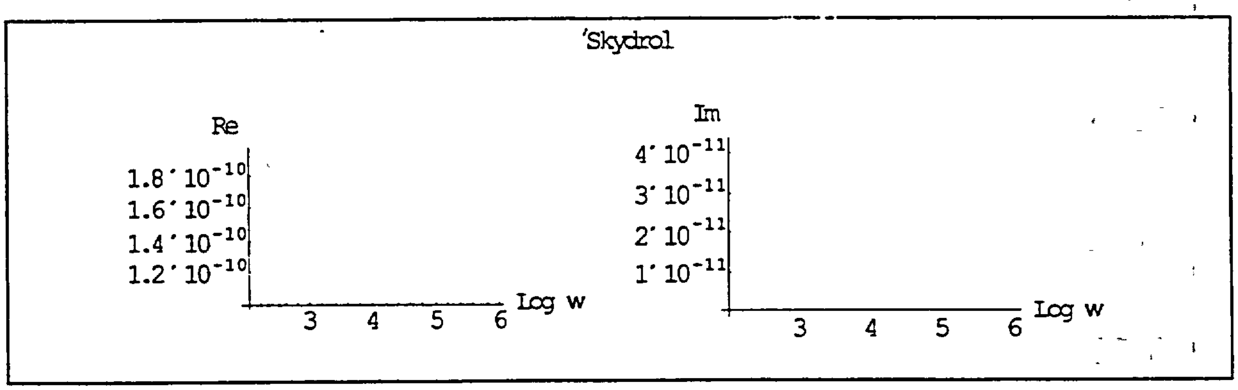


Figure (3.1.10): Comparison of $\varepsilon(\omega)$ for EFTE (green), KYNAR (blue) and POLY (red) wiring immersed in Skydrol maintained at a temperature of 35°C

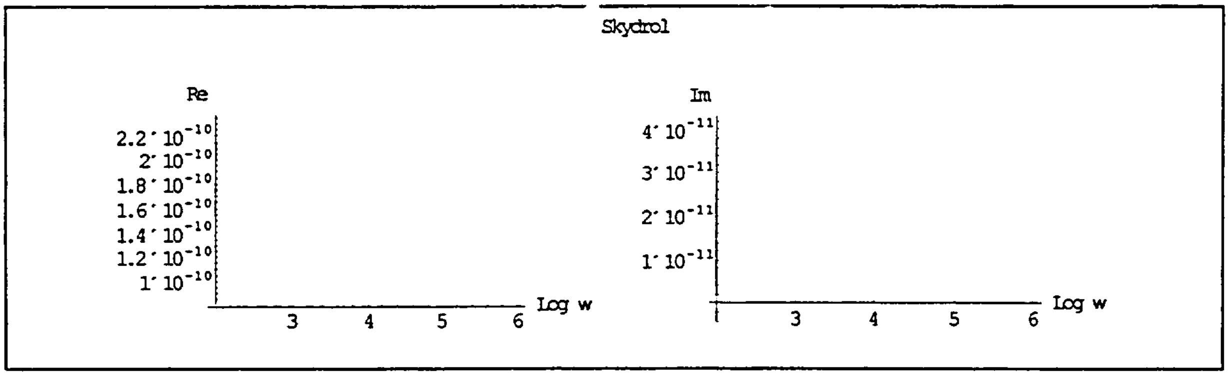


Figure (3.1.11): Comparison of ε(ω) for EFTE (green), KYNAR (blue) and POLY (red) wiring immersed in Skydrol maintained at a temperature of 90°C.

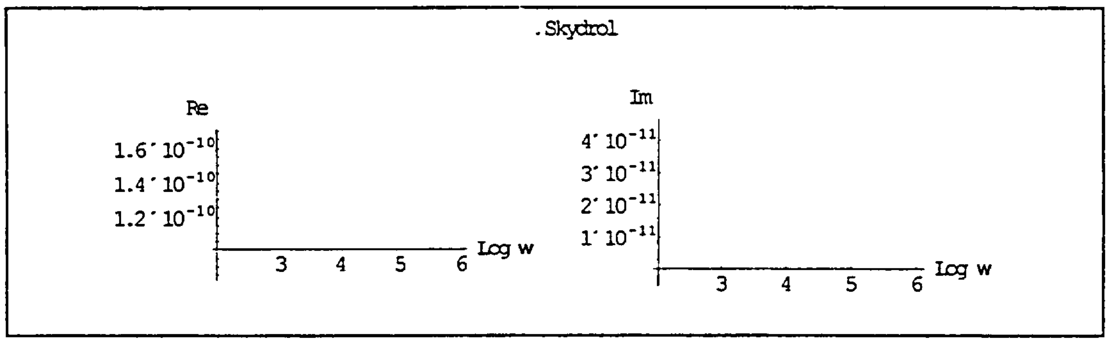


Figure (3.1.12): Comparison of ε(ω) for EFTE (green) and POLY (red) wiring immersed in Skydrol maintained at a temperature of 150°C,

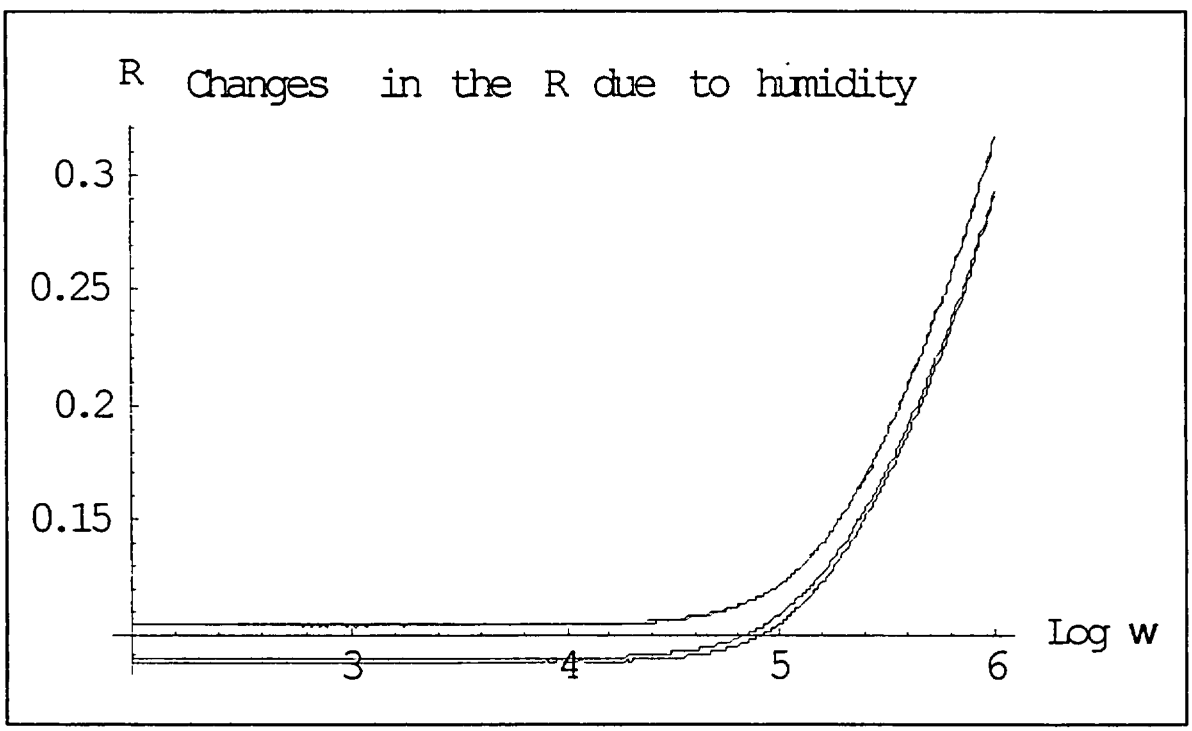


Figure (3.2.1): Compares the resistance of EFTE wiring exposures to controlled humidity. Here baseline (black), two days at 85°F/85% of humidity (green), same a week (red) and have dried out (blue).

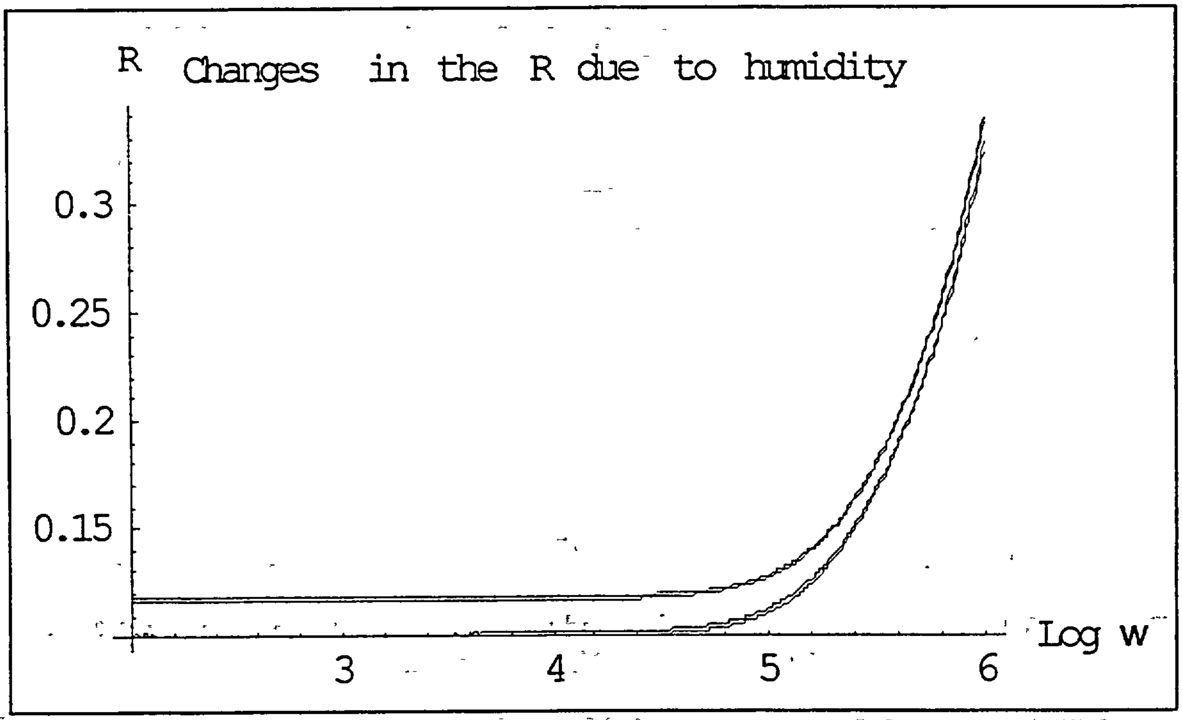


Figure (3.2.2): Compares the resistance of KYNAR wiring exposures to controlled humidity. Here baseline (black), two days at 85°F/85% of humidity (green), same a week (red) and have dried out (blue).

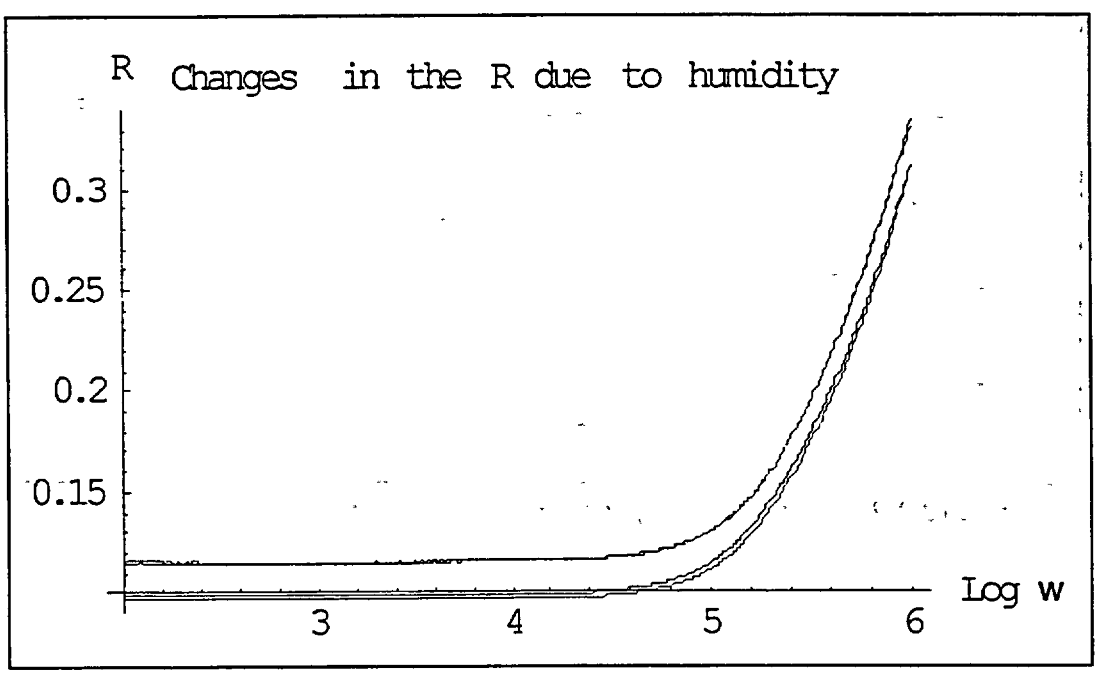


Figure (3.2.3): Compares the resistance of POLY wiring exposures to controlled humidity. Here baseline (black), two days at 85°F/85% of humidity (green), same a week (red) and have dried out (blue).

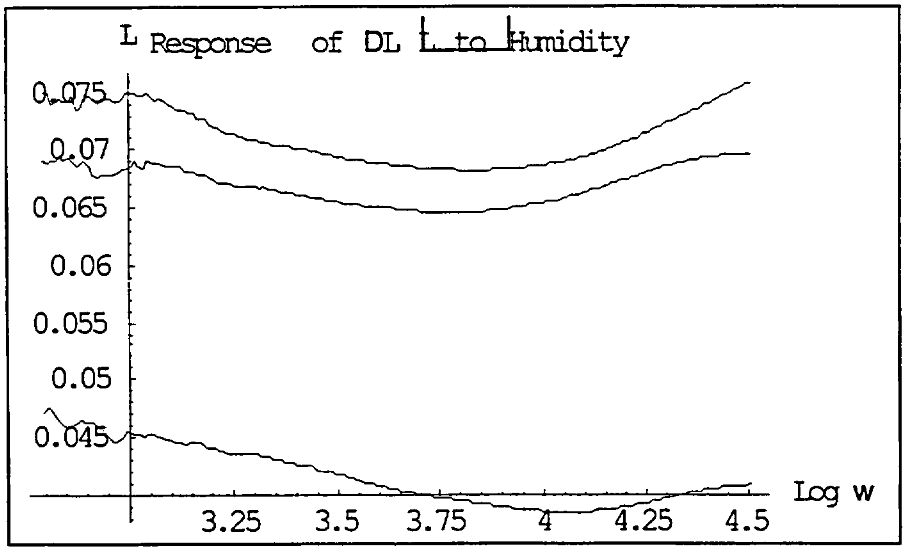


Figure (3.3.1): Depicts the response of the inductance to humidity (85°F/85). Here green is EFTE, blue is KYNAR and red is POLY

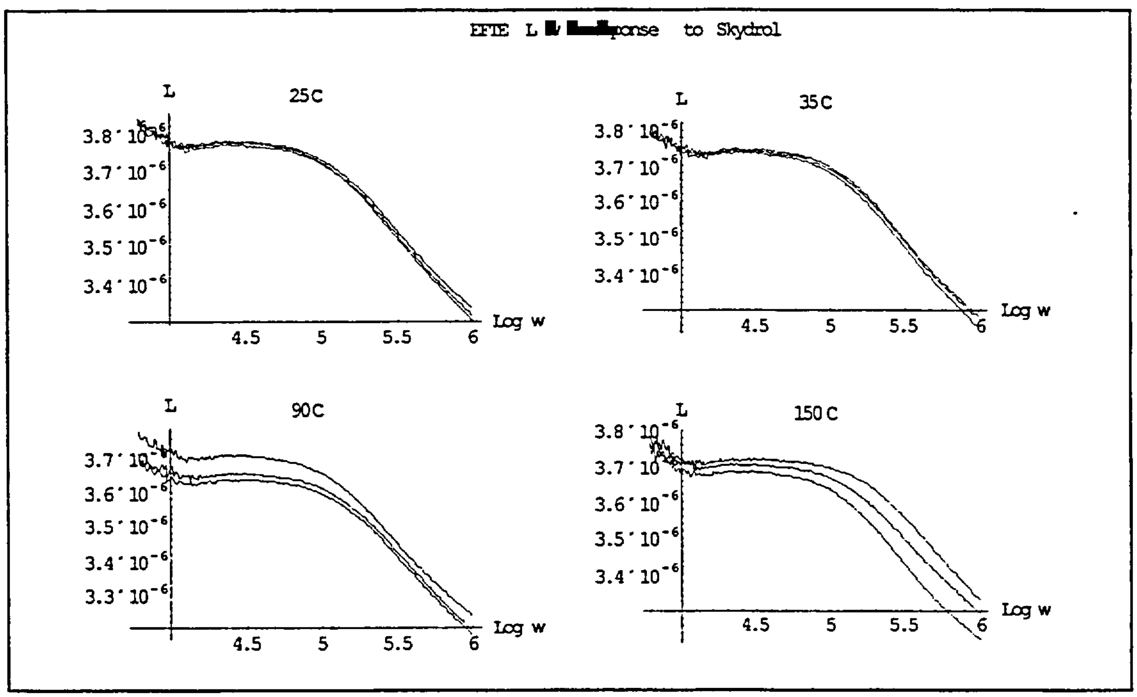


Figure (3.3.2): Depicts the response of the EFTE's inductance to Skydrol.

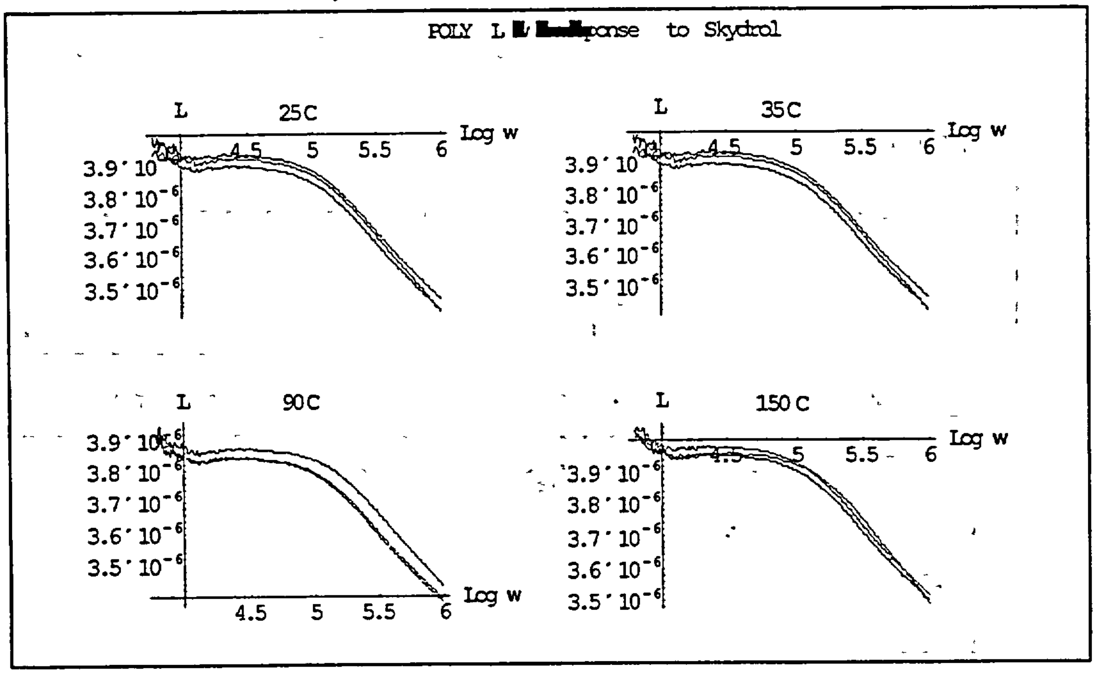


Figure (3.3.3): Depicts the response of the KYNAR's inductance to Skydrol.

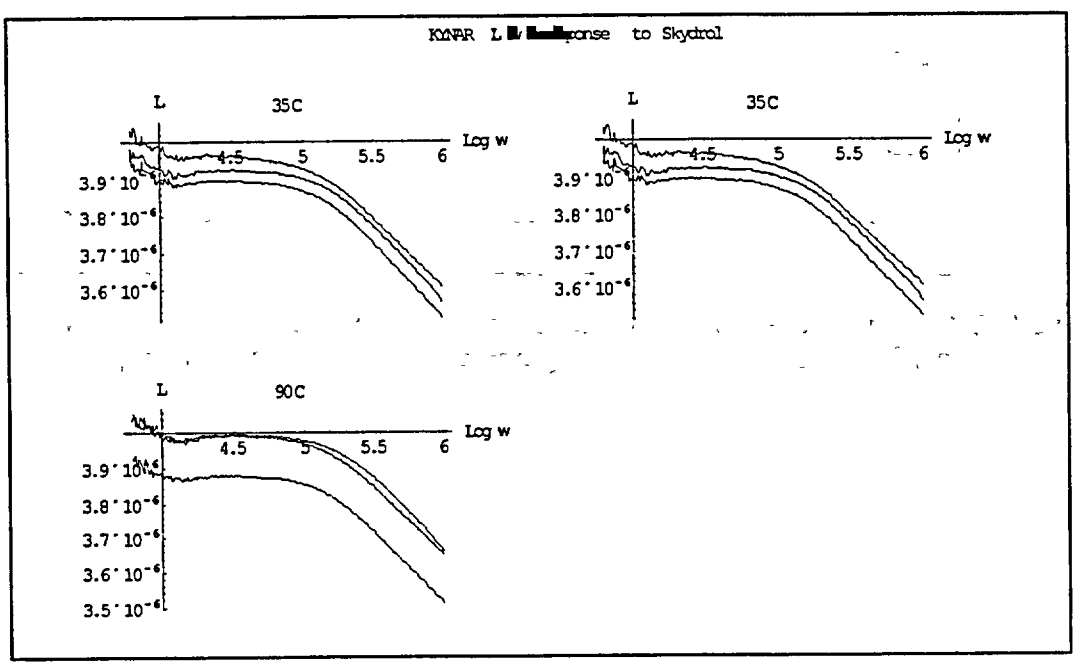


Figure (3.3.4): Depicts the response of the POLY's inductance to Skydrol.

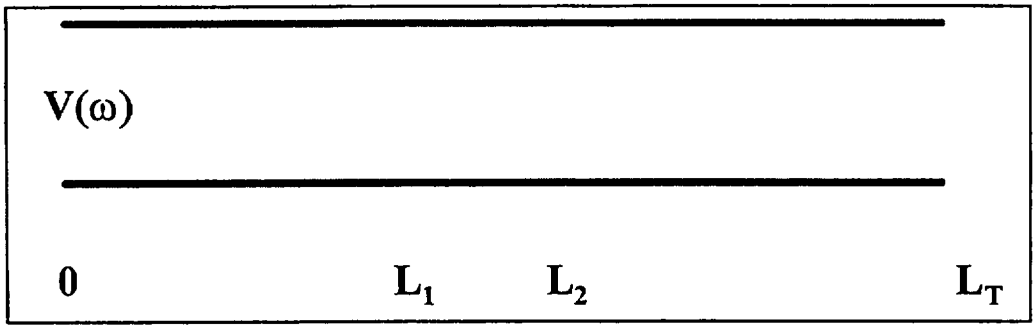


Figure (4.1.1): Depicts the model for a degraded transmission line.

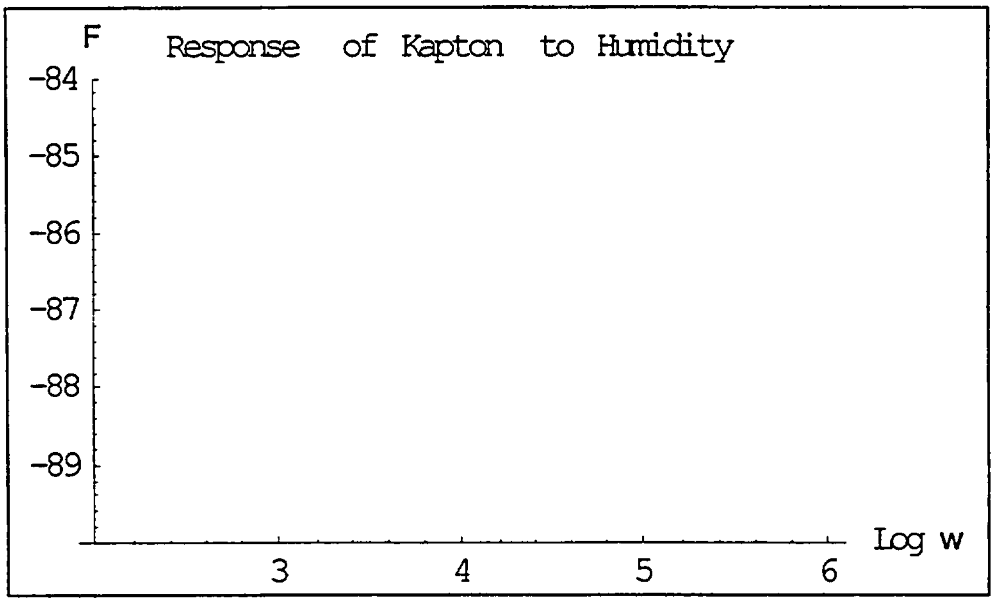


Figure (4.2.1): Simulations of the magnitude phase impedance spectra of POLY in which a different amount of the wiring has been degraded by humidity.

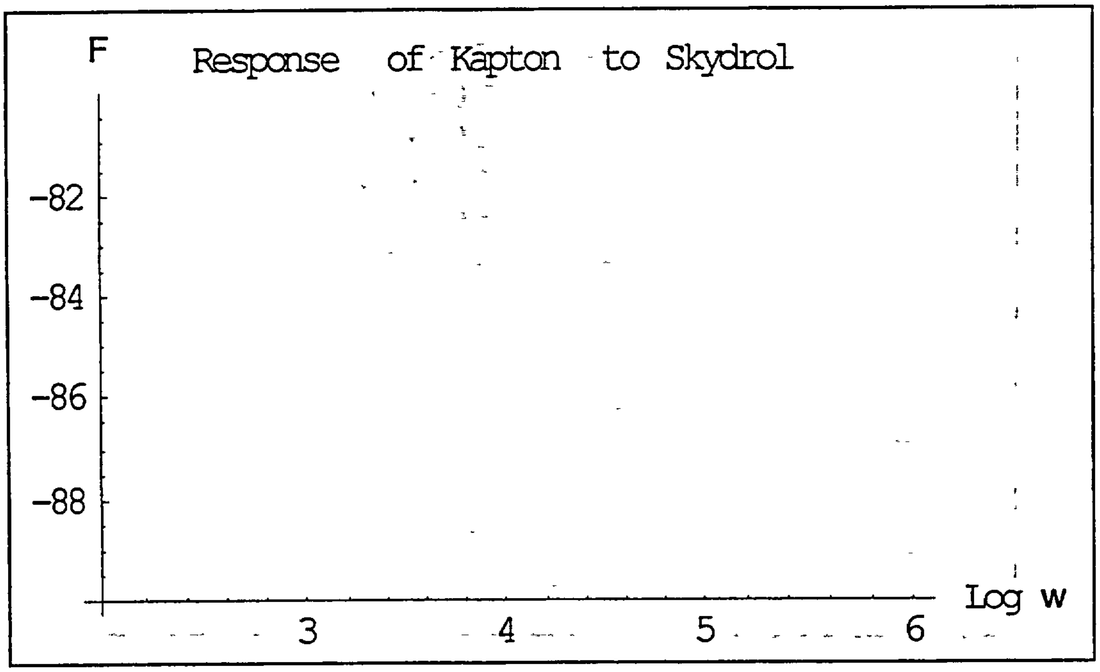


Figure (4.2.2): Simulations of the magnitude phase impedance spectra of POLY in which a different amount of the wiring has been degraded by Skydrol.

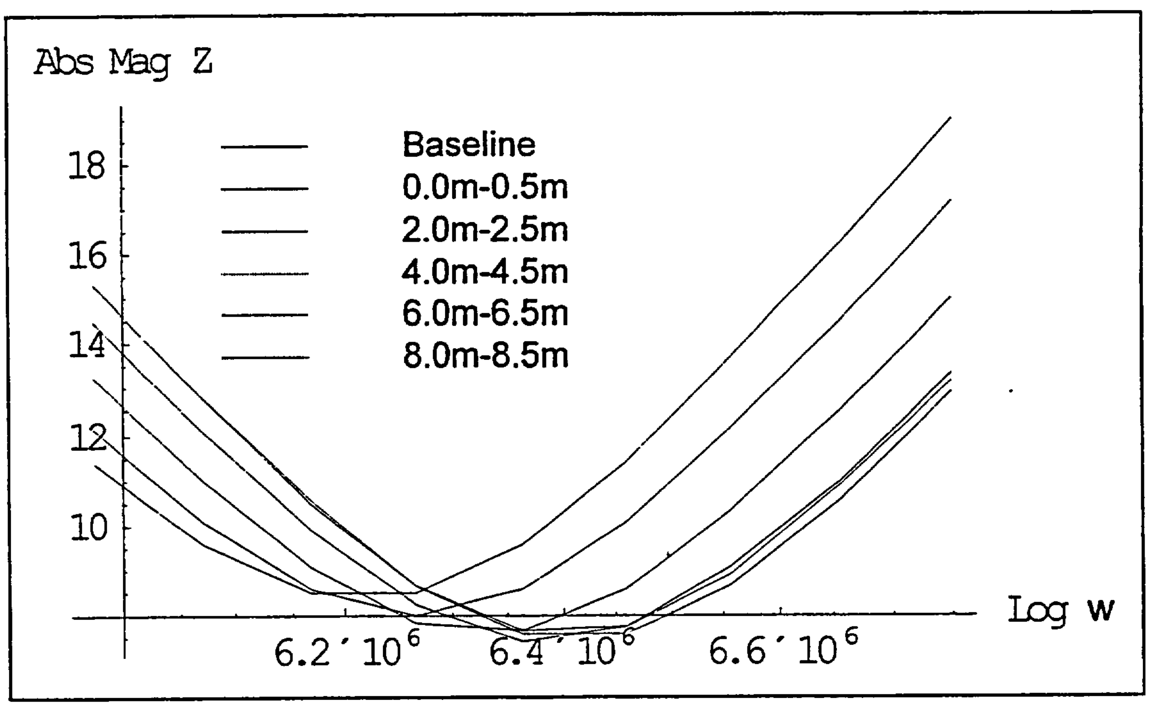


Figure (4.3.1): Simulations of a portion of the high frequency magnitude impedance spectra of POLY in which a 0.5m segment of the wire has been degraded. The location of the damage effects the position of minimum of |Z(ω)|.

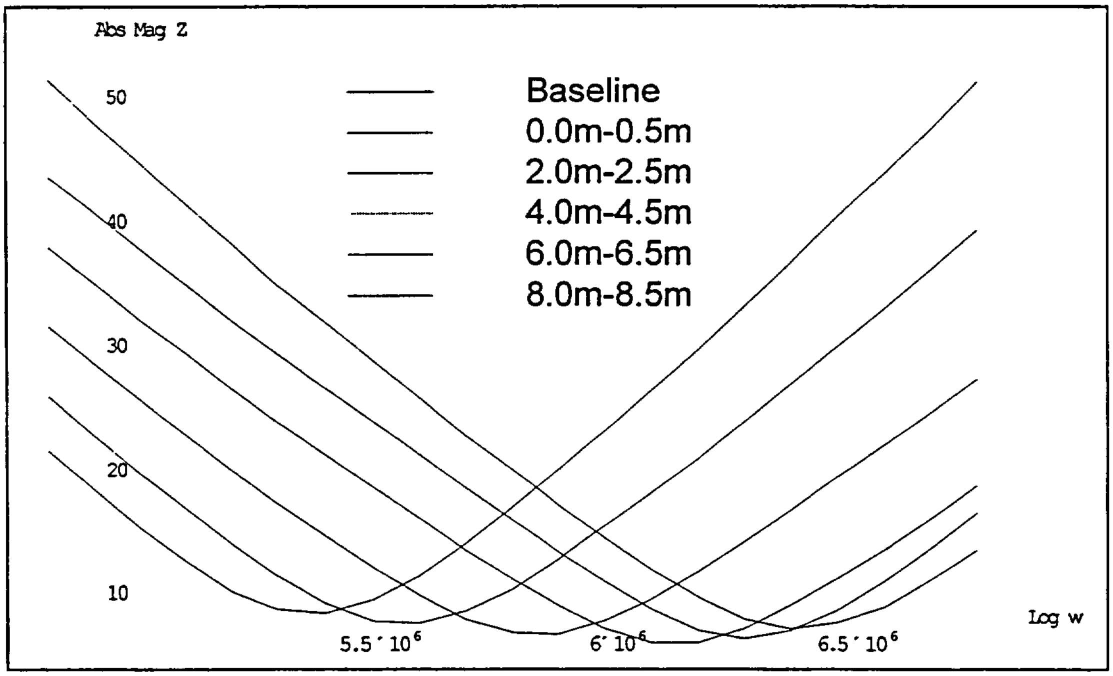


Figure (4.3.2): Simulations of a portion of the high frequency amplitude impedance spectra of POLY in which a 0.5m segment of the wire has been degraded by Skydrol. The location of the damage effects the position of minimum of $|Z(\omega)|$.

Assessing Cable and Wire Condition Using the Excited Dielectric Test Method

Greg Allan, Rollin Van Alstine
CM Technologies Corporation

CM Technologies...

- **Manufacture instrumentation for determining electrical characteristics of installed wiring and cable systems**
  - **Time Domain Reflectometry (TDR), Impedance, Insulation Resistance**
- **Provide testing services to the nuclear industry and military**
  - **Condition Assessments**
  - **Troubleshooting**

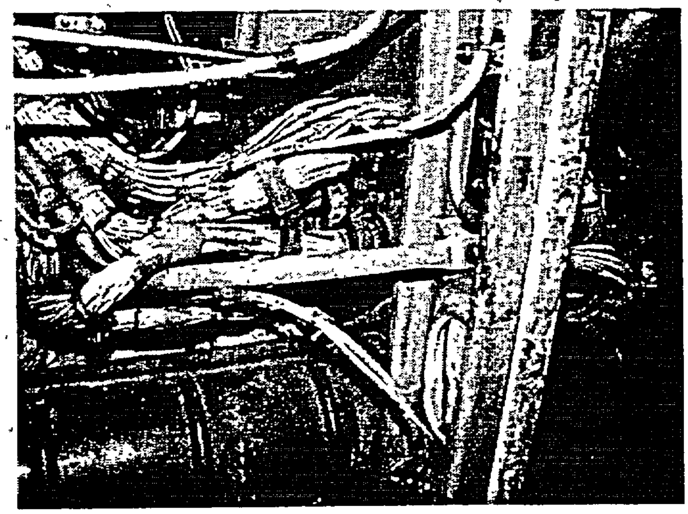
EDT Overview

- **New technology**
  - Funded through an FAA BAA
  - Combination of TDR and Dissipation Factor
- **Benefits include:**
  - Detect and locate defects which are not visible
  - Non-destructive
  - Wire condition can be determined through a single set of tests (no baseline)
  - Can also determine the condition of other wiring system components (e.g., connectors, splices)

Project Overview

- **Significant Tasks**
  - Gain consensus among industry and the military regarding wiring defects
  - Evaluate commercially available instrumentation
  - Condition wire samples
    - Polyimide (Kapton™)
    - Cross-linked ETFE (Tefzel™)
  - Field testing
  - Validation of test method

Challenge



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Theoretical Overview

- Wire/cable modeled as an RF transmission line
  - Focus on insulation
  - Modeled as a parallel RC circuit
- Physics of a capacitor
  - Capacitors store charge
  - At some low frequency, dielectric dipoles can rotate with the applied electric field
    - The quality of the capacitor is very poor at this frequency
  - Dissipation factor is a measure of "capacitor quality" or wire insulation quality

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Theoretical Overview

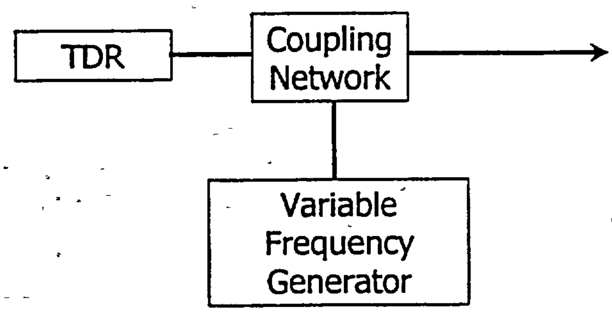
- An increase or decrease in capacitance (or dissipation factor) result in a corresponding change in impedance
- Time Domain Reflectometry (TDR) Basics
  - Voltage pulse is injected into the wire
  - Reflections occur as the voltage pulse encounters impedance discontinuities
  - Reflections are captured vs. time

Theoretical Overview

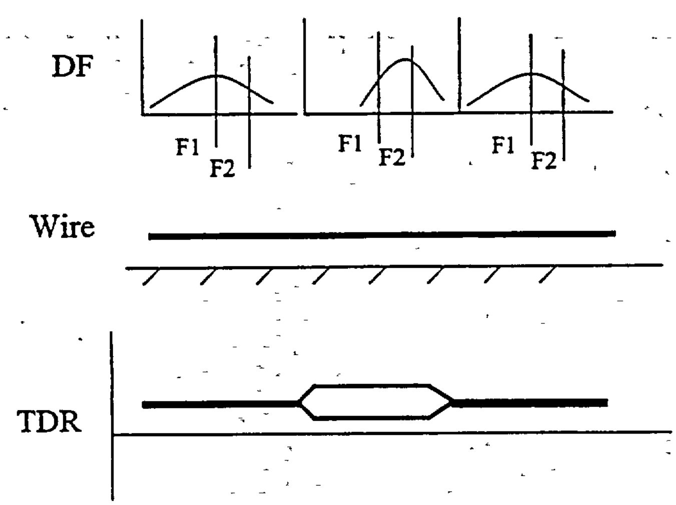
  - The reflected voltage waveform represents the distributed impedance of the wire
- EDT combines TDR and Dissipation Factor theory in a single test

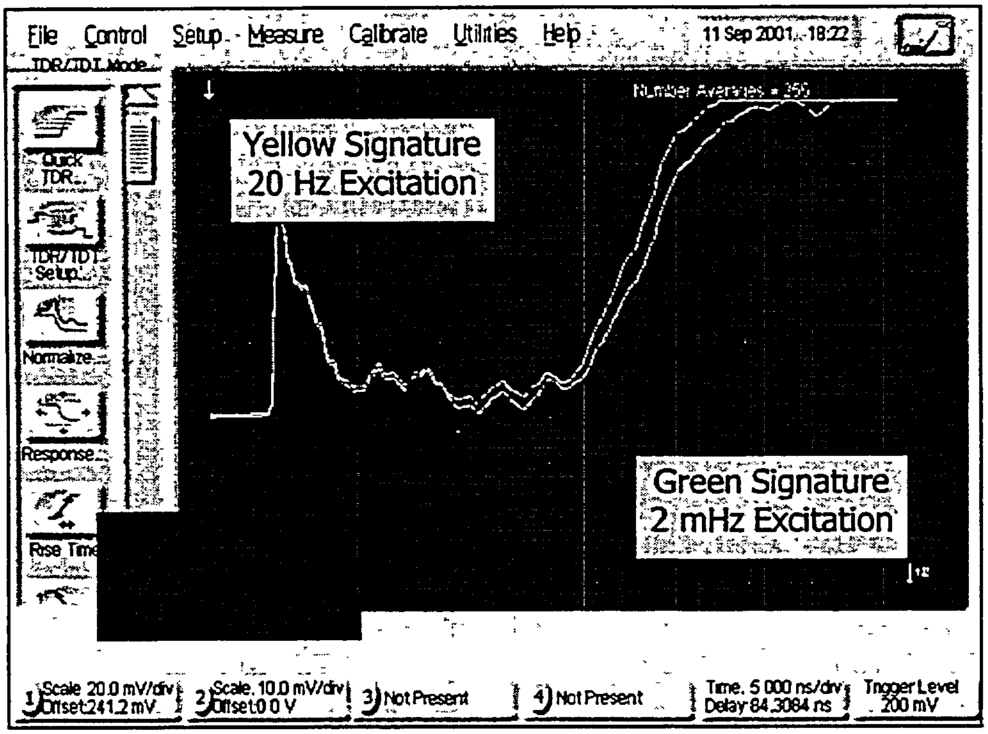
Hardware Configuration

- **TDR and forcing function applied simultaneously**



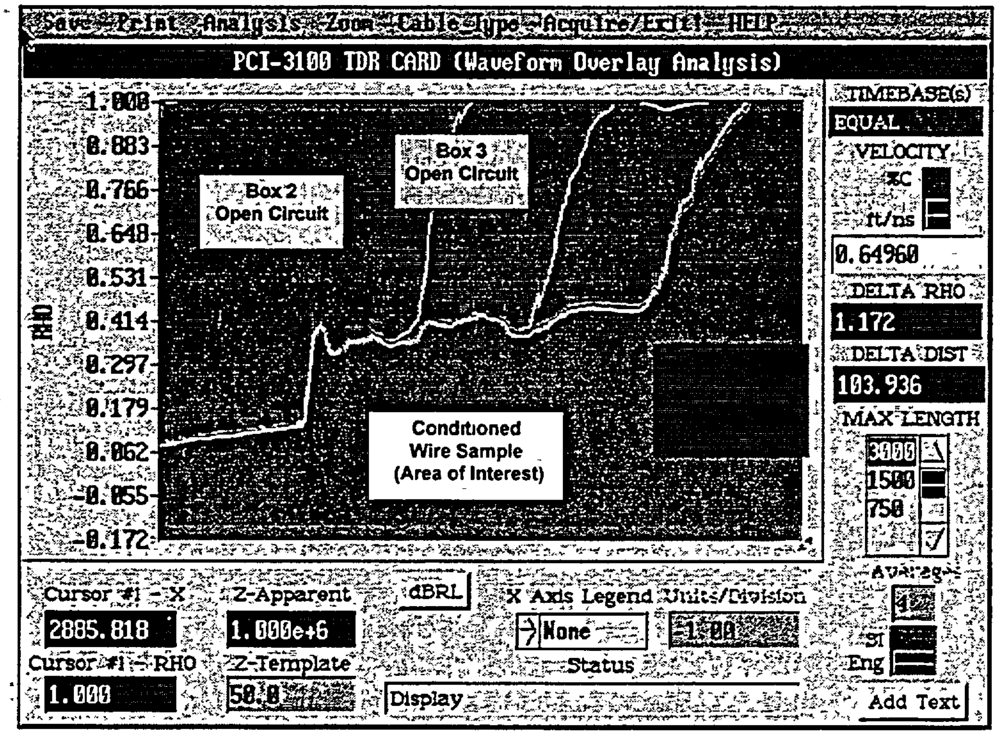
Theoretical Overview

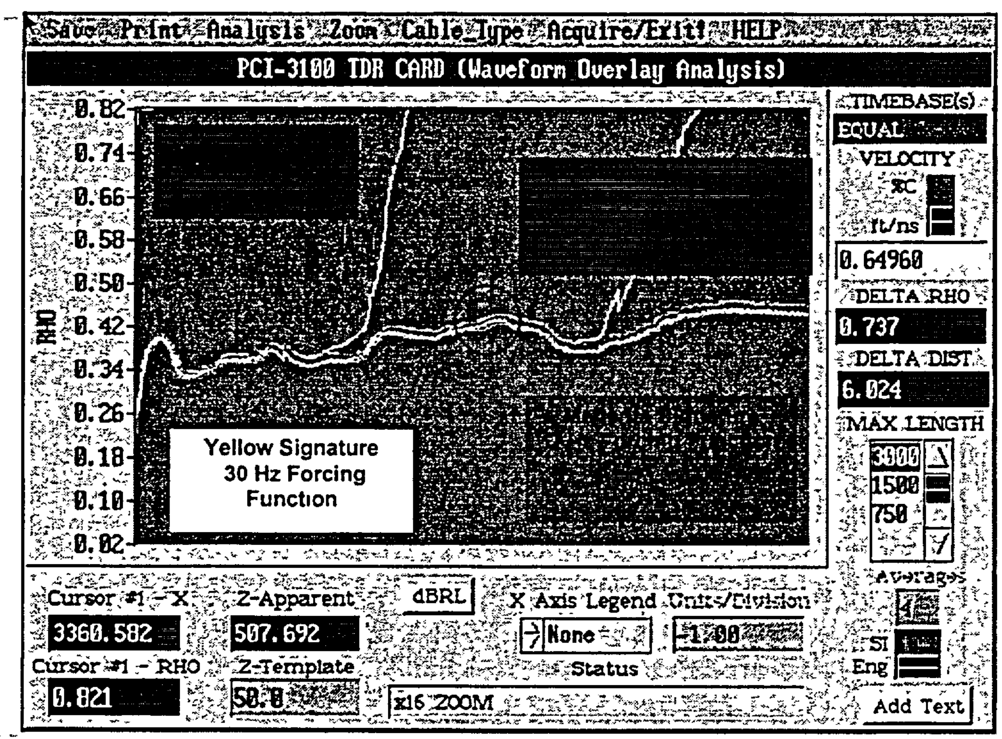


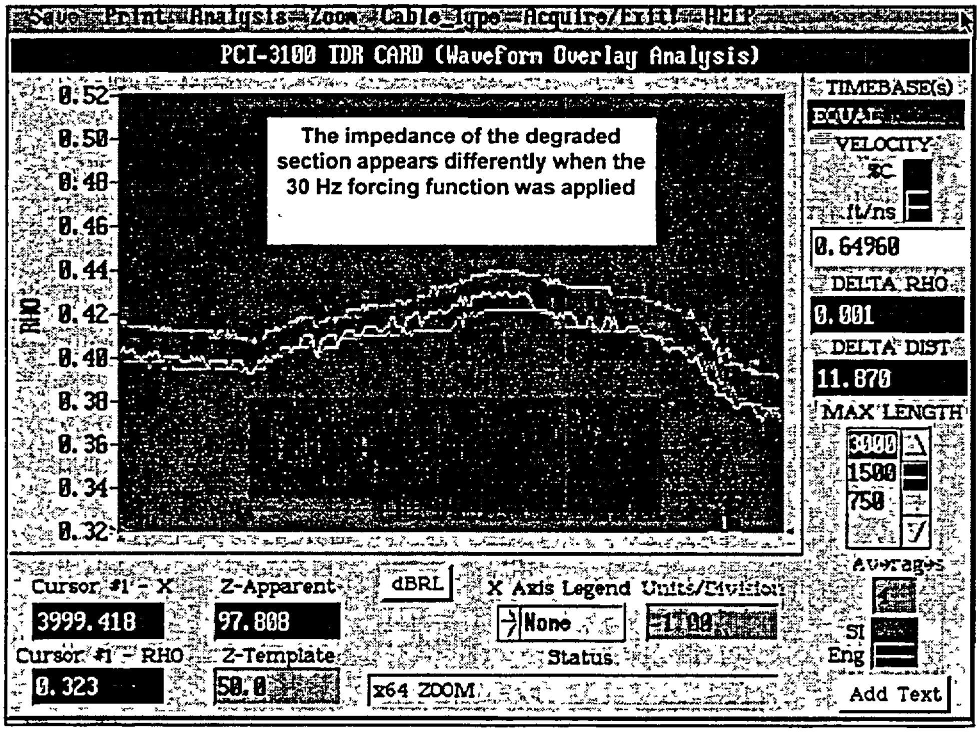


Testing Matrix

ONDITIONS	XCITATIO REQUENC	XCITATIO OLTAGE	XCITATIO WAVEFORI TYPES


Save Print Analysis Zoom Cable Type Acquire/Exit! HELP
PCI-3100 TDR CARD (Waveform Overlay Analysis)
RHO
1.000
0.883
0.766
0.648
0.531
0.414
0.297
0.179
0.062
-0.055
-0.172
Box 2
Open Circuit
Box 3
Open Circuit
Conditioned
Wire Sample
(Area of Interest)
TIMEBASE(s)
EQUAL
VELOCITY
%C
ft/ns
0.64960
DELTA RHO
1.172
DELTA DIST
103.936
MAX LENGTH
3000
1500
750
Averages
SI
Eng
Cursor #1 - X
2885.818
Cursor #1 - RHO
1.000
Z-Apparent
1.000e+6
Z-Template
50.0
dBRL
X Axis Legend
None
Status
Display
Add Text


Save Print Analysis Zoom Cable Type Acquire/Exit! HELP
PCI-3100 TDR CARD (Waveform Overlay Analysis)
RHO
0.82
0.74
0.66
0.58
0.50
0.42
0.34
0.26
0.18
0.10
0.02
Yellow Signature
30 Hz Forcing
Function
TIMEBASE(s)
EQUAL
VELOCITY
%C
ft/ns
0.64960
DELTA RHO
0.737
DELTA DIST
6.024
MAX LENGTH
3000
1500
750
Averages
SI
Eng
Cursor #1 - X
3360.582
Cursor #1 - RHO
0.821
Z-Apparent
507.692
Z-Template
50.0
dBRL
X Axis Legend
None
Status
x16 ZOOM
Add Text



Validation

- **Validation of the test method**
  - **Completed in March 2002**
  - **Double blind test**
  - **Industry participation encouraged**
- **Final Report**
  - **End of April 2002**

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Conclusions

- Data collected over the past year suggest that EDT works
  - Single conductor and twisted pair configurations
  - Two types of insulation were studied
    - Insulation materials used in the nuclear power industry are also applicable
  - Subtle insulation defects are easiest to detect when contaminated

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Conclusions

- Relative comparisons can be made with different forcing functions
  - No baseline required
- Test instrumentation hardware exists
- Defects were introduced in a scientific manner
  - New wire vs. aged wire

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Reality Check

- Improve data collection
  - Optimize Forcing Functions
    - Test Time
  - Methodology
- Recognize data interpretation needs to be automated
  - GO/NOGO
  - Pattern analysis/AI
- Hardware needs to be "field worthy"
- Evaluate switching for multiple conductor harnesses

What's Next?

- Introduce EDT to the nuclear industry as part of our testing services
  - Possible applications include hot spot detection and life extension
- COSSI program
  - 2 year program
  - NAVAIR (EA-6B) and NAVSEA (688 class submarines)
  - Software and hardware mods
  - Environmental qualification of the test kit

Assessing the Condition of Inaccessible Cables Through Correlation of Capacitance and Insulation Microstructure

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Advent Engineering Services, Inc.
Ann Arbor, Michigan

Abstract

For aging nuclear power stations and other facilities, a need exists for monitoring aging degradation effects in electric wire insulation. Our current research efforts are pursuing a non-destructive, *in situ* approach for determining remaining life of wire insulation through detection of real time age-dependent microvoid characteristics and comparison to end of life void parameters. In many cases, a critical cable may be inaccessible because of location within conduits, in concrete, or underground thus making detection of microvoids impractical. We will report on our efforts to use capacitance as a means of determining nominal microvoid content within the structure of the polyolefin based insulation systems. Our work in this area was prompted by Chang-Liao *et al* (2000) who reported on an age dependent relationship for the capacitance of EPR insulated wire.

In this paper, we will summarize three ways in which microvoid content within the insulation separating two conductors can theoretically affect the measured capacitance. The first the potential change in the insulation medium's effective permittivity (or dielectric constant) caused by the additional un-ionized microvoids within the polymer matrix. The second is a virtual decrease in the distance between the conductors caused by any ionization effects. And the third relates to ionization effects within the voids affecting the amount of energy stored in the electric field between the conductors.

Our preliminary results demonstrate that, of the three effects investigated, microvoid growth only significantly affects the energy stored within the electric field between the wires. Thus it is theoretically possible that properly measured capacitance can be correlated to microvoid content and thus to a determination of acceptable or unacceptable remaining life. Although usable for all installed electric cables and wiring, this technique would have greater value in applications involving inaccessible systems.

1. Introduction

For aging nuclear power stations and other facilities, a need exists to be able to accurately assess aging degradation and remaining life of electrical cable insulation. Our current research efforts are pursuing a non-destructive *in situ* approach for determining remaining cable insulation life through the imaging of real time age-dependent void characteristics and comparison to known end of life void parameters [1]. Although imaging techniques work proficiently for readily accessible cable, imaging is not feasible for inaccessible cables such as those found in conduit, in bundles, or running underground. Thus, an alternate void detection scheme or correlation to another measurable parameter is necessary.

In the past, attempts to measure and trend changes in per unit capacitance as a function of aging have not been successful. However, recently, Chang-Liao *et al.* [2] reported differences in cable capacitance values over time that appear to be consistent with the Arrhenius aging model for thermal exposure [3]. This paper reports on initial efforts to use our age dependent void growth model to theoretically predict the capacitance values measured by Chang-Liao *et al.*

Capacitance is the property of a cable system that permits a conductor to maintain a potential across the insulation. Any two conductors with an applied voltage and separated by an insulation medium experience capacitance effects. Capacitance, C, is generally described as the magnitude of charge, Q, per unit potential difference, V_{ab}, between conductors.

$$C = \frac{Q}{V_{ab}} \tag{1}$$

In general, the electric field developed between conductors is a function of the conductor-insulator geometry. For parallel plate capacitors, the potential difference between the plates is simply a function of the plate area and the distance between the plates. Thus, capacitance for a parallel plate capacitor is given by

$$C = \varepsilon \frac{A}{D} \tag{2}$$

where for a wire the "plate" area would equal the product of wire diameter and length.

To properly account for the geometry of a multi-conductor cable, we must derive an appropriate description of the equipotential surfaces created by a cylindrical wire. Using the principle of superposition, the voltage drop from conductor A to conductor B due to the charges on both conductors is simply the sum of the voltage drop caused by each charge alone.

$$V_{AB} = \frac{\lambda_A}{2\pi\varepsilon} \ln \frac{D}{r_A} + \frac{\lambda_B}{2\pi\varepsilon} \ln \frac{r_B}{D} \tag{3}$$

Assuming that both conductors have an equal charge ($\lambda_A = -\lambda_B = \lambda$) and combining the logarithmic terms, we can write the potential difference between two wires as

$$V_{AB} = \frac{\lambda}{2\pi\varepsilon} \ln \frac{D}{r_A r_B}. \tag{4}$$

Substituting (3) into (1) the capacitance per unit length between the two conductors is

$$C_{AB} = \frac{2\pi\varepsilon}{\ln(D^2 / r_A r_B)}. \tag{5}$$

Figure 1 compares equations (2) and (4) for an arbitrary, but equal distance between the wires. As expected, the effect of the wire geometry on the calculated wire capacitance is more pronounced the smaller the wire size. For the purposes of this paper, we only intend to discuss the feasibility of using the microvoid content to explain changes in measured capacitance. Therefore, we will ignore the geometric effects and use the parallel plate assumption throughout the remainder of this paper.

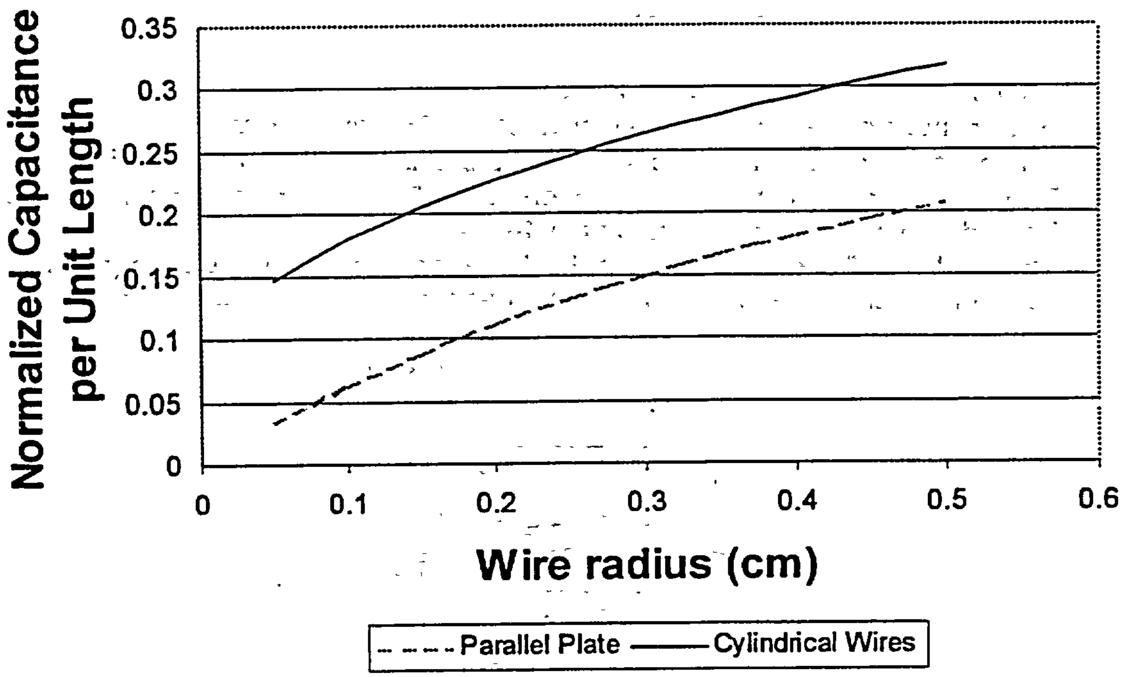

Figure 1 Geometry Effects of the Calculated Capacitance per Unit Length

2. Discussion

Every dielectric material experiences breakdown of its insulating properties when exposed to a sufficiently large electric field. The observed breakdown effect occurs because of partial ionization of the dielectric material, which leads to increased leakage and conduction currents through the insulating material. Electric cable insulation experiences environmental (usage) related breakdown of the dielectric over time. A similar process is believed to occur because of temperature dependent chemical reactions within polymeric insulation materials. These processes are generally referred to as aging.

All manufactured cable insulation materials contain some microvoids, although, the size and number of these voids (for newly produced insulation) have decreased significantly with improvements in the manufacturing process. With increased age, this void content is expected to increase in the form of larger microvoid sizes and increased microvoid density [1]. One effect of this increased content is the altered effective permittivity of the polymer matrix. Second, under exposure to a sufficiently high electric field, some of the gaseous content within the voids will ionize. One result of this ionization would be that the ionized volume would behave more like a mini-conductor dispersed within the insulation matrix. The net result is that the void ionization would extend the effective conductive portion of the conductor resulting in a reduced effective insulation thickness. A third effect of this ionization would be a change in the amount of potential energy stored in the electric field between the conductors.

The remainder of this paper focuses on a theoretical discussion of the three ways in which increased ionized void content can affect cable capacitance or effective capacitance. For this discussion, refer to the wire configuration graphically depicted in Figure 2 with the following additional stipulations and assumptions:

- Both conductors are identical 10 awg
- Each conductor has an insulation thickness of 280 mils (0.7 cm)
- An applied voltage of 1000vdc is sufficient to cause ionization of the void volume
- The void volume is modeled as nitrogen gas (N2) where one of the nitrogen atoms is ionized with a first ionization energy of 14.5 eV
- The "end of life" condition is 1% void volume throughout the insulation (corresponds to voids of 5 micron diameter at a density of approximately 500,000 per cubic millimeter).

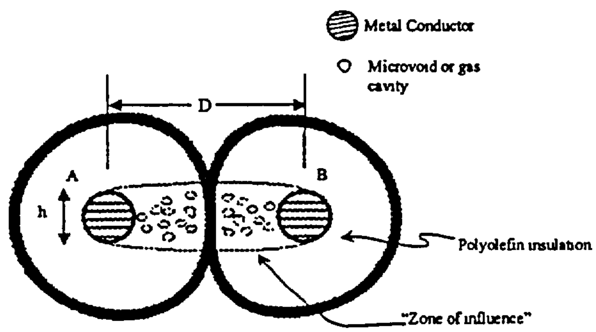

Figure 2 Cross section of two adjacent conductors.

3. Effect of Microvoids on Permittivity

Since the capacitance is always greater when a dielectric material is present between the conductors, the dielectric (or permittivity) constant, K, is always greater than unity. Since the dielectric constant of a vacuum is 1, we would expect that as voids are created or grow in size that the effective dielectric constant of the cable insulation material would decrease until it approached the limit of all of the dielectric material being converted to void. However, since "end of life" void contents are assumed to be 1% or less, the effective permittivity would be highly dominated by the dielectric material.

As a simplified illustration of the magnitude of this effect of microvoid growth with aging, consider the wire configuration depicted in Figure 2. If we assume we can treat the two long wires as a parallel plate capacitor, the capacitance per unit length is given by

$$\frac{C}{L}=\frac{\varepsilon h}{D} \qquad (6)$$

where ε is the effective permittivity, h is the wire diameter, and D is the distance between the wire centers. Assuming 1% voids (6) can be rewritten as

$$\frac{C}{L}=\frac{(0.01+0.99k)\varepsilon_0 h}{D}. \qquad (7)$$

Plugging in the appropriate values we find that the contribution to capacitance per unit length due to microvoid content is ~0.02 pF/m. The corresponding contribution associated with the remainder of the dielectric material is ~ 4 pF/m. Thus, for the above stipulated parameters, the contribution of microvoids to a corresponding decrease in capacitance is small and may not be practical for trending or correlation purposes.

4. Effect of Ionized Microvoids on the Effective Insulation Thickness

To analyze the relationship between capacitance and microvoid content, two adjacent insulated conductors are considered as previously shown in Figure 2. The insulation of the two conductors is assumed to be of the same polymer material and to be of similar age. The insulation of adjacent conductors is slightly flattened at their area of contact because of cable jacketing or bundling. The flattening, as depicted in Figure 1, allows the creation of a "zone of influence" for capacitive leakage current between adjacent conductors A and B.

Since capacitance is a function of the insulation thickness between conductors A and B, we can theoretically combine the "conductive" voids at one end of the "zone of influence", as shown in Figure 3. The effective insulation thickness is now given by the expression D-x, where x represents the effective conductance of the ionized voids.

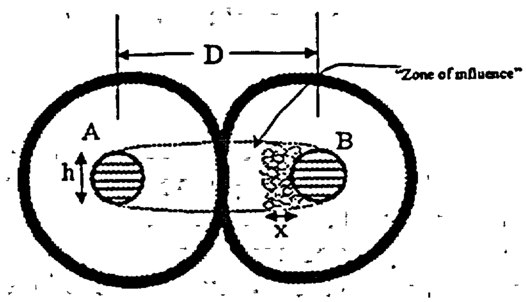

Figure 3 Electrically equivalent configuration with microvoids gathered at one end of the "zone of influence"

As previously discussed, the void approach to estimating remaining insulation life [2] says that thermal aging causes voids to grow in size and density. The primary effect of voids on capacitance is that the ionized gas volume behaves like a conductor. The net result is that the effective conductive portion of the conductor extends outward and the equivalent distance, D, between conductors decreases. (See Figure 3) Thus, the ratio for the change in capacitance due to the change in the effective distance between conductors can be written as

$$\Delta\frac{C}{L}=\frac{\varepsilon h}{D}\left(\frac{x}{D-x}\right). \qquad (8)$$

Inserting the appropriate values into (8) we find that the change in capacitance per unit length due to microvoids is ~0.08 pF/m. Although higher in magnitude than the first effect considered above, this increase in capacitance is also small compared to the normally measured value (~ 4 pF/m), and may also be too small for trending or correlation purposes.

5. Effect of Ionized Voids on Stored Potential Energy

In this example, we attempt to describe the expected increase in energy stored in the electric field and corresponding increases in quasi-capacitance per unit length based on a theoretical discussion of the effect of gaseous ionization within the voids. We call this effect a change in quasi-capacitance because although it represents a change in stored electric field energy, the current producing this effect may not be truly leading the voltage as required by the conventionally manifested capacitance property.

We begin with the energy density equation for a charged capacitor.

$$u = \frac{\frac{1}{2}CV^2}{\text{Volume}} \tag{9}$$

Assuming an applied voltage of 1000vdc is sufficient to cause a first level ionization of 1% of the void gas and for simplicity that the voids are filled with nitrogen rather than air or polymer oxidation products allows us to estimate the quasi-capacitance effect. By equating the energy density above to the energy required for ionization allows us to estimate a quasi capacitance of 600,000 pF/m. Thus, we have shown that the effect of microvoids on the electric field energy storage leads to a significant change in (quasi) capacitance per unit length – almost 4 orders of magnitude larger than normal cable capacitance. Therefore, it is theoretically possible to use the change in electric field energy storage as a correlation to microvoid content in an inaccessible cable. Various capacitance measurement devices exist. One that relies on calculating the lead angle between current and voltage will not be valid but one that relies on electric field energy storage or an RC time constant related charging rate could be applied.

6. Conclusions

Of the three potential effects of microvoids on cable capacitance, the effect of stored electric field energy appears most suitable fro detecting a measurable change in capacitance per unit length. However, more work is needed to correlate applied voltages to degree of ionization within microvoids for various expected gas concentrations, as well as, to assess the optimum measurement method for detecting and measuring the stored electric field energy changes representative of a capacitance property. This monitoring technique would theoretically allow correlation to degree of aging and remaining life using the micro-void concept outlined in [2].

7. References

[1] Horvath, David A., Douglas C. Wood, and Michael J. Wylie, Microscopic void Characterization for Assessing Aging of Electric Cable Insulation Used in Nuclear Power Stations, CEIDP, October 2000.

[2] Chang-Liao, K.S., T.K. Chung, and H.P. Chou (2000) Cable Aging Assessment by Electrical Capacitance Measuring Technique, American Nuclear Society NPIC & HMIT Proceedings.

Non-Intrusive Cable Condition Monitoring

By

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Presented at
Wire Cable Aging Conference
April 23-25, 2002

Electrical cables are part of an electrical circuit that performs a function, provides information and communicates. The loss of one or all of these functions is often not inconsequential.

For several decades, we have been performing root cause failure analyses of loss of electrical performance events that proved consequential. These electrical performance failures have run the full spectrum from some of the most sophisticated projects, putting man on the moon and harnessing the atom, to the most basic toaster heating circuits.

Great strides have been made in reliability and longevity of the electrical systems. Significant research has been performed to extend the knowledge of how equipment ages. The Nuclear Power industry has been at the forefront of evaluating aging and minimizing the impact of aging on electrical circuits.

Even the concept of condition monitoring is not new. We performed condition monitoring evaluations in 1977. CM was further reviewed during the NRC's Nuclear Plant Aging Research of the mid 1980's and extended again in the 90's and now on into the new millennium.

Elusive have been the goals that CM had to be simple, inexpensive, easy to perform and totally accurate.

The problem is the world and specifically electrical circuits are not perfect and unchanging. We live in a world that involves chance or probability and is changing.

These chance occurrences play havoc with our models. We have utilized the Arrhenius relationship in addressing aging of nuclear power cable for over 25 years now. Research continues into this of which there are few complaints.

The Arrhenius model, however, only accounts for some of the factors that lead to failure of these electrical systems. It does account for some important factors and was definitely the state of the art 25 years ago.

As a famous contemporary figure has said, you need to know your role. Arrhenius theory has a role. The Arrhenius role has been making sure that electrical circuits are constructed of materials with superior age resistance.

The nuclear industry has done a fine job at eliminating poor age-related performing materials. The qualification process in nuclear power plants includes simulating the aging. Typically a cable being qualified would be artificially aged thermally using Arrhenius Theory to the equivalent of 40 years. Specimens of aged and unaged cables are bent onto mandrels, which induce mechanical stress. The specimens are then irradiated to simulate the radiation requirement. Then, while the cable specimens are in their worst state of deterioration, they are subjected to steam exposure testing at high temperature (340 °F (171 °C)) and pressure (50 to 120 psig). Moisture is forced into the cable conductor, underneath the insulation, through spliced ends. Normal or rated voltage is applied during this testing. Then, after the steam test exposure, the cable specimen is removed from its mandrel, re-stressed by straightening, and rewinding in the opposite direction onto another mandrel. The cable specimen, mounted on its new mandrel, is then subjected to high voltage testing (80 VAC/mil) while submerged in water. At the end of 5 minutes of this stress, the cable is finally qualified.

Nuclear power qualified cable has thus demonstrated its ability to sustain extreme mechanical and electrical stresses while aged to its worst state of deterioration and fully submerged.

This testing has eliminated many cable constructions from nuclear power applications.

The electrical industry in general has rewarded the good performers and eliminated many poor performers.

But Arrhenius can be trumped.

In studying the NTSB Aircraft Accident Report, PB 2000-910403, "In-flight Break up over the Atlantic Ocean, TWA Flight 800,Boeing 747-131, N93119, Near East Moriches, NY, July 17, 1996" several electrical performance factors were noted. For instance,

- Post Accident Investigation showed that there was wiring that had cracks exposing conductors (Teflon, Tefzel, Kapton, Poly-X) in Center Wing Tank (CWT) area
- There had been several maintenances performed over the years in this area that required moving, or displacing the cables
- The area above the cable routing had a standing water from a drain problem above the area from 7-11-1996 to 7-16-1996

- The electrical bundles had 350 VAC co-bundled with 115 VAC circuits.
- There had been Intermittent Fuel Problems for 2 years prior to accident
- Before Leaving JFK
  - Another intermittent fuel problem was noted on the ground before TWA 800 left JFK (p. 47)
  - The captain's Weather Radar Display was inoperable
  - A cautionary light was lit and would not go out on Left Flap

The TWA Flight 800 aircraft was manufactured in 1971, thus the wiring was approximately 25 years old.

Based on nuclear power experience the following are noted.

- The cracking observed in the wire was premature, based on nuclear standards Kapton, Tefzel and Teflon should have showed no cracking for the equivalent of 40 years.
- Maintenance actions could add mechanical stress and new vulnerable arrangements
- Cable with cracks exposing the conductor is vulnerable to failure due to moisture and humidity.
- Cable with cracks is vulnerable from co-bundled higher voltage cable.

When unanticipated conditions are added, Arrhenius theory can be trumped. Obviously more significant failure mechanisms were present. Possibly the anomalous behavior observed in some of the electrical systems may have been precursors.

Where does this lead us? We are lead to the conclusion that the circuits themselves can provide valuable condition monitoring information.

Circuit CM and Control™ (CCMC)

GLS has a patent pending on condition monitoring from in circuit performance, Circuit CM and Control™ (CCMC).

Our method of condition monitoring cable performance uses the Watchdog™ in electric circuits to ascertain performance patterns and characteristics and identifies degraded insulation, and circuit performance, by differences in the patterns. In this method, patterns of an electrical circuit are captured and stored and each successive pattern is compared to previous pattern characteristics.

The patterns are statistically analyzed to determine distributions. These distributions are then used in a risk probability model that identifies successive patterns as to the probability that it is normal, suspect or abnormal behavior. Each pattern can then provide a diagnostic and associated probability that degradation has occurred. GLS's Circuit CM and Control™ (CCMC) is designed to:

- Detect anomalous behavior, and assign probabilities,
- Perform interrogating diagnostics,
- Provide notification of the anomaly to the pilot (operator),
- Suggest applicable actions,
- Display Required actions and Carry out Circuit Interruption tasks, if authorized,
- Carry out mitigating tasks, if authorized
- Collect Fault Related inputs and correlate with events
- Update behavior with cause and effect resolutions
- Transmit information to the network

Once degradation is suspected, interrogation of the circuit is performed, using characteristics of a good pattern to test the circuit. Confirmation of an anomaly can then be made with statistical precision using the Interrogation Module. Additional ground based or off line based maintenance can further interrogate the circuits.

Real time options are presented to the pilot (operator) from the Mitigation module. This module, preloaded with the Failure Modes, Effects and Criticality (FMECA) analysis, can provide circuit significance action options. Mitigating and terminating options are presented.

Once an action is chosen the Terminator Module is designed to show how the action is accomplished by identifying the actions necessary to the pilot, displaying the location of interrupters, double checking criticality information and interfacing with the control circuits.

The Fault Feedback Module provides the means to re-educate the Watchdog. Its main functions are to

- Provide a method to log anomalies
- Provide for the capture of information from Crew, Maintenance, Vendors
- Query Watchdog for Cause and Effect
- Add Corrective Action logging
- Update Watchdog with Cause & Effect

Summary

GLS's Circuit CM and Control™ utilizes the performance of the electrical systems to provide non-intrusive condition monitoring. It provides

- Immediate feedback of abnormal situations.
- Risk significance
- Assistance to commander / operator / pilot with options and their consequences.
- Captures cause and effect information

- Improves maintenance
- Improves reliability
- Constantly learning and sharing this information

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Appendix H: Papers and Presentations from General Session Initiatives and Insights on Wire System Aging

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Appendix H - Table of Contents

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International Conference on Wire System Aging
April 23-25, 2002
Rockville, Maryland USA

Present Status and Future Study on Aging Evaluation of Cables in Japan

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Abstract

In Japan, the cables that have passed the environmental qualification test specified in IEEE Std. 323 and 383 are used for nuclear power plants. Most of cables are considered to maintain the electric functional capabilities after passage of 60 years operation if the design basis event (DBE) should occure.

According to IEEE Std. 323 and 383, cables for testing are subjected to accelerated aging and then exposed to the DBE environment to evaluate the integrity of cables. According to the recent findings, however, synergism and ordering of aging modes should be considered for accelerated aging method for cables in order to simulate more precisely the actual cable aging.

Based on the problems of the present evaluation of the aging of cables, a study plan has been established, which consists of a thermal aging test to evaluate the activation energy of various cables used for Japanese nuclear power plants and a simultaneous aging test with thermal and radiation to establish a new aging evaluation method.

Under these circumstances, METI (Ministry of Economy, Trade and Industry) has entrusted JAPEIC with the project, "Assessment of Cable Aging for Nuclear Power Plant" from 2002 fiscal year. It plans to conduct these tests in the future, thereby establishing a highly reliable aging evaluation method for cables based on the results of these tests.

1. Aging Evaluation of Cables at Present

Thirty (30) years have already passed since the initial operation of a commercial nuclear power plant in Japan. 52 plants are under operating now, and among them, Tsuruga power plant Unit-1, Mihama power plant Unit-1 and Fukushima No.1 power plant Unit-1 have been operated over 30 years.

For these 3 plants, technical assessments of the aging and integrity of various equipment were conducted by the three electric utilities, and the final report was released in February 1999 [1]. Aging of cables were evaluated in these reports because polymer materials used as insulation materials of cables were known to be degraded by exposure to heat and radiation.

In Japan, cables that have passed the environmental qualification test specified by Japanese Electrotechnical Committee technical report based on IEEE Std. 323 and 383 are used for nuclear power plants. Though the three plants mentioned above had already started commercial operation before the standards were established, the final reports reveal that most of cables used for 3 plants maintain the electrical functional capabilities even after 60 years operation where the DBE is taken into consideration [1].

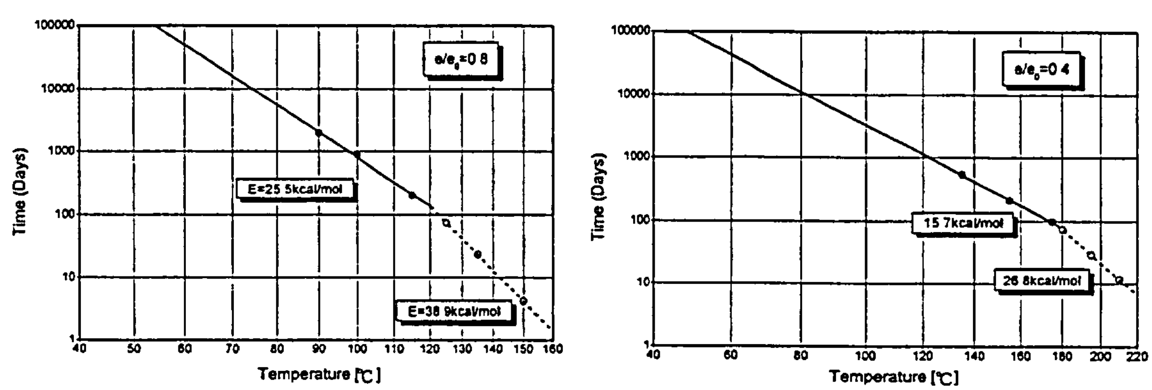
According to the procedure of cable integrity evaluation test specified in IEEE Std. 323 and 383, cables for testing are subjected to accelerated aging and then expose to the DBE environment. Recent findings of studies in Japan show the effects of the accelerated aging procedure to simulate the actual aging of cables. Based on the fact that more than 20 years have already passed since the establishment of IEEE Std.323 and 383, it is time to review the aging evaluation method to assess more precisely for cables.

2. Extraction of Problems with Aging Evaluation of Cables

The activities on the aging of cables in Japan has already presented in detail elsewhere[2]. In this particle, the following present problems with aging evaluation of cables are pointed out based on the latest findings in Japan.

(1) Accelerated Thermal Aging Method

At present, Arrhenius's law is used to find the accelerated thermal aging conditions for life time prediction. The activation energy of an insulation material obtained by high-temperature range (120-200°C) tests is extrapolated to the operating temperature range. As shown in Fig.1, however, a break point in trend straight lines is observed and the activation energy in the low-temperature range is lower than that in high temperature range [3), 4)]. It is considered that the surface portion of insulation materials deteriorate substantially during thermal aging in a high temperature range against uniform deterioration in low temperature and the evaluation of this behavior results in high activation energy[4].



(a) EP rubber (b) Silicon rubber

Fig.1 Arrhenius plot of Insulation Polymer Materials [4]

That means an extrapolation based on the activation energy at high temperature would give an underestimation for the prediction of aging of cables in actual plants.

A similar fact is pointed out in the IAEA-TECDOC-1188 "Assessment and management of aging of major nuclear power plant components important to safety: In-containment instrumentation and control cable". According to that paper, an extrapolation based on the data measured at high temperature would give a significant underestimation of the aging at lower temperatures. It is recommended to be the temperature difference range within 25 degrees Celsius between the lowest temperature used in the accelerated aging test and the actual operating temperature for more accurate evaluation.

Based on these circumstances, it is required to use the activation energy obtained in a range close to the operating temperature of actual plants, in which the insulation material will deteriorate uniformly over the cross-section, and conduct an accelerated thermal aging test in such a narrow temperature range in order to simulate more precisely the aging of cable by heat of an actual plant.

(2) Dose Rate for the Radiation Aging Test

At present, cables for testing are irradiated at a high dose rate of several kGy/h to simulate the radiation aging during normal operation. However, recent studies reveal that degradation is severer in case of radiation with low dose rate than that with high dose rate for the same dose [3), 4), 5)]. The mechanism of this behavior is considered caused by the diffusion of oxygen in the material [3), 5)]. Furthermore, it is proposed to conduct radiation tests with the dose rate at which the insulation material for testing deteriorate uniformly over the cross-section determined for the insulation material and thickness [3), 5)].

In conditions where the oxygen diffusion is sufficient and degradation of an insulation material is uniform, degradation by radiation apparently tends to be also severer with low dose rate than with high dose rate for same dose. For these cases duration of tests are extended and the thermal effect is considered to increase. For further lower dose rate test, thermal aging becomes dominant [4)].

A similar finding is pointed out in IAEA-TECDOC-1188. It reveals that oxidation is the dominant degradation mechanism for most cable insulation materials with long- termed aging, and requires radiation test should be conducted under the limit of dose rate that oxygen is able to diffuse into the cable material during the test period. And it also requires extremely low dose rates (20-30 Gy/h) for testing some insulation materials sensitive to the dose rate.

Based on these findings, it seems to be desirable to irradiate an insulation material within the range of dose rate by which an uniform degradation will be observed for radiation aging test. Close controlling the dose rate leads to precise simulation for the aging of cables due to irradiation of an actual plant.

Furthermore, it seems to be desirable to reassess the dose rate during the service period of an actual plant to the value which contains an appropriate margin.

(3) Sequence of Thermal Aging and Radiation Aging

Cables in nuclear power plants sustain thermal aging and radiation aging simultaneously. It is known that there is synergism on organic polymer aging.

Based on IEEE Std. 323 and 383, accelerated aging is conducted in the order of thermal aging followed by radiation aging, but there are reports that thermal aging after irradiation causes severer degradation [3][5]. Degradation of simultaneous aging by heat and radiation is intermediate of those by two sequence conditions above- mentioned [3].

It is also described in IAEA-TECDOC-1188 that thermal aging after irradiation causes severer degradation than the case of irradiation after thermal aging when degradation due to heat and radiation is caused sequentially, and it is necessary to take margin into account adequately to anticipate the influence when irradiation is conducted after thermal aging; which is the ordinary sequence.

In view of such findings, it seems to be desirable to establish simultaneous aging procedure of heat and radiation as accelerated aging test in order to obtain correctly simulated data for the aging of cables of actual plant.

(4) Judging Method of Cable Integrity

Some problems exist in the present judging method of cable integrity. At present, the judgment of cable integrity is made on the basis of the behavior of tested cable in bending immersing voltage withstand test as specified in IEEE Std.383 after accelerated aging and exposure to the DBE condition. In case of low-voltage cables (low power/control/instrumentation cables), for example, the test voltage is set at 2.6-3.6 kV (3.2 kV per millimeter in thickness of insulation material) though the value of 1.5 kV (when a conductor size is 8 mm^2 or less) is specified in JIS (Japanese Industrial Standards) for a pre-service test. This causes a discrepancy.

According to the specification, a sample cable must be straightened and then coiled to a specified diameter before a withstand voltage test, which is intended to make the influence of degradation greater.

The specification may be properly conservative because some margin will be provided to compensate for the uncertainty of accelerated aging. However, establishment of an accelerated aging method that correctly simulates the aging of cables due to heat and radiation in an actual plant may make the withstand voltage value set more precisely and the bending operation to magnify the influence of degradation unnecessary.

3. Study Planning for Optimization of Aging Evaluation of Cables

In order to cope with the problems described in the foregoing paragraph, study activities have been planning to conduct a thermal aging test for evaluation of activation energy of various cables (19 types of cables in total. Classified into 8 groups based on manufacturer and degree of importance) for Japanese nuclear power plants as well as to conduct a simultaneous aging test with heat and radiation under various conditions in order to establish a new aging evaluation method of cables.

(1) Thermal Aging Test

A thermal aging test is planned to conduct to evaluate the activation energy of cable insulation materials.

The thermal aging test is planned to be conducted at 3 temperatures at which degradation reveals uniformly inside the insulation material with adjusting the lowest test temperature within 25°C higher from the actual operating temperature. In that case, it will be desirable to make one point of which the temperature coincides with the test temperature used for the simultaneous aging test with heat and radiation mentioned later.

It is possible to determine the test temperature based on the results of existing thermal aging test conducted at comparatively low temperature for EP rubber and silicone rubber [4]. It is also planned to conduct a preliminary test in advance to confirm the temperature range that ensures uniform degradation inside the insulation material.

In the thermal aging test, different types of insulation materials are to be tested separately to prevent mutual influence and the maximum duration of a thermal aging test at the minimum temperature is planned to be around 4 years.

(2) Simultaneous Aging Test with Heat and Radiation

Evaluation of the cable integrity in one assumed environmental condition is possible by one simultaneous aging test with heat and radiation. Actual environment of nuclear power plants, however, is various combination of heat and radiation conditions, and it will be necessary to select and to conduct the most comparable cable environmental qualification tests according to a specific heat and radiation environment. Therefore, it is desirable to establish an aging estimation model of cables, namely the aging master curve of cables (hereinafter called a "master curve").

As for methods to establish a master curve, "Superposition of time dependent data" and "Superposition of DED (Dose to equivalent damage) data" are proposed in IAEA-TECDOC-1188 and ICE 1244-2 "Determination of long-term radiation aging in polymers - Part 2: Procedures for predicting aging at low dose rates".

To establish a master curve by "Superposition of time dependent data", it is necessary to combine various dose rates and temperatures to obtain data using the "elongation at break" as a degradation parameter.

Meanwhile, a prospect for application of "Superposition of time dependent data" to EP rubber and silicone rubber has been reported.[4]

Therefore a simultaneous aging test with heat and radiation, in which various dose rates and temperatures are combined, is planned so as to establish a master curve that will be an aging estimation model of cables. The test is planned to be conducted under 9 conditions which consist of 3 dose rates of approx. 1-100 Gy/h and 3 temperatures near the maximum operating temperature of an insulation material are combined, thereby obtaining continuous degradation data for a maximum of 4 years.

(3) DBE Exposure Test

In succession to the simultaneous aging test with heat and radiation, DBE exposure test, including radiation, is planned to be conducted for cables used within the containment vessel of nuclear power plants.

As both dose rate and temperature are to be high during the DBE it will be unnecessary to reexamine the conditions including the procedures of the present radiation aging test and steam exposure test that simulate the DBE. According to IAEA-TECDOC-1188, the radiation aging test for the DBE is usually conducted at a high dose rate of 1-10 kGy/h.

However, it is considered to be necessary to confirm the appropriateness of the post LOCA test conditions (temperature and period) during the steam ambience exposure test by means of the activation energy obtained in item (1).

(4) Condition Indicator (Aging index)

Cables are used to supply power or transmit control and instrumentation signals; therefore, the function of insulation materials must be maintained. Whether the insulation function is maintained or not can be confirmed by the insulation resistance test or the withstand voltage test (breakdown voltage). However, the insulation resistance and breakdown voltage are not suitable as aging parameters, and the "elongation at break" is used in general as an aging index of cables.

IAEA-TECDOC-1188 also states that "the change in electric characteristics of most cables is not great, and whether the function of a cable is lost or not is usually determined by cracks in the insulation material, which indicate a change in mechanical characteristics". It also states that "the elongation at break is a good condition indicator. It decreases gradually with the amount of induced degradation for most polymeric materials, this degradation being either thermally or radiation induced. This is the reason why condition monitoring techniques mentioned here have been correlated to elongation at break measurements".

Based on the above, the "elongation at break" is the suitable parameter as the aging index of cables for aging evaluation of cables, and the elongation at break are planned to be measured in the thermal aging test and simultaneous aging test with heat and radiation.

4. Conclusion

According to IEEE Std. 323 and 383 that are currently used for aging evaluation of cables, cables for testing are subjected to accelerated aging and then exposed to a DBE environment to evaluate the integrity of cables. According to the recent findings, however, synergism and ordering of aging modes should be considered for the accelerated aging method for cables in order to simulate more precisely the actual cable aging.

Based on the problems of the present aging evaluation method for cables extracted, a study plan which consists of a thermal aging test and a simultaneous aging test with heat and radiation has been established.

Under these circumstances, METI has entrusted JAPEIC with the project, "Assessment of Cable Aging for Nuclear Power Plant" from 2002 fiscal year. It plans to conduct these tests in the future with the fruit of establishing a highly reliable aging evaluation method for cables based on the results of these tests.

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Managing Cable System Aging of Nuclear Power Plants in Korea

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Abstract

This paper presents the status of managing cable aging of Kori unit 1 nuclear power plant in Korea and the test results of a new condition monitoring method. Kori unit 1 is the first Korean nuclear power plant that constructed by the Westinghouse and started the commercial operation in 1978. In order to manage cable aging in the plant that have very few EQ documents, the investigation of a plant environmental condition and cable composition is essential to predict the residual lifetime of cables. The investigations included the environmental conditions such as temperature, humidity and radiation dose rate distribution, the survey of cable design criteria, cable chemical composition, actual voltage, and maintenance histories in the Kori unit 1 nuclear power plant's files.

A new approach of condition monitoring using the 3rd harmonics frequency analysis was performed. Thermal accelerated aging at 130 °F have been carried out on two groups of cross-linked polyethylene (XLPE) cable models. The condition monitoring test results showed that the magnitudes of the 3rd harmonic component measured on these cables were proportional to the cable aging.

1. Introduction

The construction of the first nuclear power plant in Korea, Kori unit 1, was permitted in 1972. At that time the plant design lifetime was 30 years. Even if all components are designed to maintain the functional integrity during their design lifetime except their qualified lifetime are shorter than the full plant lifetime, but any components can be failed due to the unexpected cause. The major components or system important to safety has been replaced and checked with periodic interval during operational period. If some components exceed a safety margin or calibration tolerance, these components must be inspected and replaced when some defects are found.

Among many components in a nuclear power plant, cable system are difficult to check their integrity during plant operation period and to replace damaged cables that are placed in harsh environments such as the in-containment building. The cables inside the containment building are exposed to various environmental stresses. The most important factors are temperature, humidity and ionizing radiation, to which the nature of the environment should be associated.

The old nuclear power plants constructed almost nearly 30 years ago have very few environmental qualification (EQ) documents that provide information on equipment qualification lifetime and environmental specifications. The Kori unit 1, one of the old nuclear power plants, has the same problems. It was very difficult to find out design documents that are necessary to evaluate cable integrity and residual lifetime. In order to estimate the residual lifetime of the cable installed in Kori unit 1, cable specifications, actual environmental condition, and the failure histories of cable were investigated. The result of such inspection of the plant is helpful to managing cable aging in the future in the Korean nuclear industry.

A new condition monitoring method was introduced. The result of the analysis using the 3rd harmonic components showed that the magnitude of the 3rd harmonic was increased in proportion to the cable degradation.

2. Investigation for managing cable system aging in Kori unit 1.

2.1 Environmental condition (temperature)

The environment where cables are installed may affect the degradation rate of cables. Cables installed in a relatively mild environment would be expected to produce a lower aging rate than cables in a harsh environment. The cables can be exposed to a number of different adverse conditions, such as elevated temperatures and radiation fields, or high humidity. They can also be exposed to physical stresses, such as liquid impingement or adverse handling during activities such as maintenance and testing. Each of these stresses can affect the rate at which cables degrade. Therefore, the environmental qualification of cables must account for the environment in which the cables are expected to perform during their service life.

Temperature is one of the most important elements affecting the degradation rate of cables. This temperature is usually determined using information from plant design specifications and analyses; which provide a reasonable estimate of the global conditions in a certain area of the plant. However, little design data are available in Kori unit 1. Owing to the lack of the data, almost all information about temperature is able to be got through the measurement.

Two type of instrumentation were used to measure cable surface and atmospheric temperature of the room where cables were installed. One is an electronic infrared thermometer, the other is an electronic recorder with digital thermometer which is possible to measure for a long time. Actual temperatures in auxiliary, control and the turbine building were measured with an electronic infrared thermometer. An electronic recorder with a digital thermometer sensor was used to measure surface temperature in containment and auxiliary buildings during 18 months. Table 1 shows the representative temperature samples measured in nuclear power plant buildings.

Table 1. Design and measurement temperature in buildings

Buildings	Area		Temperature (℃)	
			Actual	Design
Aux.	M21-01	SI Pump Rm.	33.1	40
	M30-06	Boron Evaporator Rm.	38.0	
	M40-01	Evaporator Filter Rm.	38.0	
Control	K32-02	Cable Spreading Rm.	28.3	
	K40-01	Circuit Brk. Rm.	26.8	
Cont'	SG/RCP A	SG/RCP A	50	49
	SG/RCP B	SG/RCP B	50	

Fig. 1 shows the surface temperature profile of the cable installed under the pressurizer in the containment building. The profile reveals temperature variations from 25℃ to 38℃ which is in-constant due to the pressurizer operational condition.

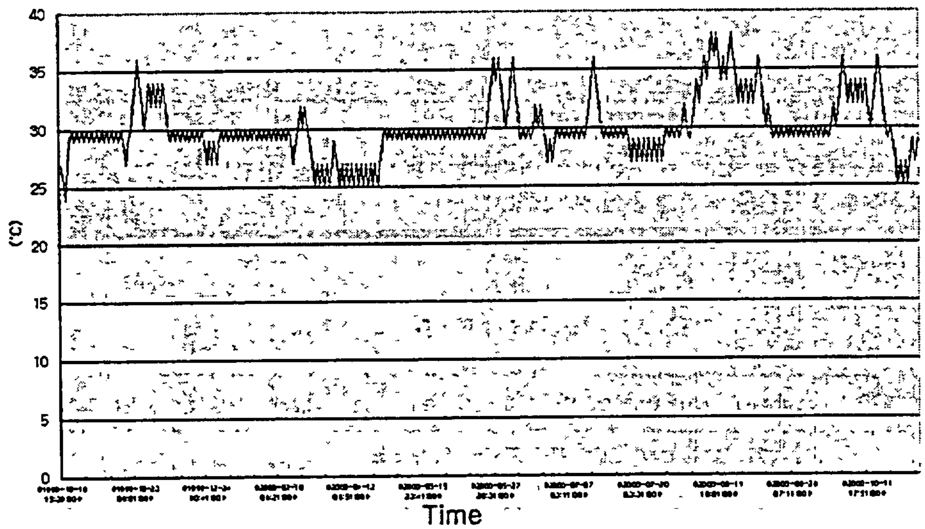

Figure 1. Surface temperature of the cable under pressurizer.

The temperature in steam header area is shown in Fig. 2. This figure shows that surface temperature of the cable is higher than the atmospheric temperature (48℃) of steam header room. This means that ohmic heating contribute to the temperature rising on the cable surface. As the results of the investigation, peak temperature on the surface of Ethylene Propylene Rubber (EPR) cable was 68℃ which does not exceeds a limit temperature that guarantees cable functional integrity for 60 years in EPR cable insulation material.

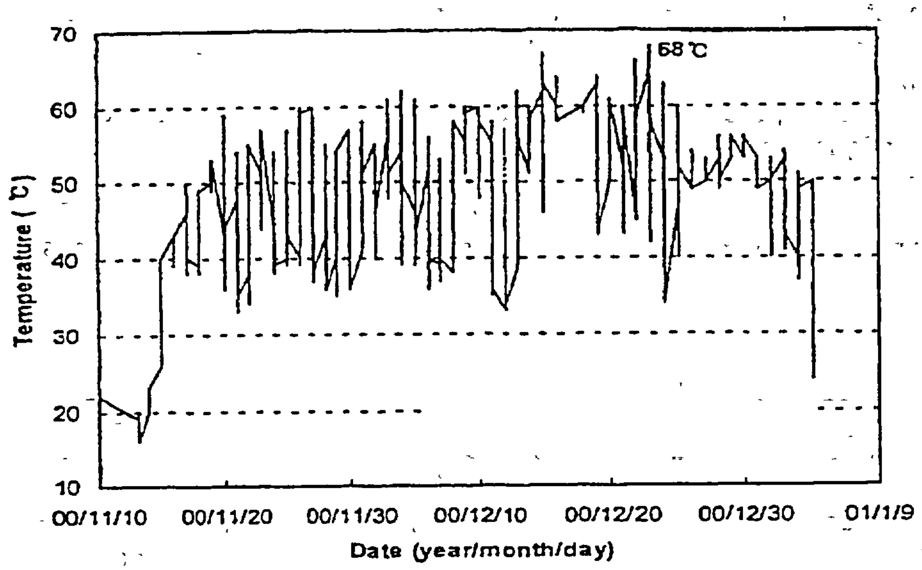

Figure 2. Surface temperature of the cable in steam header room

2.2 Failure history

The table 2 shows the failures caused by aging of cable or connector in the Kori unit 1. These failures were provided from the replacement history documents since commercial operation of the Kori unit 1.

Table 2. Failure events in Kori unit 1

Year	Area	Failure type
1994	RCS pump power cable	- Degradation of insulation - Cable header crack
1994	CRDM cable	- Aging - Tree on jacket
1993	Condensate extraction pump Cable	- Degradation of insulation
1993	Main feed water pump cable	- Degradation of insulation
1988	High voltage and instrumentation cable near penetrations	- Embrittlement
1988	Pressurizer heater cable	- Oxidation

2.3 Investigation of cable material

For the condition monitoring of installed cables, the design specifications about the type of material used for the insulation and jacket are essential information. The information are important from a safety standpoint, with the ultimate goal of performing condition monitoring to providing a means of predicting accident survivability for the cable. Also, it would be valuable input for deciding whether existing cables can remain in service throughout the licensed period, and possibly through an extended license period, or whether they need to be replaced.

The material used, the number of conductor, the thickness of insulation and jackets, and the cable configuration were investigated through the site walk-down and the examination of design documents. These variations, together with the environment in which the cables are installed, will affect the rate and degree to which the cables will degrade. The results of the investigation are summarized in table 3, which indicates cable specifications in each area of Kori unit 1.

Table 3. Cable specifications in Kori unit 1

Building	Area	Cable specification
Containment Building	RCS pump	6600V, EPR/CSPE
		600V, Copper conductors, PVC insulated, PVC sheathed
	Under Pressurizer	Okonite, OCOZE, 1C

Turbine building	General area	LG 600V, EPR/Neoprene, 1P ×16AWG
		600V, FR-XLRE/CSP, 3C × 6AWG
		Goldstar 600V, CVV-S
	Aux. Boiler	LG 600V EPR/Neoprene, 4C ×14AWG
Control building	Cable spreading Rm.	Goldstar 600V, EPR/CPS, 2C ×14AWG
		Rockbestor Firewall , 600V, 12/C, 16AWG
	MCC Rm.	Goldstar 600V, EPR/CSP
Aux. Building	SI pump Rm.	AEI Electric, 6600V
	Boron Evaporator Rm.	Green Gate Elcectric, 600/1000

3. Introduction of a new condition monitoring

3.1 Condition monitoring method using 3rd harmonic component

Fig. 3 shows a condition monitoring system used in the simulation studies presented herein. It comprises of a current transformer (CT), band-pass filter, amplifier and Odyssey; the nominal power frequency is 60 Hz. The measurement and analysis of the 3rd harmonic component has been carried out using the Odyssey.

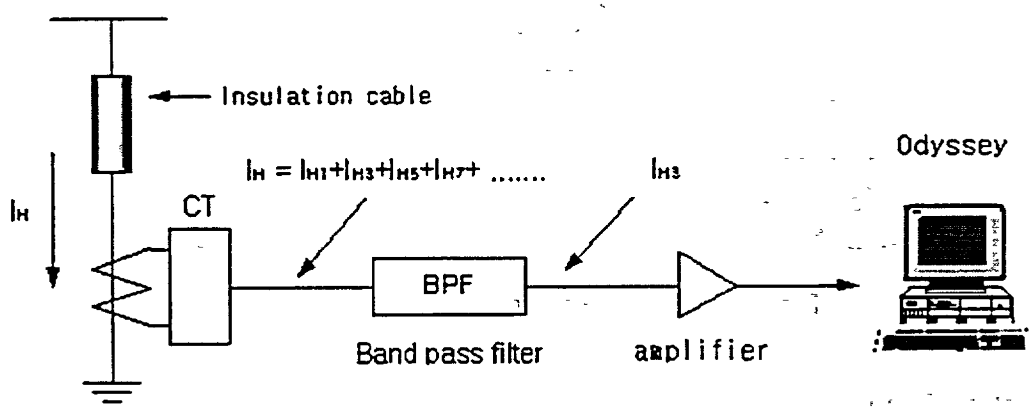

Figure 3. Condition Monitoring method using the 3rd harmonic.

Fig. 4 shows the cable degradation detection procedure of the proposed method, where IHb is the 3rd harmonic component of current before degradation of cable. IHa is the 3rd harmonic component of current after degradation of cable. ε(degradation criterion) is the signal magnitude threshold as the lower limit of 3rd harmonic current component that is used to detect the degradation. This is to discriminate between non-degradation cable and degradation cable. As can be seen, when absolute value of difference between IHb and IHa is greater than ε, this indicates a degradation of cable. The whole process is based on a moving window approach whereby the 1-cycle window is moved continuously by 1 sample.

It is apparent from the foregoing decision logic that the criteria for cable to detect degradation is such that absolute value of difference between IHb and IHa must stay above the threshold level ε continuously. In this respect, an extensive series of studies have to be performed in order to maintain cable stability for degradation.

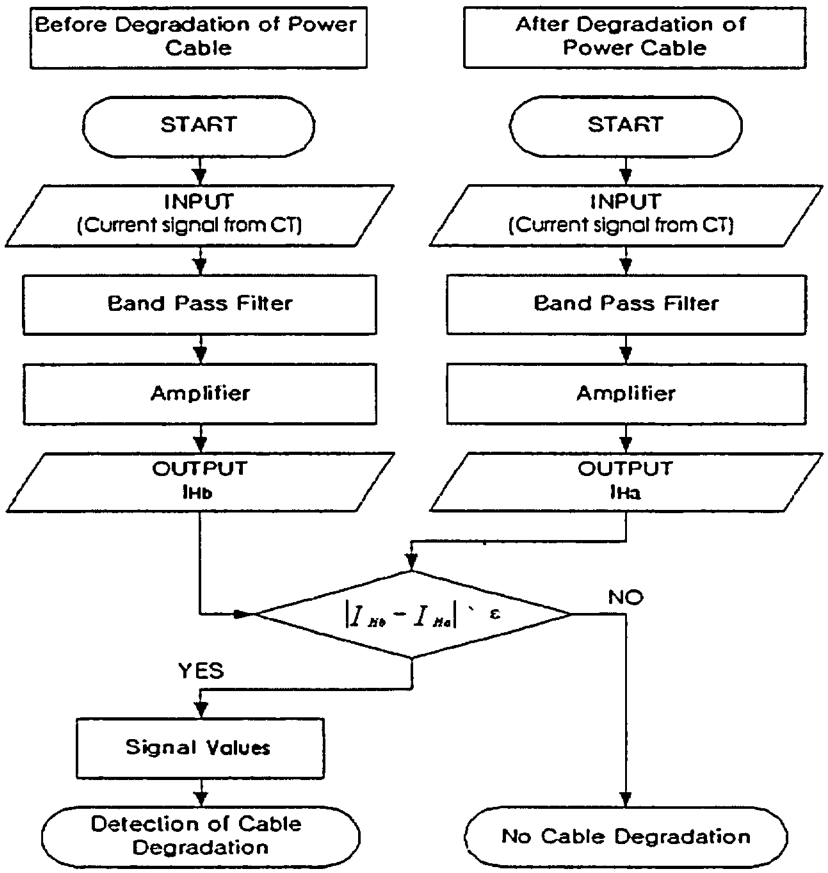

Figure 4. Flowchart of proposed algorithm

3.2 Simulation Results

Some typical results illustrating the performance of the detection technique of cable degradation developed. It should be noted that although not shown herein, responses/limitations due to CTs, band-pass filters, etc have been taken into account in the simulation.

We have used two types of cable for the cable aging. One is cable A(600V, CV 2CX2.0 SQMM), the other is cable B(600V, CVX3.5 SQMM). Accelerelated Cable aging was performed during an equivalent time for 30, 40, 50, 60 and 70 years using an oven.

Figs. 5 and 6 show the analysis result of the 3rd harmonic component for samples of non-degradation, and 30, 40, 50, 60, 70 years aging of cables (XLPE in insulation). The magnitude of the 3rd harmonic component was increased in proportion to the cable degradation.

An extensive series of studies have revealed that in all cases, the magnitudes of the 3rd harmonic component increase as cable-aging years increased. This effectively means that the condition monitoring method using the 3rd harmonic component of current signal will be able to detect the cable degradation. The technique developed is based on current signals only and therefore requires the use of current transformers (CTs) and band-pass filter. Work is currently under progress to extend the work on degradation detection/lifetime estimation in low voltage cable.

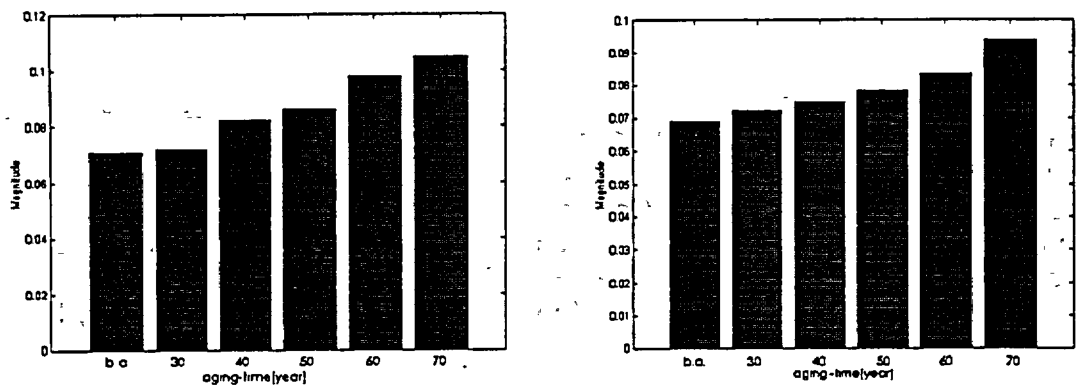

Figure 5. The result of the analysis using the 3rd harmonic component for two type of cable

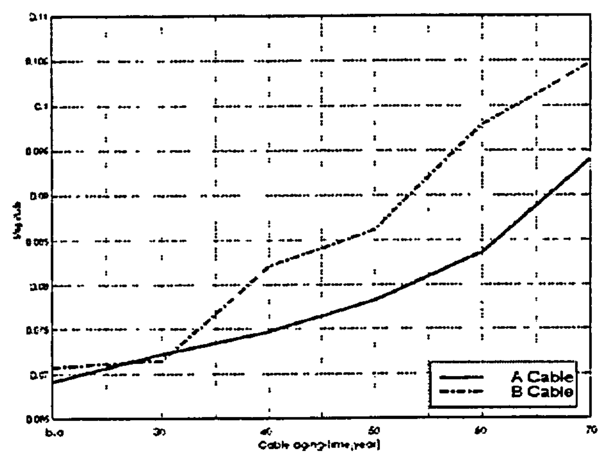

Figure 6. The results of the 3rd harmonic component for different aging samples of cable A and B

4. Results

According to the results of investigation of the plant's documents, walk-down and condition monitoring tests using the 3rd harmonic components, the following conclusions can be made:

- Almost all room temperature measured in each building did not exceed design temperature.

- Atmospheric temperature in steam header area (48℃) and RCP area (50℃) exceeded the design temperature.
- Surface peak temperature (68℃) of the cable in steam header area is higher than atmospheric temperature (48℃) measured by the infrared thermometer. This means that ohmic heating of cable conductor affects the temperature rising in cable insulation and jacket.
- As the result of analysis using the 3rd harmonic, the magnitude of the 3rd harmonic components increase in proportion to the cable degradation.

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ON UNCERTAINTIES IN ENVIRONMENTAL QUALIFICATION CABLE TESTING

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Abstract

The environmental qualification practice indicates that the results can have a high degree of uncertainty in the prediction of the qualified life. The reasons are largely high acceleration factors for thermal and radiation ageing, dose rate effects and questionable DBE and post DBE simulation. That is why on-going qualification in Czech NPPs was started in the frame of cable ageing management program. The main features of this program are environmental monitoring, cable condition monitoring and software program for the cable life assessment.

1. Introduction

Electrical cables are vital components of nuclear power plant (NPP) instrumentation and control systems located both inside and outside containment. Safety related cables must be qualified to perform their functions under specified service condition, including design basis event (DBE) and post-DBE conditions. The users of cables for safety systems are required to provide evidence that such system will meet or exceed its performance requirements throughout its installed life (usually 40 years). Qualification may be accomplished in several ways-type testing, operating experience or analysis. The type testing of actual cable using simulated operational conditions is the preferred method. In practice, a test programme which simulates normal operational conditions and accidental conditions is carried out. The simulation of ageing effects constitutes an important part of qualification and its uncertainties due to shortened exposure to more severe environmental conditions must be taken into account. These points will be discussed in this paper.

2. Accelerated ageing

The objective of accelerated ageing is to put cable samples in a condition equivalent to the end of its life. This qualification step is of special importance, as it ensures that the cable is aged by an accelerated but realistic ageing process before submitting it to accident conditions.

Realistic simulation of ageing depends on detailed knowledge of the factors which influence cable ageing and of the synergies which take place. The dominant ageing processes in the case of safety-related cable are simultaneous thermal and radiation ageing and simulation of design basis event (DBE) and post DBE.

In practice, the ageing tests are almost always carried out according to the sequential method when thermal ageing is followed by radiation ageing. In our previous paper [1] it was published the elongation at break values for five polymerical materials which were subjected to two different orders of sequential ageing. The experimental results have shown that radiation ageing followed by thermal ageing is more severe than thermal ageing followed by radiation ageing.

In air environment, oxidation is a common degradation mechanism in polymeric materials exposed to elevated temperature, ionizing radiation or mechanical stress. Polymeric materials often undergo diffusion-limited heterogeneous degradation with significant oxidation occurring only near the surfaces. Such degradation may occur in accelerated ageing tests, where the size of the oxidized region can depend on the dose rate used in the experiment. For accelerated ageing experiments using high dose rates (> 1 kGy/h), degradation in the interior regions of materials will take place under anaerobic condition. Such high dose rate experiments generally cannot be expected to yield predictive information on degradation behaviour in long-term application environments having low dose rate < 1 Gy/h, where homogeneous oxidation proceeds throughout the sample. This problem requires finding for accelerated tests such a low dose rate at which homogeneous oxidation is reached. In our study [2] the radiation oxidation of a fire – retarding polymeric blends of ethylene vinyl acetate (EVA) and ethylene propylene rubber (EPR) in the form of plates was studied. Yields of the oxygen consumption, the formation of gaseous products and the time of absorption of one-half of the equilibrium oxygen content were determined. For example, the one-half of the equilibrium oxygen content for the sample thickness 1.2 mm is 0.3 hour and for the sample thickness 2.4 mm is 1.2 hour. On base of these results we calculated the irradiation conditions ensuring that homogeneous oxidation will occur[3]:

- at a dose rate of 0.1 kGy/h at the sample thickness less than 3.3 mm
- at a dose rate of 0.3 kGy/h at the sample thickness less than 1.2 mm.

Note that these results are valid only for the polymeric plates which are irradiated in air at room temperature. In real cable construction containing insulation, tape wraps, shielding, armor and sheating, the diffusion of oxygen into materials is significantly reduced. Consequently, applicability of these results for accelerated radiation ageing of cables does not lead to conservatism. In practice, the application so low dose rates (0.1 – 0.3 kGy/h) in EQ testing is quite exceptional, giving evidence for heterogeneous oxidation in contrast with service ageing under homogeneous oxidation condition. Only under reliable conditions a simulation of operational ageing may image reliable base for next DBE survival tests and further for assessment of qualified cable life.

Very significant feature of the accelerated ageing is the diffusion – limited oxidation (DLO). For cable samples subjected to thermal ageing a criterion for highest sample thickness L at which DLO is negligible was calculated [4]:

$$L = \left(\frac{2p \cdot P_{ox}}{\varnothing} \right)^{0.5}$$

where p is the oxygen partial pressure surrounding the sample,

P_{ox} is the oxygen permeability coefficient,

$\varnothing$ is the average consumption rates of oxygen.

For many elastomers, the $\varnothing$ value is ~ 10^{-10} mol/g.s and P_{ox} ~10^{-9} cm^3/cm.s.cm Hg at ageing temperature 100 °C. Under standard air pressure and elastomer density of ~ 1.2 g/cm^3 the L-value corresponds to about 1 mm [4]. Thus, the accelerated thermal ageing of the samples, having thickness greater than the L- value can be characterized as heterogeneous oxidation caused by DLO. Concerning the role of the cable construction on difussion of oxygen into cable interior we can conclude that most of the accelerated ageing at environmental qualification tests proceeds under heterogeneous oxidation conditions.

3. Long-term thermal degradation

Thermal energy absorbed in cable polymeric materials initiates chemical reactions (esspecialy oxidation) leading to polymer degradation. The rate of degradation depends on many factors, mainly on environmental conditions and material composition.

To demonstrate that the material is capable to fulfill its functions toward at the end of its service life the material is in-laboratory accelerated aged. The most easier way how to proceed accelerated thermal ageing is to use higher temperatures. For calculation the time to equivalent damage at different temperatures the Arrhenius equation is usually used:

$$t_1 = t_2 \cdot e^{\frac{E_A(T_2-T_1)}{k_B T_1 T_2}}$$

t_1 - time of accelerated ageing, t_2 - required service life, E_A - activation energy in eV, T_1 - temperature of accelerated ageing (K), T_2 - service temperature (K), k_B - Boltzmann constant.

Applying this equation we assume that the short-term simulation of thermal ageing at higher temperature caused the same degradation as the service long-term ageing at lower temperature. This means that we assume that the chemical mechanisms leading to ageing do not change with temperature and thus, the E_A does not change in the extrapolated region. Considering the DLO- effects this assumption need not be fulfiled.
The maximum allowed testing temperature is limited by the range of chemical stability or by any thermodynamically transition in the cable material, like glass transition (Tg), melting point or material softening. If between the test and service temperature occurs such a phenomena the testing would be in this case not very reliable. A very good tool, which can easy and fast find out if such a process appears in the temperature of interest is differential scanning calorimeter (DSC). DSC records all processes, which are joined with heat consumption or evaluation. Since all considered transitions or processes are either exothermic (oxidative degradation, etc.) or endothermic (melting, Tg-point, etc.), the benefit of using DSC is quite evident.
A very important parameter of the Arrhenius model is the activation energy (E_A). From its position in the Arrhenius equation is clear, that small change in the E_A value causes great changes in the test time. An established and generally acceptable method [5] used in the cable industry for estimating of single value of E_A consists in accelerated ageing of cables in thermal chambers at various temperatures for different times and subsequent determination of their mechanical properties. From the ageing curves, which show the plot mechanical properties vs. time of ageing, the points of 50 % decline of prime elongation at break for different temperatures are determined. The E_A is than calculated according the equation. This procedure, in spite of its best reliability, is often not acceptable, it takes too much time.
Therefore it is advisable to accelerate the process of E_A determining. The conventional method can be accelerated by temperature or by oxygen pressure increase [6]. Another way is to use thermal analysis: the thermogravimetry or diferential scanning calorimetry [7, 8]

It must be mentioned, that the degradation process of commercial polymers is usually a sum of several multistage, overlapped reactions that involve several compounds besides material - antioxidants, stabilizators, fillers, pigments etc. and these reactions have several different activation energies. Besides, the chemical reactions of solids are often complicated by physical processes (diffusion, sublimation, adsorption – desorption, etc.), which are also characterized by their own activation energies. The relative contributions of these individual steps to the overall reaction rate tend to vary with temperature and extent of conversion [9]. Therefore, the effective E_A, which is determined from the overall data and is generally a function of these variables, can vary with the testing conditions. It is obvious, that the determination of E_A by various methods, when measured different properties, can lead to different results [10]. Considering these facts the E_A should be determined by evaluating the changes of such a property, which will be also used as the acceptance criterion after the testing. For calculating E_A from the thermal endurance curves should be used the same change of selected property as will be the acceptance criterion (e.g. 50 % elongation at break). Also the temperature of E_A determination should be not too far from that, which will be under service.

4. Dose rate effects

In plant environment, for most cable materials, the polymer oxidation is the main degradation mechanism. A significal feature of this mechanism may be dose rate effect which can be defined as an effect on a material that differs in magnitude or type (for the same absorbed dose) according to the irradiation rate. Physical dose-rate effect is caused largely by DLO, while chemical dose-rate effect occurs whenever a rate-limiting step in the oxidation exists during experimental time, e.g. breakdown of intermediate hydroperoxide species or the long lived radicals reactions in polymers.

In a compilation of the radiation stability of polymeric materials [11] have been mentioned the dose rate effects in typical cable materials – low density, high density and chlorsulfonated polyethylene, ethylene vinylacetate copolymer, polyvinyl chloride, silicon and chloroprene rubber. In our study of the oxidation-induction time profiles in EPR/EVA cable compound and HDPE material irradiated in air at dose rate in a range of 0.008 – 8.55 kGy/h the dose rate effects have been explicitly demonstrated [12]. The dose to equivalent damage of 1 mm thick HDPE sample was about 10 – times higher at dose rate of 1 kGy/h than at the dose rate of 0.01 kGy/h.

It should be accentuated that dose rate effects are also generally of potencial significance for DBE simulation.

5. DBE and post DBE simulation

For safety – related cables the DBE and post DBE simulations follow after usually 40 years operational ageing simulation. We will discuss here the generic accident environmental profile given in EPRI EQ Manual [13], Figure 6.28 "Typical PWR combined LOCA/MSLB in – containment profile" and the results of the accidental dose calculation for SURRY NPP published in NUREG/CR – 5175 [14].

On base of these accidental dose calculations we have calculated the average dose rates for gamma and beta radiation, respectively. We have separated the DBE and post DBE into following periods, which are schematically shown in Figure 1:

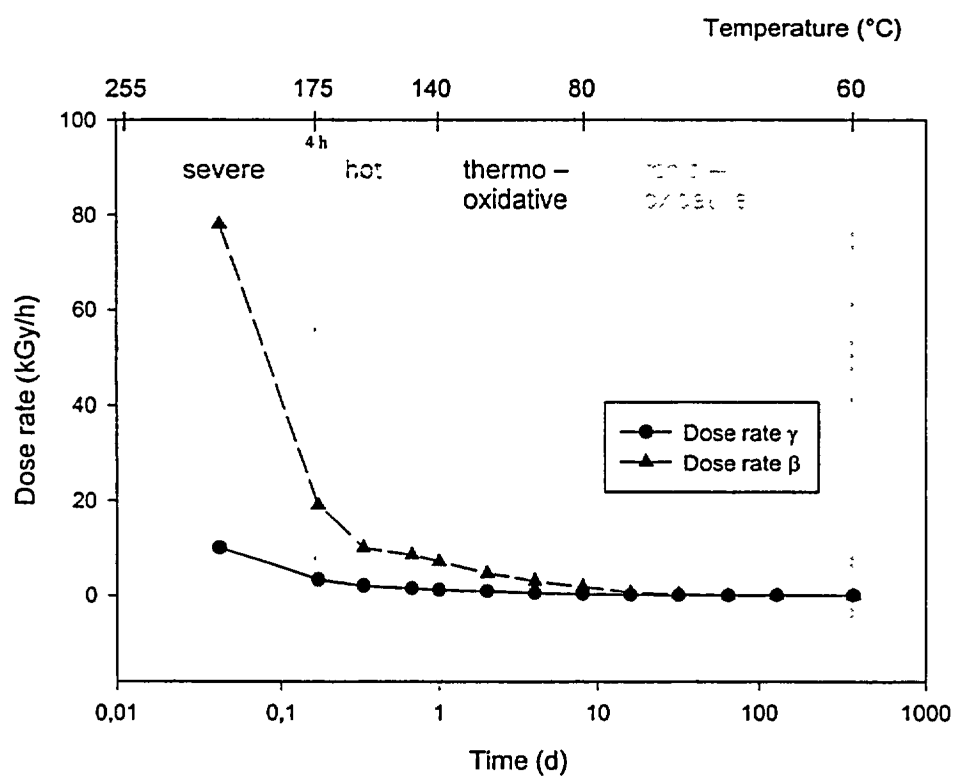

Figure 1. Schematic separation of DBE and post DBE

- Severe – characterized by saturated steam shock followed by steam – chemical exposure and simultaneous radionuclide release into containment. Duration of this period is about 4 hours with high pressures, corresponding to 175 – 255 °C saturated steam, gamma and beta radiation with dose rates in a range of 3.2 – 78 kGy/h up to total dose of 170 kGy (Table 1). The average energy of gamma radiation is ~ 1 MeV and beta radiation ~ 0.45 MeV. Ageing of cables may run typically heterogeneous oxidation with severe surface stress due to high beta radiation absorption and simultaneous radiolytical effects in complex chemical system with spray solution aerosol.
- Hot – characterized by high pressures of 140 – 175 °C saturated steam and high dose rates of ionizing radiation (1.2 – 10 kGy/h). Cables undergo combined radiation/thermal heterogeneous ageing with heavy surface stress in cable jacket. Duration of this period is 20 hours, hence thermal load becomes significant. At the end of the first and the second period a total radiation dose is significant ~ 360 kGy, but only about 50 kGy belongs to high penetrative gamma radiation.
- Thermo-oxidative – characterized by enhanced temperature in a range of approximately 80 – 140 °C during 2 – 8 days after initiation of accident. Dose rates of gamma radiation are in a range of 0.3 – 1.2 kGy/h and in conjunction with enhanced temperature may form appropriate conditions for homogenous oxidation, depending on individual cable type. The effect of beta radiation on cable degradation will diminished even more than in previous periods because lower average energy ~ 0.2 MeV of beta radiation leads to practically complete absorption on surface of cable jacket not deeper than 0.3 mm. Total dose for this period includes 72 kGy for gamma radiation and 414 kGy for beta radiation.
- Radio-oxidative - long term period with low dose rates both gamma and beta radiation at moderated temperatures around 60 °C. The cables will undergo homogenous radio-oxidation in moisture during ~ 360 days at the dose rates of gamma radiation ~ 20-100 Gy/h to total gamma dose ~ 250 kGy. The effect of beta radiation may influence only surface of cable jacket with a total dose ~ 630 kGy.

These results lead to an important conclusion, namely, the DBE and post DBE should be simulated in two gamma irradiation regimes – high dose rate irradiation at more than 2 kGy/h and low dose rate irradiation at less than 0.1 kGy/h. The first regime leading to heterogeneous oxidation and followed by thermodynamic DBE simulation may be appropriate solution of the severe and hot periods. The second regime should simulate long term post DBE under homogeneous oxidation conditions. This conclusion is not practical for the testing but enables to simulate DBE and post DBE more realistically.

An uncertainty is the role of beta radiation on cable degradation. Considering fact that virtually full beta rays absorption is achieved within jacket surface we may suppose that cable functionality will not be jeopardized. Beta radiation dose of ~ 300 kGy at energy of 0.45 MeV will be absorbed in thickness less than 1.5 mm followed by dose absorption of ~ 1MGy at 0.2 MeV in thickness of ~ 0.3 mm. If average cable jacket thickness is 2 mm, it is obvious, that influence of beta radiation on cable degradation will be limited on jacket material, which has for cable functionality a second-rate importance. Nevertheless, it has to be taken into account. Hence, a research of an influence of soft electrons on polymer degradation is necessary for better understanding of cable behavior under accidental conditions.

The DBE and post DBE separation into four periods is quite schematic with a goal to analyze a load of cable during accidental conditions and elaborate proposal for more reliable DBE and post DBE simulation under that the cable survival may be verified. It should be accentuated that further issues as synergistical effects of temperature, radiation, humidity and high pressure in course of DBE and post DBE exist and their understanding is necessary.

Time h/(d)	Dose rate (kGy/h)		Dose (kGy)			Energy (MeV)	
	$\dot{D}_\gamma$	$\dot{D}_\beta$	Total	D_γ	D_β	E_γ	E_β
1	10	78	88	10	78	1.0	~ 0.45
4	3.2	19	170	19.4	150.6		
8	2	10	219	27.4	191.6		
16	1.5	8.5	298	39.4	258.6		
24	1.2	7	363	49	314		~ 0.2
48	0.9	4.5	489	70.6	418.4		
96/(4)	0.5	3.0	659	94.6	564.4		
192/(8)	0.3	1.8	851	123.4	727.6		
384/(16)	0.1	0.6	996	142.6	853.4		
768/(32)	0.05	0.3	1145	161.8	983.2		
1536/(64)	0.03	0.03	1414	184.8	1229.3		
3072/(128)	0.03	0.03	1506	230.9	1275.1		~ 0.2
↓	↓	↓					
8760/(365)	0.02	0.03	1729	373	1356	1.0	~ 0.2

Table 1. LOCA Radiation Parameters for the Surry NPP (steam generator A cubicle, case 2) [14]

6. Cable ageing management in Czech Republic

Czech Republic has operated Dukovany NPP (WWER 4x400 MW) since 1981 and just starts up the operation of 1. unit Temelín NPP (WWER, 1000 MW).

EQ of the Dukovany NPP cables proceeded from the condition reflecting the history of construction and service of the plant which meant limited availability of technical documentation, lack of stored original cables and control deposite samples from plant operation. The initial work had to proceed from the determination of activation energy of insulation and jacket materials. The circumstance that majority of the cables materials was made on base of polyvinylchloride

(PVC) has resulted in a number of experimental works tended to finding the dose rate effects and the sequence of radiation/thermal ageing effects. The method based on the oxidation-induction time determination of cable microsamples enabled to assess the cable lifetime in EDU. This technique was published earlier [1] and the results of the cable qualification [15] were committed to the owner (ČEZ plc., Prague).

Our experience indicates, that EQ results have a high degree of uncertainty in the prediction of the qualified life. The reasons are largely high acceleration factors for thermal and radiation ageing, significant dose rate effects and complicated DBE simulation. Therefore, we have started on-going qualification with environmental monitoring in 1. – 4. unit Dukovany NPP[16,17]. The following environmental parameters were observed:

- Temperature by using termometer with Ni thermocouple, type COMETER (battery powered pocket datalogger) enabling graphic processing of experimental results on PC. Temperature was measured after 6 or 12 hours in different locations during one reactor period about 1 year.
- Dose rate of ionizing radiation by using dozimetric system alanine/EPR. Alanine dozimeters were placed in about 100 locations.
- Fluxes of thermal and fast neutrons by using cobalt and nickel foils, respectively, in 10 locations.
- Relative humidity by using battery powered datalogger with PC input.

The dose rates values were in a range of 0.02 – 0.7 Gy/h, the maximum thermal neutron flux was 5×10^5 n/cm^2.s, the maximum fast neutron flux was 4×10^4 n/cm^2.s. As a hot spots were found various positions in steam generator box where a temperature more than 80 °C were measured and dose rates were in range of 0.1 – 0.4 Gy/h. The record of temperature course in Dukovany NPP is shown in Figure 2. The values in Gy are the total absorbed dose of ionizing radiation after one reactor operational period measured in individual positions.

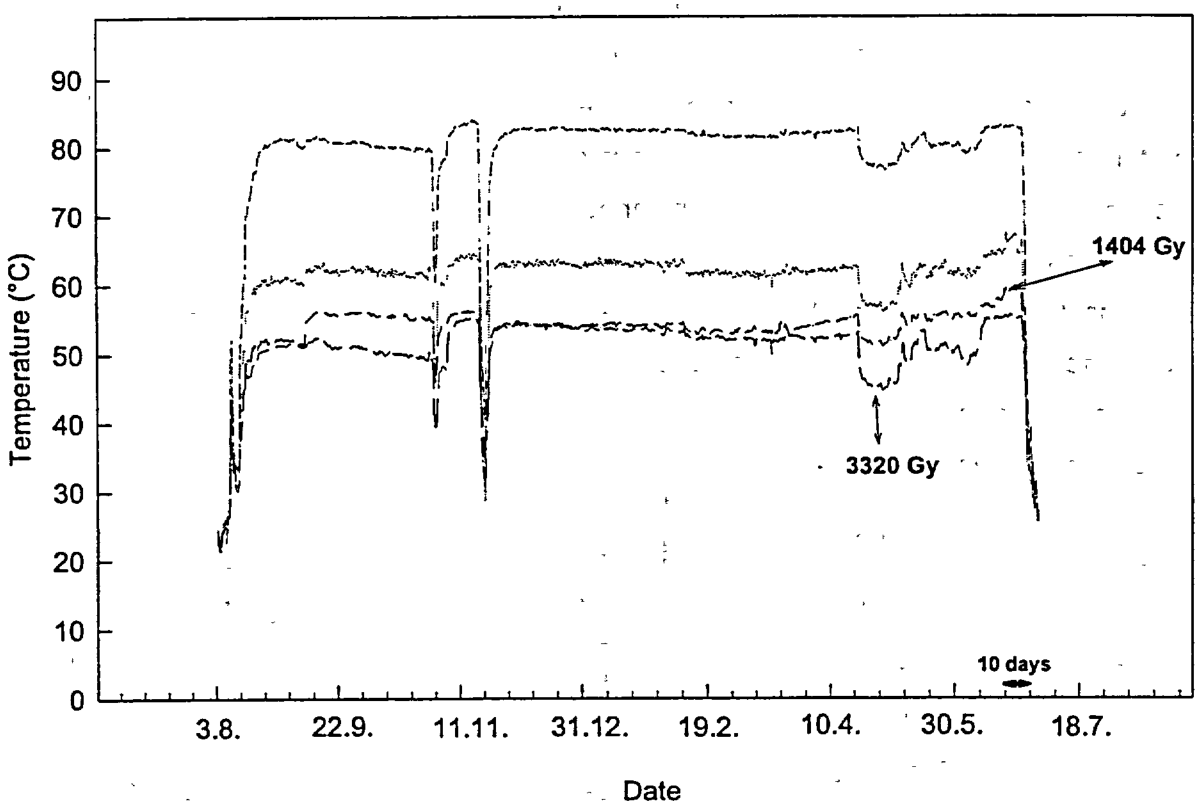

Figure 2. Temperature monitoring in steam generator box [15]

For on-going verification of the safety-related cable lifetimes, the cable deposit in steam generator box is under construction. About 10 safety-related cables reprezentative (10 m in length) will be simultaneously aged at 80 °C and at dose rate lower than 10 Gy/h. The combined radiation and thermal ageing under appropriate parameters will enable a new low intensity cobalt irradiation chamber PANOZA. This irradiation arrangement is planned for long-term irradiation of massive equipment, e.g. long cables, cable penetrations and splices, pumps, motors, etc. at enhanced temperatures up to 100 °C.

In Temelín NPP, four cable deposits were installed in both units. The ring-shaped cable deposits are located at the leg between the reactor vessel and the steam generator (Figure 3). Temperature and humidity monitoring (by using a datalogger capable of recording temperature and humidity every 4 hours for up to one year) and radiation monitoring equipment (alanine/ESR dosimeter together with cobalt/nickel activation monitors) are installed in various deposit positions. Each ring-shaped deposit contains several safety-related cable reprezentative. Different types of these cables include low voltage control, instrumentation and power cables and one medium voltage power cable. Each cable type is deposited in 3 parts (7 m in length). One part is planned for cable sampling for the measurement of mechanical and physico-chemical properties (elongation at break, oxidation-induction time, density, etc.). Second part is planned for the measurement of electrical properties (insulation resistance, polarization index, tg δ etc.). Third part is planned for the verification of the cable survival during DBE and post DBE. The cable samples will be periodically measured and the period of measurement will be dependent on the actual elongation values. The complete DBE-simulation test will perform when the half-value dose is reached. The initial values of mechanical, electrical and physico-chemical properties were determined[18] and the first sampling after 5 years NPP operation is expected.

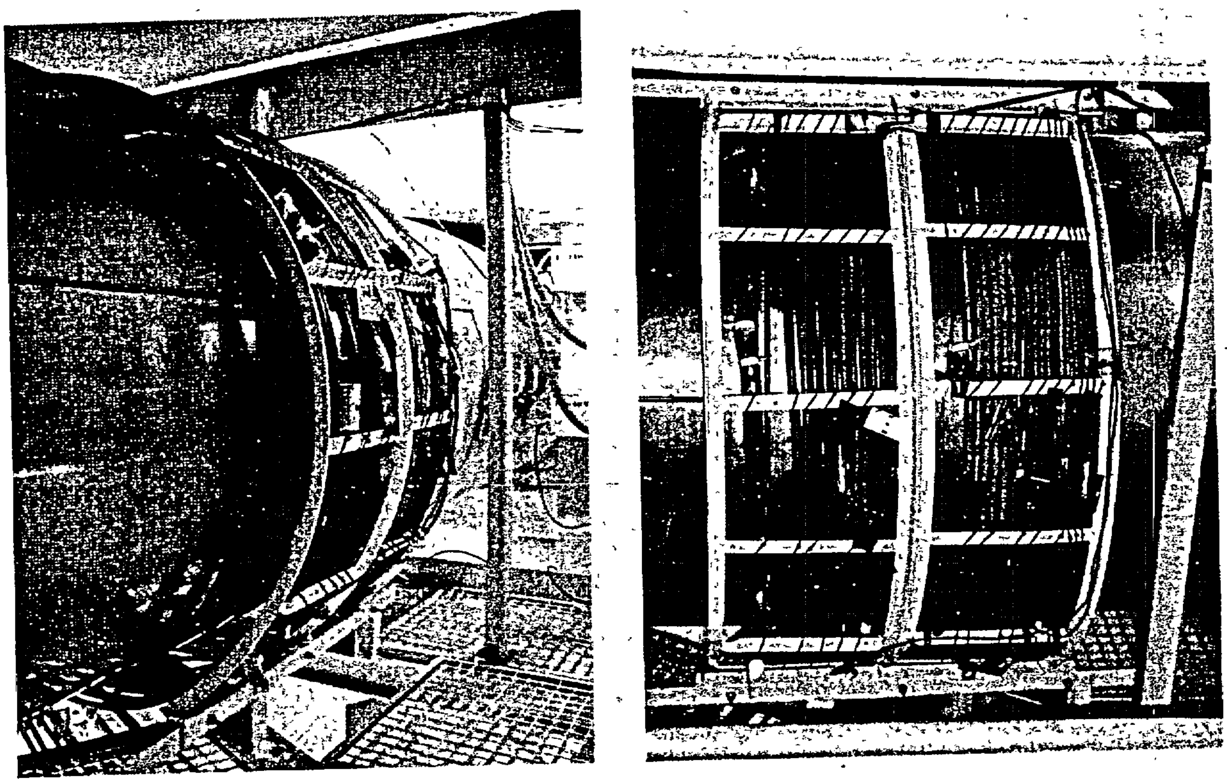

Figure 3. Cable deposits in Temelín NPP[18]

The main advantage of cable deposits is that all cables age under real plant condition which can be monitored and whenever checked. The on-going nature of a cable deposit programme means that the predictive information data are relatively reliable, subject to changes in the plant environmental conditions. Considering that in Temelín NPP there are further 5 cable deposits (except ring – shaped deposits), located inside and outside of containment, we mean that the efficient cable ageing programme has been established.

Simultaneously with the activities described above, we have started the development of the software programme for assessment of cable lifetime at each NPP location. This programme together with a cable database will be powerful tool for cable ageing management.

7. Conclusions

The main sources of the uncertainties in EQ cable testing – diffusion limited oxidation, dose rate effects, limitations of activation energy values, synergistic effects and above mentioned complex problem of the DBE and post DBE simulations – indicate that the qualification margins included in EQ tests need not ensure sufficient conservatisms. Our solution – cable ageing management programme is based on the ageing of cables located in exactly defined plant environment from point of view of temperature and radiation. The results from periodic measurements of selected mechanical, electrical and physico-chemical properties of safety-related cables representatives and knowledge of environmental conditions of individual NPP cables are basic stones for the reliable cable lifetime prediction.

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Assurance of Aged Cable Performance in Nuclear Power Applications

International Conference on Wire System Aging

April 23-25, 2002
Rockville, Maryland

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PRESENTATION OBJECTIVE

- Summarize Nuclear Power Generating Station (NPGS) Regulatory Schemes, Practices and Experience Which May Have Applicability to Aging Management in Other Infrastructure Cable System Applications

2

Potentially Shared Infrastructure Characteristics

- Highly Regulated
- Safe Operation Important to Public Health & Safety
- Aging Cannot Prevent Critical System Functionality During Normal and Upset Conditions/Situations
- Interest in Maximizing Asset Life
- Balancing of Risks and Costs

3

Presentation Outline

- NPGS Overview
- Regulations and Practices Which Can Minimize Adverse Aging Effects
- Recent Regulatory Initiatives
  - Plant License Extension
  - Risk-Based Regulatory Changes
- NPGS Research Highlights

4

NPGS Cable Systems

- Normal Operating Environments are:
  - similar to conditions in many industrial facilities
  - especially fossil fuel electric generating stations
  - notable exception: radiation
- Elastomeric Cable Materials - EPR, XLPE, Silicone, Hypalon
- Typical NPGS building general area normal operating conditions:

	Containment	Auxiliary & Turbine	Control Complex
Temperature (°C)	10 – [illegible]	[illegible] – 65	15 - 30
Pressure	Atm.	Atm.	Atm.
Humidity (%)	10 - 90	20 - 90	20 - 60
Radiation (Gy)	10 - 10^5	[illegible]	1 - 10
Corrosive Gases	minimal	minimal	none

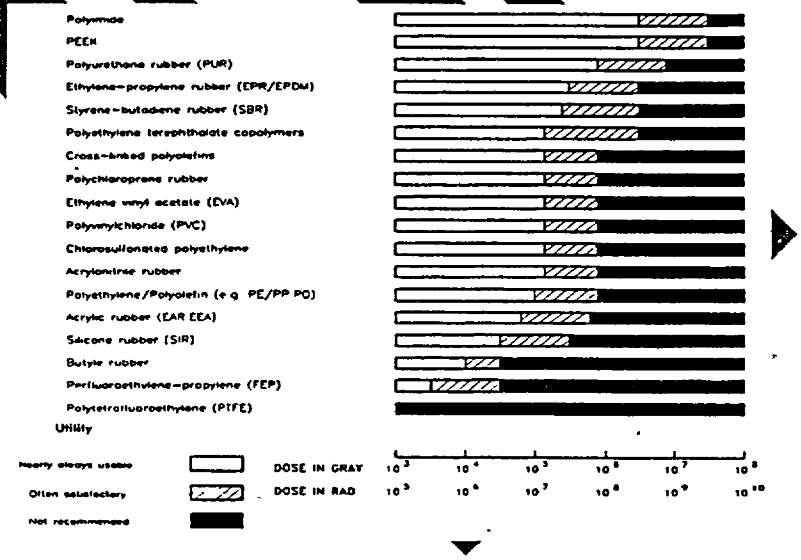
5

Cable Systems - Radiation Resistance

- Radiation conditions during normal operation - Gamma and neutron
  - Relatively benign radiation levels for cable systems in most plant areas
  - Integrated dose (40 years) typically < 1E7 Rad (1E5 Gray) in virtually all general plant areas
  - Higher levels near reactor vessel, primary piping, and some other components and piping
  - Elastomeric materials are tolerant of normal radiation levels in most cable applications
  - Cables requiring higher radiation resistance (e.g., very near reactor vessel) are typically mineral insulated (MI).

6

Cable Material – Radiation Resistance



7

Regulations & Practices Minimize Adverse Cable Aging Effects

- Cable Derating and Loading Assumptions
- Defense-in-Depth, Redundancy & Diversity
- Plant Operational Limitations and System Periodic Tests
- Quality Assurance and Corrective Actions
- Operability Evaluations
- Reporting Mechanisms
- Maintenance Rule
- NRC Oversight and Inspections

8

[redacted] Regulatio[redacted] Pra[redacted] ces
[redacted] ize [redacted] verse [redacted] Effects

- [redacted] amp[redacted] calculations [redacted] n [redacted] rous, co[redacted] incl[redacted]:
  - A[redacted]-426 [redacted] ilar ampacity s[redacted]
  - Assu[redacted] multan[redacted] y loaded
  - Load cu[redacted] cable [redacted] ilities and not a[redacted]
  - Conservativ[redacted] n tem[redacted] re (e.g., 40°C [redacted]
  - Cables assume[redacted] case [redacted] ration
- Most plant cables [redacted] pow[redacted] nstrument, & control applications
- Cumulative effect – most [redacted] ume[redacted] and control cables operate at temperatu[redacted] lly lower that their design rating (90°C).

9

Regula[redacted] & [redacted] ctices
[redacted] Minim[redacted] Adverse [redacted] ing Effects

- [redacted] h:
  - [redacted] sures [redacted] or mitigate dam[redacted] ven[redacted] cidents
  - S[redacted] depend[redacted] a single element [redacted] sig[redacted] const[redacted] ance, [redacted] tion
  - Redunda[redacted] safety [redacted]
  - Multiple-ba[redacted] ion pro[redacted] leases
  - Net effect - pla[redacted] olera[redacted] ures and challe[redacted]
- NPGS Technical Speci[redacted] 50.36[redacted]
  - Operational & safety li[redacted] for th[redacted] and it safety systems
  - Limiting conditions of ope[redacted] t prohi[redacted] longed operation with degraded safety systems
  - Periodic surveillance (test, calibr[redacted] on) requirements to demonstrate operability of safety sy[redacted] uipment

10

[redacted]egulatio[redacted]ces
[redacted]iz[redacted]dverse [redacted] Effects

- [redacted]rance[redacted]C.F.R. Par[redacted]
  - [redacted]al cri[redacted]ncluding desi[redacted]on, pr[redacted]ective[redacted]) apply to all [redacted] plant [redacted]
  - Criterio[redacted]ely c[redacted]e action and, [redacted]an conditions, [redacted]ses a[redacted]ons to prevent [redacted]e.
- Operability Eva[redacted]C Ge[redacted] Letter 91-1[redacted]
  - If nonconforming c[redacted]tified,[redacted]ding unanticipated aging or deficiency in [redacted]licens[redacted]t take specific actions.
  - Prompt determination of ope[redacted]bility, and resolution of nonconformance through co[redacted]n program

11

[redacted]egulati[redacted]ctices
[redacted]mize[redacted]dverse [redacted] Effects

- [redacted]echa[redacted]s - Multiple [redacted]ards
  Li[redacted]ion to [redacted]RC of potentia[redacted] sa[redacted]ues
- Signi[redacted]eporti[redacted]echanisms i[redacted]
  10 C.F.R P[redacted]nd No[redacted]liances – Licens[redacted]s an[redacted] contractors al[redacted]ility, ac[redacted] or basic compo[redacted]
  10 C.F.R. 50.72 - [redacted]cation[redacted]ements for enu[redacted] adverse conditions
  10 C F.R. 50.73 - Licens[redacted] Syste[redacted]me, and similar, conditions
  10 C F.R. 50.9 - Conditions w[redacted]licatio[redacted] safety
- Industry Experience Reporting –[redacted]

12

Regulations & Practices Minimize Adverse Cable Aging Effects

- NRC Maintenance Rule – 10 CFR 50.65
  - Level of monitoring based on equipment performance (plant-specific and industry)
  - Equipment and systems important to safety
  - Licensee monitoring against established goals
  - Monitoring adjusted based on performance
  - Licensee management of maintenance activities to minimize overall plant risk

13

Regulations & Practices Minimize Adverse Cable Aging Effects

- NRC Inspections
  - Resident inspectors at each NPGS, ongoing observation and inspection
  - Topical Area Inspections (e.g., Electrical Distribution System Functional Inspection)
- NRC Enforcement – Revised Reactor Oversight Process
  - Risk-Informed Significance Determinations
  - Additional Oversight dependent on Risk Significance
- NRC Generic Communications – Notification by the NRC of issues of problems of generic interest (e.g., Regulatory Issues Summary)
  - Numerous notifications of aging related equipment issues
- NRC Generic Safety Issues - (NRC Office of Research)
  - Generic Safety Issue 168
- NRC Backfitting Rule – 10 CFR 50.109 – Imposing new NRC positions requires balance of safety and burden

14

Cable Systems Performance During Events and Accidents

- NPPs designed, operated, & tested to maintain plant & public safety for a range of postulated events including design basis accidents.
- Certain cable systems supporting critical safety functions must be capable of functioning during the adverse conditions associated with some of these accidents.
- Design basis conditions most challenging to cable systems are:
  - earthquakes (cable support systems)
  - exposure fires (both transient and fixed combustibles)
  - high temperature/pressure steam & radiation from certain pipe break accidents
    examples are Loss Of Coolant Accident (LOCA) and Main Steam Line Break (MSLB)
- Earthquake tolerance established by design of cable support systems

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NPGS Fire Protection Features

- Extensive defense in depth approach to fire protection
- Plant safety for postulated fires achieved by numerous plant features
- Cables are not required to tolerate fire conditions
- Physical separation and isolation of minimum sets of safety equipment including associated cables for all postulated fires
- Applicable NRC regulations and guidance:
  - 10 CFR Part 50 Appendix A Criterion 3
  - 10 CFR Part 50 Appendix R - Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979
  - 10 CFR 50.48 – Fire Protection
- Fire protection practices have minimized the use of PVC insulated cables in NPGS

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Pipe Break Accident Protection Features

- ■ [illegible] / protection of all safety critical systems (including cables) not possible for certain pipe break events.
- ■ Certain plant systems and associated cable systems must function during these accident conditions.
- ■ Typical [illegible] accident conditions inside reactor containment building:
  - Atmosphere [illegible] steam & [illegible]
  - Temperature (peak) [illegible]°F – 340[illegible]
  - Pressure (peak) [illegible] psig – 65 psi[illegible]
  - Radiation (total) [illegible] MRd (combined Beta and Gamma)
  - Building sprays B[illegible] (pH 10[illegible]) or distilled water
  - Submergence (reactor fluid and spray) Cables [illegible] excluded from these areas
  - Duration 30 days – [illegible]

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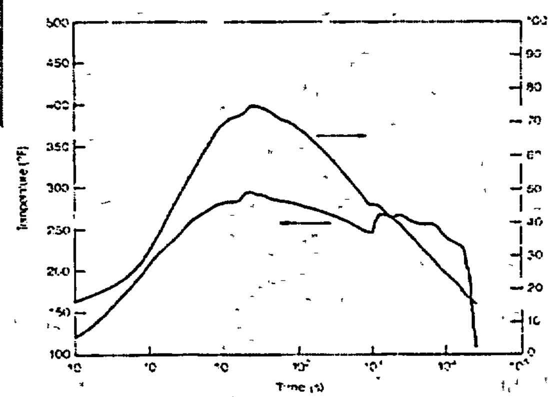
Pipe Break Accident Protection Features



- Typical Pressure & Temperature Accident Profile
- PWR double-ended guillotine break of [illegible] system piping (from EPRI EQ Reference Manual)

18

Pipe Break Accident Protection Features

- Regulations, standards, and practices require a demonstration of cable system performance during accident conditions (harsh environment)
- Since accident conditions are significantly more severe than normal conditions, aging may promote failures during accident yet not adversely affect equipment performance during normal conditions.
- Demonstration must consider the effects of in-service aging on performance during accident
- If the demonstration cannot accommodate cumulative effects of aging for the entire plant life the equipment must be periodically repaired or replaced
- Demonstration - “Environmental Qualification” or EQ
- Allowed aging duration before repair or replacement “Qualified Life”

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EQ of Cable System Components

- Applicable NRC regulations and guidance:
  - 10 CFR Part 50 Appendix A Criterion 4 - Environmental and dynamic effects design bases
  - 10 CFR 50.49 - Environmental Qualification of Electrical Equipment Important to Safety for Nuclear Power Plants
  - Regulatory Guide 1.89 - Environmental Qualification of Certain Electrical Equipment Important to Safety for Nuclear Power Plants
- Applicable IEEE Standards
  - IEEE 323 - Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations
  - IEEE 383 - Standard for Qualifying Class 1E Electric Cables and Field Splices for Nuclear Power Generating Stations
  - IEEE 317 - Standard for Electrical Penetration Assemblies in Containment Structures for Nuclear Power Generating Stations
  - IEEE 572 - Standard for Qualification of Class 1E Connection Assemblies for Nuclear Power Generating Stations

20

[redacted]EQ[redacted]Cable Sy[redacted]ponents

- [redacted] in th[redacted]ulations, sta[redacted]nd [redacted]ices a[redacted]ith es[redacted]hing and ma[redacted]g E[redacted]
- NR[redacted]-eval[redacted]n of electrica[redacted] for all operati[redacted] 197[redacted] established[redacted](10 CFR 50.4[redacted]
- Re-evaluatio[redacted]pecif[redacted] required ag[redacted] addressed.
- 10 CFR 50.49 requi[redacted]see t[redacted]ablish and maintain for the life of the plant [redacted]quali[redacted]on record permitting verification tha[redacted]ill p[redacted]erly perform when subjected to the specifi[redacted]nditions.

21

[redacted]Cable Sy[redacted]mponents

- [redacted]ystem[redacted]ponents (e.g., ca[redacted]ices,[redacted]ectors) [redacted]OCA c[redacted]ions, qualifica[redacted]ly [redacted]es s[redacted]entat[redacted]mponents to th[redacted] se[redacted]ial qua[redacted]nditio[redacted]
  - Acc[redacted]l agi[redacted]n aging) to si[redacted] temper[redacted]condi[redacted]
  - Simulatio[redacted]orma[redacted]ion using a hi[redacted]e, short time ga[redacted]xpos[redacted]., Cobalt-60 a[redacted] Mrd/hour).
  - Simulation of integr[redacted]diatio[redacted]g high dose rate, short time gamma radi[redacted](e.g., [redacted]-60 at 0.5 – 1.0 Mrd/hour)
  - Simulation of steam, tempera[redacted]pray conditions for 30 – 100 days.

22

EQ of Cable System Components

- Steam simulation test facility includes pressurized test vessel, steam boiler, and other associated hardware.
- Components must be monitored during the accident simulation to verify performance capability.
- IEEE 383 (cable and splice qualification) specifies a post-simulation mandrel bend, immersion, high potential test to demonstrate margin.

23

10 CFR 50.49(e)(5) *Aging*

- Equipment qualified by test must be preconditioned by natural or artificial (accelerated) aging to its end-of-installed life condition. Consideration must be given to all significant types of degradation which can have an effect on the functional capability of the equipment.
- “If preconditioning to an end-of-installed life condition is not practicable, the equipment may be preconditioned to a shorter designated life. The equipment must be replaced or refurbished at the end of this designated life unless ongoing qualification demonstrates that the item has additional life.”

24

NRGS License Renewal

- 1982 – NRC workshop on aging and extending plant licenses
- 1982–1995 – regulatory process results in issuance of 10 CFR Part 54 – License Renewal Rule
- 10 CFR Part 54 technical focus on passive, long-lived structures and components relied upon to maintain plant and public safety
- Per 10 CFR Part 54, licensee must perform an aging management review for passive components, including certain cable systems, as part of an Integrated Plant Assessment (IPA).
- The aging management review must demonstrate that the effects of aging will be adequately managed so that the intended function(s) will be maintained for the period of extended operation.
- Aging review must include all applicable plant cable system components
- In addition, documented aging analysis for EQ'ed cables must be revised to reflect extended plant operation per 54.21(c)(1)

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NRGS License Renewal

- 10 plants have submitted renewal applications
- 4 plants have received NRC approval
- Licensee aging management reviews have included both low and medium-voltage cable systems
- Review process typically involves evaluating:
  - Plant cable operation and maintenance history (e.g., maintenance work requests)
  - Industry cable operation and maintenance history
  - Capabilities of cable insulating materials (thermal and radiation)
  - Operating conditions at cable locations
  - Results of plant cable inspections

26

[redacted]GS Li[redacted]ewal

- [redacted]see e[redacted]have confirme[redacted]pl[redacted]bles have the [redacted]aintai[redacted]ionality throu[redacted]ne[redacted]riod.
- Ge[redacted]d lice[redacted]views confirm[redacted]xp[redacted]e:
  - co[redacted]e syst[redacted]gn and operat[redacted]
  - operat[redacted]ce, an[redacted]pment periodic[redacted]am[redacted] effective[redacted]cable [redacted] problems
  - corrective a[redacted]effec[redacted]resolving cab[redacted] problems
- Isolated, unanticipate[redacted]probl[redacted]nerally limited[redacted] localized conditions:
  - hot spots
  - mechanical damage
  - chemical/water submergence ([redacted])
- Generally licensees have identified, r[redacted]ted, and corrected cable system problems under existing re[redacted]chemes (i.e., not found during aging management reviews).

27

U[redacted]f Risk i[redacted]Regulation

- [redacted]NRC r[redacted]ions:
  - [redacted]gely o[redacted]rministic anal[redacted]
  - [redacted]ithout[redacted]itative or mea[redacted]ima[redacted]risk
  - [redacted]early[redacted]s of reactor te[redacted]nt
  - base[redacted]erie[redacted]ting programs,[redacted]nt
  - relied o[redacted]design[redacted]ins
  - used the pr[redacted]se-in-[redacted]to protect pub[redacted]nd safety
- Deterministic approac[redacted]adver[redacted]ditions can occ[redacted]d requires safety systems t[redacted]inimize[redacted]ent consequences.
- Probabilistic Risk Analysis [redacted]
  - examines a broader spectru[redacted]vents [redacted]eir frequency
  - asks "How likely is it that some[redacted]rong?"
  - analyzes and ranks the consequence[redacted]quency and associated risk

28

Use of Risk in Nuclear Regulation

- 1995 NRC PRA policy statement:
  - The use of PRA technology should be increased in all regulatory matters to the extent supported by the state-of-the-art in PRA methods and data and in a manner that complements the NRC's deterministic approach and supports the NRC's traditional defense-in-depth philosophy.

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Use of Risk in Nuclear Regulation

- In the reactor safety arena, risk-informed activities occur in 5 categories:
  - applicable regulations
  - licensing process
  - revised oversight process
  - regulatory guidance
  - risk analysis tools, methods and data
- Activities in these categories include:
  - revisions to technical requirements in the regulations
  - risk-informed technical specifications
  - new framework for inspection, assessment, and enforcement actions
  - guidance on risk-informed in-service inspections
  - improved standardized plant analysis risk models

30

Use of Risk in Nuclear Regulation

- Use of risk insights with respect to cable system aging/condition
  - Prioritize issues and concerns based on [illegible] public safety risks
  - Focus resources on those topics and cables with the greatest risk impact
  - Justify minimizing resource allocation to risk-insignificant topics and cables
  - Evaluate the risk significance of unanticipated conditions (e.g., aging)

31

Use of Risk in Nuclear Regulation

- NRC examples
  - NRC sponsored "Equipment Qualification (EQ) Risk Scoping Study" (NUREG/CR 53[illegible]) concluded that several technical issues regarding EQ practices were not safety significant.
  - South Texas Project (STP) using PRA as part of risk classification scheme has reduced by 75% the number of plant components considered to be risk-significant and modified the "special treatments" applied to these components.
  - Licensees and NRC have eliminated regulatory requirements for certain hydrogen control equipment that was deterministically required but did not effectively reduce public risk.

32

NPGS Cable Research

- Significant NRC, industry, and internationally sponsored research on NPGS cables and related cable system components
- Focus of cable research has evolved:
  - demonstrating cable performance during harsh accident conditions (initial focus)
  - effects of aging simulation methods on cable performance during accidents
  - adequacy of accelerated aging methods
  - cable condition monitoring methods and practices (recent focus)

33

NPGS Cable Research

- Research Overview documents:
  - NUREG/CR-4301, Status Report on Equipment Qualification Issues Research and Resolution – summarizes most Sandia National Labs qualification and aging research prior to [illegible]
  - EPRI Report TR-[illegible], Nuclear Power Plant Equipment Qualification Reference Manual, Chapter 13 identifies EPRI and other EQ-related research prior to 1992.
  - NUREG/CR-6384 Vol. 1, Literature Review of Environmental Qualification of Safety-Related Electric Cables, Summary of Past Work provides a more recent look at NPGS qualification and aging research

34

[illegible]PG[illegible]Cable R[illegible]Results

- [illegible]on-at-[illegible] remains an [illegible] be[illegible]ark for [illegible]g mat[illegible]ondition.
  - [illegible]nditi[illegible]ngation & fl[illegible] is g[illegible] pre[illegible]oltag[illegible]le capabilitie[illegible]or[illegible]d accide[illegible]
  - Except fo[illegible]ion, c[illegible]nsulating ma[illegible]h s[illegible] residual flex[illegible]equa[illegible]nction durin[illegible] radiation and s[illegible]ons.
  - Chemical and phy[illegible]ften [illegible]d by excessiv[illegible]ging acceleration, can co[illegible]rrela[illegible]f accelerated and natural aging for both r[illegible]erma[illegible]g conditions.
  - To best approximate natur[illegible]erate[illegible]ing simulations should minimize [illegible]f acceleration by reducing temperatures and dose [illegible]tending exposure times.

35

[illegible]PG[illegible]Cable [illegible]h Results

- [illegible]er o[illegible]e condition [illegible]g [illegible]ods are [illegible]o est[illegible]h physical/m[illegible]l c[illegible]condition [illegible]" cab[illegible]es.
  - Ele[illegible]etho[illegible]etermine "[illegible]n[illegible] do not ap[illegible]e for [illegible]voltage uns[illegible]bl[illegible]
  - Knowled[illegible]ste[illegible]rating condi[illegible] important to[illegible]usin[illegible]g managem[illegible] activities.
  - Operating conditi[illegible]n co[illegible]d with knowledge of comp[illegible] cap[illegible]ies useful for determining the need f[illegible]ging[illegible]agement activities.
  - Cable system inspections at p[illegible]entified selective locations can be informative ab[illegible]verall system condition.

36

Aircraft Wiring System Integrity Initiatives- A Government and Industry Partnership

10 Oct 2001

George Slenski
Materials Directorate
Air Force Research Laboratory

Presenter: David Johnson,

Introduction

- Wiring is a complex and critical system
  - Increased emphasis on avionics, fly-by-wire, glass cockpit
  - 150 miles of wiring & over 500 connectors in a transport
  - Continuous exposure to harsh environments
- AF maintenance databases provide inadequate insight into wiring system issues
  - Navy reported in 1999 62,000 maintenance events due to wiring system- $20M+ cost
  - Review of F-16 data in 2000 revealed over 900 documented wiring failures -many failures not recorded
  - Analysis of ten years (89-98) of AF mishap data show 43% of the 271 mishaps attributed to electronics were related to wiring systems
  - One failure this year required 45 days to repair damage- replacement part cost $190K
- Current wiring maintenance is reactive- practice is to fly to failure.
  - Common to AF, Navy, NASA, and FAA (documented in White House Report)
- AF Wiring integrity summer 2000 study revealed
  - Wiring failures creating extensive downtime during troubleshooting (2-3 days)- LRUs replaced three times before wiring considered
  - No effective field level diagnostics capability exists- limited to a multi-meter
  - Inspections and troubleshooting limited to visual invasive techniques
  - No permanent repair options are available

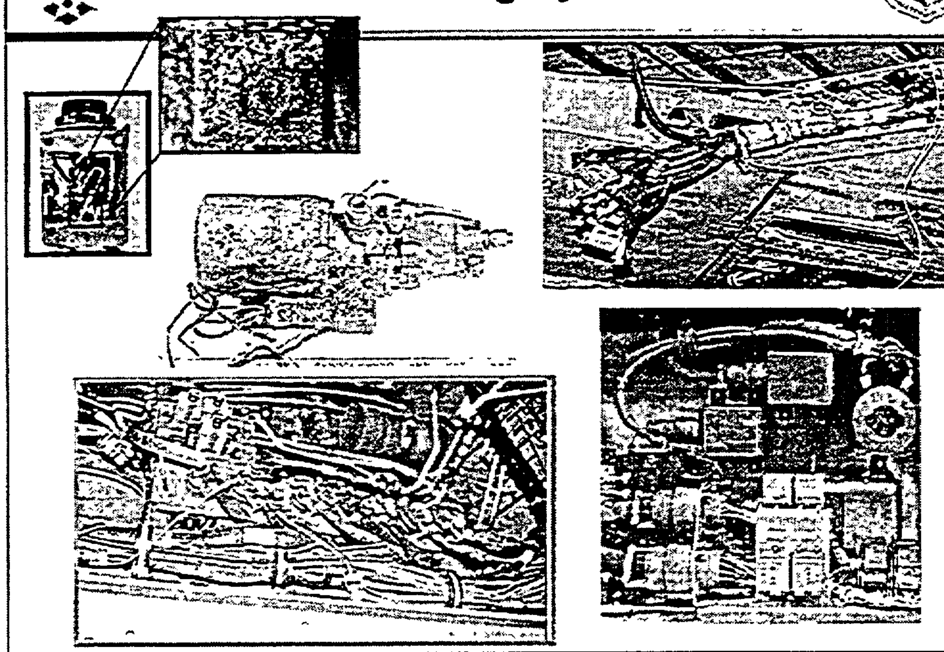
2

Aging Wiring Defined

- Wiring is just one part of the electrical interconnection system
- Components that make-up the wiring system include:
  - Power and control conductors, signal and instrumentation conductors, fiber optic cables, connectors, circuit breakers, relays, power distribution and control panels, and generators
- Aging wiring systems can result in degraded performance due to accumulated damage from long-term exposure
  - Damage is from chemical, thermal, electrical, and mechanical stresses
  - Stresses are often induced by the operational environment installation or maintenance practices

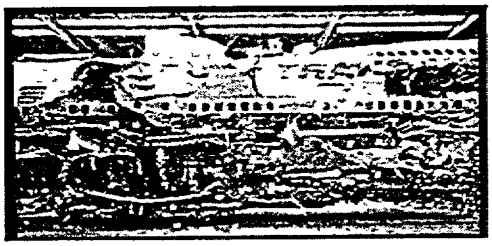
3

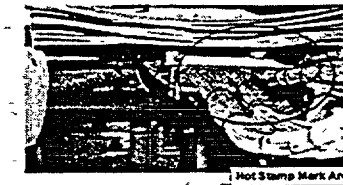
Wiring System



4

TWA 800 INVESTIGATION





NTSB investigation findings:

- Identified wiring damage in areas traditionally not inspected, showed visual inspection limitations in locating wiring defects
- Showed how a low voltage electrical system could become a fuel ignition source
- Aging/degradation in wiring and other electrical systems documented

5

Space Shuttle Independent Assessment Team Summary

- In-flight mishap could have resulted in loss of vehicle
- Shorted wire found
- Shuttle program grounded 4 months

1999 Shuttle mission STS-93 experienced loss of two main engine controllers 5 sec. after launch

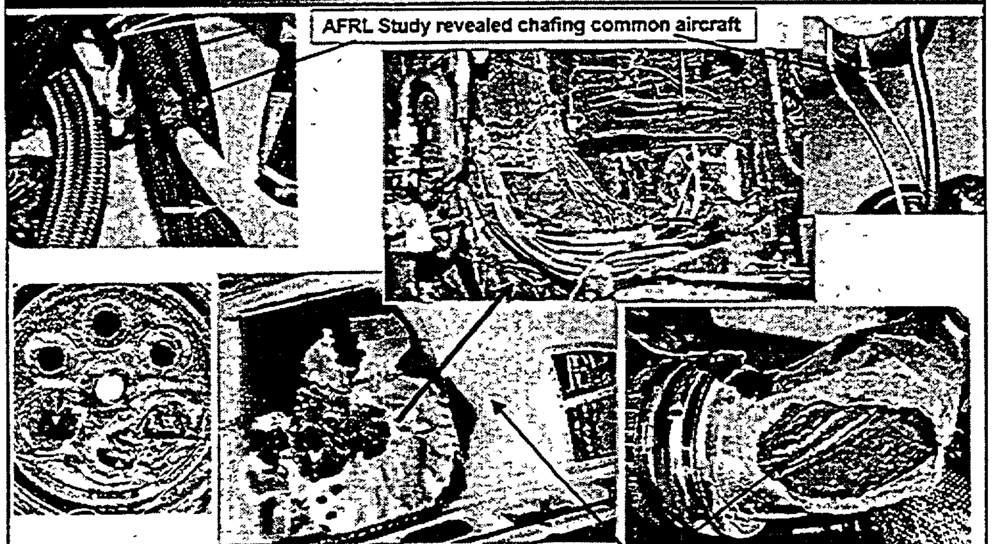
- Established damage was a pre-existing condition
- Determined wire was damaged during a maintenance action
- Inspection revealed hundreds of wiring damage sites from installation and handling

Shuttle wiring inspection by AFRL personnel

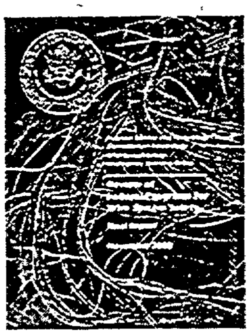
- Aging of wiring has occurred due to handling damage, environmental damage, chafing/vibration, exceeding wire bend radiuses, and the large number of wire repairs
- Visual inspection of wiring is inadequate
- Single point failure conditions exist in wiring which compromises system redundancy

6

The Need for Improved Wiring Integrity for AF systems



Aging Wiring Safety Interagency Working Group (IWG)



- Chartered to identify wire system safety issues common to various federal programs
  - White House Initiative in 2000
  - OSTP, DOT (FAA, FRA, FTA, US Coast Guard), DoD (AF, Navy, Army), NASA, NRC, UL, etc
  - Provide technical guidance to federal agencies
  - Identify common efforts, gaps, and overall needs
- Final Report sent to President in November 2000

IWG Report Summary

- Wire system safety is a national public health and safety issue that transcends government agencies
  - Develop national strategy
- Maintain a focused and disciplined approach among industry and the government
  - Understand failure and aging mechanisms
- Develop standardized design tools - models
- Improve damage prevention with diagnostic and prognostic tools
- Promote proactive technology development and deployment
  - Repair technologies, interconnection technologies, and new materials

Recommendations

- Four basic strategies are necessary to improve wire system safety:
  - Alter the perception of wire systems.
  - Increase collaboration between industry, academia, and the government.
  - Improve the management and functionality of wire systems.
  - Improve wire system technology.

From: The Review of Federal Programs for Wire System Safety dated November 2000

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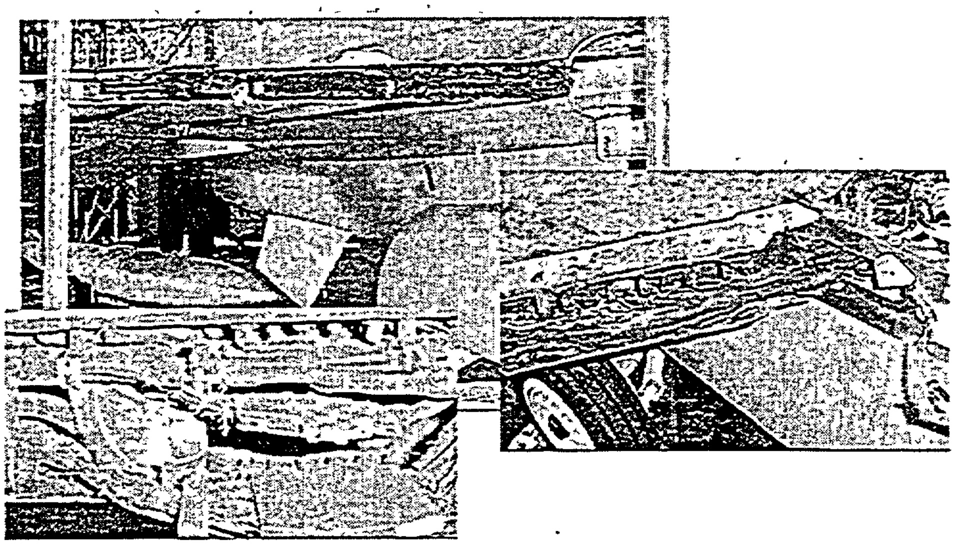
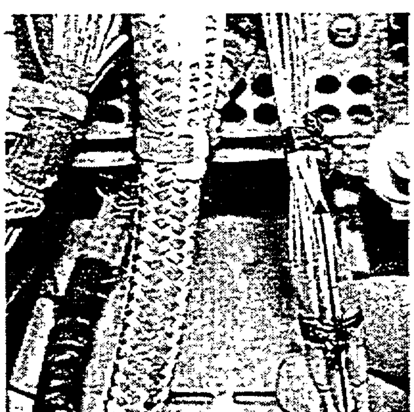
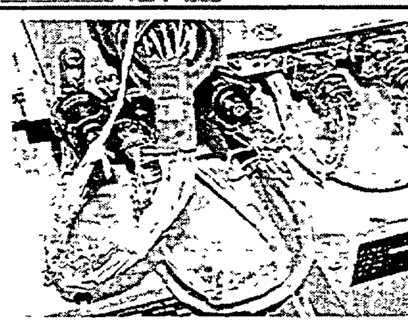
In-flight Aircraft Wiring Mishap

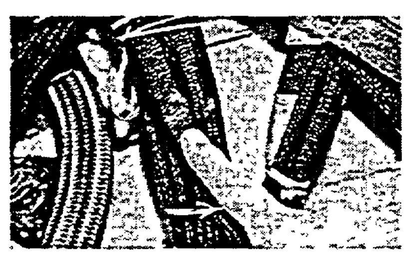


11

Wiring Installation Issues







Avionics Wiring

Crack in Wiring

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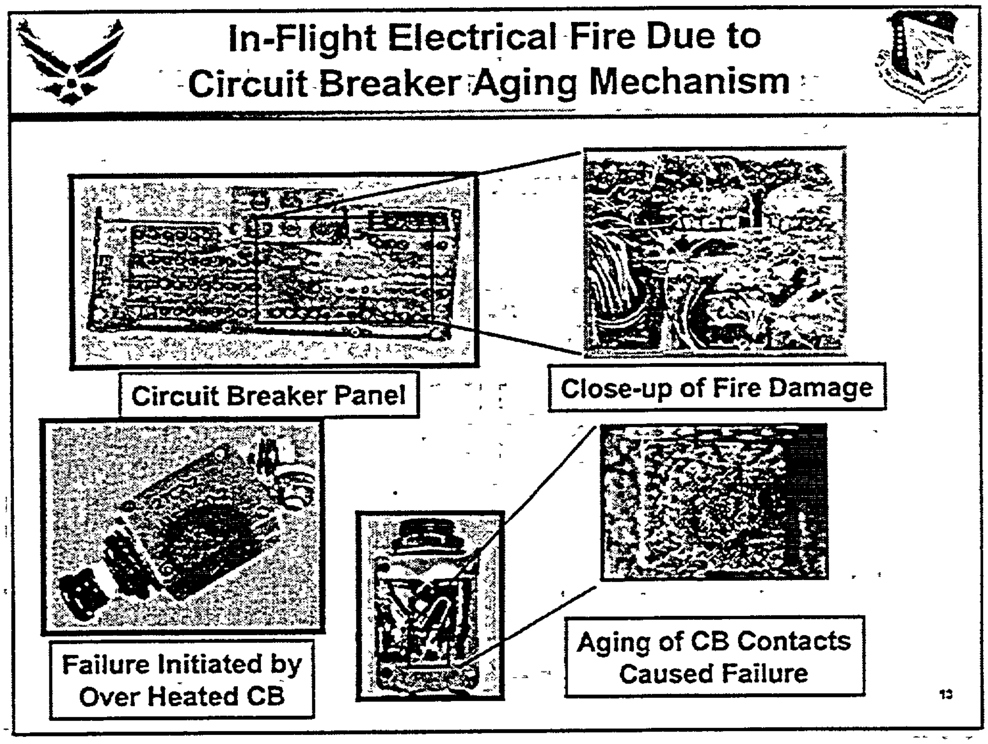
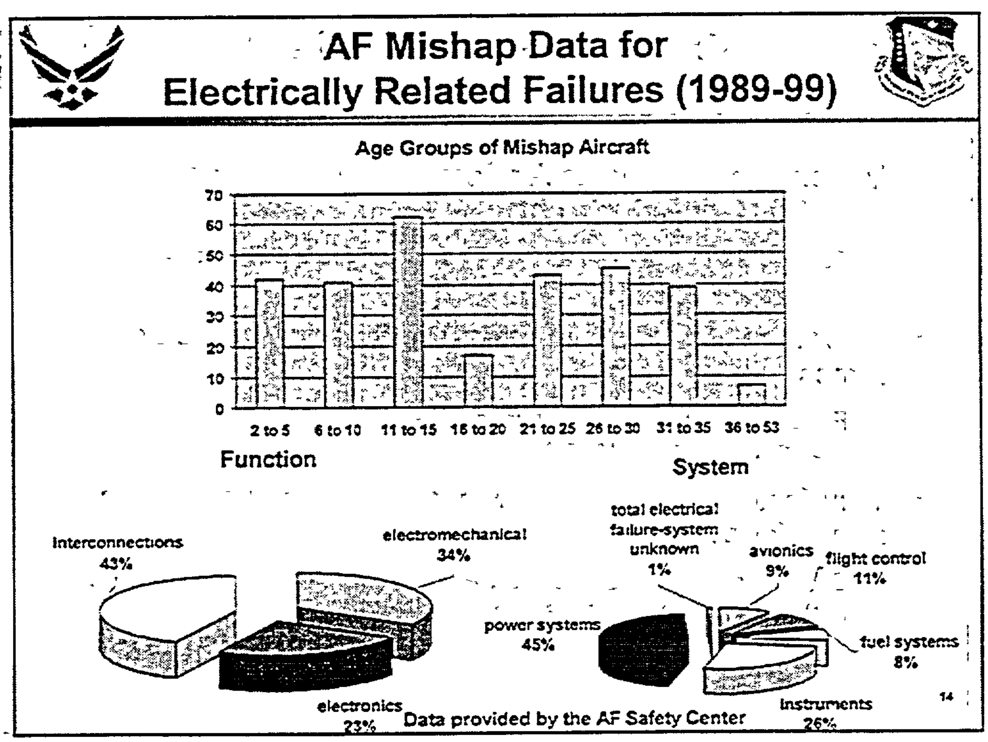
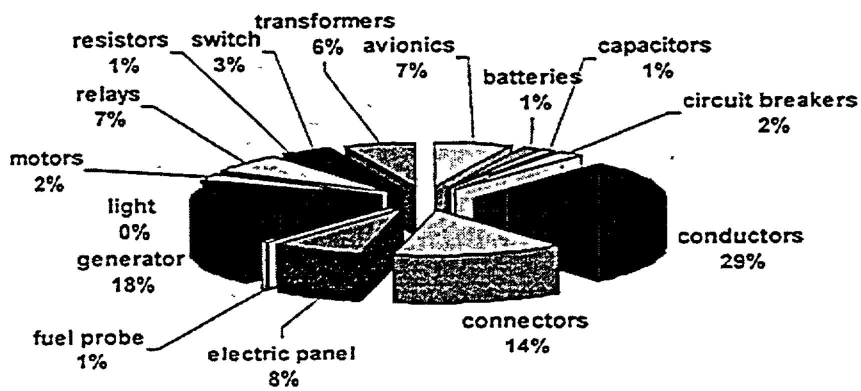

In-Flight Electrical Fire Due to
Circuit Breaker Aging Mechanism
Circuit Breaker Panel
Close-up of Fire Damage
Failure Initiated by
Over Heated CB
Aging of CB Contacts
Caused Failure
13


AF Mishap Data for
Electrically Related Failures (1989-99)
Age Groups of Mishap Aircraft
70
60
50
40
30
20
10
0
2 to 5
6 to 10
11 to 15
16 to 20
21 to 25
26 to 30
31 to 35
36 to 53
Function
interconnections
43%
electromechanical
34%
electronics
23%
System
total electrical
failure-system
unknown
1%
avionics
9%
flight control
11%
power systems
45%
fuel systems
8%
instruments
26%
Data provided by the AF Safety Center
14

AF Mishap Data for Electrically Related Failures (1989-99)

Components Contributing to AF Mishaps



Data provided by the AF Safety Center

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Aircraft Electrical Failure
Background

- Aircraft operated by the Air Force have experienced partial loss of D.C. power in flight
  - 40 Ampere circuit breakers tripped (provides the D.C. power to instruments and other avionics)
- Failures related to overheated 10/12 gage wire butt splice crimps
  - Field inspection of the butt splices revealed the insulation covering the splices was overheated
- Manufacturers provided new butt splice and ring terminal crimps for evaluation
  - Crimp termination resistance was measured and representative samples were pulled to failure

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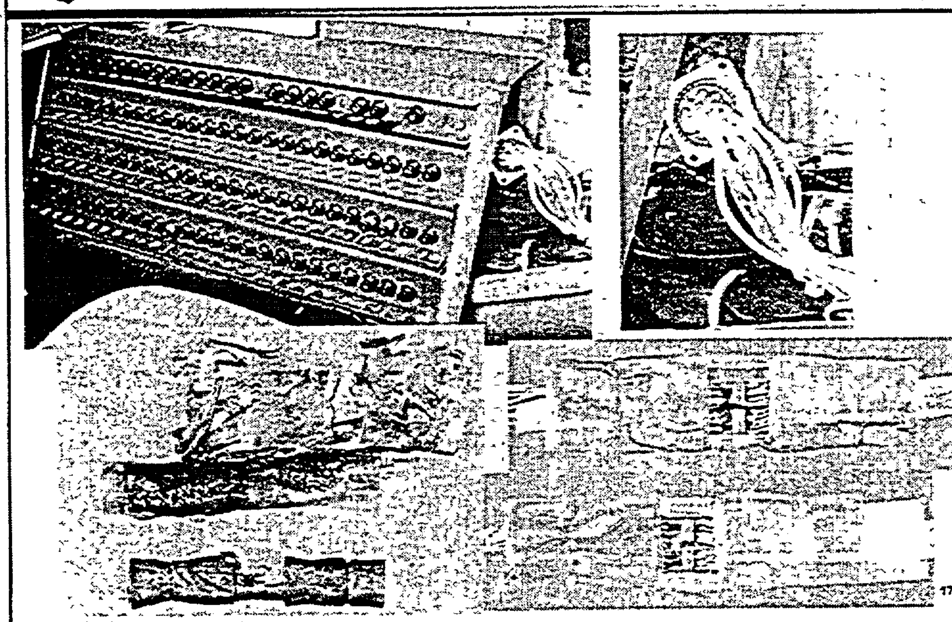
Splice Failures



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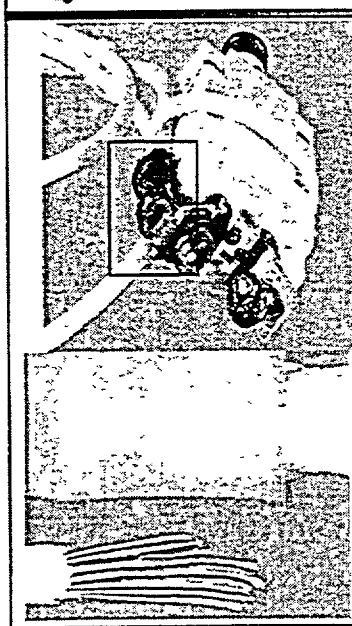
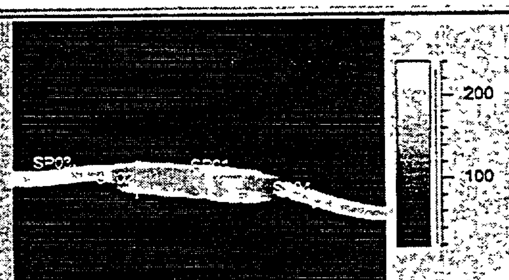
Crimp Connections





SP01-246 C, SP02-211 C, SP03-206 C, SP04-189C
10/12 butt splice from the field J237 pin F at 45A,

Tripping of the 40A D.C breakers is due to load currents and heat generated by high resistive ring terminals and nearby butt splices

- A gas tight interface is not being formed in the crimp terminals
- 12 gage wiring provides inadequate heat sinking for the breaker
- A high resistance crimp connection leads to I²R heating that propagates heat into the 40A CB causing it to trip
- Inadequate crimps are the result of minimum diameter wire conductors and the type of tool used to form the 12 ga crimp
- Crimp tool, even when used correctly, creates marginal or inadequate crimps on 12 ga. butt splices and ring terminals

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Aircraft Electrical Failure Conclusions

- Electrical failure was due to the interaction of the aircraft current loads, terminations, wiring, connectors, and circuit breakers
- Maintenance community considered periodic replacement of terminations and circuit breakers a standard practice
- Engineering community was unaware of the failures- due to the ineffective data reporting process
- Both communities were also unaware of the changes that had occurred in the wire and crimp tool or the increased avionics loading that had occurred over several years

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What can We Learn From This Incident?

- Electrical failures rarely result in the loss of an aircraft
  - Robust designs and materials are used and we have well trained aircrews
  - Electrical failures can place stress on the aircrew and impact mission effectiveness
- Present maintenance philosophy is reactive
  - Aging/degradation of electrical systems not emphasized
  - Wiring system components treated as inexpensive commodities
  - Maintenance data collection does not give insight into wiring system failures
- Wiring system integrity is dependent on the interaction of linked components
  - Power and signal distribution components make up a complex system
  - Changes (over time) in power requirements, mission use and component design, manufacturing and materials can affect system integrity

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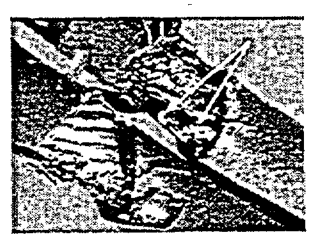
How Do We Improve Wiring Integrity?

- Move from a reactive to a proactive wiring system maintenance approach
  - Technologies to make this a reality are available
  - Infrastructure to make them successful has yet to be fully developed
- Use a industry and government team to:
  - Apply new technologies and assess their effectiveness
  - Accelerate implementation of the most promising technologies
- A proposed strategy is to develop research initiatives in five broad technology areas
  - Failure characterization, diagnostics, new materials, interconnection technologies, and maintenance tools

Aging Wiring System Emphasis Areas

- Failure Characterization
  - Time dependent failure mechanisms/models
  - Degradation mechanisms- electrical effects
  - Defect sensitivity/sizes analysis



- Diagnostics/Detection
  - Nondestructive evaluation techniques
  - Prognostics
  - Sensors (MEMs)
- New Materials
  - Conductors (polymer replacement for copper)
  - Insulation (more robust with balanced properties)

Aging Wiring System Emphasis Areas

- Interconnection Technologies
  - Circuit breakers (arc fault sensitive)
  - Relays and switches (MEMs technology)
  - Connectors (resistant to corrosion, maintains electrical bonding resistance and minimizes the use of heavy metals)
  - Fiber optics and wireless communication
- Maintenance (Managing aging wiring)
  - Tools for collecting wiring component field data
  - Systems for documenting and monitoring wiring system architectures and performance requirements
  - Extended and predictable failure-free operating periods
  - Development of permanent repair technologies

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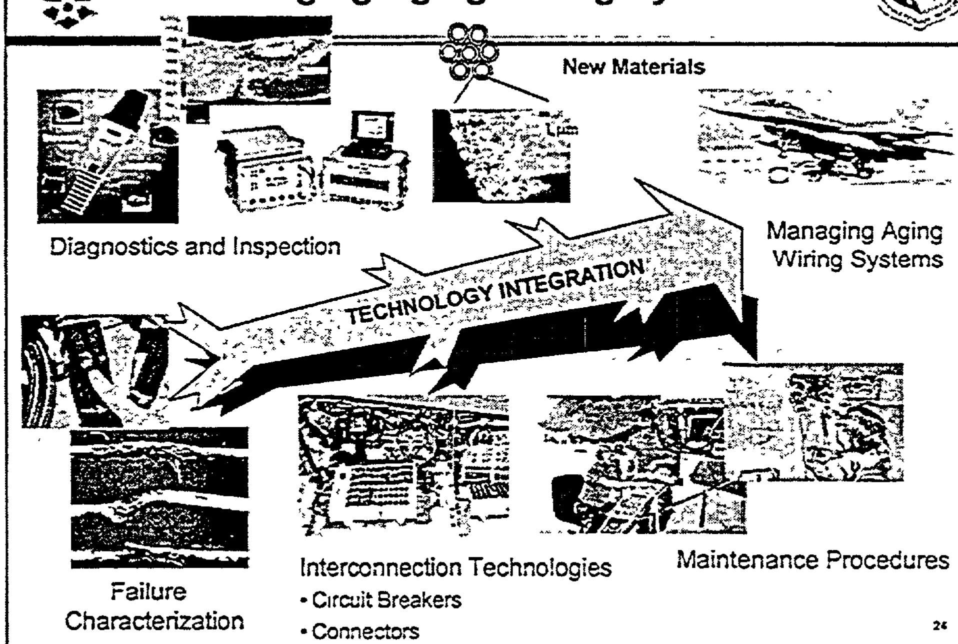
Managing Aging Wiring Systems



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USAF WIRE INTEGRITY TESTER TRIALS

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Improvement of Wire System Integrity for Legacy Aircraft

Sponsor: AF Aging Aircraft SPO

Funding:

FY01	FY02	FY03
435K	300K	100K

Start Date: 26 January 2001

PURPOSE: To place a wire integrity system directly into the depot and field which will allow the Air Force to effectively manage wiring as an aging sub-system.

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Objective & Status (Completed)

- ✓ Conduct surveys to ascertain the extent of wire system failures, types of failures, and typical failure locations on the F-16 aircraft.
- ✓ Review current F-16 wiring system diagnostic techniques and obtain maintainer input regarding current field and depot equipment.
- ✓ Build laboratory test beds using fault induced harnesses with wire types characteristic of those found on F-16 C/D aircraft.

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Objective & Status (Current)

- Evaluate handheld (2) and portable wire/harness technologies (10) against the laboratory test bed.
- Evaluate handheld and portable wire/harness technologies against actual F-16 harnesses in the laboratory.
- Evaluate handheld and portable wire/harness technologies in the field.
- Compile data and assemble system requirement specifications for a wire system integrity system suite.
- Transition technology to Air Force depots and field units.

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Laboratory Test Bed Evaluation

- Stage 1
  - Precision capacitance measurements
  - Precision resistive measurements
- Stage 2 (A & B)
  - Electrical opens
  - Conductor damage
  - Electrical shorts
  - Distance to fault
  - Verify wire continuity
  - Insulation damage
  - Insulation resistance
  - Remote data access
  - Data archiving
  - Setup time / Ease of use
- Stage 3
  - Validation and wire characterization of (8) F-16 wire harnesses.

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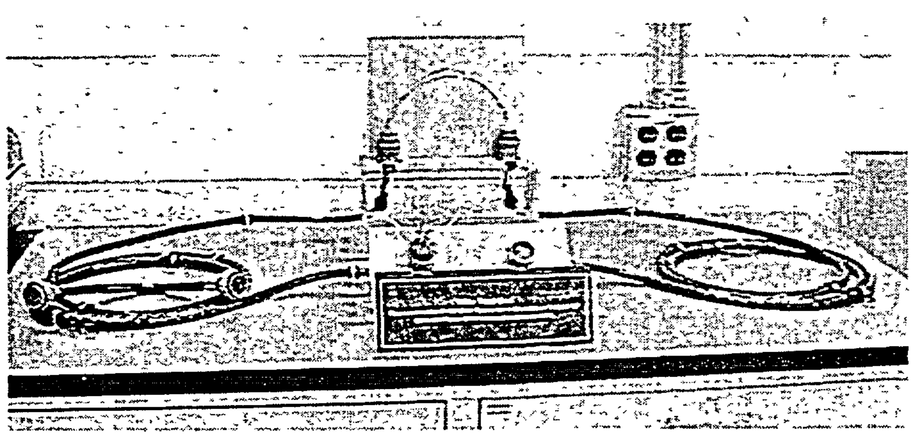
Laboratory Test Bed Evaluation

- Stage 2 (Long Test Bed)



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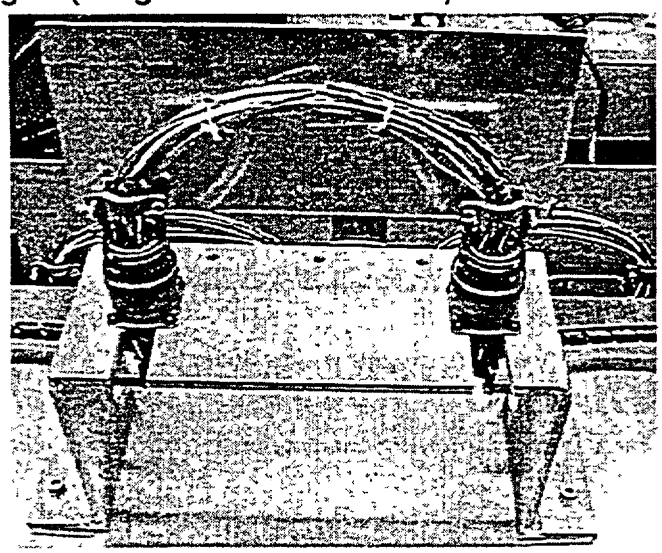
Laboratory Test Bed Evaluation

- Stage 2 (Long Test Bed Test Patch)



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Laboratory Test Bed Evaluation

- Test Patch Wire Types

MIL SPEC	P/N	NSN	DESCRIPTION
1. MIL-C-27500	M81381/7-20-2	6145-01-087-1278	Twisted Triplet, Shielded, Jacketed Wire, Electrical, Fluorocarbon Polyimide Insulated, Light Weight, Silver Coated Copper Conductor,
2. M22759/11	26433/30147K-2	6145-01-204-3481	Twisted Pair, Shielded, Wire, Electrical, Plastic Fluorinated Ethylene Propylene Insulated, Silver Core Stranded
3. MIL-DTL-22759	22759/91-20		Wire, Electrical, PTFE/Polyimide Insulated, Light Weight, Silver Coated, Copper

Wire Type Used In Both Long and Short Test Beds (01AGRC1 & A2GRC2)

Wire Type Used In the Long Test Bed (01AGRC1)

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Laboratory Test Bed Evaluation

- Test Patch Wire Types (cont.)

MIL SPEC	P/N	NSN	DESCRIPTION
4. MIL-C-27500	M81381/11-22-5	6145-01-085-4606	Twisted Pair, Light Weight Without Shield or Jacket, Wire, Electrical, Fluorocarbon/Polyimide Insulated, Silver Coated Copper
5. C-17D	10598-9	6145-01-114-9089	Cable, Radio Frequency, Flexible Triaxial, 95 Ohms
6. MIL-W-22759	M22759/34-22-9	6145-01-110-8894	Wire, Electrical, Fluoropolymer-Insulated, Cross-Linked Modified ETFE, Normal Weight, Tin-Coated Copper
7. MIL-W-M81381	M81381/7-20-2	6145-01-087-1277	Wire, Electrical, Fluorocarbon/Polyimide Insulated, Light Weight, Silver Coated Copper

Wire Type Used In Both Long and Short Test Beds (01AGRC1 & A2GRC2)

Wire Type Used In the Long Test Bed (01AGRC1)

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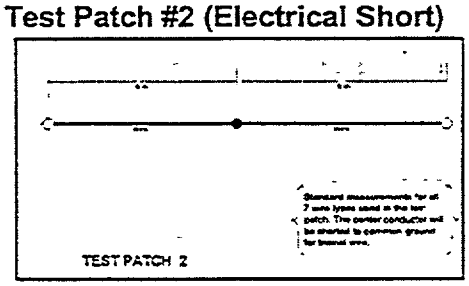
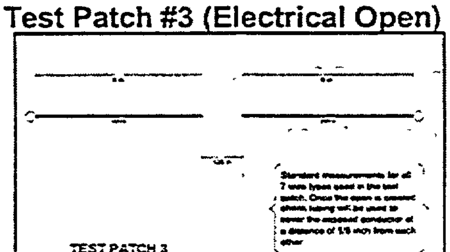
Laboratory Test Bed Evaluation

- Test Patch #1 (Control Sample)
- Test Patch #2 (Electrical Short)



- Test Patch #3 (Electrical Open)



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Laboratory Test Bed Evaluation

- Test Patch #4 (Insulation Damage)
  - Wire 1: Insulation penetration by known gauge test probe
  - Wire 2: 100 Megohm resistance (conductor to shield)
  - Wire 3: 100 Megohm resistance (conductor to ground)
  - Wire 4: One wire stripped .25 inches in center of the length (360 degrees)
  - Wire 5: 25% depression in center of wire with known pressure
  - Wire 6: Crush wire to 50% -Visible shape change
  - Wire 7: Undamaged wire

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Laboratory Test Bed Evaluation

- Test Patch #5 (Conductor Damage)

- Wire 1: 270 Degrees of outer shield removed, .5 inch length
- Wire 2: Undamaged wire
- Wire 3: Resistive component added, 50% resistance increase
- Wire 4: Resistive component added, 10% resistance increase
- Wire 5: Undamaged wire
- Wire 6: Chafe .5 inches in length, 50% conductor damage
- Wire 7: All but 2 strands broken, .25 inch length

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Laboratory Test Bed Evaluation

- Test Patch #6 (Splice/Crimp Connections)

- **Wire 1:** Solder splice all three conductors, reconnect shield
- **Wire 2:** Undamaged wire
- **Wire 3:** Environmental crimp (incomplete)
- **Wire 4:** Environmental crimp within resistive tolerance
- **Wire 5:** Undamaged wire
- **Wire 6:** Non-environmental crimp (incomplete)
- **Wire 7:** Non-environmental crimp within resistive tolerance

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Weight Factors for Test Conditions

Test Condition	Frequency of Failure (1-5)	Seriousness of Failure (1-10)	Importance of Test (1-5)	Weight Factor
Electrical open	5	7		12
Electrical short	3	10		13
Distance to fault-open	5		4	9
Distance to fault-short	2		5	7
Insulation resistance	3	6		9
Insulation damage	5	5		10
Conductor damage	2	4		6
Verify wire configuration			5	5

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Field Evaluation

- Stage 1
  - Equipment evaluation on ABDR F-16 aircraft
    - Induce faults / locate faults
    - Lockheed Martin equipment certification for test equipment
    - Aging Aircraft SPO sponsorship

- Stage 2
  - Equipment evaluation on field F-16 aircraft
    - Train F-16 maintainers on the test equipment utilization
    - Request feedback from maintainers for further improvements
    - Coordinate T.O. modifications for new test equipment

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Summary of Wiring Technologies

Technology	Need	Current Effort	Future
Diagnostics	Detection of wiring system faults	Shorts and opens	Intermittent and damaged wiring
Failure Characterization	Models/Life predication	Define model needs	Models that can predict field performance
New Materials	Stronger, lighter and higher temperatures	Shield conductor applications	Shield and signal conductor and insulation applications
Interconnection technology	Mitigate arc propagation	Fault sensitive CBs for transports	Fault sensitive CBs for fighters
Maintenance tools	Effective application of tools	Integration for current tools	Complete suite of tools for managing aging wiring system

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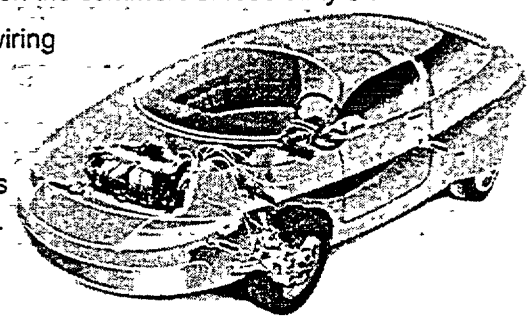
Brake-By-Wire Project

- Design, build, and demonstrate a commercially viable brake-by-wire system within a two year timeframe.
  - Delphi Automotive and AFRL initiative
  - Drive-able vehicle
  - Manufacturing and cost analysis
  - Detailed engineering reports on the commercial feasibility of:
    - Reliable connectors and wiring
    - Re-configurable controls
    - Reliable force sensors
    - Fault tolerant architectures
    - High temperature actuator



Strategy from a Management Perspective

- Alter the perception of wiring systems
  - Ensure wire systems are designed, installed, and maintained for long-term integrity using technology forums and new standards
  - Emphasize prevention of damage to wiring systems through training, diagnostics and prognostics
  - Transition from a reactive to a proactive maintenance approach
- Increase collaboration between industry, academia, and the government
  - Develop a partnership between industry, academia, technical associations and the government- eliminate barriers
  - Improve field data collection and promote data sharing to guide technology investment
  - Focus resources on the identified wiring issues

Strategy from a Management Perspective

- Improve the management and functionality of wire systems
  - Standardize design tools for developing and tracking design parameters and changes in the configuration of wire systems
  - Develop detailed training for the installation, inspection, and maintenance of wire systems
  - Promote the development and rapid deployment of diagnostics, prognostics, and new repair technologies
- Improve wire system technology
  - Promote the use of advanced connection technologies- wireless, micro-electronic(MEMs), multiplexing, and fiber-optic systems
  - Pursue revolutionary improvements in wire systems by developing new technologies and materials through aggressive research initiatives

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Overall Summary

Wiring system integrity can be managed through an industry and government partnership

- We need to transition from a reactive to a proactive wiring system maintenance approach
- Our challenge is to embrace a common strategy that leverages and builds upon industry and government efforts
- We need to agree that wiring systems should operate for extended failure-free periods and not accept unscheduled failures
  - Acknowledge that wiring systems age/degrade over time
  - Develop tools and technologies that improve wiring integrity

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Appendix I: Presentations from Panel Session

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Appendix I - Table of Contents

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United States Nuclear Regulatory Commission

Panel Session Overview

Nilesh Chokshi
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research

April 25, 2002

Page 1

United States Nuclear Regulatory Commission

Purpose

- Obtain consensus on wire system safety issues that remain unresolved and should be addressed by new research
- Identify parties interested in participating in collaborative research to resolve wire system issues

Page 2

United States Nuclear Regulatory Commission

NRC's Role

- NRC has organized this conference for the sole purpose of facilitating collaborative research on issues related to wire system aging and safety.

- NRC is very interested in this research area, and may participate in some of the collaborative research programs identified at this conference, however, sponsorship by outside agencies is strongly encouraged.

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United States Nuclear Regulatory Commission

Format

- Each session chair will provide a summary of their session, including:
  - Session Highlights
  - Needs for Research and Development

- An open discussion will then take place with the panel members to reach consensus on issues for new research and identify interested parties for a collaborative effort.

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United States Nuclear Regulatory Commission

Participation

- All attendees are welcome to participate in the discussion. An open dialogue and good technical discussions are encouraged.
- Reminder - This is an open public meeting. Sensitive information should not be discussed.

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Summary of Session 1:
Reliability Physics Modeling of Wire System Aging

Ken Gillen, Session 1 Chairman
Sandia National Laboratory

April 25, 2002

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Session Highlights
Reliability Physics Modeling of Wire System Aging

- Difficult subject with little current work
- Sandia paper
  - Improvement of Arrhenius
  - Wearout approach
  - Chemistry-based modeling
- Martin/Horvath paper
  - Void growth
  - Correlation to degradation
- Larsen paper
  - Most faults human-related
  - Chemical aging-hydrolysis important, oxidation
  - Differences between nuclear and aircraft wires

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Session Highlights
Reliability Physics Modeling (cont.'d)

- Degradation Model Summaries
  - Nuclear
    - Combined radiation and temperature
    - Several models in IEC report
    - JAERI model
    - Very complex chemistry – further progress difficult
  - Aircraft
    - Combined humidity and temperature
    - Model exists – experiments at constant RH vs. temp.
    - Recent surprise from nuclear weapons aging – synergism between H_2O and O_2

Page 3

Session Highlights
Reliability Physics Modeling (cont.'d)

- Comment – 3 most critical aging issues
  - Nuclear power plants
  - Aircraft
  - Nuclear weapons (huge current effort)
- Collaboration/interaction with nuclear weapons aging may be fruitful
  - UOC, wear-out, modulus profiling and NMR all developed from weapon aging work
- Wear-out
  - Satisfies critical need for residual lifetime method
  - Predictive even when CM methods useless
- Conclusion
  - Reasonable models exist, however, more testing is needed

Page 4

Summary of Session 2:
Fire Risk Assessment of Wire System Aging

Peter Fardell, Session 2 Chairman
Fire and Risk Sciences

April 25, 2002

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Session Highlights
Fire Risk Assessment of Wire System Aging

- PVC insulating materials produce high levels of smoke and acid gases in ***some*** tests.
- EPR/EVA+PE zero halogen formulations perform well even after aging.
- Even high performance cables can be made to burn.
- How can test performance be translated into real hazard in real installations?
- Aging studies can be inconclusive.

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Session Highlights

Fire Risk Assessment (cont.'d)

- Arc-fault and ground-fault circuit breakers are valuable.
- Standard tests are not always representative of "real" fires.
- Many problems with cables packed into hidden voids.
  - Many generations of good and poor cables
  - High fire load builds rapidly
  - Reduced oxygen can be problematic
  - Rarely have suppression or detection systems

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Needs for R&D

Fire Risk Assessment of Wire System Aging

- Global survey of installations and fire frequencies in nuclear plants
  - To provide a statistical database to assist a risk assessment of aged cable fires.
- Review and experimental study of cable flammability in hidden voids
  - To determine relevance of standard fire tests
  - Investigate new FR technologies e.g., nano composites
- Effects of oxygen depletion

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Needs for R&D

Fire Risk Assessment (cont.d)

- Study of emissions during cable fires
  - Smoke, toxicity, irritancy, and corrosivity
- Preparation of guidance/code of practice
  - Specifiers, installers, users, etc. (including risk assessment tools)
- Further studies of reliability of arc-fault and ground-fault circuit breakers

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Summary of Session 3:

Risk Significance of Wire System Aging

Art Buslik, Session 3 Chairman
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research

April 25, 2002

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Session Highlights

Risk Significance of Wire System Aging

- Four papers, three associated with cables in nuclear power plants and one with aircraft.
- All made use of event-tree/fault-tree methodology
- My (Buslik) paper outlined a method for including cables, and their aging into PRA.
- Glen Schinzel discussed the risk-informed approach used by South Texas to determine component importance and treatment changes. Many safety-related components (approx. 90%) are not safety significant, and a small number (approx. 1%) of the components are not safety related, but are safety significant

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Session Highlights

Risk Significance of Wire System Aging (cont.'d)

- Pranab Samanta presented a paper giving, for a PWR and a BWR, sensitivity studies given the increase in core damage frequency if cables failed. One system taken at a time. Cables in redundant trains failed. Human error probabilities were treated parametrically.
- The paper by Doug Wood and R. Steinman showed application of risk methods to aircraft. Conventional methods of ensuring safety goals for aircraft flight may not be adequate without inclusion of wiring failures. Some "basic events" on the fault tree were at the system train level, while in other cases basic events were at the wire level.

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Needs for R&D
Risk Significance of Wire System Aging

- Additional work in the development of reliability physics models to predict the failure probability of cables, and the determination of the parameters of the model.

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Summary of Session 4:
Prognostics and Diagnostics for Installed Wire Systems

Gary Toman, Session 4a Chairman
Electric Power Research Institute

Jit Vora, Session 4B Chairman
U.S. NRC,Office of Nuclear Regulatory Research

April 25, 2002

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Wire Inspection Technologies Under Development at NASA Langley

Infrared evaluation of cable with ohmic heating excitation from conductor

- Cyclic current excitation and evaluation of surface at same point on excitation curve.
- Identifies significant flaws and physical damage in conductor insulation

Wire Inspection Technologies Under Development at NASA Langley

Combustion by-Products analysis

- Potential for use of micro-sensors distributed through out wire system
- Faults and over-temperature conditions produce detectable volatiles
- Work in development phase using portable gas chromatograph

New Methods of Monitoring Aging of Cable Polymers (Sandia)

NMR

- Requires small specimen
- Places polymer in solution at 70 C and NMR is performed
- Order of magnitude change observed from unaged through aged condition
- Useful for common insulations (XLPE, EPR) that are difficult to test by mechanical means

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New Methods of Monitoring Aging of Cable Polymers (Sandia)

Micro-Modulus

- Requires small specimen
- A physical test that can detect small change in hardness
- Can evaluate differences in aging through depth of material

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Optical Diagnosis of Aging of Low-Voltage Cable (Hitachi)

Evaluation of absorption of light by cable surface with aging

- Range of wavelengths evaluated and slope of line indicating the amount of absorption indicates degree of aging

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Overall Conclusions of Prognostics and Diagnostics Session

- 5 new techniques discussed
- All are promising
- Each requires either access to surface of cable or removal of a specimen for lab use
- Insights in aging of overall system based on assessment of a local site where test is performed or sample has been removed

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Tasks for Consideration

Risk Assessment of Cable Under LOCA

- Problem:
  - Risk assessments of safety cable failure under LOCA are being performed
  - No failure rate data for LOCA environment related to degree of aging is available
- Resolution:
  - Series of informal workshops including risk, EQ, Systems and materials personnel to discuss knowns and unknowns and what can be done to improve PRAs and assure accuracy of results

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Condition Monitoring Practical Demonstration

Sandia Cable Test Facility

- Built by DOE
- Has documented flaws in cables within conduit system
- Allows blind testing of electrical assessment techniques

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In-plant Practical Application Tests

- Many CM techniques developed
- Few tried in plant or on plant specimens
- A shakedown and proof of methods is highly desirable to identify needed improvements and practicality under plant conditions

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NASA/FAA/Nuclear Overlap

Two cooperation areas:

- Software for documenting assessment results for long-lived cable systems – allows later assessors to understand and use results from previous assessments
- Mission success risk assessment (flights and assurance of generation) based on criticality of cables important to operation/mission

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Condition Monitoring Forum

EPRI Cable Condition Monitoring Working Group (CCMWG)

- Brings researchers together with senior utility cable personnel
- Guides research
- Provides feedback to utility industry
- Open to all cable researchers and utility personnel
- Contact: gtoman@epri.com

Summary of General Session:

Initiatives and Insights on Wire System Aging

Cornelius Holden, General Session Chairman

U.S. NRC,Office of Nuclear Reactor Regulation

April 25, 2002

Needs for R&D

Initiatives and Insights on Wire System Aging

- Research of synergism in cables degradation including slow thermal and low radiation dose rate aging
- Research on the effects of beta radiation (0.2 – 0.6 Mev) on polymer degradation
- Research on the 3rd harmonics and the relationship to cable aging

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Needs for R&D

Initiatives and Insights (cont.'d)

- Development of a reliable simulation of DBE and post-DBE
- Visual inspection is the leading method to detect failures for aircraft and nuclear applications – can a uniform method to predict wire system performance be developed?

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NRC FORM 335
U S NUCLEAR REGULATORY COMMISSION
(2-89)
NRCM 1102,
3201, 3202

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1 REPORT NUMBER
(Assigned by NRC, Add Vol , Supp , Rev , and Addendum Numbers, if any)

NUREG/CP- 0179

2 TITLE AND SUBTITLE

Proceedings of the International Conference on Wire System Aging

3 DATE REPORT PUBLISHED

MONTH	YEAR
November	2002

4 FIN OR GRANT NUMBER

Y6410

5 AUTHOR(S)

Conference papers by various authors;
Compiled by Robert Lofaro, BNL

6. TYPE OF REPORT

Conference Proceedings

7 PERIOD COVERED *(Inclusive Dates)*

April 23-25, 2002

8 PERFORMING ORGANIZATION - NAME AND ADDRESS *(if NRC, provide Division, Office or Region, U S Nuclear Regulatory Commission, and mailing address, if contractor, provide name and mailing address)*

Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

9 SPONSORING ORGANIZATION - NAME AND ADDRESS *(if NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U S Nuclear Regulatory Commission, and mailing address)*

Same as 8 above.

10 SUPPLEMENTARY NOTES

J. Vora, NRC Project Manager; Proceedings prepared by Brookhaven National Laboratory

11 ABSTRACT *(200 words or less)*

This document contains papers and presentations related to the aging of wire system aging used in various applications, including nuclear power plants, aircraft, space vehicles, and others. These papers and presentations were prepared by various authors for presentation at the International Conference on Wire System Aging, held April 23-25, 2002 at the Double Tree Hotel in Rockville, Maryland, USA They describe ongoing and completed research in the areas of reliability physics modeling, fire risk, risk impact, and prognostics/diagnostics as they relate to the aging of electrical wire systems.

12 KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

Wire systems; equipment aging; condition monitoring; electric cables; nuclear plant risk; reliability physics modeling; prognostics; fire risk.

13 AVAILABILITY STATEMENT

Unlimited

14 SECURITY CLASSIFICATION

(This Page)
Unclassified

(This Report)

Unclassified

15 NUMBER OF PAGES

16 PRICE

Printed on recycled paper

Federal Recycling Program

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300