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Acceptance Criteria for AMS FDR Measurements to Support Cable Aging Management Initiatives

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This document provides the details of cable testing technologies used by AMS to support of cable aging management programs in nuclear power plants. The purpose of the testing is to help evaluate the effective aged condition of the cables under test. The primary test technique used by AMS to evaluate the aged condition of nuclear plant cables is the Frequency Domain Reflectometry (FDR) technique; however, AMS also performs classical electrical tests using the CHAR Cable Condition Monitoring System to include Time Domain Reflectometry (TDR), Insulation Resistance (IR), and Impedance (LCR). Descriptions of these classical measurements can be found in Section 3.0.

The FDR technique is a non-destructive in-situ electrical test that uses the principle of transmission line theory to locate and quantify impedance changes in a cable circuit. These impedance changes can result from connections, faults in the conductors, or degradation in the cable polymer material itself. The FDR data can be used in conjunction with other electrical measurements made by the CHAR Cable Condition Monitoring System as well as traditional cable aging management tools such as the cable indenter to inform maintenance activities and to support justification for continued use of installed plant cables. More details about the FDR test are provided in Section 3.0.

1.0 CABLE LIFE ESTIMATIONS

Over the past several years, AMS has performed extensive accelerated thermal aging research in order to develop an FDR aging database for a variety of cable insulation polymers used in nuclear power plants in the U.S. and worldwide. These experiments included the most widely used cable polymer types in the nuclear industry, Ethylene Propylene Rubber (EPR) and cross-linked polyethylene (XLPE). The results of this work have demonstrated that FDR results trend with increasing cable degradation and can be correlated to the industry standard elongation at break (EAB) test to help better evaluate the degree of localized thermal aging in cable insulation material. By correlating FDR to EAB, the aging condition of cables routed through harsh environments can be better understood in relation to its ability to perform its intended function.
Figure 1 contains overlays of FDR results for an XLPE insulated cable aged in the AMS laboratories with various degrees of thermal degradation. This localized aging, or 'hot spot', enlarged in Figure 2, shows progressive changes in the FDR data relative to the cable's baseline

characteristic impedance. The changes are a result of continuous thermal aging performed over a one year period. As the cables were aged, EAB data was also acquired so a correlation could be established with the FDR data.

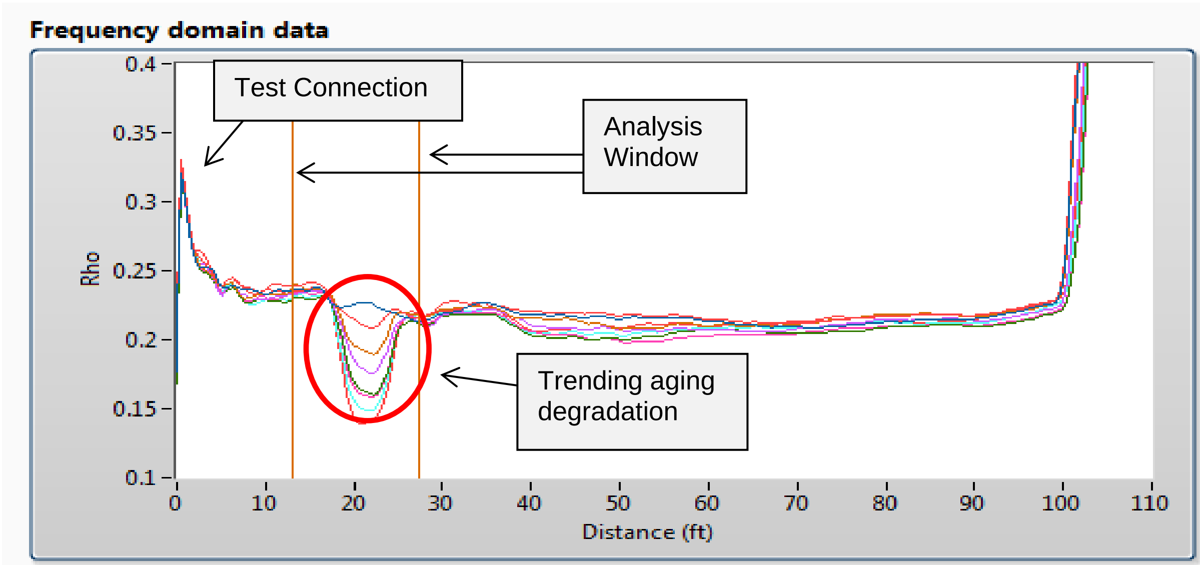

Figure 1. FDR Data that Shows Thermal Degradation or 'Hot Spot' for XLPE Insulation

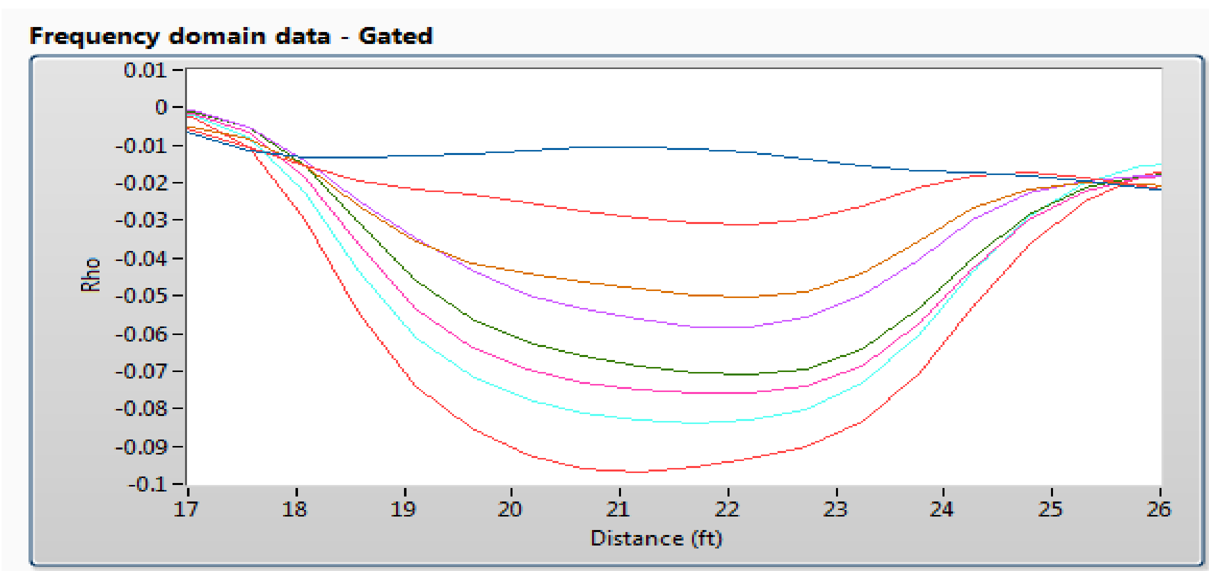

Figure 2. FDR Enlarged 'Hot Spot' Data for XLPE Insulation that Shows Continued Changes in the FDR Data During the Aging Process

The correlations between the FDR data and EAB for XLPE and EPR cable insulation types have been categorized by AMS based on the percent of their aged life so as to define general acceptance criteria that can be used when performing in-plant testing. These FDR aging categories for cable insulation are divided as shown in Table 1. Each category represents an "% Aged" estimation for the cable under test as it relates to the EAB "end-of-life" condition, defined by industry guidance as 50% EAB (see Section 2.0 for more details). For example, FDR measurements that fall into "Category 1" show minimal change from the unaged cable insulation indicating that little to no degradation has occurred. FDR measurements that fall into "Category 2" have been aged between 33% and 66% of the remaining useful life. FDR measurements that fall into "Category 3" have been aged between 66% and 99% of the remaining useful life and cable data that falls into "Category 4" would be expected to be at or near an EAB measurement of 50%. The example plot shown in Figure 3 contains baseline FDR data overlaid with data that was collected after the cable was thermally aged until reaching a "Category 3" condition.

Table 1. AMS Acceptance Criteria for FDR Testing of Nuclear Power Plant Cables

FDR Category	**% Aged**	**Comments *1**
1	0 – 33	Little to no indication of age related degradation
2	33 – 66	Initial indication that age related degradation has occurred
3	66 – 99	Cable insulation has significant aging but is expected to function normally
4	>99	Cable insulation is at or near its end-of-life condition as defined by 50% EAB[Note 1]

Note 1: A cable with an EAB of more than 50 percent is considered by the nuclear industry to be able to perform its function not only during normal operation, but also in accident and post-accident conditions. In contrast, a cable with an EAB of 50 percent or less may not be able to function after subjected to adverse conditions. [EPRI TR-1008211 "*Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets*".]

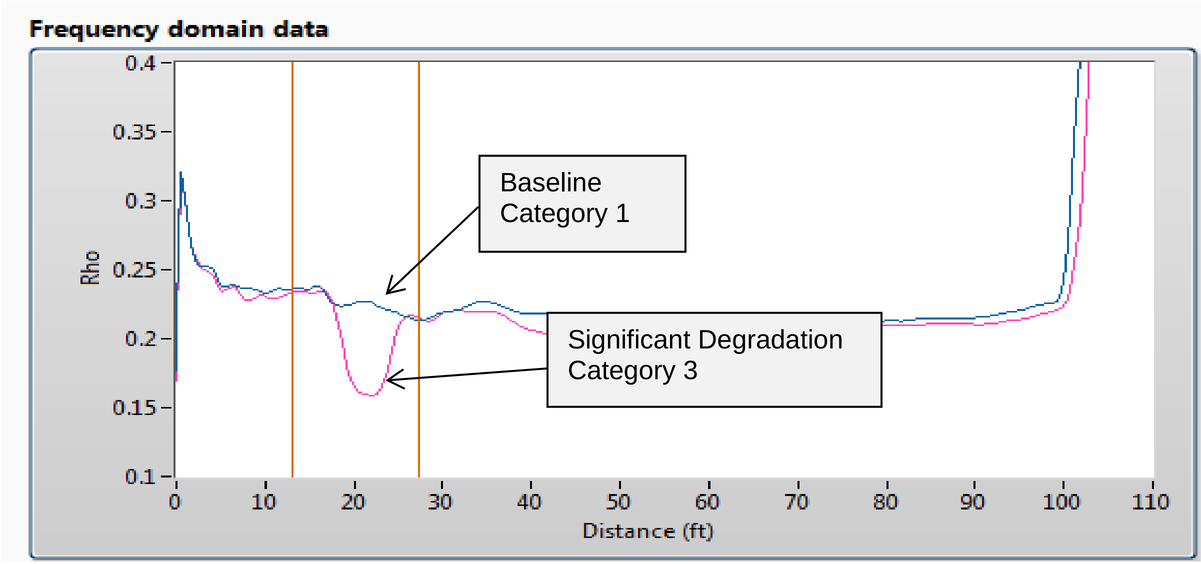

Figure 3. FDR 'Hot Spot' data for XLPE Insulation – Significant Degradation Versus Baseline (Unaged)

2.0 END OF LIFE CRITERIA FOR CABLE INSULATION MATERIALS

A cable with an EAB of more than 50 percent is considered by the nuclear industry to be able to perform its function not only during normal operation, but also in accident and post-accident conditions. In contrast, a cable with an EAB of 50 percent or less may not be able to function after subjected to adverse conditions. [EPRI TR-1008211 "*Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets"*.]

3.0 DESCRIPTIONS OF ELECTRICAL TESTS

The following is a brief description of the electrical measurements that are typically performed by characterization testing of nuclear plant cables to assess their health and integrity for continued operation. This includes descriptions of not only FDR testing but other electrical testing performed by the CHAR Cable Condition Monitoring System.

Frequency Domain Reflectometry (FDR) Technology

To perform an FDR test, one end of a cable is connected to a signal source which sends a sequence of sine waves of constant amplitude and varying frequency through the cable. The waves travel the length of the cable and a portion of them are reflected back from the locations where the impedance is different from the rest of the cable. The reflected signal is separated, measured, and then correlated with the outgoing or incident signal. This correlation is established for each individual frequency within the measured spectrum. The frequency domain data is then converted to the time domain using an inverse Fast Fourier Transform (FFT). Once in the time domain, the distance-to-fault is calculated using the velocity of propagation (Vp) for the cable under test. The FDR test can be adjusted to specific frequency ranges to compensate for bandwidth attenuation from losses that result from the distributed impedance along the length of the cable.

Impedance Measurements

The AC impedance of an electrical circuit is measured to determine if a cable circuit is changing due to the degradation of the insulating materials, which influences capacitance, or the degradation of the electrical wiring, which influences inductance. AC impedance is a combination of the resistance, inductance, and capacitance of the circuit, and must be defined at a given frequency. AC impedance measurements for a particular electrical circuit are evaluated to determine if they are as expected for the type of circuit being tested. Imbalances, mismatches or unexpectedly high or low impedances between the cable leads would indicate problems due to cable degradation and aging, faulty connections and splices, or physical damage.

Insulation Resistance (IR) Measurements

The Insulation Resistance (IR) measurement provides information about the insulation quality of cables, connectors, and electrical end devices. The IR measurement is typically made by applying a DC voltage between a cable conductor and ground, and measuring the resulting leakage current. The IR is then calculated using Ohm’s Law from the applied voltage and leakage current. The voltage is selected at a level that eliminates measurement noise while preventing stress to the insulation. In addition, the test current is limited to prevent inadvertent damage to the electrical system for the case where the IR is abnormally low. As the voltage is applied, the leakage current through the insulating material is measured with respect to time to establish the cable insulation’s quality and determine if there are any contaminates (moisture, grease, dirt, etc.) in the cable or connections. The data is typically analyzed as a ratio of the IR value at two different times.

Time Domain Reflectometry (TDR) Testing

The TDR test is performed by sending a voltage step with a fast rise time into a transmission line. Reflected voltage waves occur when the transmitted signal encounters impedance mismatches that are caused by faults in connectors or conductors. The resulting wave is captured in the time domain and is a ratio of the incident signal and the reflected signal expressed in terms of Reflection Coefficient (rho). The speed that the incident and reflected signals travel in the transmission line is known as the velocity of propagation (V_P) which is a percentage of the speed of light in a vacuum. This V_P is determined by the relative permittivity or dielectric constant of the media’s insulating material. Distance to any impedance change can be determined by multiplying the V_P of the transmission line by half the time it takes for the incident wave to travel to the impedance change and get reflected back to the source.