A Cable Condition Monitoring Strategy For Safe And Reliable Plant Operation

Trevor Toll
Analysis and Measurement Services Corporation
Knoxville, USA
trevor@ams-corp.com

Casey Sexton
Analysis and Measurement Services Corporation
Knoxville, USA
casey@ams-corp.com

Bryan McConkey
Analysis and Measurement Services Corporation
Knoxville, USA
bryan@ams-corp.com

Gary Harmon
Analysis and Measurement Services Corporation
Knoxville, USA
garyh@ams-corp.com

Abstract— **Electrical cables provide essential functions such as delivery of power or instrumentation signals for most industrial monitoring systems. Most cables installed in plants use polymer insulation materials that can become brittle, crack, or degrade over time from exposure to harsh environmental conditions such as elevated temperature, moisture, vibration, mechanical shock and radiation. Wholesale replacement of cables can be expensive, time consuming and impractical. Therefore, implementing a condition monitoring (CM) strategy to identify and quantify degradation and estimate the remaining useful life (RUL) of the cables can be an effective way of managing aged cables.**

An overall CM strategy includes several steps to assess the health and manage the aging of cables during the operating life of an industrial facility. These steps include performing As-Found evaluations to determine the current condition of installed cables. These As-Found assessments are performed using a combination of destructive, semi-nondestructive, and/or nondestructive CM tests. Destructive and semi-nondestructive CM testing are performed by removing cable and jacket/insulation polymer samples from service and evaluating the mechanical, thermal, chemical, and electrical properties of the materials to determine their overall condition. Nondestructive CM tests are used to perform in-situ testing to identify and assess the condition of degraded sections of cable insulations as well as to identify potential issues in the electrical circuits including degraded terminations, splices and/or connections. Each of these CM methods provides unique and important information on the overall health and performance of cables and insulation polymers. Moreover, a combination of some or all of these methods can be used to assess the condition of installed plant cables, depending on the cable configuration, insulation materials, and the needs of the plant.

Predicting RUL is accomplished by performing laboratory accelerated aging of samples for each representative cable polymer type. The accelerated aging methodology involves exposing the cables to elevated environmental conditions that cause the cable polymers (insulation materials) to age faster than the installed cables. During aging, CM tests are periodically performed to trend changes in the electrical, mechanical, thermal, and chemical properties of the cable and insulation material during aging. The Arrhenius method is then used to normalize the accelerated aging data to the cables' in-service temperatures, and this normalized data is then used to estimate the cable's RUL. The focus of this paper will be to describe an overall strategy for condition monitoring of cables installed in harsh environments using in-situ (i.e. nondestructive) and laboratory (destructive and semi-nondestructive) aging assessment techniques.

Keywords— cables, condition monitoring, aging assessments, remaining useful life

I. Introduction

The aging of electrical cables has been the subject of substantial research and development (R&D) projects performed by national and international laboratories, universities, and vendor organizations for many years [1]. This R&D was conducted to develop guidance, equipment and techniques to support aging management of in-service cables in industrial facilities such as nuclear power plants, research reactors, waste facilities and fuel fabrication plants.

Over time, exposure to harsh environmental conditions such as elevated temperatures, radiation, and humidity can result in age-related degradation and failure of cable insulation materials. In the current fleet of nuclear reactors, there are thousands of miles of cabling, many of which are exposed to harsh environmental conditions. As the cables age, the jacket and insulation polymers harden and become brittle making them more susceptible to crack formation and growth, moisture intrusion, and other issues that can lead to cable failure. Wholesale replacement of these cables can be expensive, time consuming and impractical. Moreover, the existing U.S. fleet of 98 nuclear reactors is aging with the average age of operation being 37 years [2]. The majority of these plants have applied for license renewals to operate beyond their original 40 year life for an additional 20 years with almost all given regulatory approval to extend their life [3]. Further, a second license renewal referred to as subsequent license renewal or SLR is underway with some sites in the process of applying to operate up to 80 years. As these reactors pursue operating life extensions, the utilities must find a way to address issues associated with age-related degradation of cables. One way to address this issue is to implement a cable condition monitoring (CM) strategy to identify and quantify degradation and estimate the remaining useful life (RUL) of the cables.

Today, a variety of cable CM techniques have been developed and successfully used for low voltage cable evaluations. These techniques include in-situ (i.e.

nondestructive) and laboratory (i.e. destructive and semi-nondestructive) tests that are used to identify aging degradation and assess the condition of cables to determine if their insulation characteristics have changed with age. TABLE I. lists some of the mechanical, electrical, thermal, and chemical techniques commonly used as cable CM tools.

TABLE I. CONDITION MONITORING TECHNIQUES COMMONLY USED FOR CABLE AGING ASSESSMENTS

CM Test Methods	Description
Dielectric Spectroscopy	Nondestructive electrical CM test
Fourier Transform Infrared Spectroscopy (FTIR)	Semi-nondestructive chemical CM test
Thermo-gravimetric Analysis (TGA)	Semi-nondestructive thermal CM test
Indenter Modulus (IM)	Nondestructive mechanical CM test
Elongation at Break (EAB)	Destructive mechanical CM test
Oxidation Induction Time/and Temperature (OIT/OITP)	Semi-nondestructive thermal CM test
Visual and Microscope Inspections	Destructive CM test
Relative Density	Semi-nondestructive chemical CM test
Dielectric Strength	Nondestructive electrical CM test
Frequency Domain Reflectometry (FDR) and Time Domain Reflectometry (TDR)	Nondestructive electrical CM tests

Each of these CM tests can provide a measurement of age-related degradation of a cable; however, there is no single CM technique that can be used by itself to quantify the degradation of all varieties of insulation materials, cable configurations and installations that is non-destructive and can be performed both in-situ and in the laboratory. Moreover, each of these CM tests provides valuable information about the age-related degradation process of cable insulation polymers and together they can be used to provide an objective means of assessing the condition of installed plant cables. As such, a holistic cable CM strategy that incorporates multiple CM technologies provides the most effective way of performing aging evaluations of cables.

- Implementing a cable CM strategy that includes both in-situ and laboratory testing provides industry with the means to:
- Support cable aging management programs in the nuclear industry by providing a quantitative means to verify the health and performance of cables, which is needed to support SLR approval.
- Identify aged or degraded cables before they cause operability issues in facilities including nuclear power plants, research reactors, nuclear fuel processing and fabrication facilities, and nuclear waste disposal plants.
- Avoid unnecessary and costly replacement of cables that can continue to operate safely and reliably.

This information related to the overall health and reliability of cables helps plant personnel make informed decisions for evaluating the condition of cables and how to prioritize maintenance activities for in-service cables. The sections below summarize the holistic cable CM strategy, how aging assessments are performed, and provide examples on how the data is used to identify and trend age-related degradation, determine the current aged condition, and estimate the RUL of industrial cables.

II. CABLE CONDITION MONITORING STRATEGY

Using in-situ and laboratory cable CM technologies, aging assessments can be performed on industrial cables to:

1) Identify potential issues in cable circuits including degraded terminations, splices and/or connections as well as identify and trend age related degradation of cable insulation.
2) Quantify the severity of age-related insulation degradation and determine the current condition of cables.
3) Estimate the RUL of cables to determine if/when they will need to be repaired or replaced.

As mentioned previously, all of the CM techniques used to conduct these aging assessments have the ability to trend aging degradation. However, each of these tests offer advantages and disadvantages such as being in-situ, non-destructive, only trending with certain polymers, or only being applicable for certain cable configurations (e.g. single conductor or multi-conductor). As such, different combinations of CM techniques may be needed to perform aging assessments of industrial cables, depending on the cable configuration, insulation polymers, aging mechanisms, needs of the plant, etc.

The three (3) case studies provided below illustrate how different types of CM techniques can be used to perform aging assessments of industrial cables. These examples include cable testing that was performed for two nuclear power plants and a large industrial data center.

A. Case Study 1

The example provided in this section shows how in-situ CM techniques are used for aging assessments of industrial cables. In-situ cable CM testing is performed to locate, identify, and quantify age related degradation of installed plant cables without having to extract sacrificial samples. This information can help identify localized insulation degradation or "hot spots" in a cable that are exposed to harsh environmental conditions (e.g. elevated temperatures, radiation, etc.) as well as determine which cables have experienced significant age-related degradation while in service and need increased testing or repair/replacement. CM technologies including IM and frequency domain reflectometry (FDR) are examples of tests used to perform in-situ aging evaluations.

For this case study, indenter modulus (IM) testing was performed in-situ to assess the current condition of cables that have been in service at a nuclear power for over forty (40) years. Fig. 1 shows engineers performing IM testing of the cables included in the project. The results of this testing helped support the work being performed by the plant to pursue a subsequent license renewal for continued operation (i.e. 60 to 80 years). These cables are located in cable trays inside the reactor containment building, and during plant operation are exposed to

Fig. 1. Engineers Performing IM Testing of Cables Installed in Reactor Containment

elevated temperatures of approximately 50˚C (120°F) and other environmental stressors (i.e. radiation) that can accelerate the natural aging process.

The IM test is performed to measure and monitor changes in the hardness of cable insulation and jacket polymers as they age. It is a localized in-situ non-destructive mechanical test that is applied using a system that clamps around the cable under test and uses an instrumented probe that is pressed against a polymer to measure the localized hardness. The testing discussed here involved performing IM measurements on the jacket materials of ten (10) cables installed in reactor containment and using the data as a leading indicator of cable insulation degradation. IM data was also collected for the jacket materials of seven (7) cables that were harvested from a benign environment and never placed in service. The results of these tests were used as reference data for comparison to the cables installed in the harsh environment. Based on the information provided by the plant, each of these cables were manufactured by Boston Insulated Wire (BIW) and constructed with neoprene jacket polymers.

For the ten (10) cables tested in containment, the jacket IM data ranged from 9.5 N/mm to 16 N/mm and the average IM value was 12.2 N/mm with a standard deviation of 2.6 N/mm

TABLE II. Jacket IM Data for Cables Installed in Containment

Item	Cable Tag ID	IM Value (N/mm)
1	1V4V5002A	16.0
2	1V4V5002B	13.0
3	1V1V5002L	15.5
4	1V1V5002M	14.2
5	1V1V5002N	9.5
6	1V2V5002N	9.7
7	1V2V5002L	14.4
8	1V2V5002M	14.5
9	1V3V5002N	9.6
10	1V3V5002K	9.5

(0). The IM data acquired for the jacket materials of the seven (7) harvested cable samples (i.e. reference samples) ranged between 8.4 N/mm and 11.4 N/mm and the average IM value was 9.5 N/mm with a standard deviation of 1.6 N/mm. Therefore, after approximately 43 years of service the average jacket IM value for the cables installed in reactor containment is 2.7 N/mm higher than the average jacket IM value for the reference cables that were installed in a benign plant environment and never placed in service. Moreover, the average jacket IM values of both the in-containment and reference cables are within one standard deviation of each other.

The results of this testing show that the IM values acquired for the cables installed in containment and the reference cables were not significantly different. Thus, the jackets of the in-containment cables do not show signs of significant age-related degradation after 43 years of service. Based on these results, it is reasonable to conclude that the underlying cable insulation has not experienced significant age-related degradation during service, and the cables are not near their end of useful life.

B. *Case Study 2*

Laboratory aging assessments of cables are performed to both assess the aged condition and/or estimate the RUL of cable samples removed from service. This is accomplished by using a combination of the electrical, mechanical, thermal, and chemical tests listed in TABLE I. . The example provided below shows how laboratory-based CM techniques are used to perform aging assessments of industrial cables.

For the laboratory cable aging assessment discussed here, a comprehensive series of measurements was performed to assess the aged condition of four (4) cables that were removed from service at an operating U.S. nuclear power plant. Prior to their removal, three of the cable types had been in service for over 40 years, and one cable had been in service for 15 years. These cables were installed in areas of the plant where they were exposed to elevated temperatures (i.e. up to 150°F during operation) and other environmental stressors that can accelerate the natural aging process. Moreover, each of these cables were manufactured with types of cross-linked polyethylene/polyolefin (XLPE/O) insulations. The goal of this project was to determine both the current aged condition of the cable polymers and how much time the cable insulation materials could remain exposed to their in-service environmental conditions before reaching their end of life condition.

The work involved performing a series of tests to evaluate the As-Found condition of the cables after they were removed from service. Following the collection of the As-Found data, the cables were placed in environmental ovens where they were exposed to a temperature of 135°C (275□F) to accelerate the thermal aging process. Various mechanical, thermal, and chemical tests were performed to determine the As-Found condition of the cables and periodically trend the characteristics of the cable polymers during the thermal accelerated aging process. These tests included elongation at break (EAB), oxidation induction time (OIT), visual and microscope inspections, and thermogravimetric analysis (TGA).

TABLE III. below includes the cable type and installation years for each of the cable samples as well as the results for some of the CM tests performed during the As-Found evaluation. The data shows that the Pyrotrol III had experienced the significant age-related degradation during service, and both it and the two Flamtrol cable insulation polymers, which were in-service for over 40-years prior to removal, had experienced more significant age-related degradation than the Firewall III insulation, which had been in service for 15-years prior to removal.

TABLE III. AS-FOUND CM TEST RESULTS FOR PLANT CABLES

Cable Type	EAB (%)	Visual Inspections	OIT (Minutes)	Insulation Resistance
Pyrotrol III	74	Insulation Surface Cracks	5.5	>100 GΩ
Flamtrol	181	Outer Layer Insulation Cracks	15.0	>100 GΩ
Firewall III	199	No Cracks	23.5	>100 GΩ

The RUL estimates for the insulation polymers were determined by applying the Arrhenius method to the accelerated aging EAB results for the cables and using the 50% absolute EAB end of life criteria to determine their end of life condition. Application of the Arrhenius method involves using the Arrhenius equation (1) to normalize EAB data taken during the accelerated aging process to the in-service temperatures of the cable. Fig. 2 illustrates how the Arrhenius method is applied to accelerated aging EAB data (blue trace) to normalize it to in-service environmental conditions (red trace).

$$t_2 * e^{\left(\frac{E_a}{R}\right)*\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} \qquad (1)$$

t_1 = service time
T_1 = service temperature (in Kelvin)
t_2 = laboratory aging time
R = gas constant (8.3114 J/mol*K)
T_2 = lab aging temperature (in Kelvin)
Ea = activation energy (in kJ/mol)

The Arrhenius equation used to calculate a RUL estimate for each insulation polymer are provided in TABLE IV. . 0 is an example EAB vs. years in service aging curve produced for the Pyrotrol III insulation using EAB data acquired during

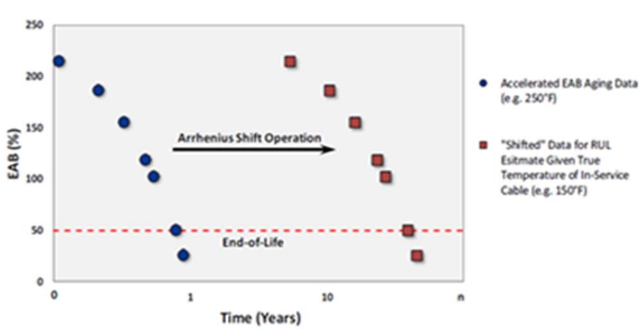

Fig. 2. Example of RUL Estimation Using Accelerated Aging EAB Data

thermal accelerated aging normalized using the Arrhenius equation in- service temperature of the cable. Based on the results of the conservative end of life calculations performed during this work, the Pyrotrol III XLPE/O insulation polymer would have reached the end of life condition within the next 15 years, the Flamtrol insulation would have reached end of life in the next 5 years, and the Firewall III insulation polymer would not have reached the end of life condition during an extended period of operation (e.g. 60 to 80 years of service).

TABLE IV. PARAMETERS USED IN ARRHENIUS EQUATION FOR RUL CALCULATION

Cable ID	Activation Energy (eV)	Service Temperature (°F/°C)	Aging Temperature (°F/°C)
Pyrotrol III	0.86	150/65	275/135
Flamtrol	0.90	140/60 and 150/65. End of life estimations for both are provided in the final report.	275/135
Firewall III	1.34	140/60 and 150/65	275/135

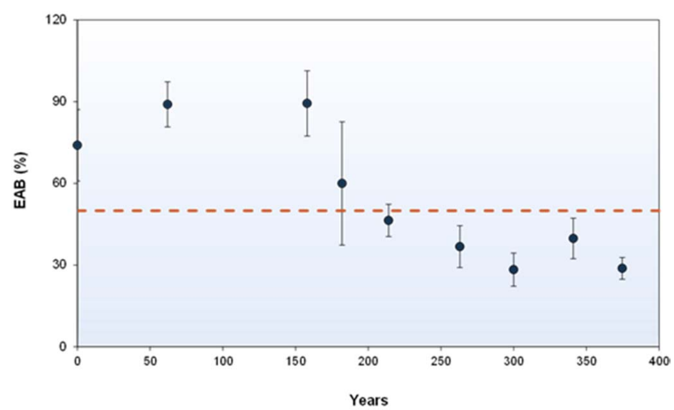

Fig. 3. Example EAB Aging Curve

C. *Case Study 3*

The example provided here shows how both in-situ and laboratory CM techniques are used together to assess the condition of industrial cables. Using both in-situ and laboratory CM techniques to perform condition assessments of industrial cables, complementary data and results can be acquired from both methods that would otherwise not be available using only one approach. Unlike the previous examples, the main environmental stressor in this case is moisture and not heat, oxidation, or radiation. The work described here was performed to assess the condition of 480 VAC three phase power cables installed at a large industrial data center. The testing performed during this project included onsite electrical measurements of nine (9) feeder circuits, laboratory assessments of three (3) of these feeders after they were removed from service, and comparison testing of newly installed replacement cables. All the cables included in this work were manufactured with polyvinyl chloride (PVC) insulation. Prior to testing, the site had experienced problems with these low voltage power cables, and several of the cables had to be replaced after only one year of service. The objectives of this work were to 1) assess the condition of the originally installed cables and insulation materials, 2) identify any defects, anomalies, or degradation that may adversely affect their normal operation, and 3) determine the root cause of performance degradation for these cables.

Some of the results acquired during the onsite testing are provided in TABLE V. and Fig. 4. As shown in the table, each of the nine (9) originally installed feeder circuits had IR values measured from Phase A to Phase B that were lower than expected, and the phase to phase capacitance measurements shown here for each of the feeders was significantly higher than expected. Moreover, the IR values of the originally installed cables were up to three orders of magnitude lower than the IRs of the newly installed cables, and the capacitance values for the original cables were all an order of magnitude higher than the capacitances of the new cables. In general, low insulation resistance values and high capacitance values are typical consequences of moisture intrusion into cable insulation.

In addition to the insulation resistance and capacitance test results, the phase to phase and phase to ground reflectometry data identified impedance changes along each of the nine (9) originally installed feeder circuits. As shown in the example time domain reflectometry (TDR) provided in Fig. 4, the data acquired for the originally installed cable (blue trace) shows atypical changes in reflection coefficient (y-axis Rho values)

TABLE V. EXAMPLE CAPACITANCE AND IR DATA ACQUIRED FOR ORIGINALLY INSTALLED CABLES AND NEW CABLES

Item Number	Feeder Identification	1 kHz Capacitance (pF/foot) (Three Phase Average)		Insulation Resistance (Ω @ 500VDC) Measured from Phase A to Phase B	
		Original Feeders	Newly Installed Feeders	Original Feeders	Newly Installed Feeders
1	RPP-SB-8A-1	144.2	25.00	53.1 M	18.2 G
2	RPP-SB-8A-2	149.3	23.27	93.4 M	17.8 G
3	RPP-SB-8A-3	133.4	24.62	59.5 M	19.6 G
4	RPP-SB-8A-4	168.6	25.27	81.4 M	22.3 G
5	RPP-SB-8A-5	134.8	30.50	83.6 M	15.7 G
6	RPP-SB-8A-6	122.8	32.59	110.8 M	16.1 G
7	RPP-SB-8A-7	126.1	36.24	69.1 M	13.1 G
8	RPP-SB-8A-8	139.4	27.86	90.2 M	6.9 G
9	RPP-SB-8A-9	142.8	25.55	158.4 M	23.9 G

at various locations that are not present in the data from the newly installed cable (red trace). Overall, the in-situ testing results revealed that the electrical properties of the nine (9) feeder circuits removed from service were significantly impacted by moisture exposure during operation. In addition, this data shows that there are no significant effects of moisture on the newly installed cable circuits.

After completing in-situ testing of the originally installed cables, laboratory testing was performed to:

1) Identify any defects in the insulation materials that either allowed moisture to migrate into the polymers or were caused by moisture migration into the cables.
2) Determine if and to what degree these insulation polymers absorbed water.
3) Assess the overall condition and performance of the insulation polymers.

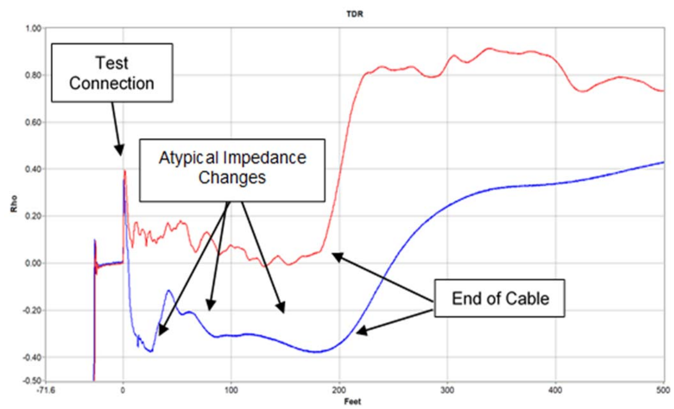

Fig. 4. Example Reflectometry Data Acquired for Originally Installed (Blue Trace) Cables and New Cables (Red Trace)

These laboratory evaluations were performed on the three phases of one of the originally installed cables that had the highest average phase to phase capacitance per foot (168.6 pF/foot) and a low phase to phase insulation resistance (46.9 MΩ). The testing performed included visual inspections, microscope inspections, electrical permittivity, OIT, FTIR and EAB testing.

The results of the laboratory assessments of the cable and insulation materials showed that:

- When submerged in water, the PVC insulations of the originally installed cables exhibit elevated moisture content through the thickness of the materials.
- As shown in the microscope images provided in Fig. 5, micro-voids are present in the insulation of the originally installed cables. These micro-voids make the cable polymers more susceptible to moisture intrusion and as a result moisture related degradation including decreasing insulation resistance.
- Discoloration of the insulation and jacket materials were observed in different sections along the cable length. These sections also show signs of chemical structure changes due to water exposure.

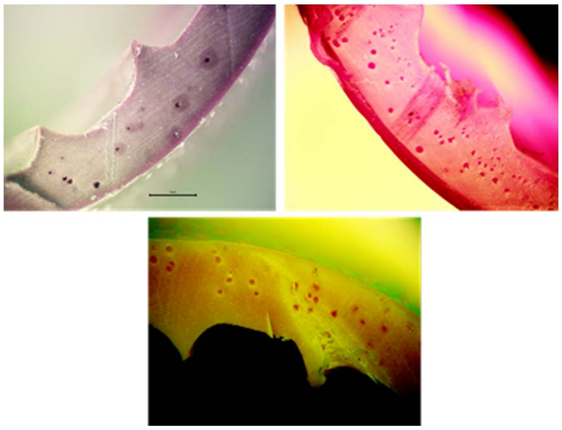

Fig. 5. Microscope Images Acquired at 20X Magnification showing Examples of Micro-voids in PVC Insulation of Originally Installed Cables

- As shown in TABLE VI. , the insulation materials of sections of the originally installed cables that were exposed to water had a lower average EAB, higher electrical permittivity, and lower OIT than the newly installed cables. Thus, exposure to water during service has negatively impacted the mechanical, electrical, thermal, and chemical properties of the PVC insulation polymers of the originally installed cables.

Overall, the results of the in-situ laboratory cable condition assessments show that the micro-voids in the insulation materials of the originally installed cables make these polymers more susceptible to moisture related degradation. These types of issues can lead to degradation of the electrical properties of the cable (e.g. decreasing insulation resistance) and cause problems the with normal operation of the feeder circuits.

TABLE VI. EXAMPLE CAPACITANCE AND IR DATA ACQUIRED FOR ORIGINALLY INSTALLED CABLES AND NEW CABLES

Item #	Cable Section	Insulation Material	Average EAB (%)	Electrical Permittivity	OIT (Minutes)
1	**Originally Installed Cable Samples (Sections Exposed to Water)**	PVC	172	4.6	20
2	**Newly Installed Cable Sample**		242	3.8	38

III. CONCLUSIONS

The in-situ and laboratory cable CM testing methods and the three (3) case studies described in this paper show how multiple combinations of cable testing technologies can be used to assess the aged condition and estimate the RUL of installed cables. This strategy of performing in-situ and laboratory cable aging assessments provides nuclear plants with the means to: 1) objectively determine the condition of installed plant cables and 2) estimate when the cables will reach their end of life. This information can assist plant personnel in assessing the health and performance of cables, identify aged or degraded cables or cable sections before they cause operability issues, and avoid unnecessary and costly replacements of cables that can continue to operate safely and reliably.

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