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OVERVIEW OF RESEARCH ON NUCLEAR PLANT CABLE AGING AND LIFE EXTENSION

G.E. Sliter

Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, CA 94303, USA

ABSTRACT

Safety-related cables potentially subject to accident conditions have typically been qualified for the entire 40-year licensed term of U.S. plants. This paper briefly describes U.S. cable design, qualification practices, and failure mechanisms. It also discusses life extension methods and research efforts aimed at resolving lingering technical issues related to the aging and accident performance of cables.

1 U.S. CABLE DESIGN AND QUALIFICATION

There are fifty to several hundred miles of power, control, and instrumentation cables in U.S. nuclear power plants. Almost all of it is low voltage (600v or less) installed in trays or conduits. The principal polymeric cable-insulating materials include cross-linked polyethylene (XLPE), ethylene propylene rubber (EPR), silicone rubber (SR), and chlorosulfonated polyethylene (CSPE) (DuCharme, 1989). A jacket surrounds the insulation of a single-conductor cable or an entire bundle of single-conductor cables in multi-conductor construction. The main function of the jacket is to protect the insulation from damage during installation. The most common jacket materials are neoprene and CSPE (Hypalon). Instrumentation cable is shielded electrically with metallic foil between the insulation and outer jacket. Almost all power and control cable is unshielded, with an insulation layer protected by an outer jacket.

The cable within containment buildings is of most interest because much of it is safety-related and exposed to harsh steam and radiation environments during design basis accidents after years of thermal and radiation aging. Qualification testing according to U.S. standards and regulations (e.g. IEEE, 1974) exposes a sample cable specimen to artificial, accelerated thermal and radiation age conditioning and then to simulated accident conditions including high temperature, pressure, and radiation, as well as moisture and chemical sprays. Using such an approach, safety-related cables in harsh environments have been qualified typically for a life of 40 years.

Extensive activities are under way to extend the license term of older operating plants from 40 to 60 years. It would be costly -- at least tens of millions of dollars -- to allow continued operation after 40 years by replacing all cables. It is expected that a longer qualified life of the cables can be demonstrated. Efforts are under way to establish the criteria and techniques for cable life extension. This paper identifies the methods being considered for cable life extension, lingering technical issues, and research efforts aimed at resolving these issues.

2 HOW CABLES FAIL

To understand what limits the useful life of cables, it is important to understand their aging mechanisms and how they can fail under design basis conditions.

It is generally known on the basis of decades of plant experience and environmental testing in qualification and research laboratories that the mechanical properties of cable insulation degrade prior to aging degradation of electrical properties. When aging has advanced to the stage of severe embrittlement of the insulation, its electrical properties (such as dielectric strength) remain at a level more than adequate to function, so long as the integrity of the insulation is not lost due to cracking. Even if cracking through to the conductor occurs, the cable can perform its function while operating in a dry condition, because the air in a crack is a better insulation than the elastomeric insulation material! But an aged, cracked cable will almost certainly fail to function electrically in the wet, chemical-laden environment produced by a loss of coolant accident. In fact, the thermal stresses produced by the accident might cause an age-embrittled cable to crack and then fail electrically. In most cases, structural integrity of the insulation layer of cables is sufficient to ensure operability. But there are situations in which integrity of the jacket may also be necessary (e.g. where the jacket is bonded to the insulation* or jacket failure could compromise the qualification of connectors).

Shielded cables can also fail under accident conditions due to low insulation resistance, but the decrease in insulation resistance due to aging has been shown to be small compared with the decrease caused by the hot, wet environment.

Other aging mechanisms such as conductor/shield corrosion, loss of fire-retardants, and electrical treeing do not produce significant aging degradation in low-voltage cables.

Because cables are designed and constructed to operate under accident conditions and fail during accidents only if their insulation is damaged by age-induced cracks, it is not surprising that cables in U.S. plants, which have been in operation as long a 30 years, have been very reliable. Less than ten Licensee Event Reports in a twenty-year period involved aging degradation of cables.

3 CABLE LIFE EXTENSION METHODS

The most straightforward and cost-effective method of extending the qualified life of cables is to reevaluate the original testing or analysis basis for qualification. The 40-year qualified life usually was based on conservative estimates of service conditions during operation and conservative practices in the aging analysis or age-conditioning of samples prior to accident testing. These conservatisms usually exceeded the margins required by standards and regulations. The method of reevaluation reassesses the qualified life based on knowledge of actual plant environments and on any new data produced since the original qualification. For example, if the original qualified life was limited by thermal aging and if temperature measurements show that the average operating temperature of a cable is 10°C less than assumed for qualification, the qualified life of a cable would be about 80 rather than 40 years.

If straightforward reevaluation is not sufficient to provide the desired life extension, either supplemental monitoring or reconfiguration/operational changes can be used. The former provides additional information on the actual condition of the installed cable as opposed to the condition predicted by accelerated aging or analysis. The latter can mitigate aging by mitigating service conditions (e.g. ambient temperature, self-heating, or radiation).

If the above methods are not sufficient to provide the desired life extension, the cable can be requalified by test or can be replaced. Both of these, of course, would negatively impact the cost of nuclear plant life extension. Fortunately, it is expected that virtually all of the high quality industrial grade cables installed in operating plants can be demonstrated to be qualified for 60 years.

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* Research tests in which failures occurred when cracking of a bonded jacket propagated into the insulation have led to NRC Information Notice 92-81, "Failure of Electrical Cables with Bonded Hypalon Jackets."

4 LINGERING TECHNICAL ISSUES AND RESEARCH TO RESOLVE THEM

Despite the margins and conservatisms built into cable qualification and despite about fifteen years of cable research, the process of establishing license renewal requirements in the U.S. is focusing attention on several lingering issues related to the aging behavior and accident performance of cables. Some of these issues and research efforts to resolve them are discussed in the following paragraphs.

One broad issue is the ability of short-term (days, weeks, months) accelerated aging in qualification testing to adequately simulate long-term (60 years) natural aging in the plant. Does the "baking " of cables for weeks or months on the basis of the simplistic Arrhenius equation adequately simulate years at lower plant temperatures? Does the equal dose/equal damage assumption used for high-dose-rate radiation aging adequately address possible "dose-rate effects? Do significant synergistic effects under natural aging conditions give more degradation than the separate imposition of thermal and radiation aging used for qualification aging? Are there significant aging mechanisms for plant cables that are not explicitly addressed by traditional qualification practice?

Extensive cable research programs conducted by the U.S. Nuclear Regulatory Commission (NRC) and the utility-sponsored Electric Power Research Institute (EPRI) have addressed and are continuing to address the broad issue of natural versus artificial aging.

NRC-sponsored research at Sandia National Laboratories has gone on continuously since the seventies. Much of the research examined aging technology such as sequential versus simultaneous aging, synergistic effects, dose-rate effects, and humidity effects. Generally, it was found that for the most common cable insulations (XLPE and EPR) synergistic, dose-rate, and humidity effects are not significant, but they can be significant for some polymers. To err on the conservative side, radiation aging should precede thermal aging for some materials (the opposite order was used for most qualification aging).

In a recent NRC/Sandia research effort (Jacobus, 1992), twelve common cable types were artificially aged with simultaneous heating and gamma radiation at lower rates than in traditional qualification testing. Except for a few anomalous failures, all twelve types were able to function under LOCA conditions after a 9-month aging treatment equivalent to 60 years of typical plant service.

As careful as the aging treatment in these Sandia tests was, it was still accelerated compared with natural plant aging. Recognizing that questions about the differences between artificial and natural aging could continue to plague nuclear plant owners, EPRI launched a long-term natural-versus-artificial aging test program in 1985. Hundreds of specimen "bundles" (Figure 1) were placed at 17 location within the containments of nine nuclear plants between 1985 and 1987. The specimens include segments of five types of cables as well as various types of small electrical devices. None of the specimens are energized.

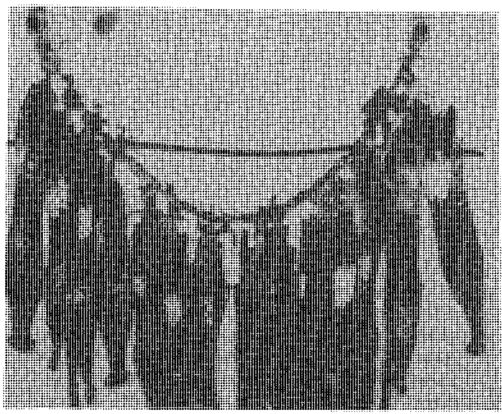

Figure 1: Specimen bundles at on of the seventeen locations in nine U.S. reactor containments in the EPRI in-plant aging program

Temperature and radiation are being measured at each location. Bundles are being removed during scheduled outages. Measured material properties (tensile elongation to break, tensile strength, and density) of the naturally aged specimens will be compared to those of specimens aged in conventional qualification programs. The objective is to improve predictions of the qualified life of long-lived equipment by examining differences, if any, between natural and artificial aging. There are enough specimens in the plants to last forty years if necessary.

Although many material property measurements have been made to date, (Shaw, 1992) almost no changes within the scatter of measurements have been observed. The program needs to progress to at least the 10-year point before degradation is expected to be significant.

5 CABLE CONDITION MONITORING TECHNIQUES

Cables in operating plants are so conservatively designed and of proven reliability that there are currently little or no surveillance or condition monitoring requirements for them. However, it may happen that the reevaluation of remaining design life on the basis of existing information may not cover the desired license renewal target period for certain cable types in relatively severe operating environments in some plants. As a last resort to additional qualification testing or replacement, it may be possible to demonstrate additional qualified life by monitoring the condition of installed cables. The monitoring may show that natural aging has not degraded the insulation as much as was predicted by the conservative qualification practices called for by standards and regulations.

One method of condition monitoring is to simply remove sacrificial samples of cable runs and measure/trend elongation-to-break. Results could be compared to similar measurements on new cable specimens age-conditioned in the same manner as in the original qualification testing. Since this would be expensive, nondestructive methods are under development. Among the condition indicators being considered for tracking aging of cable insulation are mechanical properties, electric properties, and chemical properties.

Since the most important failure mechanism is cracking of embrittled insulation during an accident, EPRI has identified and developed a nondestructive technique for tracking mechanical condition. The hand-held cable indenter aging monitor (Figure 2) measures the compressive modulus of the exposed polymeric element (insulation or jacket) of a cable. It uses this parameter as an indicator of the brittleness of the insulation and its ability to withstand handling, loss-of-coolant-accidents, and seismic events without cracking. Comparison of the in situ values with those obtained from artificially aged samples can be used to justify extending the qualified life of the cable. Laboratory tests (Jacobus, 1991) have shown that the compressive modulus changes systematically with thermal and radiation aging for rubbery cable materials such as EPR, SR, neoprene, and Hypalon (it does not work for semicrystalline materials such as XLPE). A commercial version of the indenter (Toman, 1991) is currently being used for trial cable evaluations in nuclear plants owned by Commonwealth Edison and Electricite' de France.

Among other cable condition monitoring techniques receiving R&D attention are oxidation induction time (time to complete oxidation of a sample is a measure of remaining antioxidant and hence aging), time domain reflectometry (effective for detecting corroding connections, but not insulation aging), and time domain spectroscopy (tracks electrical losses as a function of excitation frequency). Holzman and Sliter (1992) give an overview of cable qualification and condition monitoring.

6 CONCLUSION

Most cable types installed in operating nuclear plants probably have a useful life of 60 years under design service conditions. Reevaluation of the original qualification basis will suffice if measured plant environments are shown to be significantly less than design/qualification values or if the original qualification basis can be shown to be conservative in terms of performance requirements and assumptions about material aging properties. For marginal cases (e.g. cable segments in hot locations or cable types found by research testing to have adverse synergistic behaviors), in situ condition monitoring such as with a portable cable indenter may be able to demonstrate that natural aging has been kinder than predicted by the traditional qualification process. Only where monitoring fails to demonstrate sufficient remaining life would costly requalification testing or replacement be needed.

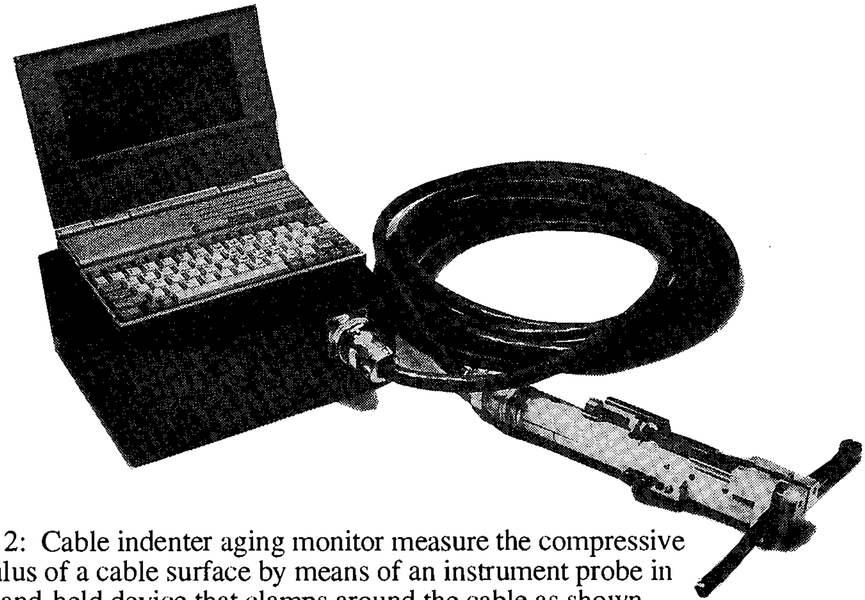

Figure 2: Cable indenter aging monitor measure the compressive modulus of a cable surface by means of an instrument probe in a hand-held device that clamps around the cable as shown

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