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Inspection, Surveillance, and Monitoring of Electrical Equipment Inside Containment of Nuclear Power Plants—With Applications to Electrical Cables

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INSPECTION, SURVEILLANCE, AND MONITORING OF ELECTRICAL EQUIPMENT INSIDE CONTAINMENT OF NUCLEAR POWER PLANTS — WITH APPLICATIONS TO ELECTRICAL CABLES

S. Ahmed S. P. Carfagno
G. J. Toman

In Support of
Nuclear Plant Aging Research

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EXECUTIVE SUMMARY

The purpose of this report is to describe currently available methodology for determining the amount and rate of age-related deterioration of safety-related equipment. The goal is to identify methods of inspection and surveillance of components that are effective in detecting significant aging and service wear effects prior to loss of safety function, so that maintenance can be performed in a timely manner to restore the components' functional capabilities. The continued capability of a device to be able to function during a design basis accident is included in the consideration of the extent of deterioration. Section 2 of the report describes the general concepts of equipment deterioration monitoring. Section 3 provides a discussion of the methodology applicable to electrical cables located inside containment.

Condition monitoring entails continuous or periodic observation and evaluation of critical parameters to assess the ability of an equipment item to continue to perform its specified function during a period following the moment of observation. Through the use of condition monitoring, the need for performing maintenance is determined by evaluation of the amount and type of deterioration rather than performing maintenance at fixed intervals. Ideally, there would be a single parameter that could be monitored to give a direct indication of the level and rate of deterioration of an equipment item. Realistically, condition monitoring of most equipment will require monitoring several parameters. Furthermore, criteria for making decisions about maintenance and replacement may not exist for some types of equipment; for others, the rate of deterioration after it begins may be too great to allow adequate advance warning.

Condition monitoring of cable will require periodic nondestructive, in-situ electrical testing and periodic destructive laboratory testing of samples. Because of the various types and applications of cables, no one set of tests is applicable to all cables. The results of the electrical and physical testing of cable insulation must be trended to determine the rate of deterioration. One proposed method for determining the criteria for the allowable level of deterioration prior to maintenance is to evaluate the

condition of cable that was aged in qualification tests. The properties of such cable indicate the degree to which the cable may be allowed to deteriorate and still successfully pass a DBA test. However, it must be recognized that such criteria are approximate at best, since real-time, in-service deterioration mechanisms and rates may vary from those incurred during accelerated simulation of aging in qualification programs.

This report also discusses limitations on testing (such as the problems associated with disconnecting and reconnecting cable circuits for testing) and the potential for damage to cable and equipment during high voltage testing. Until further development takes place, cable monitoring should concentrate on critical safety-related applications. Insofar as destructive laboratory tests are included in monitoring programs, these should encompass the tests performed at the time of manufacture to allow a determination of changes in physical and electrical characteristics.

When cable failures occur in service, evaluation of the failed section should be performed to determine the cause of failure. Findings from these evaluations should be incorporated into the condition monitoring program to verify that a parameter indicative of the type of deterioration observed is monitored by the program.

ABSTRACT

The general concepts of equipment condition monitoring as applicable to the detection of age-related deterioration of safety-related equipment are described. The goal is to detect deterioration in the incipient stage, prior to in-service failure and prior to the point at which equipment can no longer be expected to perform its function when exposed to design basis accident conditions.

The application of condition monitoring is discussed specifically for electrical cables. The goal of cable condition monitoring is to determine the degree of cable degradation and to predict the remaining useful life. In-situ nondestructive testing and destructive laboratory testing are discussed. Interim recommendations are given for the implementation of a cable condition monitoring program.

1. INTRODUCTION

The nuclear plant aging research (NPAR) program initiated by the Nuclear Regulatory Commission (NRC) has the following objectives:

- to identify and characterize aging and service wear effects associated with electrical and mechanical components, interfaces, and systems likely to impair plant safety.
- to identify and recommend methods of inspection, surveillance, and condition monitoring of electrical and mechanical components and systems which will be effective in detecting significant aging effects prior to loss of safety function so that timely maintenance and repair or replacement can be implemented.
- to identify and recommend acceptable maintenance practices which can be undertaken to mitigate the effects of aging and to diminish the rate and extent of degradation caused by aging and service wear.

The research activities, the expected product, and its regulatory impact are illustrated in Figure 1-1. This interim report addresses specific issues pertaining to maintenance and replacement based on inspection, surveillance, and condition monitoring of electrical equipment inside the containment of nuclear power plants. A specific discussion of cables is provided in Section 3. The study is being conducted under a subcontract with Martin Marietta Energy Systems, Inc., operator of Oak Ridge National Laboratory (ORNL), as part of the NPAR task entitled "Detection of Defects and Deterioration Monitoring of Nuclear Power Plant Safety Equipment."* The objective of this project is to develop interim recommendations, within the state of the art, for inspection, surveillance, and monitoring of aging effects for selected equipment. Further, criteria are to be established for the equipment of interest for decision making related to continued operation, maintenance, replacement, and repair. However, at this stage of the investigation, emphasis is placed on developing a framework to arrive at criteria and guidelines.

At present, it is well recognized that there are many unknowns concerning the identification of age-related degradation, such as the rates of degradation in normal and harsh environments and their effect upon the ability of equipment

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* The statement of work for this project as written by ORNL is given in Appendix A.

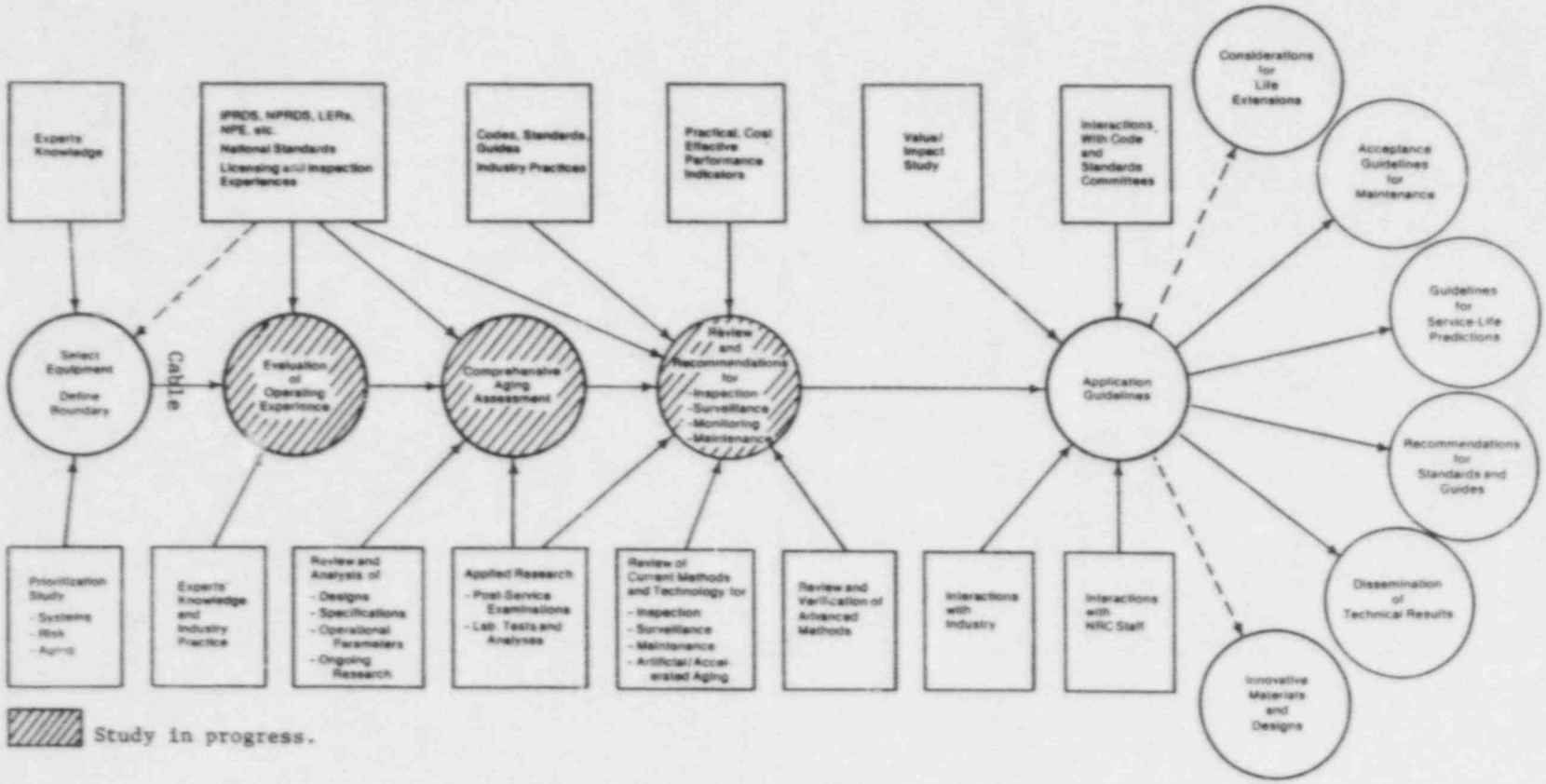

Figure 1-1. NPAR Program Strategy

to continue to perform its safety function. Of particular interest is the ability to detect degradation and incipient failure conditions so that preventive action such as maintenance or replacement may be taken.

Cost-effective techniques for adequate monitoring and detection of degradation and incipient failures are still in the developmental stage for most electrical equipment. In many instances, research may be required before practical techniques can be recommended. However, the existing state of technology has not been fully exploited; therefore, it is useful to identify effective uses of existing technology as well as the research and development efforts that are most likely to be productive.

Effective use of condition monitoring in nuclear power plants can improve plant safety and availability. Condition monitoring technology has the potential to allow relaxation of some of the stringent requirements for preventive maintenance and replacement of safety equipment by providing quantitative assessment and prediction of equipment degradation. Evaluation of condition monitoring results will allow establishment of maintenance and replacement intervals based on actual rates of equipment deterioration, thereby allowing improved allocation of resources. Less frequent maintenance will be performed on equipment found to deteriorate more slowly than expected, while more frequent maintenance will be performed on those that degrade more rapidly. The result will be an overall improvement in plant safety.

Section 2 provides an overview of various conceptual aspects of condition monitoring, including a basis for developing a strategy for surveillance, maintenance, and replacement; problem areas; and development of criteria for taking preventive measures. The status of cable condition monitoring (based on a literature review, experience, and communications with cable manufacturers and users) is documented in Section 3. A Licensee Event Report (LER) search relating to cable failures is documented in Appendix B, and a summary of selected cable tests that may be useful for condition monitoring is given in Appendix C.

A glossary of frequently used terms pertaining to condition monitoring is provided in Appendix D. Where terms may have various interpretations, the definitions given in Appendix D identify the meanings intended in this report.

2. CONCEPTUAL ASPECTS OF CONDITION MONITORING

2.1 INTRODUCTION

This section describes generic failure patterns of electrical equipment and the various aspects of condition monitoring. Electrical equipment in nuclear power plants experiences degradation and functional impairment with time, beginning as soon as an item is manufactured. The rate of degradation depends on the properties of the materials and parts and their interconnections; the stresses imposed on the equipment through shipment, storage, installation, and service; and whatever restoration of functional capability is achieved through maintenance, calibration, and repair. For some types of equipment, the degradation of materials and parts is reflected in a corresponding reduction of functional capability; for other types of equipment, the degradation of materials and parts may progress without noticeable functional degradation until a trigger event causes sudden failure of the equipment [2].

The consideration of age-related deterioration was formally introduced in IEEE Standard 323-1974 [2], which requires demonstration that the safety-related equipment can perform its required function during the most severe service conditions not only when new, but also after having been in service for its entire installed life. One method for meeting this requirement is artificially aging equipment by accelerated techniques prior to exposure to simulated accident conditions during environmental qualification. Artificial aging approximates some aging phenomena; however, accelerated aging techniques are not proven for all stressors, and concern has arisen that accelerated exposure to some stressors, such as radiation, may produce totally different rates of degradation in some materials than actual rates of exposure do. To assure the continued capability of equipment to perform its safety function, it is desirable to be able to determine and trend the rate and amount of deterioration of equipment during its service life. One approach to determining the level of deterioration is to monitor age-related parameters of the equipment during service life.

Through the monitoring of equipment parameter deterioration and the establishment of acceptable levels of deterioration, preventive actions may be

taken to preclude failure of safety equipment both during normal service and design basis accident (DBA) service conditions.

2.2 CONDITION MONITORING AS A STRATEGY FOR MAINTENANCE, REPAIR, AND REPLACEMENT

Condition monitoring of equipment may be defined* as continuous or periodic observation and evaluation of critical parameters to assess the equipment's ability to continue to perform its specified safety functions during a period following the moment of observation. Observation may take the form of measurement or inspection. The specified functions of the equipment include those required in the event of applicable accidents as well as normal service. As used in this report, the term "condition monitoring" is distinguished from surveillance and diagnosis. In general, the intent of surveillance and diagnosis is to determine if a device is functioning properly at the time of observation. The intent of condition monitoring is to determine whether or not a device will be capable of functioning for a period after an observation. Condition monitoring is expected to reveal not only the functional state at the moment of observation, but also the ability of the equipment to remain capable of performing as specified for a period following the observation. Therefore, to be considered as condition monitoring techniques, diagnostic techniques must provide a basis for assessing the expected functional capability of the equipment should a DBA occur subsequent to the observation. Ideally, monitoring a single functional parameter would suffice to indicate the functional capability and exact criteria would exist to decide, based on the observed value of the parameter, what action to take at the time of observation, i.e., to continue operating without change, to perform maintenance or calibration, to repair the equipment, or to replace the equipment.

Condition monitoring requires a data-collection and analysis system to determine the extent of degradation and the nearness of incipient failure. The monitored parameter must be evaluated to decide what corrective actions, if any, are to be taken. Analysis of data collected over a long time can

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*Appendix D contains a glossary of terms relating to inspection, surveillance, and condition monitoring.

help to determine the causes of degradation and the systematic preventive actions (such as scheduled inspection, preventive maintenance, or replacement) that will help avoid or reduce equipment degradation.

A simple picture of the ideal situation is given in Figure 2-1. The solid line represents the functional capability of the equipment, and the dashed lines represent parameters (or indicators) that have strong correlation to the functional capability or equipment degradation with time. An "acceptable" indicator for condition monitoring is one that shows a larger rate of change than that of the functional capability, thus providing a warning of impending functional degradation that may not yet be apparent. Conversely, if the rate of change of the indicator is slower than that of the function capability, then the indicator is not useful (labeled "unacceptable" in Figure 2-1). An indicator having a high rate of change (relative to the rate of change of functional capability) and good correlation with functional capability would be a good candidate for condition monitoring. Over a period of time, as shown in Figure 2-1, the functional capability may remain relatively constant and therefore may not provide sufficient evidence of equipment deterioration, whereas the condition monitoring indicator may indicate equipment deterioration and reveal an incipient failure condition.

Criteria can be established that require maintenance to be performed when condition monitoring parameters deteriorate to a specific level or vary in a specified manner. These criteria may be established on the basis of plant experience or laboratory research. In Figure 2-1, the interval between the moment of observation and the time corresponding to the minimum allowable functional capability is an estimate of the remaining life of the equipment if no corrective measures are employed to enhance the life of the equipment.

The criteria for performing preventive actions must be set so that adequate functional capability remains during the period required for preparation for the preventive actions.

Conceptually, a criterion may take the form of a statement such as: When the level of the functional indicator reaches the value A, preventive action B should be taken. For the purpose of illustration, consider an instrument cable (with all its connections) between an alarm in the control room and a pressure transmitter in the containment of a nuclear power plant. Suppose it

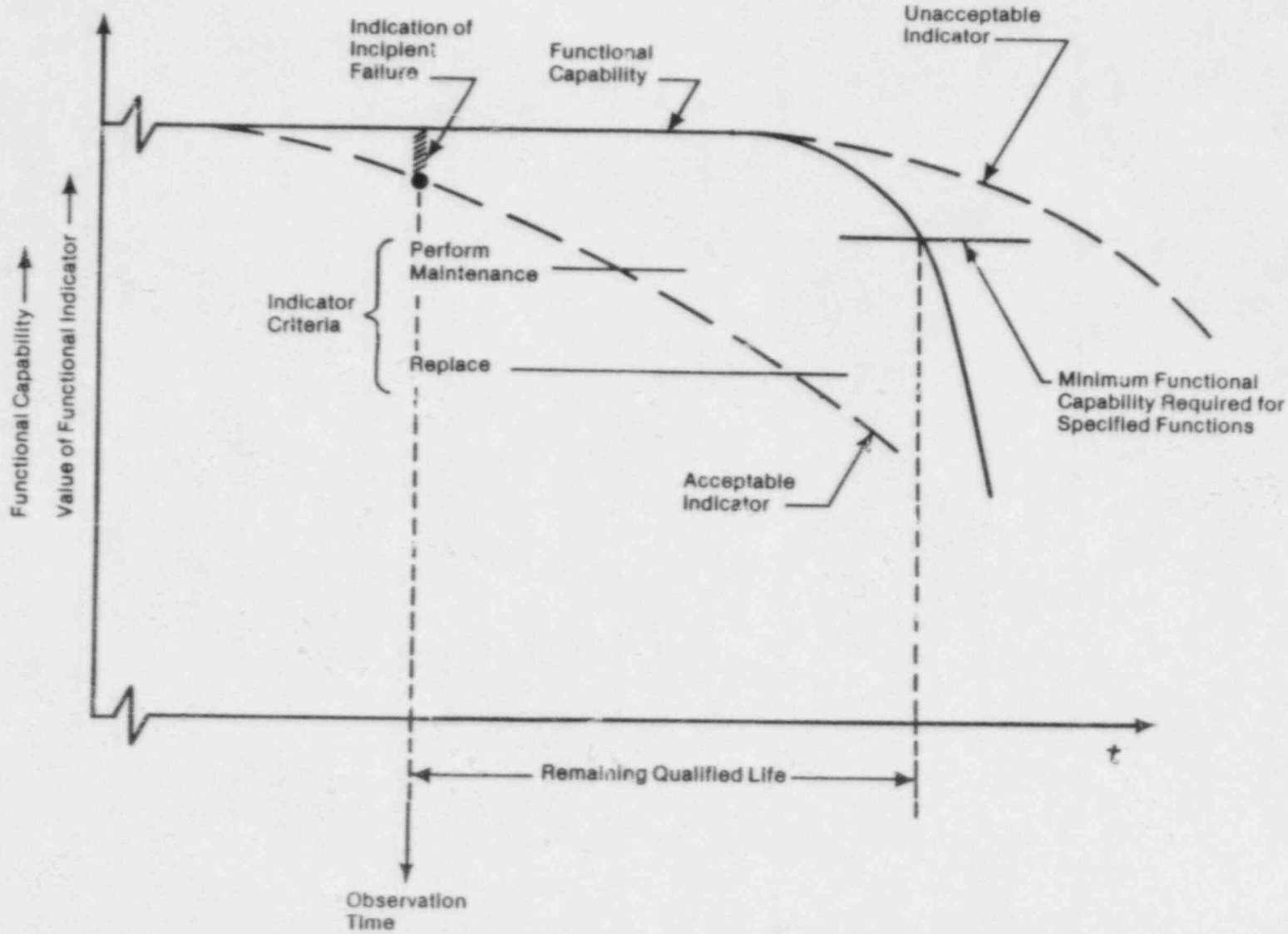


Figure 2-1. Use of Functional Indicators for Condition Monitoring

has been established that, when the leakage current in the line measured at 500 Vdc exceeds 5 mA, the pressure transmitter signal may have excessive error should a LOCA occur 1 year after the observation. The condition monitoring criterion could take the following form: If the leakage current of the line measured at 500 Vdc exceeds 5 mA, the line must be examined within 1 year for defects and the appropriate corrective action must be taken. It may also be required that the frequency of monitoring be increased after the 5-mA warning level is reached.

It must be emphasized that quantitative, predictive criteria of the type used for illustration, i.e., identifying incipient problems well in advance of potential malfunction under DBA conditions, are not currently available for most equipment. However, current experience and technology are consistent with the formulation of qualitative criteria for many applications. The guidelines for surveillance and maintenance will become more nearly quantitative and practical through experiences gained as increased emphasis is placed on these practices by utilities. It is essential, however, that the experience be evaluated with respect to upgrading surveillance and maintenance guidelines and that the results be disseminated throughout the nuclear industry.

The actual picture of deterioration monitoring is more complex than the one represented in Figure 2-1. It may not be feasible, in some cases, to represent the actual performance of the equipment by a single functional parameter; it may be necessary to measure performance by a composite of several functional measurements. In some applications, the minimum functional capability may be known, but the rate of degradation of the equipment may not be known. In such cases, it is much more difficult to estimate the remaining life of the equipment after an observation. Condition monitoring becomes very useful for equipment that exhibits a drastic decrease in its functional capability (over a relatively short period of time) after a period of operation where the functional capability essentially shows no degradation, as depicted in Figure 2-1. In this case, ideally, a smoothly decreasing indicating parameter is desirable for condition monitoring, and maintenance or replacement of the equipment can be carried out at the predetermined levels of parameter degradation.

With each maintenance, as shown in Figure 2-2, the equipment is upgraded and the condition monitoring indicators as well as the functional capability curves move to the right, until they reach a point at which it becomes more cost-effective to replace the equipment.

2.3 FAILURE PATTERN AS A BASIS FOR CONDITION MONITORING AND MAINTENANCE STRATEGY

The previous section discussed the formulation of a maintenance strategy on the basis of condition monitoring. At present, however, either sufficient data are not available or systematic evaluation of the data (data trending) has not been performed for much of the safety-related equipment, so that a maintenance strategy for the equipment of interest cannot easily be developed through condition monitoring.

Another approach to arriving at such a strategy is to evaluate the statistical pattern of equipment failure over a period of time. The equipment failure pattern will indicate whether or not condition monitoring is necessary during the initial and intermediate periods of equipment life. The failure pattern can also be used to determine the frequency of inspection, preventive maintenance, and equipment replacement. It must be recognized that the determination of the frequency of such efforts must take the demands of accident service conditions into account. In other words, the frequency of surveillance and preventive action must be adequate to provide reasonable assurance of satisfactory performance not only during a future period of normal service, but also during the usually more demanding conditions of a DBA occurring at the end of the period. The different types of degradation patterns that may apply to different types of equipment are presented here to indicate their influence on the approach to condition monitoring, surveillance, maintenance, and replacement.

The failure patterns discussed here are statistical in nature, i.e., they indicate when the equipment will have a higher probability of failure. If significant statistical data are available for such failure predictions, then surveillance, periodic preventive maintenance, or replacement can be scheduled more effectively on the basis of failure trends. If the failure pattern of a device shows that the probability of failure increases significantly after a

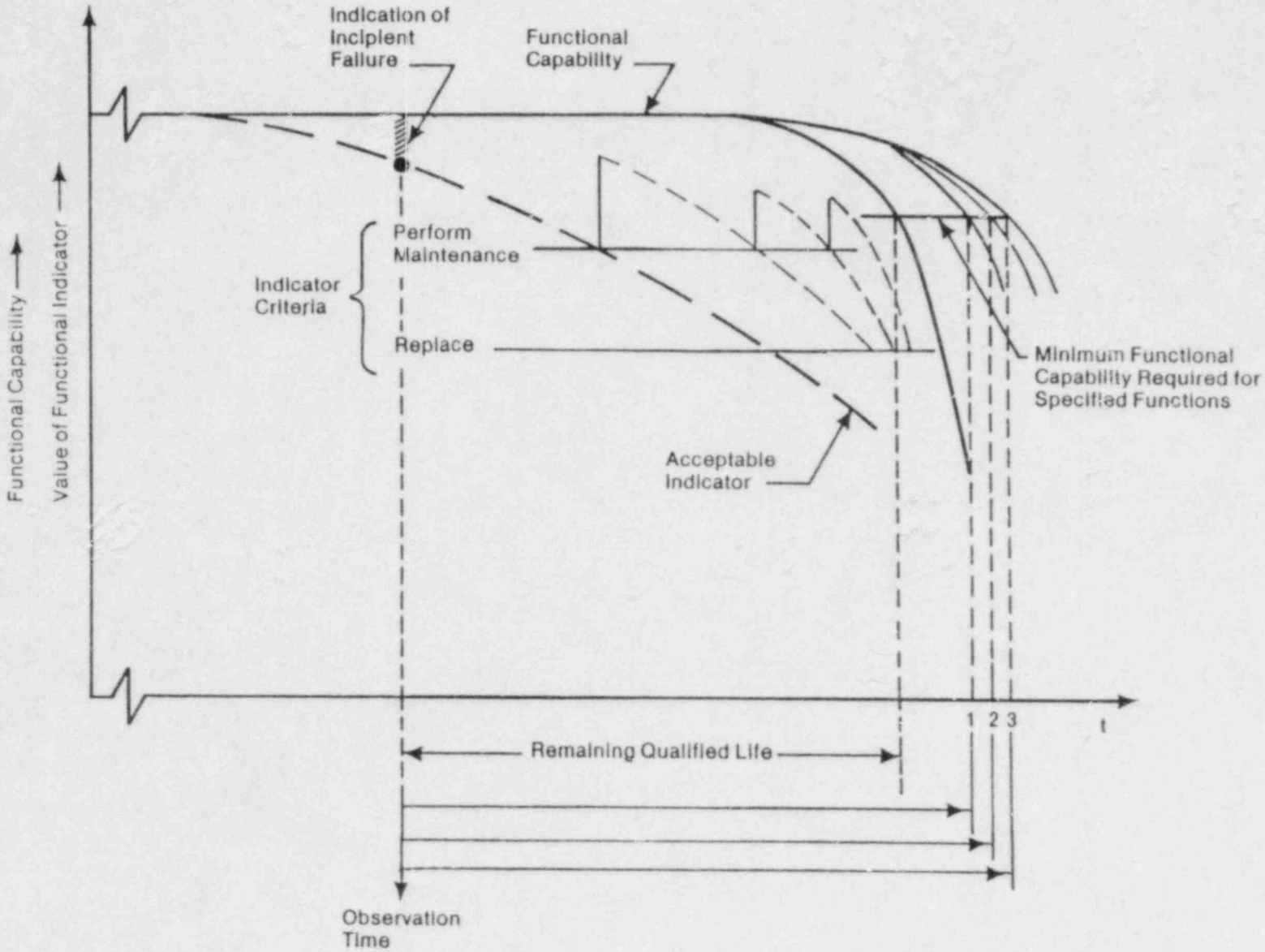


Figure 2-2. Effects of Preventive Maintenance on Functional Capability and Remaining Qualified Life

certain service life, fixed interval periodic replacement of the equipment, rather than replacement based on condition monitoring results, may be used.

The failure rate of components as a function of time is given by the well-known bathtub curve, shown in Figure 2-3 [3]. In their early life, which is called the infant-mortality (or burn-in) period, components experience a high failure rate. For a large portion of their useful life, the failure rate of components is characterized by random failures, and the failure rate is constant. Components experience an increasing failure rate in the late part of their life, which is characteristic of the wearout period. As shown in Figure 2-3, electrical components generally experience a more constant failure rate in the useful life period than do mechanical components. The initial high failure rates of an equipment item can be eliminated in some cases by burn-in testing. A proper condition monitoring and maintenance program can help to ensure that prompt corrective action is taken when the wearout region is reached.

Some of the failure patterns that have been observed for numerous components in the aircraft industry are shown in Figures 2-4, 2-5, and 2-6 [4]. However, an equipment item, whether from the nuclear or aircraft industry, will not necessarily follow any one of these failure patterns. The failure pattern of any equipment item can best be established through evaluation of statistically significant failure data.

Most components exhibit the failure pattern shown in Figure 2-4, in which a large number of failures occur at early stages of operation. Burn-in testing may be employed for some equipment to reduce or eliminate the infant-mortality or decreasing failure rate portion of the curve. Either continuous or periodic condition monitoring of the equipment may be necessary during the infant mortality period. For the stable period of equipment operation, periodic inspection and testing should be emphasized. The maintenance program should be subject to modification on the basis of condition monitoring.

Another failure pattern, shown in Figure 2-5, occurs when the failure rate is constant, which means the equipment failure will be random in nature. Fixed interval periodic maintenance or maintenance based on condition

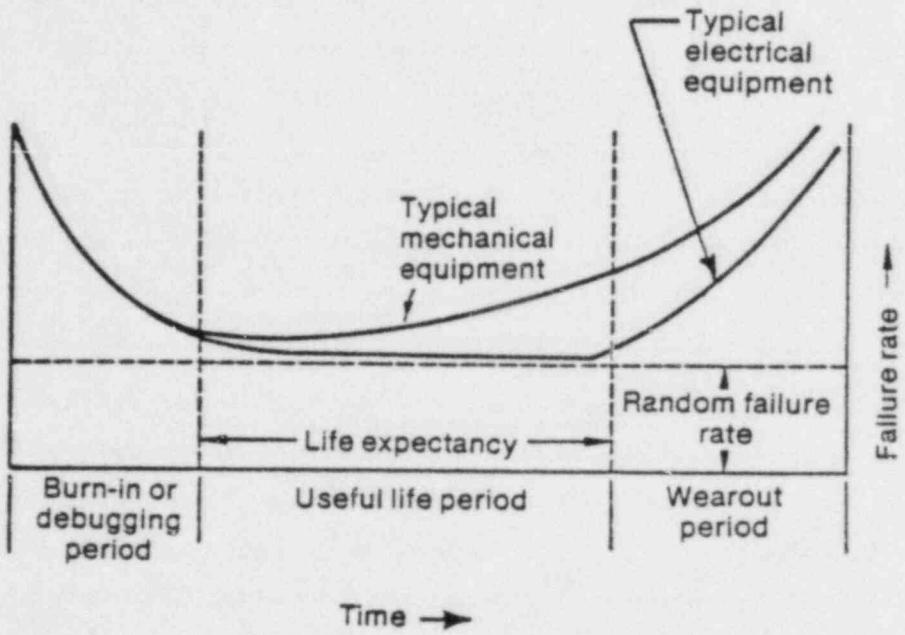


Figure 2-3. Time Dependence of Failure Rate

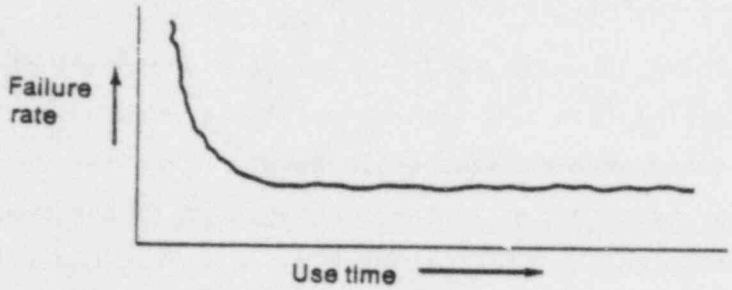


Figure 2-4. Failure Pattern of Components with Initial High Failure Rate Followed by Constant Failure Rate

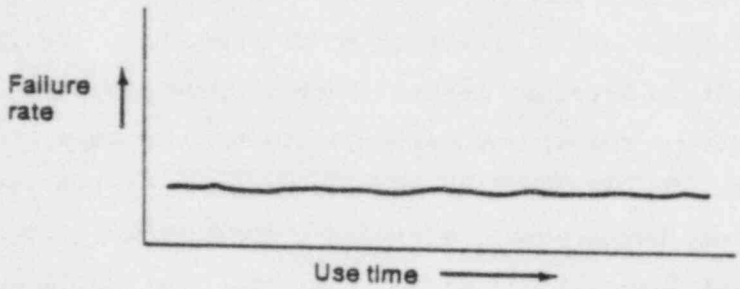


Figure 2-5. Failure Pattern of Components with Constant Failure Rate

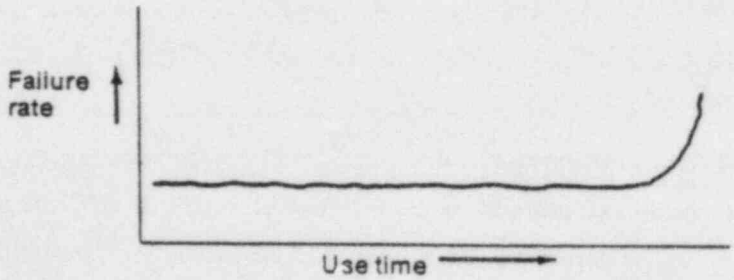


Figure 2-6. Failure Pattern of Components Showing Wear After Constant Failure Rate

monitoring is not required for such equipment since wearout and deterioration do not occur, but periodic surveillance may be required to ensure quick discovery of random failures.

The failure pattern shown in Figure 2-6 is for equipment that is stable for a long period of time before it starts to exhibit wearout failures. For such equipment, condition monitoring should be performed periodically, but no preventive program is required until the equipment is in the wearout region. The preventive maintenance can then mitigate aging of the equipment.

Condition monitoring may also be based on simple wearout or logarithmic (Arrhenius) degradation models [5]. Examples of the simple wear and logarithmic models are illustrated in Reference 5 for a pressure transmitter, where set point drift is considered the critical parameter to be monitored. In the example, a failure is considered to be a drift of 10% of the initial calibration (a calibration error of $\pm 2\%$ is considered, i.e., maximum acceptable drift is 8%). After an initial surveillance period t_1, the life of the transmitter can be reevaluated (from t_2 to t_3), using a simple wear or logarithmic model. On the basis of new evaluations, the initial surveillance period may be revised. A simple wearout model will provide a conservative (shorter) surveillance period than the logarithmic model.

The above examples of failure rate patterns relate to normal service conditions. Establishment of frequency of inspection and maintenance must include consideration of the effect of postulated DBA service stresses. Figure 2-7 shows the effect of normal and accident service stresses on accumulated deterioration. The DBA service condition will cause stresses that are usually more severe than normal service stresses. Care must be taken in development of inspection and maintenance intervals such that sufficient capability to withstand a DBA condition remains throughout each interval. The combined effect of normal and possible DBA-related deterioration must be such that the equipment is not caused to significantly enter the wearout region (see Figures 2-3 and 2-6) where failure rates become exponential and the bulk of the equipment would be expected to fail.

Statistical data for normal service failure rates for nuclear power plants equipment are being gathered for use; however, at present, these data are insufficient or have not been analyzed for use in establishing frequency

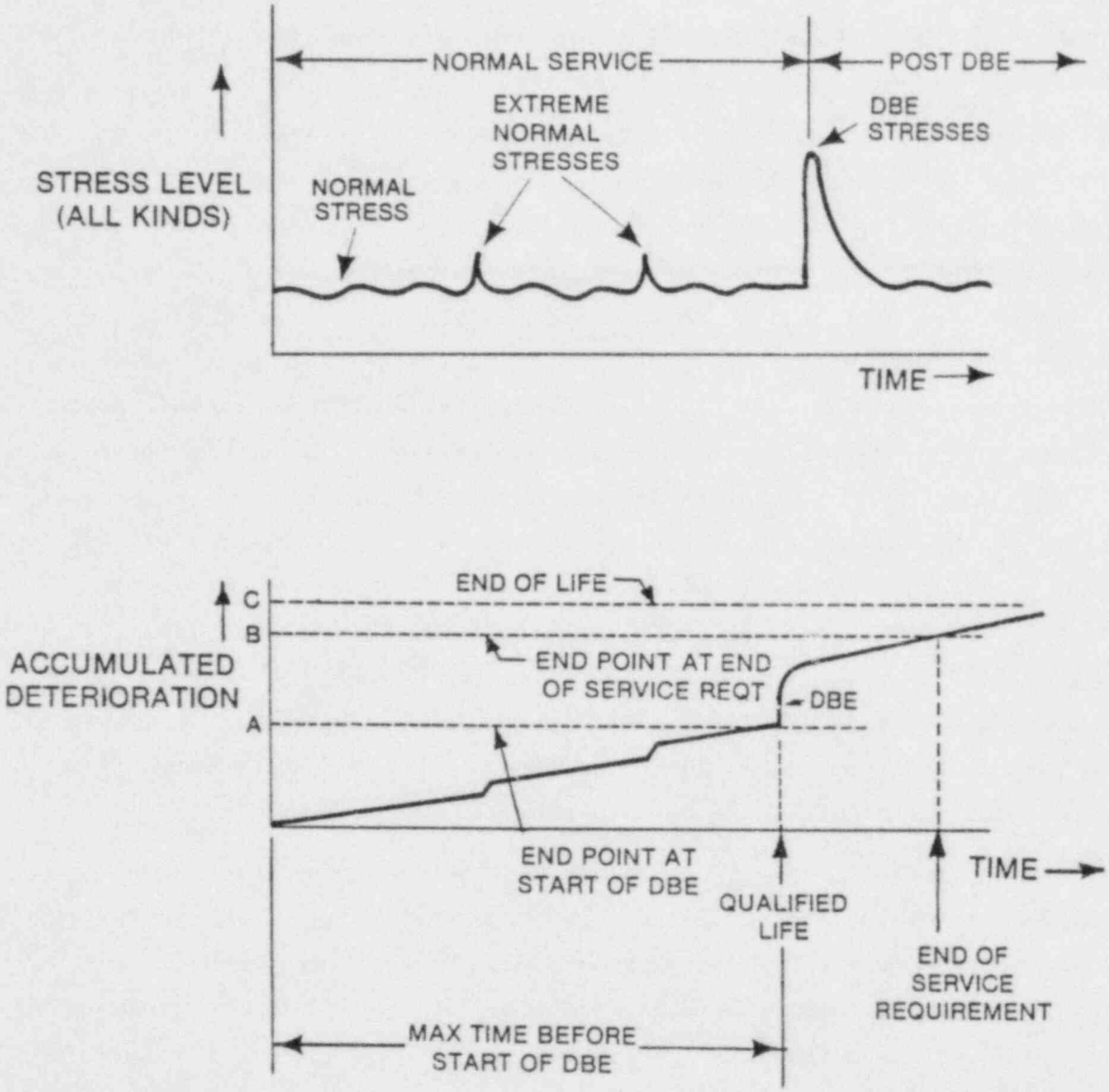


Figure 2-7. Accumulated Deterioration Related to Service and Design Basis Event Stresses (seismic, LOCA, MSLB) (Adapted from Figure 6-7, Ref. 7)

of surveillance and maintenance. Basically, very few data exist relating the effect of DBA service conditons to changes in failure rate. Therefore, to use failure rate data as a basis of determining intervals, considerable conservatism must be incorporated to account for the effect of postulated DBA service conditions.

An approach to the control and enhancement of a preventive maintenance program is to evaluate the impact of additions and deletions of preventive maintenance actions upon the future performance of equipment. This approach requires identification of important plant equipment based on the frequency of failure and its contribution to plant unavailability. Effects of maintenance actions are then predicted with regard to changes in plant availability. A recent EPRI report [6] provides guidance for implementing such an approach. The report describes the methodology for delineating and ranking the frequency of maintenance actions to allow selection through cost-benefit analyses of the combination of actions having the greatest potential for return.

2.4 AREAS OF DEVELOPMENT REQUIRED IN INSPECTION, SURVEILLANCE, AND CONDITION MONITORING

Condition monitoring for nuclear power plant equipment is in a state of development, and there are a number of areas for which theoretical and technological development are required.

For equipment inside the containment of nuclear power plants, a major problem in condition monitoring is lack of accessibility during plant operation due to the radiation environment. For such equipment, it is necessary to monitor aging parameters either remotely (on a continuous or periodic basis) or during plant shutdowns.

Continuous or periodic condition monitoring may be justified for equipment essential for the safe or continued operation of the plant. However, considering that there are many safety-related equipment items inside containment, condition monitoring of all the safety-related equipment may be excessively expensive. For example, monitoring the degradation of hundreds of valves and hundreds of miles of electrical cable on a continuous or periodic basis does not appear to be economically feasible. Therefore, guidelines for

condition monitoring (as well as guidelines to develop realistic and quantitative criteria for surveillance and maintenance) need to be established. The guidelines should provide, for specific equipment, the critical parameters most indicative of age-related degradation; criteria for using condition monitoring data to make decisions concerning the type and timing of corrective maintenance or replacement; and the technology applicable to condition monitoring. The guidelines should also provide the sample size of a population of similar equipment that should be monitored (e.g., how many cable lengths need to be tested to predict the condition of similar cables that are not tested). Further, the guidelines should provide the actions to be taken for other equipment within the population if a certain number of equipment items being monitored degrade to an unacceptable level. For example, if a certain number of power cables, exposed to high humidity and temperature, are being monitored and show signs of unacceptable insulation degradation, then direction must be provided for testing and maintenance of the unmonitored cables that are operating under a similar environment.

Another problem area in developing a condition monitoring program for much of the safety-related equipment is the inadequate knowledge of the mechanisms of degradation of the materials, parts, and interconnections that make up the equipment. For many of the equipment items related to nuclear power plant safety, the degradation mechanisms have not been fully identified. Even for equipment such as cable, which has undergone extensive research into its degradation mechanisms and failure causes, and for which extensive basic research, laboratory experiments, and field experience exist, there are no conclusive findings on many aspects of cable monitoring. For example, an increase in power factor from one test to the next does not pinpoint the type of cable insulation deterioration that is being experienced. The power factor change may occur for many different reasons such as absorption of water, development of electrochemical trees, or changes in chemical composition. The type of deterioration of cable insulation is also dependent upon the application and environment. For example, electrochemical treeing could be expected for medium voltage (15 kV) cables in a wet environment, but would not be expected for low voltage cable in a dry environment.

At present, an adequate correlation between the measurable aging parameters and the future functional capability during normal and DBA conditions of many types of equipment does not exist. Therefore, replacement or repair decisions are heavily based upon prior experience and engineering judgment with regard to test results rather than firm predetermined criteria.

The parameters that are used to monitor the aging of equipment are based on the aging mechanisms of the materials, parts, and interconnections involved. Assuming that the critical parameters indicative of the degradation of the equipment with aging can be identified and the correlation between a parameter and the functional capability is known, one must identify methods that can be used to monitor the parameters of installed equipment. In many cases, suitable techniques are not available that can be applied for continuous or periodic monitoring of the critical parameters. For example, in the case of power cables, the ability to perform in-situ partial discharge testing of long cables is limited. The available portable power supplies for the test are limited to approximately 30 kVA [8], which may be insufficient for long lengths of cable. For some significant aging parameters, no adequate and cost-effective technology for monitoring is currently available.

An area where major development is required is the establishment of criteria for the determination of the degradation level at which corrective maintenance of an equipment item is required to ensure safe operation of the plant. After condition monitoring has revealed the extent of equipment degradation due to aging, it is necessary to determine how much longer the equipment will be able to perform its specified function in a DBA environment. If it cannot perform its safety function if a DBA were to occur during the predetermined minimum period, preventive maintenance must be performed prior to the loss of capability to perform under DBA conditions. Thus, the major benefit of condition monitoring is improved guidance for the frequency and extent of maintenance of equipment.

Establishing criteria for initiating preventive action based on the level of present or projected equipment degradation presents a serious problem. At this time, the level may have to be based solely on engineering judgment and prior experience. Analytical solutions based on the theory of material and

component aging are generally not available within the present state of the art. This does not mean that development of corrective action criteria is not possible. At present, a consensus of the considerations used in making engineering judgment decisions would help in the program to develop such criteria and would be useful in developing and implementing a condition monitoring program.

In light of the developmental work that may be required to bring condition monitoring into full fruition for some equipment, it is interesting to note the level of success in the development of such techniques for flaw detection in piping, reactors, steam generators, and turbines. The EPRI progress report on its NDE program [9] provides discussions of various techniques including ultrasonic, eddy current, magnetic particle, and infrared detection. Included are discussions of methods for producing specific types of flaws for use in demonstrating the capability of the test equipment and of further advances in each type of technology. These efforts are designed to both improve the technology and reduce the cost of in-service inspection programs. While such development programs cannot be expected to be successful for each type of condition monitoring application, the development of flaw detection and analysis techniques for reactor system components is indicative of the advances that can be made in a relatively short period.

3. INSPECTION, SURVEILLANCE, AND MONITORING OF ELECTRICAL CABLES LOCATED INSIDE CONTAINMENT

3.1 SUMMARY

This portion of the report describes the types of cables that are used in nuclear power plants, the causes and mechanisms of their failure, and the means of detecting age-related deteriorations that may lead to failure.

The most prominent modes of age-related failures of cable are electrical insulation degradation and termination failure. A discussion of failure causes and mechanisms appears in Section 3.7.

Cable insulation parameters that can be evaluated are insulation resistance, polarization index, high potential withstand capability, tensile strength, elongation, dielectric strength, partial discharge level, and dissipation factor. Section 3.8 describes test methods and implications of results. The limitations of performing in-situ testing are discussed in Section 3.11.1. Section 3.11.3 describes development of quantitative decision criteria for corrective action.

An acceptable correlation of cable inspection, surveillance, and monitoring results with the continued ability to withstand DBA conditions is not presently available. Artificially aged cable has been used in accident simulation tests; however, data regarding the level of deterioration in the parameters of the aged cables prior to DBA simulation are not available to allow determination of acceptable levels of deterioration in cables that are in service.

Current utility practices pertaining to surveillance and testing of cables are discussed in Section 3.12. Tests to measure insulation resistance are being conducted at some plants to identify trends for cable deterioration. Periodic high-voltage testing of cables connected to large motors is performed by some utilities but is considered by other utilities to be a source of substantial degradation to the cables.

The purpose of existing utility cable testing programs is to determine whether significant deterioration has occurred and whether replacement or further investigation is required. These tests are not condition monitoring

tests in that remaining life is not estimated nor is the continuing ability to withstand DBA conditions evaluated.

Information obtained during this study was analyzed to develop interim recommendations for condition monitoring, surveillance, and maintenance of cables. It was found that sufficient data do not exist to formulate quantitative criteria; however, significant condition monitoring parameters were identified, and various observations were made in this report that can help formulate a basis for developing quantitative criteria. Discussion pertaining to interim recommendations is provided in Section 3.13, which concludes that further investigation is necessary to develop criteria for choosing between continued operation of cables and taking corrective measures.

3.2 INTRODUCTION

At first glance, electrical cables appear to be simple devices that should be easy to monitor for age-related deterioration. The two primary components are insulation and conductors. However, further evaluation indicates that monitoring and evaluation of cable aging is a relatively complex subject. Many types of insulations are presently in use, most of which are organic in nature. The types of deterioration vary for the different organic materials and may be significantly different for the same material when it is subjected to different stresses, combination of stresses, and different stress levels. Besides being composed of different materials, different types of cables are used for different functions. Instrumentation cable is significantly different from power cable both in construction and in the stresses to which it is exposed.

The testing of cables in a nuclear plant is limited by many concerns. The number of cable circuits is of a proportion that precludes testing of all circuits. Disruption of circuits for testing can lead to reduction of safety if restoration is not properly controlled. In some cases, tests that are of interest may be precluded by practical limitations of test equipment and suitability of the test to in-situ applications.

The following sections describe the complexities of cable monitoring and provide methods for handling them. Monitoring of aging parameters of cables is not simple; however, it is not impossible nor impractical.

3.3 FEATURES AND APPLICATION OF CABLES IN NUCLEAR POWER PLANTS

3.3.1 Types of Cables

Four basic types of electrical cables are used in nuclear power generating stations:

- o low voltage power cables (600 V rating)
- o medium voltage power cables (usually voltages of 4 to 13 kV)
- o control cables (low voltage, below 600 V, at a few amperes. Used to control devices such as valve operators)
- o instrumentation cables (typically thermocouple wire, resistance temperature detector [RTD] cables, twisted pairs, and coaxial cables for transmission of data or instrument power. Also used for current-controlled devices [e.g., 20 to 50 mA], signal transmission, etc.).

Table 3-1 provides further breakdown of cable types and applications. It should be noted that 4-kV safety-related cable is not used inside primary containment and that 13-kV power systems are generally not safety-related. Figure 3-1 shows some typical constructions of cables.

For a new BWR, the amount of cable within primary and secondary containment is approximately as follows:

Low voltage power	300,000 feet
Control	240,000 feet
Instrumentation (general)	1,300,000 feet
Instrumentation (neutron monitoring)	30,000 feet

Cable mounting configurations vary with the type and vintage of the plant. Cable may be located in trays or conduits inside of containment. In some newer BWR plants, most of the cable is located in conduits inside of primary containment. However, small sections of this cable may be exposed between the device housing and the end of the conduit section. Outside of containment, most cable is located in cable trays.

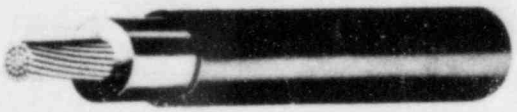
3.3.2 Types of Insulation

A comparison of typical insulation and sheathing (jacketing) materials used in electrical cables that may be found in nuclear power plants is

Table 3-1. Cable Types and Applications

Cable Description	Inside Containment		Outside Containment	
	Safety-Related	Non-Safety-Related	Safety-Related	Non-Safety-Related
Instrumentation coax, twinax, triax	Radiation detection instruments, neutron monitoring	Radiation detection, small signal instrumentation	Same as inside containment	Same as inside containment
Instrumentation twisted, shielded pair	4-20 mA instrument signals, RTDs	4-20 mA instrument singals, RTDs	Same as inside containment	Same as inside containment
Control cable 600 V 12 to 20 AWG	Position switches, pressure switches, level switches	Same as safety-related	Same as inside containment	Same as inside containment
Power cable 600 V 12 AWG and up	Cooling fans, MOV power supplies	Pressurizer heaters, misc non-safety feeds	MOVs, fans, local panel feeders	Same as safety-related
Power cable 600 V 4.16 to 6.9 kV	None	Reactor recirculation pumps	ECCS pump feeds, emergency power primary wiring	Non-IE primary distribution, circulating water pump motor feed
Power cable 13 kV	None	None	None	13 kV distribution and bus system. (Supplies normal feed to safety-related ac power system but is not safety-related)

1. Single conductor, stranded control or power cable, 600 V. Cross-linked polyethylene insulation is typical.

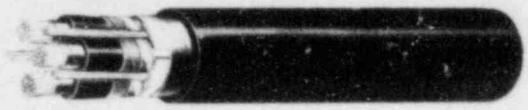


2. Single conductor, stranded power cable with insulation and jacket. Ethylene propylene rubber insulation and chlorosulfonated polyethylene jackets are typical.

3. Single conductor, shielded power cable 5 to 15 kV. Conductor, semiconducting tape, insulation, semiconducting tape, tinned-copper concentric wire shield, polyester film tape jacket.

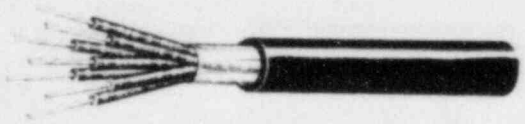
Figure 3-1. Typical Cable Construction

(This figure provides examples of cable construction and is not intended to represent all types of cables in use at nuclear power plants.)



4. 3-phase shielded power cable, 5-15 kV.

   Conductors covered with semiconducting tape, insulation, semiconducting tape and copper shielding tape; cable with fillers and a stranded copper ground wire; covered with tape and jacket.



5. Multiconductor control cable.

   Depending on size and number of conductors, fillers may be used to attain round shape.

6. Coaxial Instrument Cable

   Stranded conductor, insulation, braided concentric shield, and jacket.

Figure 3-1 (Cont.)

Table 3-2. Cable Insulation and Jacket Material Comparisons

Material	Use	Advantages	Disadvantages
Cross-Linked Polyethylene (XLPE)	Control and power up to 15 kV	Smaller diameter, thermally stable, moisture and chemical resistant, sturdy, fire retardant version available	At higher voltages (13 kV and up) may be sensitive to "treeing failures" especially in wet conditions
Ethylene Propylene Rubber (EPR)	General purpose up to 15 kV	Flexible; heat, ozone, water, and moisture resistant	Requires jacket for mechanical and chemical protection; larger diameters are required for same voltage levels as XLPE
Butyl Rubber	Power and control to 15 kV	Flexible; heat, ozone, and moisture resistant	Requires jacket for mechanical and chemical protection
Polyvinyl Chloride (PVC)[1]	Power and control to 600 V	Mechanically tough, resistant to moisture acid, oil, alkalies	May give off chlorine during fire; subject to deterioration from radiation
Polyethylene (PE)[1]		Moisture resistant, good electrical properties	Poor heat and flame resistance; subject to deterioration from radiation
Silicone Rubber		For high temperature applications	
Chlorosulfonated Polyethylene (CSP)	Jackets	Tensile strength, abrasion resistant, radiation and fire resistant	
Tefzel	Control wire	Radiation and temperature resistant, low friction, flame resistant	
Kapton[2]	High temperature applications without radiation	Temperature and chemical resistant	Teflon glue used between layers fails at low radiation dose levels
Mineral Insulation Metal Jacketed	High temperature applications requiring insulation stability	Good temperature stablity not sensitive to thermal or radiation aging	Ends must be well sealed to prevent water and moisture incursion. Sensitive to repeated flexure and mechanical vibration

1. Use of PVC and PE is discouraged for nuclear power plant applications.
2. Use of Kapton is not recommended for applications subject to radiation doses above 0.01 Mrads.

contained in Table 3-2. It should be noted that polyethylene (PE) and polyvinyl chloride (PVC) are no longer used in most nuclear applications and have been precluded from use by architect/engineer's cable specifications. PE has been found to be age sensitive in nuclear applications and PVC produces toxic fumes during fires. Kapton insulations are also not in use due to the limited radiation resistance of the Teflon binding materials between layers. Likewise, Teflon insulations are also not used in applications subject to radiation. Cross-linked polyethylene (XLPE) is one of the most common insulation materials used, and chlorosulfonated polyethylene is a common jacketing material. Ethylene-propylene rubber (EPR) is also used as an insulation but requires a jacket for mechanical protection.

3.3.3 Conductors and Terminations

Most conductors of cable for nuclear power plants are made of stranded copper. A stranded conductor is used to allow greater flexibility than a solid conductor. The terminations of most power and control cable conductors are formed through compression-fitted ring lugs. For splices at containment penetrations or motors, butt compression fittings or bolted ring lug compression fittings may be used. Insulation is provided by heat shrink tubing or layered tapes covered with conformal coatings.

3.4 CABLE PERFORMANCE PARAMETERS

This section lists the parameters available for monitoring age-related degradation of cable insulation material. The various parameters are grouped under mechanical and electrical properties [10].

Parameters Related to Mechanical Properties

- Tensile strength
- Elongation
- Modulus of elasticity
- Hardness
- Flexibility

Parameters Related to Electrical Properties

- Dielectric strength
- Partial discharge level

Dielectric constant
Dissipation factor
Insulation resistance (Polarization index)
Power factor (Power factor tip-up)

Conductor Properties

Conductor and shield resistance

Each of these parameters relates to various forms of deterioration. The five mechanical parameters are related to the toughness and flexibility of the insulation. If the hardness increases and the elongation prior to breaking decreases, the insulation is becoming harder and may eventually crack if disturbed or flexed. On the other hand, if the elongation at the break point increases and the tensile strength decreases, the insulation is softening, and the conductor may eventually creep through the insulation and short to other conductors or grounds if the cable is subjected to mechanical loadings. The imperviousness of the cable insulation is difficult to determine by mechanical tests, but can be determined through some of the electrical tests such as insulation resistance when the cable is submerged in a water bath. However, such tests are laboratory rather than in-situ tests. Insulation resistance and polarization tests will provide general information concerning the electrical properties of the cable. Dissipation factor, power factor, and partial discharge tests will provide somewhat more specific information relating to voids and imperfections in the insulation that are subject to corona discharging.

A change in the conductor resistance indicates deterioration of the the conductor-to-terminal interface or damage to the conductor. Either condition is a significant condition that should be readily evaluated and corrected.

3.5 OPERATING EXPERIENCE

Considering the number of miles of cable and the number of individual circuits in a nuclear power plant, the number of failures that have occurred to date is very low. Appendix B contains a listing of typical Licensee Event Report entries relating to cable. In the LER records available in February 1984, 109 entries related to insulation and cable failure were found. Many of these relate to termination problems rather than cable insulation failures. Many of the remaining cable failures relate to failures of cable caused by

external phenomena such as wear from vibration, pinching of insulation in junction box covers, or incompatibility of cable materials with adhesives. While cable failures have been relatively low to date, it should not be construed that failures are not going to occur. The possibility exists that the failure rate may increase nearer to the end of power plant life. In addition, experience to date has mostly involved normal service conditions. Failure rates for naturally aged cable under DBA conditions have not been evaluated to a significant extent.

3.6 STRESSES AFFECTING CABLE

The stresses that can affect the various types of cables used in harsh environments in a nuclear power plant are many and often depend on the application of the cable. Possible stresses include thermal, radiation (primarily gamma during normal operation, and gamma and beta during accident conditions), mechanical forces, voltage gradients, and moisture and chemical incursion. These stresses may act individually or in combination with each other. For example, most in-containment cables are simultaneously subjected to thermal and radiation stresses in conjunction with humid conditions. Humid conditions alone may not cause deterioration but in the presence of imperfections or gaps in insulation may provide a leakage current path. Condensation on the surface cable can affect insulation resistance measurements, but does not necessarily cause permanent damage to the cable. Temperature will affect the rate of change of chemical decomposition, especially in an oxygen-rich atmosphere. Radiation will also affect chemical bonding of insulation molecules.

With regard to mechanical forces, construction practices have been implemented to reduce the mechanical forces on a cable after installation. Such practices include elimination of tight bend radii and elimination of sharp projections on cable supports. Mechanical and abrasive forces are generally highest during installation. While good construction practices will reduce the number of high mechanical stress points, some will remain. A study is in progress at Sandia National Laboratories [11] to evaluate the effects of mechanical forces present after installation. The study is addressing the potential for conductors to creep through insulation at points of high mechanical stress, thereby shorting to surrounding conductors or structures.

In the presence of insulation voids, high voltages can cause corona discharges that will further damage the insulation as ions bombard the sides of the voids, eventually creating a fault path between the conductors. This phenomenon would be expected primarily in cables with applied voltages above 4 kV.

3.7 FAILURE CAUSES AND MECHANISMS

3.7.1 Introduction

The major age-sensitive components of electrical cables are the primary insulation and elastomeric sheathing materials; the latter also provide supplementary insulation. The remaining components of electrical cables are either not age-sensitive (e.g., metallic conductors) or perform noncritical functions (e.g., fillers). However, cable conductor terminations may deteriorate if they are improperly formed or inadequately protected against moisture and corrosive conditions. In such cases, the resistance of the junction may increase, preventing signal transmission, or in the presence of high currents, may cause overheating that could result in damage to the conductor or insulation. Another source of stress and eventual failure is the bending and pulling of terminations, which happens most often during maintenance and testing. Disconnecting leads from terminal strips often results in bending or pulling of the cable termination. Separating plug type connectors also often involves bending or pulling the cable at the connector interface. Where repeated bending or rough handling of such connectors occurs, conductor or insulation failure is highly likely.

Mineral-insulated (MI) cables are not generally considered to be age-sensitive to thermal and radiation stresses if sheathed in metal and if used outside of the nuclear power reactor vessel. However, the insulation of MI cables is vulnerable to moisture penetrating through connections, which causes rapid deterioration of insulating characteristics. MI cables must also be protected from repeated bending and mechanical vibration that can allow the conductor to wear through the insulation.

For low-voltage cable (i.e., approximately 600 V and less) under normal service conditions, it is generally understood that so long as the primary insulation is intact (i.e., has possibly degraded but retains mechanical

integrity), the dielectric properties will be adequate to permit satisfactory performance of the cable. However, when DBA conditions are considered in addition to normal service, it is less clear what amount of deterioration is allowable. Ideally at the time of environmental qualification testing, the properties of the artificially aged cables would have been determined prior to subjecting them to simulated DBA environments. These measurements would have provided screening criteria for determining acceptable levels of cable property deterioration. However, these data are generally not available, since the application of the data to condition monitoring was not considered at the time of the tests.

Degradation of dielectric properties is of greater concern for medium (15-kV) voltage cables in nuclear power plants because dielectric failures can occur even though the insulation may retain good mechanical properties. It should be noted that 15-kV systems are not safety-related; however, during normal service conditions, the safety-related power systems are fed from the 15-kV system. A failure cause for 15-kV cable is the development and growth of small semiconductive paths through a process called "electrochemical treeing" or "water treeing" generally when the cable is subjected to electrical stress and wet conditions. Treeing is believed to originate at sites containing particles or voids; tree formation and growth is caused by electrical stress concentrations which progressively increase through partial electrical discharges, ionization, etc. [12, 13]. When the tree extends between two conductors at different potentials, the conductivity of the treeing path increases rapidly and ultimately causes a catastrophic electrical fault.

3.7.2 Aging Considerations for Different Types of Cables

The metallic conductors of cable are not expected to deteriorate at a significant rate when compared with the rate of deterioration for the insulation. However, deterioration of the conductors at the terminations could occur if terminal lugs are not properly applied (insufficient denting) or if corrosion occurs at the point of termination. The deterioration of the termination would cause an increase in resistance. If the circuit carries a significant current, the conductor can burn through or a localized insulation failure may occur due to overheating and arcing. At the time of installation,

efforts are made to preclude such failures. Compression dents of terminal lugs are verified or are performed with calibrated application devices. Terminations are protected from moisture and subsequent corrosion with heat shrink tubing or terminal box housings. Inside of containment, butt splices with heat shrink tubing have been used to eliminate the possibility of corrosion and failure that may occur when terminal strip connections are used under harsh conditions. However, corrosion of the termination connections of cables at the connected equipment may still be possible due to moisture intrusion into equipment and instrumentation housings. Moisture intrusion can occur when covers are not resealed after maintenance, when seals have degraded excessively (e.g., have not been replaced at appropriate intervals), or when adequate protection against moisture sources has not been provided (e.g., when unsealed conduit is used.) Reference 14 provides a compendium of such events.

Power and control cables are usually subject to higher electrical (i.e., potential) stresses than instrumentation cable and may also experience higher temperature rises than instrumentation cable because of greater ohmic heating resulting from the higher currents in power and control cable conductors. Thus, the insulation of power and control cables may thermally degrade at a higher rate than that of instrumentation cable because the insulation on the former cables may operate at higher temperatures even though the ambient temperatures are the same. Exceptions may apply to some instrumentation cable, particularly thermocouple cable, which passes through high temperature areas. Also, as is explained in the following paragraphs, the consequences of insulation deterioration for different types of cables are not determined solely by the extent of insulation degradation.

When comparing aging implications of the various types of cables, the following should be considered:

- Although power and control cables may be subjected to higher thermal stresses than instrument cable, their associated safety function is generally more tolerant of changes in electrical characteristics of the insulation than instrumentation cable. For example, if the insulation resistance decreases, the resulting leakage current will be small in comparison with the power flowing through the conductor and will be well within the rating of the power source; the function of the connected load would be unaffected. It should be noted that power and control cables are not operated at temperatures that would allow thermal runaway in the insulation. Under such conditions, the leakage current through the insulation would produce sufficient heating to

allow a cascading temperature condition that would further increase leakage current and temperature and would result in electrical breakdown (faulting) of the cable.

- The cables for instruments that do not require exact cable impedance requirements (e.g., thermocouples, pressure transmitters) are not apt to cause significant signal error as a result of partially degraded insulation, since potentials are sensed by high impedance input instruments or the applied voltage is low enough not to cause severe leakage of signal current. However, gross insulation deterioration, or corrosion or bridging of terminations by water or other contaminants may cause significant signal error.

- Uses of instrumentation cable that depend on impedance characteristics (e.g., coaxial cables) may be subject to signal error as a result of partially degraded dielectric insulations, because the characteristic impedance and the total electric capacitance of the cable may be adversely affected. Likewise, cables that require very high levels of insulation resistance to transmit microampere levels of current (e.g., radiation detectors) may not be used reliably in a partially degraded state. It should be noted, however, that deterioration of connector interfaces may cause more serious attenuation of the signal or introduction of noise than cable insulation deterioration. Therefore, maintenance of the connector contact surfaces may be more important than cable insulation deterioration concerns during normal service. Under DBA environments, both connector integrity and insulation electrical parameters are of concern.

In summary, general statements about which cable type is more susceptible to aging considerations should be made cautiously. Such statements should consider all the factors that cause aging and the ultimate effect of such aging upon the safety function of the cable during both normal and DBA conditions.

The major age-related failure mechanisms for cable insulations and sheathings fall into two areas:

- degradation of mechanical properties
- degradation of dielectric properties.

These two forms of degradation are discussed in the next two subsections.

3.7.3 Degradation of Mechanical Properties

The usual desired mechanical properties for insulation are those of flexibility, imperviousness (i.e., no holes or cracks into which moisture and contaminants can penetrate), and the ability to withstand reasonable amounts

of mechanical stress. Considerable loss of flexibility can be tolerated if the cable is not flexed or, if flexed, the insulation does not crack (i.e., lose its imperviousness). A seismic event will probably cause some movement or flexing of cables, especially at bends, bridges between cable trays, and flexible conduit segments; however, extreme embrittlement would probably be necessary for failure of insulation to occur due to normal vibration or a seismic event. The extent to which embrittlement will affect the capability of a cable to withstand the steam, temperature, and pressure conditions of a DBA is not known.

In the event of harsh environmental conditions in the containment, such as a DBA, or in the event of an earthquake, the sheathing material provides some mechanical protection from damage to the cable insulation (i.e., protection from loss of integrity and imperviousness). For cable installation purposes, two other desired mechanical properties of sheathing are high (tensile) strength and resistance to abrasion and cutting. During installation, cables are pulled through conduits and around bends, and sheathing must withstand the associated stresses. Once the cables are in place, however, the sheathing serves the primary purposes of neatly packaging several conductors and contributing to protection from ambient environments. In some plants where certain types of fire retardants were sprayed onto cable trays, the hardened fire retardant formed an abrasive surface that can cut through cable jackets and insulations when new cable is pulled into place. Additional care (e.g., use of rollers) must be taken to protect the new cable when it is being pulled over such fire retardant coatings.*

The properties of insulation and sheathing are affected by chemical changes that occur with time. These chemical reactions result in opposing effects of cross-linking and scission. When cross-linking occurs, additional chemical bonds occur between molecules or parts of a molecule. When scission occurs, the chemical bonds break in molecular side- or main-chains. Continued cross-linking toughens insulation but will eventually cause embrittlement, whereas continued scission softens the insulation, making it susceptible to cutting or abrasion. The rate of these reactions is controlled principally by temperature

*While not an aging phenomenon, it is useful to note that, in some cases when flame retardant coatings were applied, cable ground circuits occurred that did not clear until the coating had completely dried.

availability of free oxygen, and nuclear irradiation (if present in significant amounts). There is extensive literature on individual effects of temperature and radiation on insulating materials [e.g., 10, 12, 13, 15, 16], including the processes of oxygen diffusion, cross-linking, and scission. However, less information is available concerning the combined effects of radiation and temperature. In addition, much of the information concerning radiation effects is related to high dose rates and may not be pertinent to low dose rate applications.

Tensile tests are frequently used by the industry to characterize changes in mechanical properties of elastomers such as cable insulation from one manufacturing lot to another. Although tensile strength is important, the total elongation of the specimen at rupture is more indicative of the flexibility of the insulation. Specimens of freshly manufactured elastomeric insulations and sheathings may be stretched from 3 to 8 times their original length before breaking. As the insulation and sheathing materials age, specimens generally exhibit lower elongation at rupture. The decrease of the tensile elongation property is exhibited in aged cables by increased stiffness (reduced flexibility) or a tendency of the sheath or insulation to crack when flexed or bent around a small radius. Newly manufactured single-conductor insulated wire can be bent back upon itself without cracking of the insulation.

Although the effects of aging may be reflected in pronounced loss of mechanical properties such as percentage elongation, the consequences of such deterioration may not be severe. As long as cables are not subjected to significant movement or large amplitude vibration (e.g., movement due to earthquake or electromechanical forces), they can perform their intended function under normal service environments. However, cables whose movement is not well restricted should be given more attention. Loss of percentage elongation and loss of tensile strength are important failure criteria for such cables. At present, data are not available indicating the extent to which changes in the physical parameters of cables are acceptable for cables that may be subjected to DBA conditions.

An evaluation of naturally aged cables with polyethylene (PE) insulation and polyvinyl chloride (PVC) jacketing in nuclear power plant environments is provided in Reference 17. It was found that even relatively moderate environments in a nuclear power plant (e.g., average ambient temperature of

43°C and a maximum dose of only 2.5 Mrd gamma experienced by the cable materials for 12 years of service) can produce significant material degradation in PE and PVC cable materials. The use of these materials has been discouraged for new nuclear power plants because of their susceptibility to aging and the release of toxic fumes when PVC burns. The material deterioration from radiation-induced oxidation inside containment was established in the evaluation, and the degradation rate was correlated to local levels of radiation intensity in the containment area. The degradation rate of the PE insulation material was found to depend strongly on the coloring agent used, with black having the highest stability. Also, a strong synergism was found between radiation and temperature, and effects were dose rate dependent. Even though PE and PVC are not used in present nuclear power plants, the evaluation does point out two concerns: variations in the chemistry of generic cable components (due to pigments and other additives) may produce differences in aging charactetistics; and dose rate effects in combination with thermal effects may have significant effect on the aging rates. The purpose of condition monitoring is to detect aging as it occurs, including variations in aging from synergistic effects. However, it is beneficial to recognize the potential sources of these effects in advance so that the samples of cable that are monitored include those affected by the combinations of stresses that could produce more rapid aging.

3.7.4 Degradation of Dielectric Properties

As discussed earlier for low- and medium-voltage cables (Section 3.7.2), the degradation of dielectric properties with time is expected to be more noticeable for medium-voltage applications. Although some physical and chemical changes take place as insulation ages, these changes do not necessarily significantly degrade the basic dielectric properties such as dielectric constant and resistivity. While electrical stress can result in degradation of electrical properties leading to breakdown from such phenomena as electrochemical treeing, these failure modes are related to higher voltage applications (15 kV and above) which are not safety-related.

Certain applications of low-voltage coaxial cable may depend upon the characteristic impedance of the cable for proper transmission of low-power and/or high-frequency signals. Accordingly, the performance of this coaxial

cable will be dependent upon the resistance and capacitance parameters of the dielectric materials (e.g., foams) between the central conductor and the shield(s). Significant dielectric degradation in highly aged coaxial cables appears possible. Changes in dielectric parameters of the insulation from aging will be compounded by accident environments. For example, accident temperatures may cause insulation resistance to drop by several decades. The The combined impedance change from aging and accident environment effects may prevent the cable from performing its safety function (i.e., transmitting low level electrical signals).

The above discussion concerning the failure modes and causes for electrical cables is summarized in Table 3-3.

3.8 TEST METHODS

Table 3-4 provides a summary of tests for cables. The most common in-situ test is the 500-Vdc insulation resistance test which can be used on most power and control circuits. The polarization index test is most frequently used on motor circuits, often [illegible] the associated cable in the test circuit. High potential withstand, partial discharge, and power factor tests may be performed in place; however, their use is generally limited to circuits with voltage of 4 kV and above, and may be limited to special circumstances. For example, partial discharge testing would be performed only on insulation systems that are known to be affected by corona discharge and treeing failure mechanisms. This condition is generally recognized by failure of like equipment.

Elongation and tensile tests are destructive by nature and require removal of samples for testing. High voltage tests to determine the voltage level at which failure occurs also require samples and are destructive by nature.

A nondestructive test technique that has been used at Three Mile Island Unit 2 to evaluate equipment and cable degradation due to and since the March 1979 accident is time domain reflectometry (TDR) [18]. The results of TDR testing at TMI Unit 2 indicate that TDR may be a useful cable monitoring technique. Time domain reflectometry test equipment places a short electrical pulse on the conductor of a cable and measures the timing and strength of the signal reflected by the cable and its terminating device. The general condition of the cable insulation and the physical position of significant changes

Table 3-3. Insulation Failure Causes and Mechanisms for Electrical Cables in Nuclear Power Plants*

Cable Type	Failure Causes	Failure Mechanisms
Power 600 V, 4 kV, and 13 kV	Loss of flexibility (cracks when flexed)	Chemical changes of polymeric structure resulting from exposure to heat, nuclear radiation, humidity, chemicals, etc.
	Loss of imperviousness (moisture readily reaches conductor through pores and cracks)	Same as above, plus possible physical abuse of cable (chafing, cutting, small radius bending)
	Loss of adequate dielectric properties, inability to withstand voltage stress	Excessive exposure to high electric stress, high temperature, or large radiation dose. Failure frequently coupled with presence of moisture or water. Loss of dielectric properties generally occurs after deterioration of mechanical properties. Loss of dielectric properties would be more rapid at points of insulation stress conditions such as mechanical abuse locations or areas of repeated small radius bending. For 13 kV and above cable treeing, water treeing, and electrochemical treeing may cause relatively rapid breakdown of dielectric capabilities.

* Failure of cable sheathing can also occur, but the sheathing is not relied upon for operability of cables. The major failure modes for sheathing are loss of flexibility and imperviousness; the causes are similar to those for cable insulation.

Table 3-3 (Cont.)

Cable Type	Failure Causes	Failure Mechanisms
Control	Loss of flexibility (cracks when flexed)	Same as for power cable failure causes
	Loss of imperviousness (moisture readily reaches conductor through pores and cracks)	Same as for power cable failure causes
Instrumentation	Loss of flexibility (cracks when flexed)	Same as for power cable failure causes
	Loss of imperviousness	Same as for power cable failure causes
	Adverse change in dielectric properties [e.g., insulation resistance and/or capacitance between conductor(s) and shield(s)] which may cause attenuation of signal	Exposure to heat, nuclear radiation, humidity, chemicals, etc., creating chemical and/or physical changes to the insulation. Significant changes in dielectric properties can be expected during accident conditions. These effects may be additive with slower changes due to aging.

Table 3-4. Cable Tests and Applications

Test Description	General Application	Specific Cable Application After Installation
INSULATION TESTS		
Low Voltage Insulation Resistance	Troubleshooting, locating existing short circuits	Locating failures (isolating to a particular circuit) (NDE)
Insulation Resistance (500 V)	Determination of general acceptability of insulation. Usually performed at 500 Vdc	Requires shield or ground path to detect deterioration of insulation. If return path not provided, dry air between cable and ground will provide good insulation and may invalidate results. Can be used to determine general insulation level between conductors of paired cable. Does not predict failure. May be trended. May require isolation of certain interconnected equipment from test circuits to prevent damage (NDE)
Polarization Index	Service test to determine general state of insulation system. Frequently used on larger motors. May be used on cables. Uses 500 V dc test equipment	Compares charging and leakage current values at 1- and 10-minute intervals. Requires return path such as shield for measurement between conductor and ground. (NDE)
Elongation	Manufacturing test, provides indication of general acceptability of insulation	Can be used to determine if insulation is losing flexibility and is becoming embrittled (DE)
Tensile Strength	Manufacturing test, provides indication of general acceptability of insulation	Less telling than elongation test since cable conductor provides tensile strength needed after insulation. May indicate excessive softening of insulation (DE)
High Potential Withstand Test	Manufacturing test to prove insulation capability	Usually limited to higher voltage power circuits (4 kV and above). May be performed with connected load in place (e.g., transformer, motor). Limited to applications where isolated from other circuits and cables to prevent extensive damage from flashover or induced voltages. Most often performed at 80% or less of manufacturing test level. May be destructive to insulation and cause failure if not properly performed (test is usually a DC test). If properly performed, NDE

Table 3-4. Cable Tests and Applications (Cont.)

Test Description	General Application	Specific Cable Application After Installation
INSULATION TESTS		
Dissipation Factor Power Factor	Tests to determine electrical losses within insulation. More important for higher voltage equipment. This is an ac test	The test measures and compares resistive leakage current to capacitive leakage current. The measurements are more important for high voltage systems since losses are proportional to the square of the voltage. Increasing dissipation factors and power factors at higher voltages indicate insulation deterioration due to partial discharging
Partial Discharge Test	Measures corona discharge in voids of insulation. Corona discharge causes high speed ions to attack surrounging insulation and cause further deterioration. A high voltage ac test.	Test is generally not performed on cable in-situ. Would be reserved for suspected problem equipment generally in 13 kVac and above range. Requires shield or return path
Time Domain Reflectometry (Cable Radar)	By using a pulsed signal, the location of a fault (failure) in a cable may be determined by interpretation of the reflected signal. Useful for finding the location of a fault in a long cable	May be used to detect conductor deterioration at remote termination or penetration. May indicate significant deterioration of portions of cable insulation. May indicate contamination of remote terminals. May be used to detect deterioration of series connections or splices
CONDUCTOR/TERMINATION TEST		
Continuity (Loop) Resistance	Determination of circuit resistance variations indicating conductor or termination problems. For use on power circuits	Useful for determining changes in circuit resistance. May be used on motor circuits with windings in circuit. Significant changes in resistance would indicate the need to evaluate terminations, windings, and cable conductors for cause

NDE Nondestructive Evaluation
DE Destructive Evaluation

in conductor and insulation properties may be determined from the results. At TMI Unit 2, the TDR measurements were taken in conjunction with other measurements such as conductor loop resistance (through the connected device) and insulation resistance and capacitance. The combined information was used to evaluate the meaning of the results. Figure 3-2 shows two TDR tracings. The first shows the location of the containment penetration and an impedance mismatch which is characteristic of a wet cable. A precursor to testing was the determination of the exact layout of the circuits to be tested, including all terminations, penetrations, and cable types. The circuit layouts are required for correct interpretation of the test results.

Appendix C provides further summaries of test methodology.

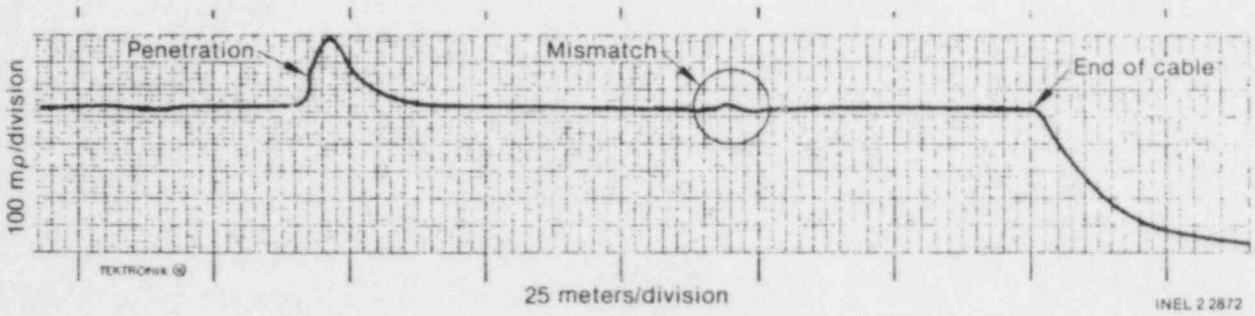
3.9 INSPECTION METHODS

The physical inspection of cables can provide insight into the condition of insulation and terminations and into the existence of unwanted stresses and contaminants. Deterioration of the physical condition of cable is frequently more readily determinable from visual inspection of the cable than through evaluation of electrical test results. The existence of damaged terminations and of conditions such as chemical contamination and water accumulations in junction boxes may also be observed before they affect electrical function.

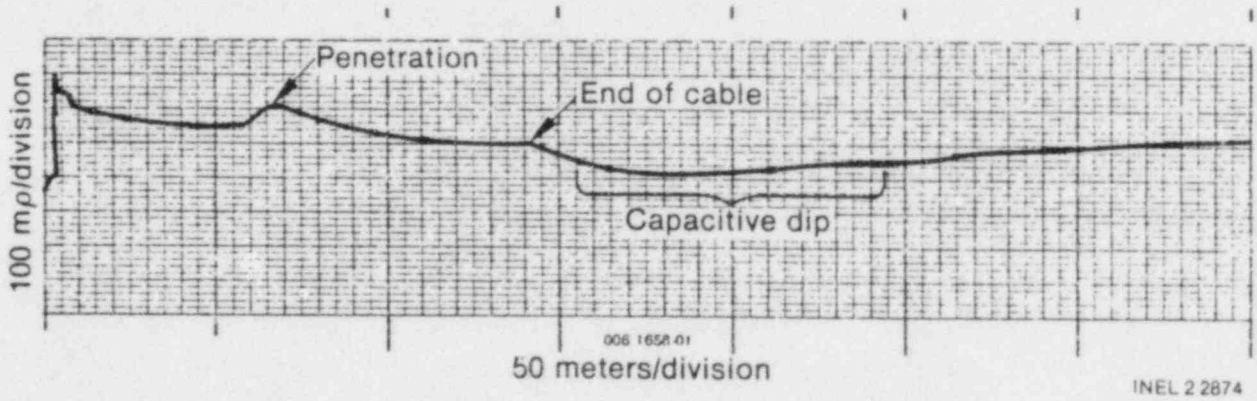
It is not practical to inspect all cables and all terminations inside of containment due to limited accessibility and cost of inspection. However, a good practice would be to train maintenance employees to recognize and report any potential aging or unwanted stress conditions relating to cable that could be observed during work on associated or nearby equipment. If aging phenomena are recognized for a particular type of cable, periodic physical inspection of exposed segments should be considered as a portion of the condition monitoring program.

3.10 CABLE MAINTENANCE

Relatively little can be done to repair safety-related cables. If significant levels of insulation deterioration are noted, replacement is generally dictated for safety-related applications. Most often this entails end-to-end replacement rather than splicing of a small segment. If



A. TDR results for a cable connected to a flow switch in the closed position. The peak at left indicates the location of the containment penetration. The mismatch is most probably caused by wet cable insulation.



B. TDR results for cable connected to a "closed" limit switch. The capacitive dip occurring beyond the cable end is indicative of corroded or wet switch contacts with high contact resistance.

Figure 3-2. Samples of Time Domain Reflectometry Results [18]

deterioration of a termination or its insulation is observed, replacement or repair is generally possible if a significant portion of the cable near the termination has not been damaged. Repair of isolated cable insulation or jacket damage from cuts or abrasion may be possible, but in general most repair techniques have not been environmentally qualified and are not used.

With regard to higher voltage cable insulation that has incurred treeing damage, some maintenance techniques such as forcing dry nitrogen or insulating liquids between the strands of conductors have been successful for restoring electrical properties for underground high voltage cable. These techniques are interesting; however, since safety-related cable for inside containment use must be environmentally qualified for service, the repair techniques would also have to be environmentally qualified. Qualification of such repair techniques will probably cost more than replacing the deteriorated cable, thereby reducing the practicality of repair. In general, replacement of all or a portion of a deteriorated cable is the maintenance technique that will be most frequently used.

3.11 CABLE MONITORING

3.11.1 Limitations of In-Situ Testing

The types and extent of cable testing that can be performed in-situ at a nuclear power plant using presently available techniques are limited by practical concerns. Electrical tests of insulation require a return path such as a shield to provide an indication of the insulation condition. If no return path is available, an insulation test between conductor and ground generally will not provide useful results since the cable may be insulated from ground by other cables in the tray or by dry air (a good insulator) between an imperfection in the insulation and ground. Insulation testing may be performed between conductors of a cable; however, the quality of the results in detecting deterioration may be less than that of measurements between shield and conductor since two insulations are in a series and the orientation of imperfections may be such as to make them less detectable.

Performance of electrical testing of cables requires a convenient and accessible point for setting up test equipment and taking measurements. Such points are limited inside of containment. At the electrical penetration, most

cables are attached by insulated butt splices that are not amenable to disconnection. Similarly, disconnection of cables from the associated equipment will require opening of sealed housings which will affect qualification. The most accessible points for testing are outside containment at motor control centers and termination cabinets. Therefore, most cable testing will include the connected device, an inside-of-containment segment of cable, the penetration, and an outside-of-containment cable. Only when electrical measurements indicate that significant deterioration has occurred is it necessary to isolate segments of the circuit to locate the source of the problem. Care must be taken in the choice of tests and test voltages to assure that they are compatible with the connected device. In the case of motors, cable and motor insulation tests are nearly identical. Not all equipment is amenable to test voltages used in cable testing; for example, electronic transmitters may fail if exposed to a 500-Vdc insulation test. It must also be recognized that isolation of cables from these devices to allow testing presents the problem of interrupting safety-related circuits which requires strong administrative controls and additional testing of the system following the insulation test to assure complete restoration of the safety function.

The use of high potential test voltages must be limited to circuits which are well isolated from one another. They should not be applied to control or instrumentation circuits that run in parallel with many other circuits or terminate in densely wired cabinets and panels. Application of high potential tests under such conditions could lead to failure of adjacent cables and electronic equipment due to induced capacitive charges or stray currents from testing. Use of high potential testing should be limited to circuits of known routing or isolation. High voltage testing also requires a return path such as a shield or parallel conductor within the cable.

A further limitation on the usefulness of the electrical measurements from long cables is that most of these cables are routed through multiple rooms that can have independently varying environments. Since temperature and humidity affect insulation tests, compensation for their effect on results will be difficult when multiple environments are involved. The temperature and humidity at the place where testing occurs should be recorded. The

results of the tests should be evaluated immediately. Variations in results caused by ambient environments should be accounted for to the extent practicable to allow detection of deterioration in cable parameters.

One final concern exists for cable used with sensitive electronic detectors that are used in extremely low current applications. If an insulation resistance is measured with a 500-Vdc source, a residual charge may be left on the cable. Upon reconnection of the cable, failure of the connected instrument may occur when the cable discharges. A possible means of removing the residual charge would be to short all of the conductors and shield together after the test. However, the short would have to be maintained for a considerable time to assure that all residual charge is removed.

The testing limitations listed above do not preclude surveillance and monitoring of the aging of electrical cables through use of presently available techniques. The existence of the limitations requires thoughtful planning to assure that test results are meaningful and that inadvertent damage to the equipment does not occur. Care in selection of tests to be performed and the sample of cables to be monitored will overcome these limitations and help assure the usefulness of results.

3.11.2 Selection of Cables for Condition Monitoring

Considerations for selection of cables for in-situ testing are relatively complex and choices are limited by practical concerns. Since the goal of condition monitoring is to detect incipient failures and prevent outright failure, care must be taken to preclude failures caused by or resulting from testing. As indicated in Section 3.11.1, choices for in-situ testing should include cables connected to equipment not susceptible to damage from the tests. Testing should interrupt as few safety circuits as possible to preclude improper restoration of the circuit.

Cables that should be considered for in-situ monitoring are:

- Power cables for all large safety-related motors while connected to the motor windings. Separation of the cable from windings and further testing should be performed only upon indication of a problem.
- Power cables for safety-related valve actuator motors within containment while connected to the motor windings as above.

- Control cable - selected circuits subject to containment or other harsh environment conditions which are connected to equipment that can withstand test conditions (e.g., most switches, most solenoid coils) and that are not in close proximity to equipment or circuitry that is sensitive to test conditions. Since most control cable is not shielded, tests will generally have to be performed conductor to conductor.

- Instrumentation cable - selected circuits subject to containment or other harsh environments that can be readily isolated from the connected instrumentation. Care must be taken to assure that adjacent circuits will not be affected by test conditions.

- Coaxial cable - selected circuits subject to harsh conditions that serve instrumentation which is sensitive to cable attenuation and noise characteristics. Care must be taken to assure that connectors are cleaned prior to and following testing of the circuit and not touched by hand, since connectors may be as critical as (or more critical than) the cable insulation with regard to loss and attenuation. Oxidation of the connector is often a significant problem.

Cable selection criteria should ensure selection of samples from all significant types of safety-related cable, e.g., cables from each manufacturer and each significantly different construction type. If possible, some samples should be subjected to individual harsh parameters such as temperature, radiation, moisture, or chemicals (e.g., airborne or from borated-water sprays), while others should be subjected to combinations of parameters. It is recognized that this may not be possible since individual cables will run through many areas and be interrupted by containment penetration assemblies.

To the extent possible, the sample size for each type of cable should be representative and large enough to allow inferences to be made concerning the other circuits of that type of cable. If the time of installation of cables varies significantly, the oldest cables should be given the highest consideration for testing.

With regard to removal of samples for destructive examination testing, options for selection of cable may be extremely limited. Most spare cable in a plant has been installed to allow modification of the plant or replacement of failed circuits. Removal of such cable may disturb surrounding cable, and total removal could require removal and replacement of firestops and disruption of penetration connections. Removal of heavy power cable may require replacement of the entire length since splicing adds an additional

potential failure zone and locations where splicing is allowable may be limited. Off-site specialized tests would be recommended for cable that has sustained a failure in order to determine the cause. The applicability of the failure mechanism should be determined for like cable in the plant.

3.11.3 Decision Criteria

At present, decisions regarding replacement and repair of power plant cables are made largely through use of engineering judgment based upon limited test data and general qualitative criteria. Many of the cable insulation tests are performed as part of corrective maintenance, and are not performed to determine remaining life. Since life projections and detection of incipient failures are not the purpose of present programs, a set of decision criteria have not been developed for use in an aging surveillance and monitoring program. One complication for determining action points for preventive maintenance and replacement of cable is determining the level and rate of deterioration that are acceptable when continued life and accident withstand capability are considered. Quantitative criteria may ultimately be developed through analysis of data from two sources. The first source of information is the operating data from nuclear power plants; these data include the surveillance and maintenance history, which may provide the degradation trend of various parameters pertaining to natural aging of cable insulation. The second source of information is research and laboratory investigation into simulated aging of cables. If significant parametric testing of aged cable had been performed on environmental qualification test samples prior to DBA testing, a rough set of decision criteria would be available, i.e., cables with parameters better than those of the aged qualification test samples would be considered for continued service. However, the development of condition monitoring criteria was not a goal of the environmental qualification programs. One potential means of gaining such information is to reperform the aging portion of qualification programs on samples of cable of the same type as was used in the environmental qualification tests and to perform basic parameter tests to determine the level of deterioration that has occurred. It is recognized that simulated aging may not provide precise data for criteria since simulated aging is a rough approximation of natural aging; however, such data present a reasonable

starting point. The evaluation of data from surveillance and monitoring programs will provide further information concerning the rate of deterioration to allow further refinement of criteria.

It is desirable to have decision criteria for taking preventive action established at parameter levels that allow adequate lead time for taking action. Present decisions for cable replacement or repair are based on review of limited test data, often based on a single parameter such as insulation resistance. It does not appear feasible or logical to establish quantitative decision criteria based wholly on any single parameter; it is more likely that decisions for continued operation of cables must be based on a group of parameters rather than one specific parameter. In any event, it was found during this investigation that technically defensible numerical guidelines for any parameter or set of parameters for rejection of aged cables have not been established.

Two basic approaches can be used to develop interim recommendations for condition monitoring of cables in nuclear power plants: (a) the absolute value approach and (b) the relative degradation approach. Either or both approaches may be used to evaluate an aging parameter.

In the absolute value approach, the acceptance limits for age-sensitive parameters are determined for each cable type. Initial values for the limits may be based on a review of applicable data, including information obtained from vendors, laboratory experiments, power plant test records, and initial condition monitoring data. In most cases, these initial limits may be no more than trial values subject to verification and modification with experience. If the measured values of the parameters obtained by condition monitoring of in-service cables show degradation below the absolute acceptance values, the cables should receive preventive maintenance or replacement. Some of the parameters for which acceptance values need to be established were provided in Section 3.4. Under the absolute value approach, when cables are operated at or beyond the acceptable values, they are considered to be in a state of incipient failure.

In the relative degradation approach, the significant age-sensitive parameters are monitored periodically (such as during scheduled plant shutdown for cables inside containment and during scheduled maintenance for cables out-

side containment) and the rate of degradation is evaluated with respect to time. If over a period of time condition monitoring reveals a consistent and relatively rapid rate of degradation, then a failure time can be predicted. Decisions for any preventive measure are based on the rate of insulation degradation changes with time and the absolute amount of degradation. A slow rate of degradation may be tolerable, and no preventive maintenance may be required until degradation reaches the unacceptable level determined by the absolute value criteria. However, a relatively significant rate of degradation, as revealed by the changes in the condition monitoring parameters, may warrant preventive maintenance or replacement before the parameters have reached the rejection levels of the absolute value approach.

The relative degradation approach is more useful in predicting that sufficient life remains until the performance of the next test than is the absolute value approach since the rate of deterioration can be evaluated under the relative degradation approach. If the absolute degradation limit is set so that a very limited amount of degradation is allowed, assurance of adequate life between tests can be reasonably assured but may result in premature replacement of good cable.

To assure that preventive action is taken, use of a combined set of absolute and relative degradation criteria may be the most appropriate approach. With such criteria, decisions can be based on both the rates of change and the absolute values of cable parameters. To implement the relative degradation approach, baseline test results must be compared to subsequent results. Trends in the results must be evaluated to determine the level of degradation and the rate at which it is occurring. Evaluation of trends is necessary since each insulation system will have different characteristics that will depend on insulation thickness, length of cable, fabrication method, and installation conditions.

3.11.4 Evaluation of Test/Inspection/Maintenance Data

As soon as possible after installation, baseline measurements should be made of cable aging parameters. Such measurements are important since some deviations from expected values may be present at the time of installation. The baseline data will provide a reference base for all resulting tests. As

new data are obtained, they should be trended. Any marked changes from expected values should be investigated to determine if a measuring error has occurred or if actual deterioration has been detected. Some parameters such as insulation resistance can be plotted by addition of new data points on a graph with respect to time. Other data such as that from step voltage and power factor tip-up tests must be evaluated by comparison of the plot of data from one test to another. Changes in shape of the plot (such as an increase in power factor at a lower voltage from one plot to another) indicate deterioration of cable parameters.

All data, whether obtained directly from condition monitoring or from data feedback from inspection or maintenance, should be evaluated. For example, electrical tests may indicate no deterioration has occurred, but physical inspection may indicate checking or cracking of insulation. All failures that occur should be evaluated to determine if a non-age-related condition (such as physical damage from a non-age-related incident) caused the failure or if the failure was caused by a condition not monitored or monitorable under the condition monitoring program. While care in selecting parameters to monitor will help assure success of the monitoring program, some adjustment to the parameters monitored and the means of monitoring must be expected during the course of the program.

3.12 CURRENT UTILITY PRACTICES

In general, in-situ testing of cables at nuclear power plants has been limited to periodic insulation resistance tests of selected power and control cables. Some periodic step voltage and polarization index tests of cables connected to large motors have also been performed. However, much of the cable insulation in the plant is only tested if a cable problem is known or suspected.

Some utilities have installed spare cables in cable trays for tests that may be required after the plant is put into operation. Some utilities have installed spare cable for performance of environmental qualification testing of naturally aged cable. However, many spares are designated for eventual use and were not installed for test purposes. Many utilities perform insulation resistance tests of selected equipment and cables using a megohmmeter.

When cable failures have occurred, some plants have used time domain reflectometry to determine the location of the failure. This is useful if splicing is the proposed repair method. Some utilities prefer to install a completely new cable rather than install splices that could be the source of later failures.

Most utilities perform end-to-end tests, i.e., the test includes the portion of the cable that is outside containment, the penetration, the portion that is inside containment, and the connected device. This precludes disruption of the tested circuit and limits errors in restoring the circuit to service. Isolated tests of in-containment cables are not performed even though these cables may be more prone to aging due to environmental conditions. If insulation problems were found during end-to-end tests, the subsections of cable would be isolated and tested individually. Segmented tests (i.e., the cable segment from the cable spreading room to the penetration, and the cable segment including the penetration, the in-containment cable, and the connected device) are possible for plants with terminal block type terminations at the penetrations outside of containment, but still require disconnection of circuits at the penetration.

For the most part, high voltage in-situ testing is reserved for circuits with large, higher voltage motors (4 kV and above) and is not performed on other equipment. High voltage testing introduces the risk of inadvertent equipment damage and requires specially trained technicians. There is some concern that even if the insulation successfully passes a high voltage test, an increment of damage occurs to the insulation as a result of the test. With regard to this concern, EPRI has instituted a 3-year project to determine the effect of dc testing on field-aged and artifically aged extruded dielectric distribution cable [19].

Periodic destructive examination of cable insulation from nuclear power plants is not a common practice. An EPRI-sponsored program has been initiated by Duke Power Company and Northeast Utilities to perform destructive tests on cable removed from service. The goal of the program is to determine the level of deterioration with time. No attempt will be made to predict remaining life.

In general, laboratory and in-situ testing of cables from nuclear power plants is performed to determine the present condition, not as a tool for

predicting the life of the cable. Condition monitoring of cables as a predictive tool for maintenance or replacement, therefore, will be a relatively new concept for the utilities.

3.13 INTERIM RECOMMENDATIONS

3.13.1 Testing Recommendations

Selection of Circuits to be Tested and Monitored

- In its present state of development, condition monitoring can probably be justified only for critical cable circuits. The vast number of circuits in a nuclear plant, limited accessibility of the cables for test and evaluation, and the varied environments through which they pass combine to make condition monitoring and testing of all circuits a formidable and expensive effort.

- The selection of specific types of cables to be included in a monitoring program should be based upon importance to safety and the continued operation of the plant. (Further selection criteria are given in Section 3.11.2.)

- Initial condition monitoring programs should include the goals of improving condition monitoring techniques and cost-effectiveness in addition to assessing the level of deterioration of the cable.

In-Situ Periodic Tests

- Surveillance and periodic testing of chosen circuits should be performed during refueling and scheduled maintenance outages. At present, technology for continuous monitoring of cable condition is not available.

- To the extent practicable, cable insulation tests should be performed while the cables are connected to their associated equipment to reduce cost of testing and to reduce the probability of improper reconnections. Separate tests of the cable and the connected equipment should be performed when initial test results indicate a problem.

- For groups of similar cable circuits, tests should be performed on sets of samples rather than on the entire group. If significant deterioration is detected in the sample circuits, the applicability of the test results must be evaluated for the remainder of the cable group.

Selection of Tests to be Performed

- Selection of the types of monitoring and testing must be based on the type and application of the cable. No one test or set of tests is applicable to all types of cables.

- To the extent possible, the complete set of tests to be performed for a cable type must be defined at the outset of the condition monitoring program to assure continuity of the program. Changing of the types of tests and test methods during the course of the program may preclude the trending and evaluation of results.

- For control and low voltage power cable, insulation resistance, conductor resistance (through connected device), and time domain reflectometry tests should be considered.

- For medium voltage cable, insulation resistance, polarization index, conductor resistance (through connected equipment), and step voltage tests should be considered. Time domain reflectometry may also be applied.

- For cables known to be subject to corona discharge or treeing types of failures, power factor tip-up, dissipation factor, and partial discharge tests can be applied.

- Baseline measurements of the cable parameters to be monitored should be taken as early in the life of the plant as possible, even if the start of the periodic monitoring is to be delayed.

Destructive Testing

- Since the amount of cable available for removal and testing is likely to be limited, additional care must be taken in selection of the frequency and types of tests performed. Availability of aged samples for use later in the program must be assured.

- Upon removal of the cable, the destructive tests performed at the time of manufacture should be repeated. These tests should include elongation and tensile strength tests of the insulation, dc and ac voltage tests, insulation resistance, and partial discharge tests, depending upon the type of cable. The results should be compared with test values from time of manufacture and any subsequent test results.

Evaluation of In-Service Failures

- If cables fail in service and the cause cannot be attributed to a localized condition such as improper installation or handling, the failed section of cable should be examined in the laboratory to determine the root cause of failure. The applicability of the failure mechanism with respect to the remainder of the cable should then be evaluated. Such evaluations may provide valuable information concerning failure mechanisms and may indicate that further or different types of condition monitoring are necessary.

3.13.1.1 Frequency of Testing

In-Situ Nondestructive Tests

- Initially, it is suggested that the period between tests be one to two refueling periods (1.5 to 3 years).

- Ultimately, the frequency of cable condition monitoring tests should be based on the results of testing. If results do not show a significant rate of deterioration after a number of tests, the period between tests should be extended. If rapid deterioration is detected, the period between tests should be shortened until stabilization of the parameters occurs or the cable is replaced.

Laboratory Tests

- Samples should be removed after 5 to 10 years of service and tested.

- The interval before the next set of tests should be based on the test results. As with in-situ tests, significant deterioration would indicate that a shorter interval is necessary; little or no deterioration would indicate that another 5- to 10-year interval is appropriate.

- Cables from plants with 15 to 20 years of service are the most interesting for immediate laboratory tests. Initial tests of such cables should concentrate on cable types that are also used in more recent plants.

3.13.1.2 Procedures for Condition Monitoring Tests

If condition monitoring is implemented, the procedures for testing and the format for reporting and evaluating results must be well defined. A part of developing the procedures for each cable circuit is to determine the interconnections of the cable and associated equipment. The identification of the terminals, cable runs, penetrations, and connected equipment for each circuit will allow evaluation of the appropriateness of proposed tests and will be useful in interpreting results of tests. A sample of an interconnection diagram used in the equipment testing program at TMI Unit 2 is shown in Figure 3-3. This diagram is for a motorized valve actuator. Insulation resistance, polarization, and conductor loop resistance tests (through the motor windings) may be performed for the motor circuit. Insulation resistance and conductor loop resistance tests (depending on switch position) may be performed for the limit switch circuit. Time domain reflectometry may be performed on both circuits.

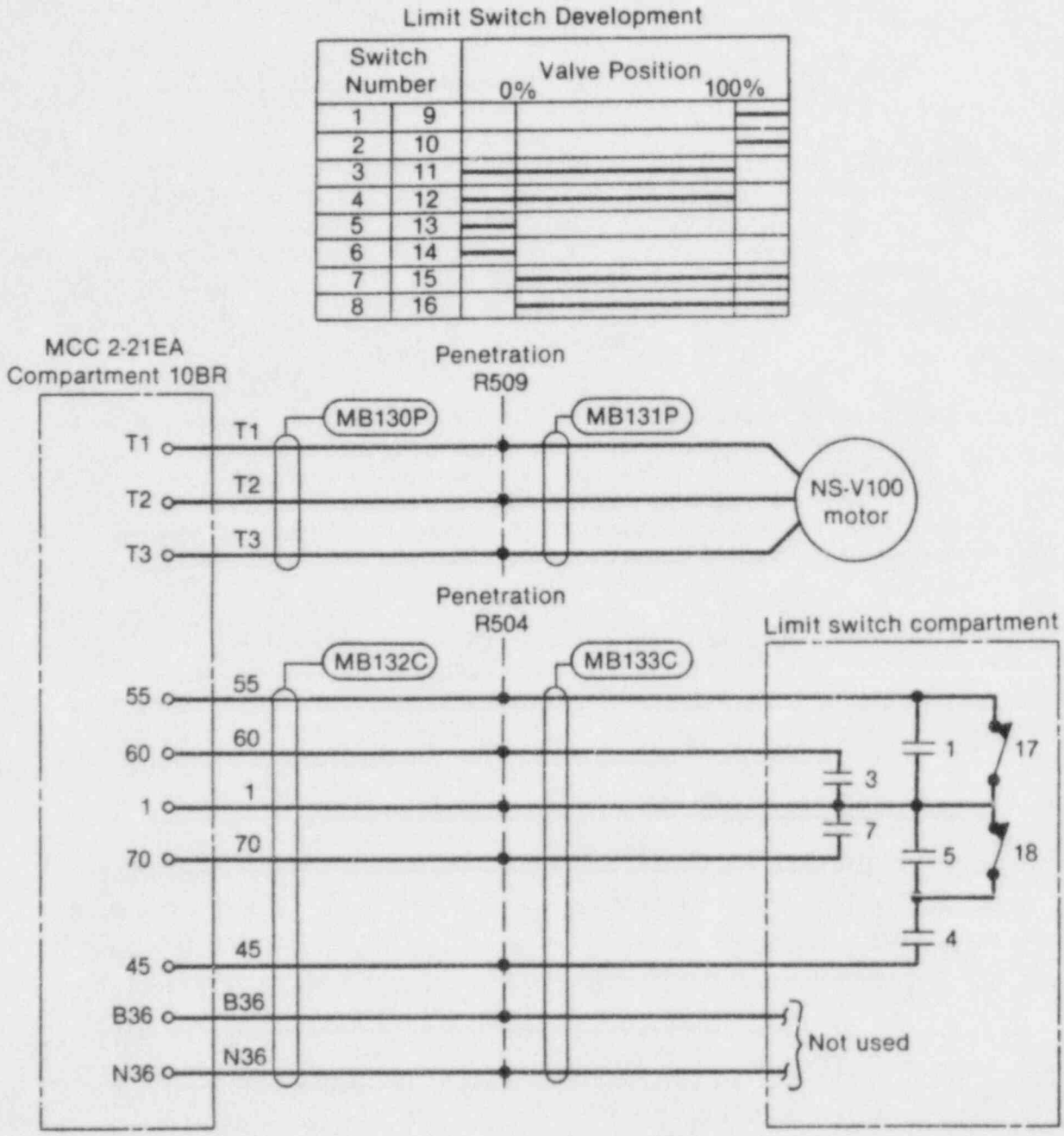


Figure 3-3. Circuit Interconnection Diagram for Motorized Valve Actuator Showing Terminations, Cable Numbers, Penetrations, and Connected Devices [18]

Since the choice of monitoring techniques and tests that can be used depends upon the type of cable and its application, a generic set of procedures is not given here. The reference section of Appendix C provides a list of industry standards for performing tests on cable and cable materials. Because monitoring of degradation of cables will occur over a long period of time, with reasonably long intervals between tests, care must be taken to assure repeatability and continuity of testing and to assure appropriate interpretation of results. Therefore, the program and procedures for monitoring must be well defined and periodically reviewed for adequacy. The procedures must clearly define the location of the terminals from which measurements will be made and the means of interrupting the circuit for tests, and a precise description of the measurements to be made must be given. The format for recording the data must be clear, unambiguous, and suitable for repeated use over many years. Attention to definition of the procedures and program structures will assure that deterioration is detected rather than masked or overestimated through evaluation of erroneous or inaccurate data.

3.13.2 Inspection

As stated in Section 3.9, a formal program for periodic physical inspection of cables is not recommended. However, a program for making maintenance and test personnel aware of the attributes of aged cable and of conditions detrimental to cable insulation and terminations is recommended. Under such a program, these personnel would report deteriorated and contaminated cable conditions observed during the normal course of maintenance and test efforts. Such a program would require means for evaluating such information and for providing corrective actions.

3.13.3 Maintenance

As stated in Section 3.10, the options for cable maintenance are relatively limited. Repair of terminations and replacement of cable sections are the main forms of maintenance. In general, cable has been qualified for the life of the plant and it is hoped that cable maintenance will be limited to repair of inadvertent damage and random failures. If deterioration of cable is detected through condition monitoring, corrective action such as

replacement will be necessary. In addition, unwanted stress conditions recognized either by casual observation or condition monitoring must be corrected. Conditions such as tight bend radii and wet or contaminated cable surfaces must be corrected.

3.13.4 Recommendations for Further Study

Following are the recommendations for further study for developing quantitative criteria for surveillance, maintenance, and replacement of cables.

- Visit selected utilities to collect available data pertaining to age-related degradation of cables concerning failures and recognized flaws.
- Obtain a description of presently established cable testing programs from selected utilities.
- Identify the relevant research activities on cables sponsored by utilities (such as the recently initiated EPRI-sponsored research on equipment aging at the University of Connecticut), or the government, both in the U.S. and abroad, and extract the necessary information.
- Select a group of experts on cables, consisting of cable users, manufacturers, and research laboratories, to provide input to formulate consensus quantitative criteria for condition monitoring, surveillance, maintenance, and replacement of cables, and to develop further practical tests to relate cable condition to remaining life.

4. REFERENCES

1. U.S. Nuclear Regulatory Commission, "Program Plan -- Nuclear Plant Aging Research for Operating Reactors Inspection, Surveillance and Maintenance," Revision 1 (Draft), July 1984

2. IEEE Standard 323-1874, "Standard for Qualifying Class IE Equipment for Nuclear Power Generating Stations," Institute of Electrical and Electronics Engineers, New York, February 28, 1974

3. W. L. Headington, M. E. Stewart, and J. O. Zane, "Fault Tree Analysis of the PBF Transient Rod Drive System," Phillips Petroleum Company, Idaho Falls, Rept. IDO-17274, pp. 139-140, 1968

4. J. D. Patton, Jr., "Preventive Maintenance," Instrumentation Society of America, Inc., New York, pp. 58-61, 1968

5. J. W. Wanless, "Condition Monitoring," Proceedings of the Workshop on Nuclear Power Plant Aging, NUREG/CP-0036, pp. 59-78, November 1982

6. H. F. Perla et al., "A Guide for Developing Preventive Maintenance Programs in Electric Power Plants," Electric Power Research Institute, Palo Alto, CA, NP-3416, May 1984

7. S. P. Carfagno and R. J. Gibson, "A Review of Equipment Aging Theory and Technology," Electric Power Research Institute, EPRI Report NP-1558, Palo Alto, CA, September 1980

8. A. Sugarman, B. Kumar, and R. Sorensen, "Condition Monitoring of Nuclear Plant Electrical Equipment," EPRI Report NP-3357, Palo Alto, CA, February 1984

9. G. J. Dau et al., "Nondestructive Evaluation Program: Progress in 1983," Electric Power Research Institute, EPRI Report NP-3347 SR, Palo Alto, CA, March 1984

10. E. Occhini, P. Metza, G. Portinari, and B. Vecellio, "Thermal, Mechanical and Electrical Properties of EPR Insulations in Power Cables," IEEE Transactions on Power Apparatus and Systems, Volume PAS-102, No. 7, pp. 1942-1953, July 1983

11. D. Stuetzer, "Status Report: Correlation of Electrical Cable Failure with Mechanical Degradation," Sandia National Laboratories, NUREG-3623, USNRC, April 1984

12. R. F. Wolff, "Predicting Remaining Polyethylene Cable Life," Electrical World, p. 80, December 1980

13. J. Sletback and E. Ilstad, "The Effect of Service and Test Conditions on Water Tree Growth," IEEE Transactions of Power Apparatus and Systems, Volume PAS-102, No. 7, July 1983

14. M. El-Zeftany, "Operating Experience Related to Moisture Intrusion in Electrical Equipment at Commercial Power Reactors," Reactor Operations Analysis Branch, Office for Analysis and Evaluation of Operational Data, USNRC, June 1984

15. "Estimating HMWPE Cable Life," EPRI Journal, p. 53, December 1983

16. M. B. Bruce and M. V. Davis, "Radiation Effects on Organic Materials in Nuclear Plants," Electric Power Research Institute, EPRI Report NP-2129, Palo Alto, CA, November 1981

17. K. T. Gillen, R. L. Clough, and L. H. Jones, "Investigation of Cable Deterioration in the Containment Building of the Savannah River Nuclear Reactor," Sandia National Laboratories, NUREG/CR-2877, USNRC, August 1982

18. F. T. Soberano, "Testing and Examination of TMI-2 Electrical Components and Discrete Devices," GEND-INF-034, U.S. Department of Energy, November 1982

19. IEEE Power Engineering Review, Institute of Electrical and Electronic Engineers, New York, Volume PER-4, Number 8, pp. 13-14, August 1984

APPENDIX A

STATEMENT OF WORK

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STATEMENT OF WORK

The goal of the investigation is to produce interim recommendations of criteria for surveillance, maintenance, and replacement programs to monitor and mitigate aging effects for electrical equipment located in the reactor containment. Specific tasks include:

1. Identify generic electrical equipment to be studied. This should include, e.g., electrical cables and penetrations, switches, relays, breakers, and other similar safety-related equipment located in the containment of LWRs.

2. Determine for each generic piece of equipment the potentially significant aging-related failure modes and causes.

3. For each failure mode, identify and describe one or more parameters that can be used to quantitatively monitor the extent and rate of aging degradation which would lead to that failure mode.

4. For each failure mode, define suitable criteria for acceptance/rejection (i.e., continued operation versus maintenance or replacement).

5. For each failure mode, identify and describe the monitoring/surveillance technology (equipment and methods) that could be used to determine if acceptance criteria are met.

6. Compile the results of the above in the form of interim recommendations for each generic piece of electrical equipment studied for criteria for surveillance, maintenance, and/or replacement programs to monitor for or mitigate aging effects.

APPENDIX B

REPRESENTATIVE FAILURE MODES AND CAUSES FOR CABLES SCREENED FROM LER DATA BASE

REPRESENTATIVE FAILURE MODES AND CAUSES FOR CABLES SCREENED FROM LER DATA BASE

A Licensee Event Report (LER) data base search was conducted in February 1984 by Oak Ridge National Laboratory, on behalf of FRC, to identify aging-related failure for cable insulation. Two printouts were produced as a result of the search, as follows:

1. 93 accessions using the keywords FAILURE, CABLES AND CONNECTORS and FAILURES, INSULATION reported as LERs.

2. 16 accessions obtained from a manual review of 80 accessions under keywords CABLES AND CONNECTORS plus FAILURES plus INSULATION.

A screening of the computer listing was conducted by FRC and the results of the representative failure modes and causes are presented in Table B-1. As can be seen from the table, effects of aging on cable insulation degradation (i.e., impact of a stress over a period of time) are not available in the LER summary data base. However, causes of cable insulation failures due to such stresses as overheating, vibration, radiation, and moisture can be observed.

Further in-depth investigations pertaining to data bases such as NPRDS, TMI failure analysis reports, and maintenance records at power plants are necessary to establish correlations of cable insulation aging to various stresses.

Table B-1 contains certain items that are not strictly considered cable problems, such as motor lead failures. These have been included because similar failures may occur in cable.

Table B-1. Representative Failure Modes and Causes for Cables Screened from LER Data Base

LER Accession No.	Event No.	Equipment	System	Failure Mode	Failure Cause
00Z0185202	1	Cable	Onsite power system and control	Insulation failure	Overheating due to installation of copper connectors on the aluminum conductors during construction
00Z0183170	2	Cable	Airborne radioactive monitor system	Insulation failure	Overheating due to short circuit
00Z0182900	3	Lead wire	ECCS and containment	Insulation failure	Insulation aging (cause not clear)
00Z0182598	4	Motor leads	Onsite power systems and control	Insulation failure	Breakdown of insulation tape on the connection
00Z0182005	5	Power cable	Air conditioning; heat, cool, vent system	Cable insulation rupture of approximate 1/2 inch length	May be due to internal pressure caused by moisture seeping into the cable and vaporizing
00Z0181648	6	Control cable (Protecto wire)	Instrumentation and controls	Insulation wear and eventual short circuit	Tray vibration causes the insulation to wear through due to friction
00Z0181069	7	Control cable	Emergency generator system and controls	Insulation degradation	Not clear
00Z0179886	8	Electrical penetration	Containment penetration system	Cracks in conductor insulation	Not clear
00Z0159135	9	Solenoid wire	Safety relief valve	Insulation brittleness	Fiberglass tape adhesive adversely affected the brittleness of the insulation

Table B-1 (Cont.)

LER Accession No.	Event No.	Equipment	System	Failure Mode	Failure Cause
00Z0158265	10	Wire in motor connection box	Ventilation system	Insulation failure	Not clear
00Z0156860	11	Wire in recirculation pump low oil level alarm	Coolant recirculation system and controls	Loss of insulation	Not clear
00Z0154717	12	Motor cables	Station service water system	Insulation failure	Moisture in the cable conduit
00Z0150356	13	Battery charger cable	Onsite power system and controls	Insulation degradation	High temperature environment
00Z0147378	14	Coaxial cable	--	Degraded insulation	Bubbles in insulation
00Z0128053	15	Cable	Containment heat removal system	Low cable insulation	Moisture intrusion into cable termination
00Z0128047	16	Wiring in Limitorque valve operators	Containment combustion gas control system	Insulation blistered, expanded, and separated from the wire	Leaking lubricant from gearbox
00Z0110369	17	Temperature monitor	--	Setpoint drift in temperature monitor	Moisture accumulation between sensor insulation and the copper lead wire

APPENDIX C

SUMMARY OF SELECTED CABLE TESTS

SUMMARY OF SELECTED CABLE TESTS

The technology for monitoring the condition of electric cables is limited. Most of the observations, tests, and measurements require that the cables be taken out of operation (i.e., be unenergized); also, in many cases, they require that both ends of the cables be electrically disconnected from power supplies (or control circuits) and the load or device being controlled, sensed, or powered. Further, electrical measurements on cables are often affected by terminations (e.g., terminal blocks) at the ends of the cables. Such terminations must be taken into account in the development of condition monitoring techniques.

As discussed in Section 3.8 of the text, continuous monitoring of the age-related parameters for cables is not practicable. Monitoring of aging parameters must therefore be performed on a periodic basis, consistent with the maintenance and shutdown schedule of the plant.

A brief summary of some of the important available tests pertaining to condition monitoring of cable insulation is provided as follows:

C-1. TESTS OF TENSILE ELONGATION AND STRENGTH

The plastic-flow properties (i.e., the ability to stretch and yet maintain physical integrity) of cable insulation and jacketing materials are usually determined by measurement of ultimate elongation and strength under tensile forces. Test methods are described in References C-1 through C-8.

Tensile specimens of insulation and jacketing materials usually consist of insulation tubes (the fabricated insulated wire with the conductor removed) and dumbbell-shaped specimens die-cut from slabs of insulating material. Dumbbell specimens are sometimes also cut out of insulation tubes (particularly jackets) of sufficiently large diameters; in this case it is necessary to grind out any corrugations or other forms of roughness produced by the fabrication process.

The main instrument required is a tensile testing machine of suitable jaw-separation speed (20 in/min).

The test is destructive and requires 1- to 3-ft lengths for each cable or insulated wire being evaluated.

C-2. INSULATION RESISTANCE MEASUREMENTS

The dc resistance of cable insulation is measured by application of a potential, commonly 500 Vdc, between the conductor and the exterior of the insulation being measured. The measurement is obtained by use of a megohmmeter which utilizes the leakage current to indicate a resistance value. Test methods are described in References C-5 through C-9.

The test is not inherently destructive and can be performed in situ. The resistance measurements will include the effects of any cable terminations or connections, including electic motors, etc.

C-3. POLARIZATION INDEX TESTS

The polarization index test measures the insulation resistance (see item C-2 above) at 1 minute and 10 minutes after the dc potential is applied. The ratio of the resistance at 10 minutes to the resistance at 1 minute is called the polarization index. The test method is described in Reference C-1; see also Reference C-12.

The test is not destructive and can be performed in situ.

C-4. HIGH-POTENTIAL-WITHSTAND TESTS

The high-potential-withstand test, also known as a dielectric-strength test, is a demonstration of the cable insulation's ability to withstand the potential applied. The potential is applied between the conductor and the conductive shield, exterior surface of the insulation, or jacket, whichever is more appropriate. The exterior of the insulation or jacket may be immersed in water or covered with a conductive material (e.g., metal braid) to provide a conductive ground (earth) reference plane for the test.

Test methods are described in References C-3 through C-8. The primary instrument is a high potential supply (ac or dc) of controllable and known voltage. A current meter in the circuit displays the leakage current (or leakage/charging current in the case of ac potentials).

The test can be performed in situ. The test is not inherently destructive, but can have a cumulative degrading effect after repeated measurements. One must be careful not to exceed the voltage limits of any equipment in the circuit to which the measurement is applied.

C-5. DISSIPATION FACTOR MEASUREMENTS

The dissipation factor is a measure of energy losses in dielectrics such as cable insulations. The dissipation factor is numerically equal to the tangent of the loss angle, i.e., the angle between the capacitive-current vector and the total charging-current vector. It is also numerically equal to the ratio of the resistive current to the capacitive current.

Dissipation factor measurements are obtained using ac potentials and a Schering or transformer bridge. Test methods are described in References C-13 and C-14. The test is not destructive.

The test is not well suited for in situ low-voltage cables which do not have conductive media such as a shield on the exterior surfaces of the cables under test. Laboratory tests may be performed with water or a metal braid as the return conductor.

C-6. PARTIAL DISCHARGE TESTS

Partial discharge extinction-level testing is the determination of the threshold potential that causes partial discharge of a small amount of electronic charge (measured in picocoulombs) from the conductor during each half cycle of ac voltage. The charge leaks from the conductor via discontinuities (e.g., voids), defects, or contamination in the insulation. Low values of threshold potential (as measured by this test) indicate the presence of degradation or imperfections in the insulation.

The test is described in References C-12 and C-15. Required test instruments include an ac potential supply with sufficient power for the cable under test, a partial-discharge measuring device including a detection stage, amplifier, and oscilloscope, and a partial-discharge calibrator.

An improvement in the partial discharge test instrumentation is claimed to have been achieved at the Purdue University, School of Electrical Engineering, West Lafayette, Indiana [C-16, C-17]. The technique is based on the cross correlation between the noisy voltage waveforms received at two positions on the cables having a peak at a certain delay. The measurement of this delay locates the source of the disturbance. The cross correlation is estimated with the aid of a digital system for comparing the polarities of the two waveforms as a function of time.

The test is not destructive and could be performed on cables in situ.

C-7. WATER TREE GROWTH EVALUATION

The phenomenon called "water treeing" is occasionally found in insulations subjected to high voltage stress for long periods. It is most likely to be experienced with XLPE insulation. It may also be present in EPR insulation but is harder to detect visually because of the opaque nature of EPR. Treeing is aggravated under humid conditions. Evaluation is performed by dissection and microscopic inspection of the cable insulation. The test is destructive and cannot be performed on cables in situ. To be representative, the cable length dissected must have been in actual high voltage use and in a plant location where conditions were most conducive to water treeing (i.e., in a high-humidity or water-immersed area).

Information on water treeing and methods for examination is available in References C-12 and C-18.

REFERENCES

C-1. ASTM Designation D412, "Standard Method for Tension Testing of Vulcanized Rubber"

C-2. ASTM Designation D638, "Standard Method for Test of Tensile Properties of Plastics"

C-3. ASTM Designation D2633, "Standard Methods of Testing Thermoplastic Insulated and Jacketed Wire and Cable"

C-4. ASTM Designation D470, "Standard Method of Testing Thermosetting Insulated and Jacket Wire and Cable"

C-5. NEMA WC3, "Rubber-insulated Wire and Cable for the Transmission and Distribution of Electrical Energy," (ICEA S-19-81)

C-6. NEMA WC5, "Thermoplastic-insulated Wire and Cable for the Transmission of Electirc Energy," (ICEA S-61-402)

C-7. NEMA WC7, "Cross-linked-thermosetting-polyethylene-inslated Wire and Cable for the Transmission and Distribution of Electrical Energy," (ICEA S-66-524)

C-8. NEMA WC8, "Ethylene-propylene-rubber-insulated Wire and Cable for the Transmission and Distribution of Electrical Energy," (ICEA S-68-516)

C-9. ASTM Designation D257, "Standard Test Methods for D-C Resistance or Conductance of Insulating Materials"

C-10. ASTM Designation D149, "Tests for Dielectric Breakdown Voltage and Strength of Insulating Materials at Commercial Power Frequencies"

C-11. IEEE Std 43-1974, "IEEE Standard Guide for Testing Insulation Resistance of Rotating Machinery"

C-12. John Reason, "Why Dielectric Failure is the Major Cause of Electrical System Breakdown," Power (magazine), Volume 125, No. 7, July 1981

C-13. ASTM Designation D150, "Standard Methods of Test for A-C Loss Characterstics and Dielectic Constant (Permittivity) of Solid Insulating Materials"

C-14. D. G. Fink, ed., Standard Handbook for Electrical Engineers, Tenth Edition, McGraw-Hill Book Company, New York 1969

C-15. ICEA Publication T-24-380, "Proposed Guide for Partial-Discharge Test Procedure"

C-16. W. L. Weeks and J. P. Steiner, "Improvement in the Instrumentation for Partial Discharge Location," to be presented at IEEE T&D Conference, May 1984

C-17. W. L. Weeks and J. P. Steiner, "Instrumentation for the Detection and Location of Incipient Faults on Power Cables," IEEE Transactions on Power Apparatus Systems, Vol. PAS-101, pp. 2328-36, July 1982

C-18. AEIC CS5-82, "Specifications for Thermoplastic and Crosslinked Polyethylene Insulated Shielded Power Cables Rated 5 through 46 KV (8th Edition)," Association of Edison Illuminating Companies, June 1982

APPENDIX D

GLOSSARY OF TERMS

GLOSSARY OF TERMS

AVAILABILITY: The capability of an item, under the combined aspects of its reliability and maintenance, to perform its required function at a stated instant in time [D-1].*

BURN-IN: The operation of items prior to their ultimate application intended to stabilize their characteristics and to identify early failures [D-1].

CATASTROPHIC FAILURE: A failure that is both sudden and complete [D-2].

CONDITION MONITORING: Continuous or periodic monitoring of a parameter (that has a strong correlation to the aging of an equipment item) to predict the ability of the equipment to continue to perform its specified functions during a period following the moment of observation.

CORRECTIVE MAINTENANCE: Maintenance actions taken to restore the functional capability of equipment following failure. These maintenance actions may include repair, replacement in whole or in part, or modification.

DEGRADED FAILURE: A failure that is gradual, partial, or both. Such a failure does not cause all function to cease but compromises a function, by any combination of reduced, increased, or erratic outputs. In time, such a failure may develop into catastrophic failure [D-2].

FAILURE: The termination of the ability of an item or equipment to perform its required function [D-2].

FAILURE MECHANISM: The physical, chemical, or other process that results in failure [D-2].

FAILURE MODE: The effect by which a failure is observed to occur [D-2].

FAILURE RATE: The expected number of failures of a given type of equipment, per item, in a given time interval (for example, valve failures per million valve hours). For cyclic items or equipment, the failure rate is the expected number of failures in a given number of operating cycles [D-2].

INCIPIENT FAILURE: An imperfection in the state or condition of an item or equipment so that a degraded or catastrophic failure can be expected to result if preventive action is not taken [D-2, modified by FRC].

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* Numbers in brackets indicate references (see page D-3) from which definitions were obtained; other definitions were written by the authors.

INSPECTION: Observation of the equipment (e.g., qualitative examination of noise, vibration, leakage, insulation brittleness, color of lubricant, etc.), to determine its general condition.

ITEM: Any level of hardware assembly -- system, equipment, component, part, and so on [D-1].

MAINTAINABILITY: A characteristic of design and installation expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time, when the maintenance is performed in accordance with prescribed procedures and resources [D-1].

MAINTENANCE PROGRAM: A set of activities that includes maintenance, and replacement.

MEAN TIME BETWEEN FAILURES (MTBF): For a particular interval, the total functioning life of a population of an item divided by the total number of failures within the population during the measurement involved [D-1].

MEAN TIME BETWEEN MAINTENANCE (MTBM): The mean of the distribution of the time intervals between maintenance actions (preventive, corrective, or both) [D-1].

MEAN TIME TO REPAIR (MTTR): The total corrective maintenance time divided by the total number of corrective maintenance actions during a given period of time [D-1].

PREVENTIVE MAINTENANCE: Maintenance performed prior to failure to assure the continued ability of equipment to perform its function. Preventive maintenance may be initiated on the basis of a set schedule or as the result of determination of the equipment condition as the result of scheduled inspections or condition monitoring. In this report, maintenance performed as the result of detection of incipient failure is considered to be preventive.

RANDOM FAILURE: Any failure whose cause and/or mechanism make its time of occurrence unpredictable, but which is predictable only in a probabilistic or statistical sense [D-1].

RELIABILITY: The characteristic of an item expressed by the probability that it will perform a required function under a stated condition for a stated period of time [D-1].

REPAIR: One form of corrective maintenance.

REPLACEMENT: Substitution of equipment performed at a convenient time when sufficient evidence is available that the equipment will fail catastrophically if allowed to function under certain conditions.

SCHEDULED MAINTENANCE: Performance of preventive maintenance of equipment at fixed intervals without regard to the level of deterioration during the interval. Scheduled maintenance is most effective for equipment that fails catastrophically, but for which detection of incipient failure is not possible.

SURVEILLANCE: The combination of inspection and testing performed periodically or as required to determine the functional status of the equipment at the time of observation.

TESTING: Obtaining information related to the functional capability by making measurements in accordance with prescribed procedures (e.g., functional tests at rated conditions, high-potential-withstand measurements, and insulation resistance measurements).

WEAROUT: The process of attrition that results in an increase of hazard rate with increasing age (cycles, time, miles, events, and so on as applicable for the item) [D-1].

WEAROUT FAILURE: A failure that occurs as a result of deterioration processes or mechanical wear and whose probability of occurrence increases with time [D-1].

REFERENCES

D-1. The Reliability Design Handbook, No. RDH 376, Rome Air Development Center, Griffiss Air Force Base, NY, April 1976

D-2. The IEEE Guide to Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear Power Generating Stations, IEEE Std 500-1984, The Institute of Electrical and Electronics Engineers, Inc.

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13. ABSTRACT (200 words or less)

The general concepts of equipment condition monitoring as applicable to the detection of age-related deterioration of safety-related equipment are described. The goal is to detect deterioration in the incipient stage, prior to in-service failure and prior to the point at which equipment can no longer be expected to perform its function when exposed to design basis accident conditions.

The application of condition monitoring is discussed specifically for electrical cables. The goal of cable condition monitoring is to determine the degree of cable degradation and to predict the remaining useful life. In-situ nondestructive testing and destructive laboratory testing are discussed. Interim recommendations are given for the implementation of a condition monitoring program.

14. DOCUMENT ANALYSIS - a. KEYWORDS/DESCRIPTORS
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