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Assessment of Environmental Qualification Practices and Condition Monitoring Techniques for Low-Voltage Electric Cables

LOCA Test Results

Brookhaven National Laboratory

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

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LOCA Test Results

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ABSTRACT

This report documents the results of a research program addressing issues related to the qualification process for low-voltage instrumentation and control (I&C) electric cables used in commercial nuclear power plants. Three commonly used types of I&C cable were tested: Cross-Linked Polyethylene (XLPE) insulation with a Neoprene® jacket, Ethylene Propylene Rubber (EPR) insulation with an unbonded Hypalon® jacket, and EPR with a bonded Hypalon® jacket. Each cable type received accelerated aging to simulate 20, 40, and 60 years of qualified life. In addition, naturally aged cables of the same types were obtained from decommissioned nuclear power plants and tested. The cables were subjected to simulated loss-of-coolant-accident (LOCA) conditions, which included the sequential application of LOCA radiation followed by exposure to steam at high temperature and pressure, as well as to chemical spray. Periodic condition monitoring (CM) was performed using nine different techniques to obtain data on the condition of the cable, as well as to evaluate the effectiveness of those CM techniques for in situ monitoring of cables.

Volume 1 of this report presents the results of the LOCA tests, and Volume 2 discusses the results of the condition monitoring tests.

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EXECUTIVE SUMMARY

As a licensing requirement for commercial nuclear power plants, electric equipment important to safety must be qualified for use in a harsh environment. Environmental qualification (EQ) requirements have evolved over the years, becoming more strict as new knowledge was gained about the aging process. The current requirements for qualification are specified in the Environmental Qualification Rule, which is documented in Title 10 of the Code of Federal Regulations, Part 50, Section 49 (10 CFR 50.49).

During a review of EQ requirements to address issues related to license renewal, questions arose as to the technical bases for allowing plants to have equipment qualified to different requirements. In addition, research in which certain types of cable failed loss-of-coolant-accident (LOCA) tests raised questions about their qualification. As a result, the issues related to EQ requirements were identified as Generic Safety Issue (GSI) 168, and a task action plan was developed to resolve them.

In support of the task action plan on EQ, and for the resolution of GSI-168, the NRC's Office of Nuclear Regulatory Research (RES) sponsored the research reported herein to resolve issues related to the process used for environmental qualification of certain electric components used in commercial nuclear power plants. Brookhaven National Laboratory (BNL) was selected as the lead laboratory to assist the RES. The initial focus of this program was on low-voltage electric cables used for instrumentation and control (I&C) applications, which is the subject of this report.

The objective of this research program was to provide information to help resolve specific issues related to the EQ process for low-voltage I&C electric cables. Initially, a comprehensive list of 43 issues was developed. Based on a thorough review and analysis of the literature, 24 issues were resolved by considering past research results, and 19 issues remained unresolved. Of the latter, six issues were identified that required additional analysis and testing of cables to resolve. These issues are summarized as follows:

- How do the properties of cables subjected to accelerated aging techniques used in the original qualification compare with the properties of naturally aged cables of equivalent age?
- What are the limitations in using an estimated value of the activation energy to predict the chemical degradation during thermal aging?
- Do multiconductor cables have different failure mechanisms than single conductor cables, and, if so, are these unique failure mechanisms properly accounted for in the qualification process?
- Do bonded jacket cables have different failure mechanisms than unbonded jacket cables, and, if so, are these unique failure mechanisms properly accounted for in the qualification process?
- Are there any effective condition monitoring techniques for determining cable condition in situ?
- Can condition monitoring techniques be used to predict LOCA survivability?

In addition to the six issues for which new testing was undertaken, six issues were categorized as unresolved with no further research recommended, and seven were identified for which the new information from the tests might help resolve. The later seven relate to addressing hot spots, impingement, physical damage, and improper installation in the qualification process. Also, the information gained from the new testing might help resolve issues related to extending the qualified life of I&C cables to 60 years.

To provide information that will assist in resolving the EQ issues of interest, the following three types of I&C electric cables commonly used in commercial nuclear power plants were tested:

- Cross-Linked Polyethylene (XLPE) Insulation with Neoprene® jacket,
- Ethylene Propylene Rubber (EPR) Insulation with unbonded Hypalon® jacket, and
- EPR Insulation with bonded Hypalon® jacket.

Testing was performed on unused cables that had undergone accelerated aging to simulate 20, 40, and 60 years of qualified life based on their original qualification parameters. Naturally aged cables from two nuclear power plants also were included. For comparison, unaged cable of the same type as the naturally aged cables received accelerated aging, using currently accepted accelerated-aging models, to match the service conditions to which the naturally aged cables had been exposed. Cables with no pre-aging were also included in all of the tests as controls. Six pre-aging/LOCA test sequences were performed to address the six EQ issues of interest. The performance results of the cables during the LOCA tests are reported in Volume 1 of this report.

Hold points were incorporated into the program to monitor the condition and performance of the cables at preselected points throughout the pre-aging and LOCA testing process. Various condition monitoring (CM) techniques were used at each hold point to obtain data on the cables, as well as to evaluate the effectiveness of those CM techniques for monitoring cable condition. Elongation-at-break (EAB) was used as a reference CM technique, against which other techniques were compared and correlated. The findings of this evaluation are reported in Volume 2 of this report.

Conclusions on EQ Issues:

Based on the results of the testing, the following conclusions are drawn:

Accelerated Aging Techniques:

- The data obtained suggest that the accelerated aging predictions using the Arrhenius model for thermal aging, with limitations, and the equal-dose/equal-damage model for radiation aging provide adequate estimates of the degradation experienced due to actual service aging. In six-out-of-six cases, material that received accelerated aging had a lower EAB, indicating more degradation than naturally aged material of equivalent age. Also, as the duration and severity of the natural aging simulated increased, the difference in degradation simulated by the models also increased. These results suggest that currently accepted artificial aging techniques provide conservative estimates of service aging, however, the limitations in the assumptions made, along with uncertainties in the data available, prevent a definitive conclusion from being drawn regarding the accuracy of the aging models.

Activation Energies:

- The data from these tests demonstrate that, for the two cable insulation materials tested, the activation energies used in the original qualification tests were representative of the materials being tested.

Multiconductor Cables:

- Test results show that differential swelling of jacket and insulation materials due to moisture absorption can occur during a LOCA. This phenomenon can contribute to rupture or cracking of the materials during steam exposure. If the insulation on the conductors of a multiconductor cable expands faster and to a greater degree than the outer jacket, the resulting stresses imparted on the outer jacket may be significant enough to cause it to rupture. While these results might suggest a potential common cause failure for multiconductor cables, it must be noted that, of the 15 cables pre-aged to 40 years and LOCA tested, 3 experienced performance anomalies that could impact their safety function.

Bonded Jacket Cables:

- The results of this study demonstrate that the bonded jacket/insulation configuration has a potential for catastrophic failure under LOCA conditions. This catastrophic failure can occur if the composite bonded jacket/insulation is first exposed to severe aging conditions, causing it to embrittle and shrink significantly, prior to its sudden exposure to steam. The steam causes swelling stresses that can initiate failure. While this phenomenon was observed for single conductor bonded jacket cables from one manufacturer in this program, it could be problematic for similar cables from other manufacturers.

Extending Qualified Life:

- The results indicate that degradation due to aging beyond the qualified life of the cables, based on extrapolation of the aging parameters used in the original qualification to a 60 year service life, may be too severe for the insulation material to withstand and still be able to perform adequately during a LOCA. For life extension purposes, the aging protocols used to establish the qualified life of the cables should be reviewed and compared to actual service environments in a plant. A determination then can be made as to whether the additional exposure to aging stressors during a period of extended operation will be acceptable for the cable materials.

Observations:

From the results of the tests, the following observations are made regarding the qualification process for electric cables:

- The currently accepted standards for qualifying various configurations of cable based on similarity to cables of the same material or construction that have already passed qualification type tests should be re-evaluated. Specifically, cables that are being qualified for use in applications requiring a multiconductor configuration should be tested in a multiconductor configuration. Similarly, cables with bonded individual jackets should be type tested in the configuration for which they are being qualified. The similarity argument may not be appropriate in all cases.

- Consideration should be given to developing more definitive acceptance criteria for determining if a cable passes a qualification type test. Currently, the qualification test results are analyzed to determine if the cable is qualified for its particular application. Typically, as long as one cable specimen passes the mandrel bend/submerged voltage withstand test at the end of the type test, and all other anomalies are determined not to be caused by global degradation of the insulation, the cable can be considered qualified. Guidance should be provided in qualification standards for the number of data points required, the number of permissible cable failures during the qualification test and how they should be addressed, and the required statistical confidence level to consider a cable qualified.

- Test sequence 5 indicated that cables with a composite EPR insulation with bonded CSPE individual jackets may exhibit catastrophic failure under LOCA conditions if they previously were exposed to severe aging, causing them to become brittle and shrink. Additional research is recommended to quantify the degree to which this type of cable can be aged before its ability to function during a LOCA is compromised. The research should determine if this observation is specific to the materials and construction of the cables of the one manufacturer for which it was observed, or if the phenomenon is generic to all cables of this construction.

- In thermally aging cables with a bonded CSPE individual jacket, consideration should be given to using an activation energy representative of the CSPE since it appears to dominate the failure mechanism for this type of cable.

- For safety-related cables, the electrical performance during accident peak conditions is a critical criteria for establishing qualification. However, current qualification standards do not provide any guidance on what electrical characteristics should be monitored or the frequency at which data should be obtained. Consideration should be given to including this information in the qualification standards (e.g., IEEE Std. 383).

- During the testing performed in this program, problems were observed on multiple occasions with moisture intrusion into splices applied to cables that had undergone preaging. In all cases, the cable jackets were degraded and cracked due to the preaging, and the moisture intrusion lead to a deterioration of cable performance. On the basis of these results, consideration should be given to evaluating the condition of a cable and developing an acceptance criterion prior to allowing the application of splices.

- For the Samuel Moore bonded jacket cables tested in this program, localized failures were observed on several of the test specimens after preaging to simulate 40 and 60 years of service, followed by simulated accident testing. While global degradation was not noted for these cables, the localized failures do raise uncertainties related to the accident performance of these cables after being in service for extended periods. On the basis of these results, consideration should be given to identifying and closely monitoring localized adverse environments in plants, and performing condition monitoring of electric cables located in those areas.

Conclusions on Cable Condition Monitoring Techniques:

It should be noted that most of the condition monitoring (CM) data evaluated in this study were obtained in a laboratory setting; therefore, conclusions regarding the application of the techniques in an actual plant setting cannot be drawn from this work. Additional testing is warranted to determine the impact of plant operating environments and logistics on the feasibility of performing these techniques in situ.

Eleven testing techniques were used throughout this research program. Nine were evaluated as potential methods for use as in situ condition monitoring techniques directly on plant cables or on in-plant sacrificial cable specimens. The remaining two techniques, the functional performance test and the post-LOCA voltage withstand test, were designed primarily to monitor cable performance during and after the LOCA exposure test. The effectiveness of each of the techniques for in situ CM is summarized below.

Visual Inspection:
- Based on the results of this study, visual inspection should be considered for inclusion in any cable CM program. While it does not provide quantitative data, it does provide useful information on the condition of the cable that is easy and inexpensive to obtain and that can be used to determine if further investigation of the cable condition is warranted. A significant limitation of this technique is that the cable must be visually accessible.

Elongation-at-Break (EAB):
- Elongation-at-break was found to be a reliable technique for determining the condition of the polymers studied. It provides trendable data that can be directly correlated with material condition. It is useful as a reference technique; however, its destructive nature prevents it from being used as an in situ means of monitoring electric cables unless sacrificial cable specimens are available.

Oxidation Induction Time (OITM):
- OITM was found to be a useful technique for monitoring the condition of electric cables. Results show that aging degradation can be trended with this technique for both XLPE and EPR insulation. Since a small sample of cable material is needed to perform this test, OITM is considered an effective in situ technique.

Oxidation Inducution Temperature (OITP):
- While it is related to OITM, OITP was found to be less sensitive to the detection of aging degradation for the polymers studied. It can be considered an in situ technique; however, OITM is preferred at this time.

Fourier Transform Infrared Spectroscopy (FTIR):
- FTIR was found to provide inconclusive results in terms of its ability to trend aging degradation in the polymers studied. Although the results show a consistent trend with aging, the technical basis for the trend remains questionable. Further research is warranted on this technique; however, it is not currently considered effective as an in situ technique for monitoring cable degradation.

Indenter:

- The indenter was found to be a reliable device that provided reproducible, trendable data for monitoring the degradation of cables in situ. While it is limited to accessible sections of cables, it was found to be effective for monitoring the condition of some cable jacket and insulation materials. Therefore, the indenter is considered an effective in situ technique for monitoring low-voltage electric cables.

Hardness:

- This technique was evaluated since it is a simple, inexpensive technique to perform. The results indicate that, over a limited range, the hardness can be used to trend cable degradation. However, different probes must be used to accommodate the change in material hardness. Also, puncturing of the cable insulating material is a potential concern with this technique. This technique is not considered to be effective as an in situ CM technique.

Dielectric Loss:

- This technique was found to provide useful data for trending the degradation of cable insulation. As the cables degrade, a definite change in phase angle can be detected at various test frequencies that can be correlated to cable condition. This technique is considered effective as an in situ CM technique.

Insulation Resistance:

- This technique was found to provide useful data for trending the degradation of cable insulation. As the cables degrade, a definite change in insulation resistance can be detected that can be correlated to cable condition. Using 1-minute and 10-minute readings to calculate a polarization index enables the effects of temperature and humidity variations to be accounted for. This technique is considered effective as an in situ CM technique.

Functional Performance:

- The use of functional performance data as a means of monitoring the condition of electric cables was evaluated since it is a simple, inexpensive technique to perform. While useful information can be obtained to determine if further CM is needed, this technique alone does not provide sufficient data to determine the degraded condition of a cable. This technique is not considered effective for in situ trending of degraded cable condition.

Voltage Withstand:

- This technique is performed as part of the currently accepted qualification process to determine the ultimate condition of the cables under test. At high voltage levels it is a potentially destructive technique that can impart damage to the cable due to the high voltage used. At low voltage levels, the technique can be non-destructive, however, its effectiveness is undetermined. It is not considered effective as an in situ condition monitoring technique.

Conclusions on the Use of CM to Predict LOCA Survivability

On the basis of this study it is concluded that no single, non-intrusive, cost effective, currently available CM method alone can be used to predict the survivability of electric cables under accident conditions. A plant instrumentation and control circuit may traverse a number of environments and localized conditions along its length. Many condition monitoring techniques are localized indicators of condition at the specific location along a cable circuit where the measurement is made. The criteria used to define survivability for a particular safety-related circuit are application-specific. Consequently, engineering judgements concerning the integrity and soundness of an electric cable must be made by experienced personnel based upon several condition monitoring tests, including visual, electrical, physical and chemical techniques. A suite of such condition monitoring tests, with periodic measurements referenced to baseline values, may then be used to make survivability assessments.

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ABBREVIATIONS

BNL .... Brookhaven National Laboratory

CM .... Condition Monitoring

CSPE .... Chloro-Sulfonated Polyethylene (also known as Hypalon®)

DBE .... Design Basis Event

DOR .... U.S. NRC, Division of Operating Reactors

EPDM .... Ethylene Propylene Diene Monomer

EPR .... Ethylene Propylene Rubber

GPM .... Gallons Per Minute

EQ. .... Environmental Qualification

I&C .... Instrumentation and Control

IE .... Inspection and Enforcement

LOCA .... Loss of Coolant Accident

NRC .... U.S. Nuclear Regulatory Commission

PSIG .... Pounds per Square Inch Gauge

QA .... Quality Assurance

RES .... U.S. NRC, Office of Nuclear Regulatory Research

XLPE .... Cross-Linked Polyethylene

XLPO .... Cross-Linked Polyolefin

1. INTRODUCTION

1.1 Background

As a licensing requirement for commercial nuclear power plants, safety-related electric equipment must be qualified for use in a harsh environment. Environmental qualification (EQ) requirements have evolved over the years, starting with the U.S. Nuclear Regulatory Commission (NRC) Division of Operating Reactors Guidelines for Environmental Qualification of Class 1E Equipment (DOR Guidelines), which were issued as part of Inspection and Enforcement (IE) Bulletin 79-01B. These were followed by NUREG-0588 requirements (Szukiewicz, 1979) which essentially established two categories of qualification, one for older plants and one for newer plants. The current requirements for qualification are specified in the Environmental Qualification (EQ) Rule, which is documented in Title 10 of the Code of Federal Regulations, Part 50, Section 49 (10 CFR 50.49). As knowledge was gained in the area of equipment aging, the EQ requirements were modified to reflect this new knowledge, and, in general, became more stringent. As an example, early EQ requirements did not specifically call for equipment to receive accelerated aging to reflect its end of qualified life condition prior to being tested, whereas the current requirements do.

During a review of qualification requirements to address issues related to license renewal, questions arose as to the technical bases for allowing plants to have equipment qualified to different standards. In addition, testing in which certain cable types failed LOCA tests raised questions related to the qualification of these cable types. As a result, the issues related to EQ requirements were identified as Generic Safety Issue 168, and a task action plan was developed to resolve them.

In support of the task action plan on EQ, the NRC's Office of Nuclear Regulatory Research (RES) has sponsored research to resolve issues related to the process used for the qualification of certain electric components used in commercial nuclear power plants. Brookhaven National Laboratory (BNL) was selected as the lead laboratory to assist RES in this effort. The initial focus of this program was on low-voltage electric cables used for instrumentation and control (I&C) applications. This report focuses on the research results specifically for I&C cables.

1.2 Program Objective

The objective of this research program was to provide information to help resolve issues related to the EQ process for low-voltage I&C electric cables. Initially, a comprehensive list of issues of interest was developed based on a workshop held in November 1993. At this workshop, national and international experts in the area of cable qualification participated in technical discussions and provided their insights on specific topics related to cable qualification that should be addressed. The results of this workshop are documented in NUREG/CP-0135 (Lofaro, et al., 1993). Using the information obtained at this workshop, a total of 43 issues related to the EQ process were identified.

Subsequent to this workshop, a thorough literature review and analysis was performed in an attempt to resolve as many of the issues as possible using prior research results before resorting to new cable testing. The literature review and analysis, which is documented in NUREG/CR-6384, Volume 1 (Subudhi, 1996) and Volume 2 (Lofaro, 1996), along with BNL Technical Report TR-6169-9/97 (Lofaro, 1998), categorized each of the issues and was very successful at resolving many of them. The results were as follows:

Category 1:	Resolved by past work; no new research recommended	24 issues
Category 2:	Unresolved by past work; no new research recommended	6 issues
Category 3:	Unresolved by past work; new research recommended	6 issues
Category 4:	Unresolved by past work; no new research recommended but may be addressed by work performed on other issues.	7 issues

As noted, 24 issues were resolved by reviewing and analyzing past research results, and 19 issues remained unresolved. Of those issues that were unresolved, six issues (Category 3) were identified that required additional cable testing to resolve. These issues are summarized as follows:

- How do the properties of cables subjected to accelerated aging techniques used in the original qualification compare with the properties of naturally aged cables of equivalent age?

- What are the limitations in using an estimated value of the activation energy to predict the chemical degradation during thermal aging?

- Do multiconductor cables have different failure mechanisms than single conductor cables, and, if so, are these unique failure mechanisms properly accounted for in the qualification process?

- Do bonded jacket cables have different failure mechanisms than unbonded jacket cables, and, if so, are these unique failure mechanisms properly accounted for in the qualification process?

- Are there any effective condition monitoring techniques for determining cable condition in situ?

- Can condition monitoring techniques be used to predict LOCA survivability?

In addition to the six issues for which new testing was performed, the literature review identified seven issues which the information gained from the new testing might help to resolve. These issues relate to addressing hot spots, impingement, physical damage and improper installation in the qualification process. Also, it was felt that the information gained from the new testing might help resolve issues related to extending the qualified life of I&C cables.

To facilitate future literature reviews on this or related subject areas, a computerized database was developed by BNL as part of this effort. In this database, each document reviewed is listed, along with publication information and a summary of the information included in the document. The database, along with a user's manual for the database, is available in BNL Technical Report TR-6169-06-96 (Hsu, 1998).

1.3 Research Approach

To provide information that would assist in the resolution of the six EQ issues of interest, BNL designed a research program in which three types of I&C electric cables commonly used in commercial nuclear power plants were tested. The cable types tested are:

- Cross-Linked Polyethylene (XLPE) Insulation with Neoprene® jacket,
- Ethylene Propylene Rubber (EPR) Insulation with unbonded Hypalon® jacket, and
- EPR Insulation with bonded Hypalon® jacket

These cable types were selected for study since they represent the most popular types of in-containment cables currently used in U.S. commercial nuclear power plants. In a study performed by EPRI (1994), it was found that approximately 89 percent of the currently operating plants in the U.S. had cables with XLPE insulation in containment, and approximately 73 percent had cables with EPR insulation. Other insulation materials used to a lesser degree in containment are silicone rubber (27 percent), chloro-sulfonated polyethylene (24 percent), ethylene tetrafluoroethylene copolymer (15 percent) and polyvinyl chloride (6 percent).

Testing for the research program reported herein was performed on unused cables that received accelerated aging to simulate 20, 40, and 60 years of qualified life based on their original qualification parameters. Naturally aged cables from two nuclear power plants were also tested. As a comparison, unaged cable of the same type as the naturally aged cables received accelerated aging, using currently accepted accelerated aging models, to match the service conditions to which the naturally aged cables were exposed. Unaged cables with no pre-aging were also included in the tests as controls.

The BNL test program was structured such that selected unaged cable specimens first received accelerated thermal and radiation aging to the desired equivalent qualified life, then they were exposed to high radiation doses followed by high temperature and high pressure steam and chemical spray, which simulated the first 7 to 10 days of a design basis loss-of-coolant-accident (LOCA). Unaged and naturally aged cables were also exposed to the same LOCA simulations, after which comparisons were made of their physical properties. Both the accelerated aging and LOCA simulation were performed in accordance with IEEE Standard 323-1974, which is the standard endorsed by the NRC in Regulatory Guide 1.89 to qualify Class 1E electric equipment for use in harsh environments in commercial nuclear power plants. The accelerated aging parameters were chosen to match those used in the original qualification of the cables.

Hold points were incorporated into the program to allow the condition and performance of the cables to be monitored at preselected intervals throughout the pre-aging and LOCA testing process. Various condition monitoring (CM) techniques were used at each hold point to obtain data on the cables, as well as to evaluate the effectiveness of those CM techniques for monitoring cable condition. Elongation-at-break (EAB) was used as a reference CM technique, against which other techniques were compared and correlated. The preliminary pre-aging/LOCA test plan is described in BNL Technical Report TR-6168/69-04-95 (Villaran, 1996). The preliminary condition monitoring research plan is described in BNL Technical Report TR-6168/69-03-95 (Lee, 1996).

Six pre-aging/LOCA test sequences were performed to address the six EQ issues of interest. In each sequence, one or more of the three cable types being studied were tested. Condition monitoring measurements were made at preselected hold points, after which the aging/LOCA testing continued, as appropriate. The CM data obtained were used to determine the condition of the cable, as well as to evaluate the CM techniques being studied. The objectives of each test sequence are presented in Table 1.1.

The pre-aging/LOCA testing parameters varied for each type of cable tested, however, each was based on the original qualification test for the cable being tested. In tests where more than one type of cable was tested, the cables were pre-aged separately, when necessary, to allow using parameters consistent with their original qualification. The LOCA test profile was selected to envelop the profiles used in the original qualification for all cables in the test. Sequential pre-aging was used with thermal aging preceding radiation aging. The LOCA tests were also performed sequentially with LOCA radiation preceding steam exposure.

Throughout this research program, periodic public meetings were held to obtain industry input and insights on the testing being performed, and to disseminate the results being obtained. Each of the program plans and test reports was made available for public review and comment. Test results were presented and discussed as they were obtained, and insights gained were incorporated into subsequent tests, as appropriate.

Table 1.1 Objectives of the six test sequences

Test Objectives	Test Sequence					
	1	2	3	4	5	6
Primary Objectives						
1. Evaluate pre-aging techniques by comparison of artificially aged cables with naturally aged cable	X	X	X			
2. Determine if any unique failure mechanisms exist for multiconductor cables as compared to single conductor cables.				X		
3. Determine if any unique failure mechanisms exist for bonded jacket cables as compared to unbonded jacket cables.					X	
4. Evaluate the effectiveness of promising cable condition monitoring techniques and determine if they can be used to predict LOCA survivability.	X	X	X			X
Secondary Objectives						
5. Provide information related to cable performance during the period of extended service past 40 years.						X
6. Provide confirmatory information on the qualification basis for the cables tested.			X	X	X	

Note: LOCA testing was not required to address the issue related to activation energies, as discussed in Section 3.7 of this report.

1.4 Quality Assurance

To ensure that the results of this research are traceable and defensible, a Quality Assurance (QA) program was developed by BNL. The BNL QA program is based on the requirements specified in Title 10, Part 50, Appendix B of the Code of Federal Regulations (10 CFR 50, Appendix B). All work was performed under this QA program, which required the development and approval of detailed test procedures for all testing activities, as well as periodic audits, both by BNL staff and by NRC. Work performed by subcontractors to BNL was also performed according to these QA requirements. The BNL QA plan is described in BNL Technical Report TR-6169-05-95 (Grove, 1996).

The results of test sequences 1 through 3 are reported in a series of interim BNL technical reports (Lofaro, et al. 1998B, 1998C, 1999A, 1999B), while those for tests 4 and 5 are documented in letter reports (Lofaro, 2000A, B). This final program report, which is comprised of two volumes, combines the results of all test sequences to provide information and draw conclusions that can be used to help resolve the issues discussed in Section 1.2. The results of the LOCA tests are presented in Volume 1 of this report. The results of the CM techniques evaluated in the program are discussed in Volume 2.

2. TESTING PROTOCOL

2.1 Cable Test Specimens

As previously discussed, this research effort involved testing of both unaged and naturally aged cable specimens, which were obtained from decommissioned nuclear power plants. There are many factors which influence the acquisition of cable samples, including cable type, installation, configuration, degree of aging, and jacket and insulation materials. Once the cables were selected, special handling precautions were implemented to insure no damage occurred to the cables during removal and testing. Also, an identification system was developed to uniquely identify each cable specimen and maintain traceability throughout the testing process. A Cable Acquisition Plan (Deem, 1995) was prepared to identify the cable types of interest, as well as the steps and precautions to be taken to mitigate handling damage to the samples during removal and transport.

2.1.1 Acquisition of Cable Samples

During the initial phases of the acquisition process, many nuclear power utilities were contacted to determine cable availability and their willingness to supply cables for this program. Naturally aged cables were requested, along with unaged cable of the same type and manufacturer, if available. Detailed plant information on the service environment seen by the naturally aged cables was also requested. Once a plant indicated a willingness to supply cables, meetings were held with utility representatives to review the types of cables available, and the environmental data available for the cables. By contacting numerous sources, BNL was successful in obtaining sufficient lengths of both unaged and naturally aged cables to meet the program objectives.

In obtaining cables from the plants, candidate cables were first identified from a review of the plant database, then located in a plant walk-down to assess the location and physical installation characteristics. Installation characteristics of interest included installation method (trays or conduits), location (potential hot spots), bends and overhangs. Special attention was given to selecting cables from areas where ambient data were available (temperature, humidity, and radiation).

Emphasis was also placed on obtaining cables from severe environmental stress areas, such as locations within the bio-shield (i.e., close vicinity to reactor coolant pumps, pressurizers, steam generators, etc.). Plant files, including EQ documentation, maintenance work requests and radiation survey reports for the candidate cable locations, were reviewed to obtain historical data on the cables. Specific information of interest included the original purchase specifications, manufacture and installation date, environmental data, and initial EQ test reports.

In addition to obtaining naturally aged cables, unaged cables of the same specifications (manufacturer, material) were also obtained from the plants. These cables were used for comparative analysis with the naturally aged specimens. Typically, these cables were obtained from warehouse stock, or mild environment areas (i.e., computer rooms, cable spreading rooms, control room).

To ensure that the cables selected for removal from the plant site were in good condition initially and after removal, in situ insulation resistance (IR) tests and visual examinations were conducted before and after the removal process. Once the acceptability of the cables was established, special precautions were taken to minimize the physical handling of the cables. The cable tray (or conduit) containing the desired cables was cut and removed as a unit. Following transfer to a lay-down area, the tray (or conduit) was carefully removed from around the cable, as opposed to physically pulling the cable. In addition to protecting the cable from physical damage, this also maintained the as-installed configuration. Procedures for cleaning and bagging the cables were also implemented.

Depending upon the cable (unaged or naturally aged), different types of packaging were utilized to protect the cables during transport between the plant site and BNL. Naturally aged cables which were installed in a straight configuration were transported in PVC tubes which were capped at both ends. Naturally aged cables with bends were attached to sheets of plywood to immobilize them and maintain their installed configuration, then placed in wooden crates to protect them during shipping (Figure 2.1). Unaged cables were coiled according to acceptable handling practices, and shipped in barrels, crates, or on pallets. Prior to removal from the plant site, each cable was radiologically surveyed to detect any fixed or loose contamination.

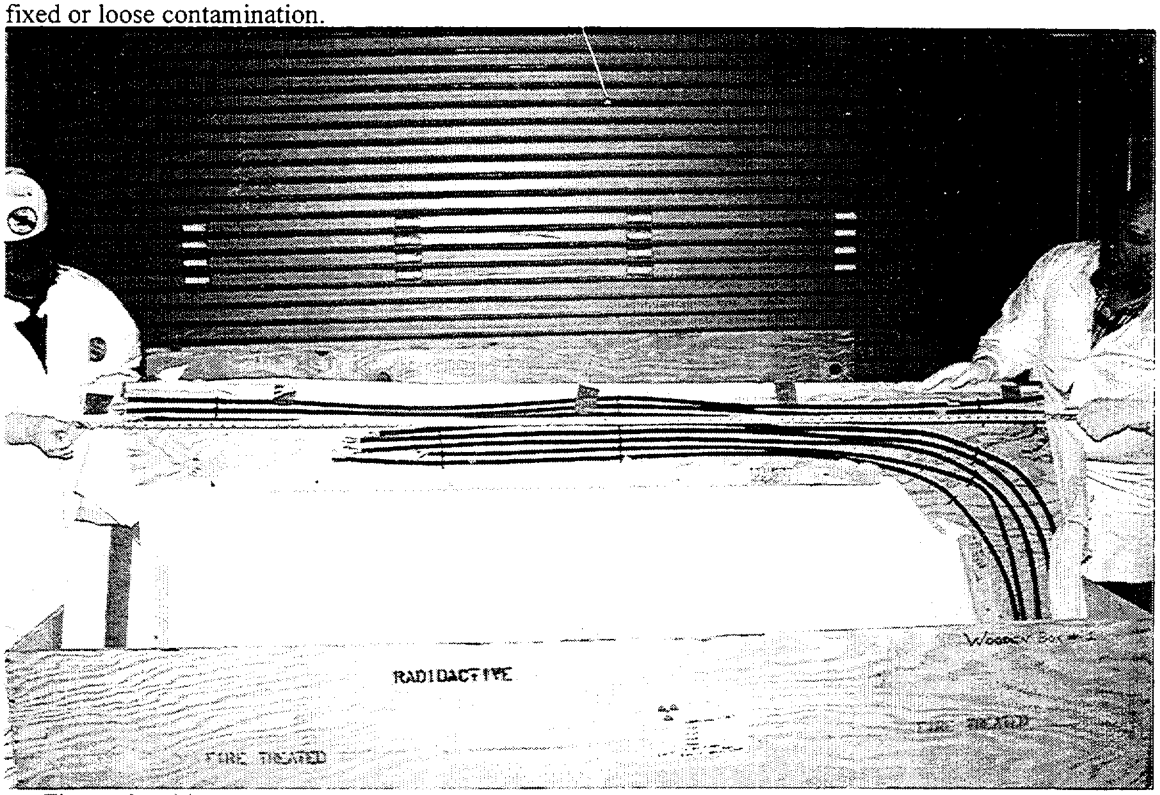

Figure 2.1 Naturally aged cables installed on plywood boards to protect them during shipping

Transportation between plant sites and testing facilities was accomplished using dedicated shippers. This minimized the required handling, and ensured that the cables were protected from damage or exposure to adverse environmental conditions.

Upon receipt at BNL (or the test site), the cable samples were inspected to ensure that there were no visible signs of damage. They were then unloaded, inventoried, and placed in a secure storage area. The temperature and humidity in the storage area were monitored continuously using a calibrated chart recorder to verify that moderate storage conditions were maintained to protect the cables from adverse environmental conditions.

In addition to the cables obtained from decommissioned plants, several cable types were acquired from Sandia National Laboratories to address two specific issues in the program. These cables, manufactured by Okonite and Samuel Moore, had been tested by Sandia in previous research programs and had exhibited performance anomalies. Samples from the same lots tested by Sandia were obtained to re-evaluate the anomalies experienced in past tests.

The cables tested in each of the six LOCA test sequences are listed in Table 2.1.

Table 2.1 Cable types used in each test sequence

Cable Manufacturer	Cable Type	Cable Description	Test Sequence 1	2	3	4	5	6
Rockbestos	I&C	• 2/C #14 AWG Firewall® III • 30 mil XLPE insulation • 45 mil Neoprene® overall jacket • 600 V	X		X			X
		• 3/C #16 AWG Firewall® III with ground • 30 mil XLPE insulation • 45 mil Neoprene® overall jacket • 600 V	X		X			
American Insulated Wire (AIW)	I&C	• 3/C #16 AWG with ground • 30 mil EPR insulation • 15 mil CSPE unbonded individual jacket • 45 mil CSPE overall jacket • 600 V		X				X
		• 4/C #16 AWG with ground • 30 mil EPR insulation • 15 mil CSPE unbonded individual jacket • 45 mil CSPE overall jacket • 600 V		X				X
Anaconda	P	• 3/C #12 AWG • 30 mil EPR insulation • 15 mil CSPE unbonded individual jacket • 45 mil CSPE overall jacket • 1,000 V				X	X	
		• 1/C #12 AWG • 30 mil EPR insulation • 15 mil CSPE unbonded individual jacket • 1,000 V				X		
Samuel Moore	I&C	• 2/C #16 AWG with shield and ground • 20 mil Dekoron® (EPDM) insulation • 10 mil Dekorad® (CSPE) bonded individual jacket • 45 mil Dekorad® (CSPE) overall jacket • 600 V				X	X	X
		• 1/C #12 AWG with shield and ground • 20 mil Dekoron® (EPDM) insulation • 10 mil Dekorad® (CSPE) bonded individual jacket • 600 V				X		
Okonite	I&C	• 1/C #12 AWG • 30 mil Okonite® (EPR) insulation • 15 mil Okolon® (CSPE) bonded individual jacket • 600 V					X	X

I&C = Instrumentation and Control EPR = Ethylene Propylene Rubber EPDM = Ethylene Propylene Diene Monomer
XLPE = Cross-linked Polyethylene P = Power CSPE = Chlorosulfonated Polyethylene AWG = American Wire Gauge

2.1.2 Preparation of Test Specimens

Upon selecting a specific cable for testing, it was retrieved from the cable storage area, and cut to length in accordance with approved program procedures. For this testing program, the cable samples were cut into both long (10-foot or 30-foot) and short (6-inch) specimens for testing. The long specimens were energized during the steam exposure and monitored for cable functional performance. Short specimens, made from the same source as the long specimens, were used for destructive testing to determine the physical and material condition of the cable at various hold points.

Several of the long cable specimens were placed in individual steel Unistrut® channels to simulate a typical physical configuration of cables installed in a power plant, i.e., straight horizontal cable trays or conduit. The Unistrut® channels also served to protect the cable specimens from damage during handling. Approximately one inch of insulation was removed from the conductors on both ends to allow splices to be made to facility wiring to energize the long specimens. The cables were held in place using Tefzel® tie wraps, which were applied by hand just tight enough to hold the cable snugly and prevent it from moving. Figure 2.2 is an end view of four typical Unistrut® channels with individual long cable specimens on a test fixture in the thermal aging chamber.

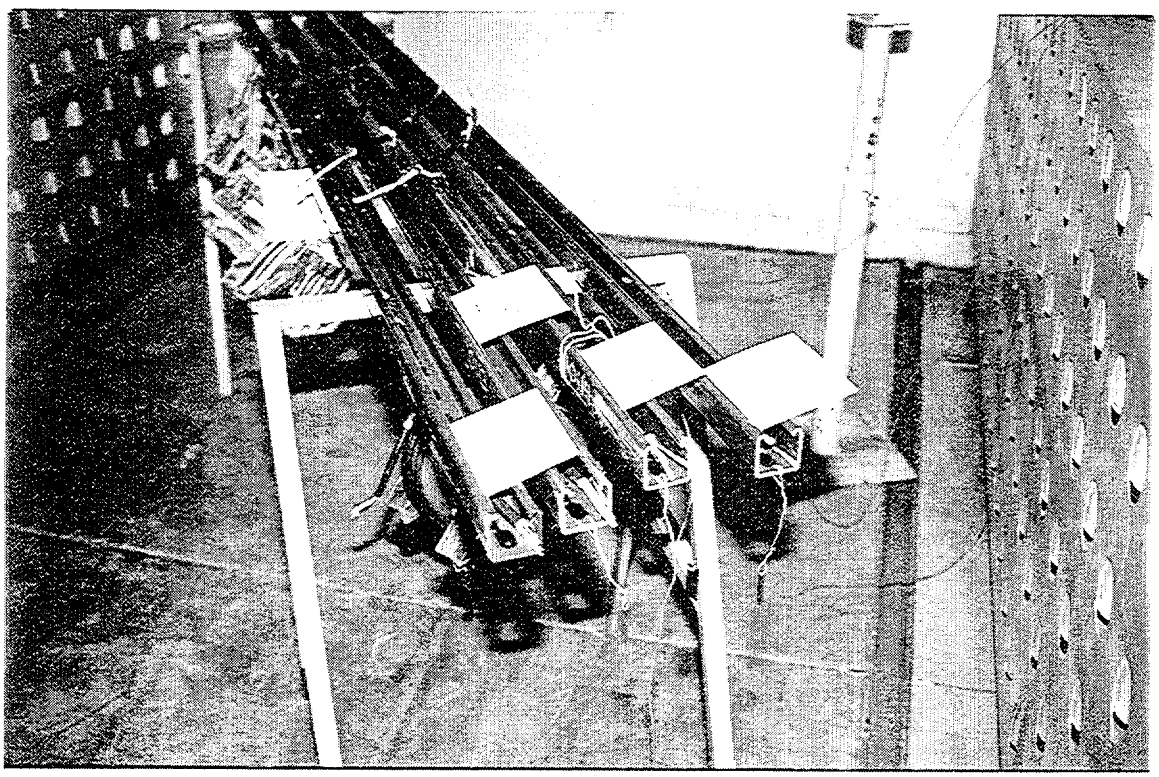

Figure 2.2 Typical long specimens installed in Unistrut® shown in thermal aging oven

The remaining long specimens were installed on stainless steel mandrels to simulate actual qualification testing. The specimens were tied to the mandrel using stainless steel wire, which was also applied by hand just tight enough to hold the cable snugly and prevent it from moving. A piece of fiberglass tape was placed between the stainless steel wire and the test specimen to prevent the wire from cutting into the test specimen jacket. Figure 2.3 shows a typical long specimen mounted on a mandrel.

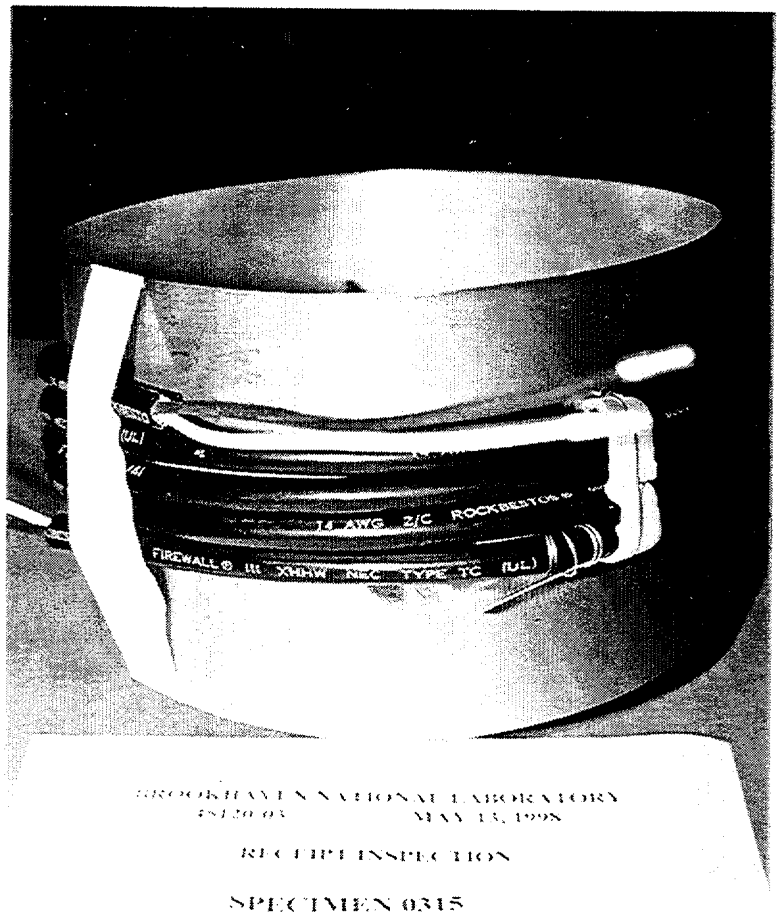

Figure 2.3 Typical long specimen installed on a mandrel

For test sequences 1, 2 and 3, un-insulated butt-splice connectors were crimped to the conductors for later connection to test leads. The facility test leads were connected to the test specimens using Raychem® nuclear grade splices after thermal aging, radiation aging and LOCA irradiation of the test specimens were completed. This procedure was modified for test sequences 4, 5 and 6 to further minimize the potential for handling damage to the specimens during splice application. In the later test sequences, the mandrels were modified to include a 2-foot arm to support the ends of the test specimen as they were routed away from the mandrel. In addition, short (2-foot to 3-foot) Teflon®-insulated pigtails were spliced to the test specimens using Raychem nuclear grade splices prior to any accelerated aging to further mitigate the potential for handling damage to the test specimens. The pigtails were shielded from the thermal and radiation aging, to the extent possible, to keep them from becoming brittle. After aging, the facility lead wires were connected to the pigtails using a second splice. Figure 2.4 shows a typical specimen mounted on the modified mandrel with pigtails attached, as used for tests 4, 5 and 6.

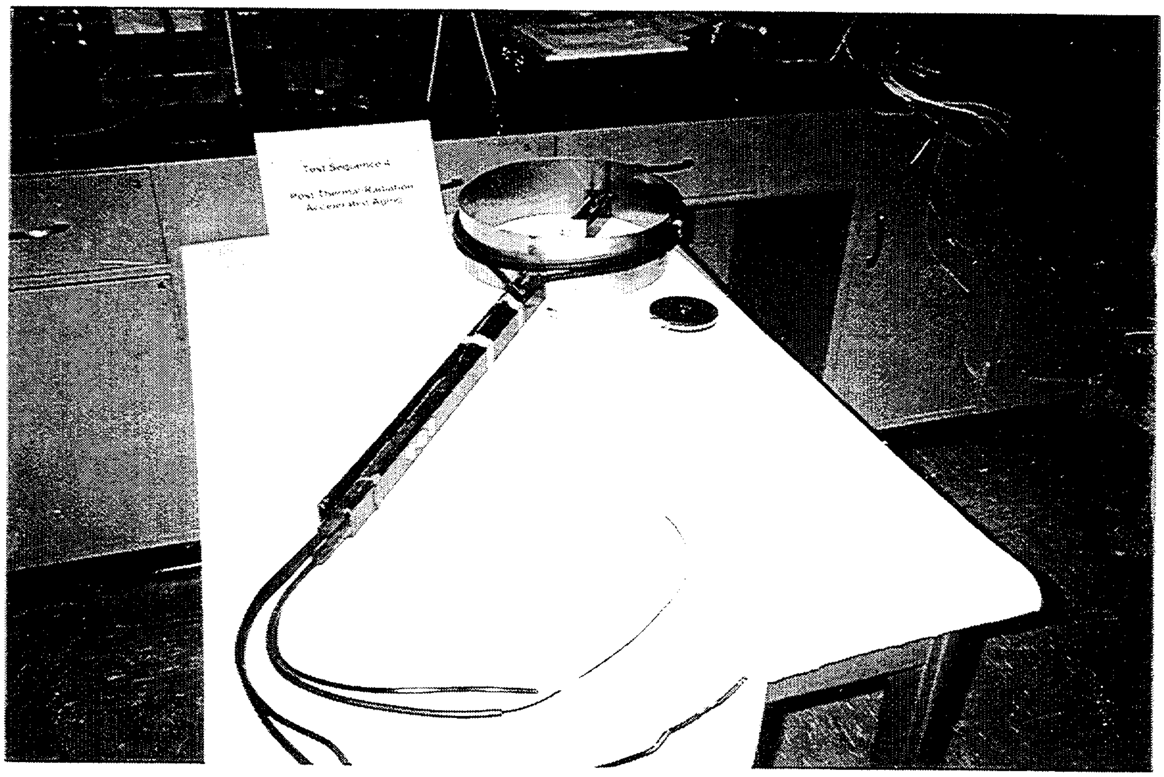

Figure 2.4 Typical specimen mounted on a mandrel with a modified design for tests 4, 5 and 6

Preparation of the 6-inch short specimens involved separating the cable outer jacket from the individual conductors, and removing the copper conductors from the insulation in accordance with approved program procedures. This allowed for tensile and hardness testing of individual jacket and conductor insulation materials. The outer jacket material specimens were punched into a standardized "dog bone" configuration for elongation-at-break (EAB) testing. The insulation was left in a tubular configuration for testing. The short specimens were placed in stainless steel mesh baskets during pre-aging and LOCA testing. Typically, seven to ten short cable jacket and insulation specimens were inserted into each basket. The baskets were then labeled for removal at specific CM points for materials testing. The exact number of long specimens and baskets prepared for each LOCA test was dependent upon the number of different cable types and CM points included in each test. Figure 2.5 shows a typical basket containing short specimens.

In order not to damage the long specimens, an additional two foot specimen was prepared from the same source as each long specimen to be used specifically for indenter testing. This 2-foot specimen followed the "parent" long specimen throughout the test sequence. Approximately 6 inches of outer jacket material was removed from both ends of the 2-foot specimen to allow indenter testing of the underlying insulation material. Figure 2.6 shows a typical 2-foot specimen used for indenter testing.

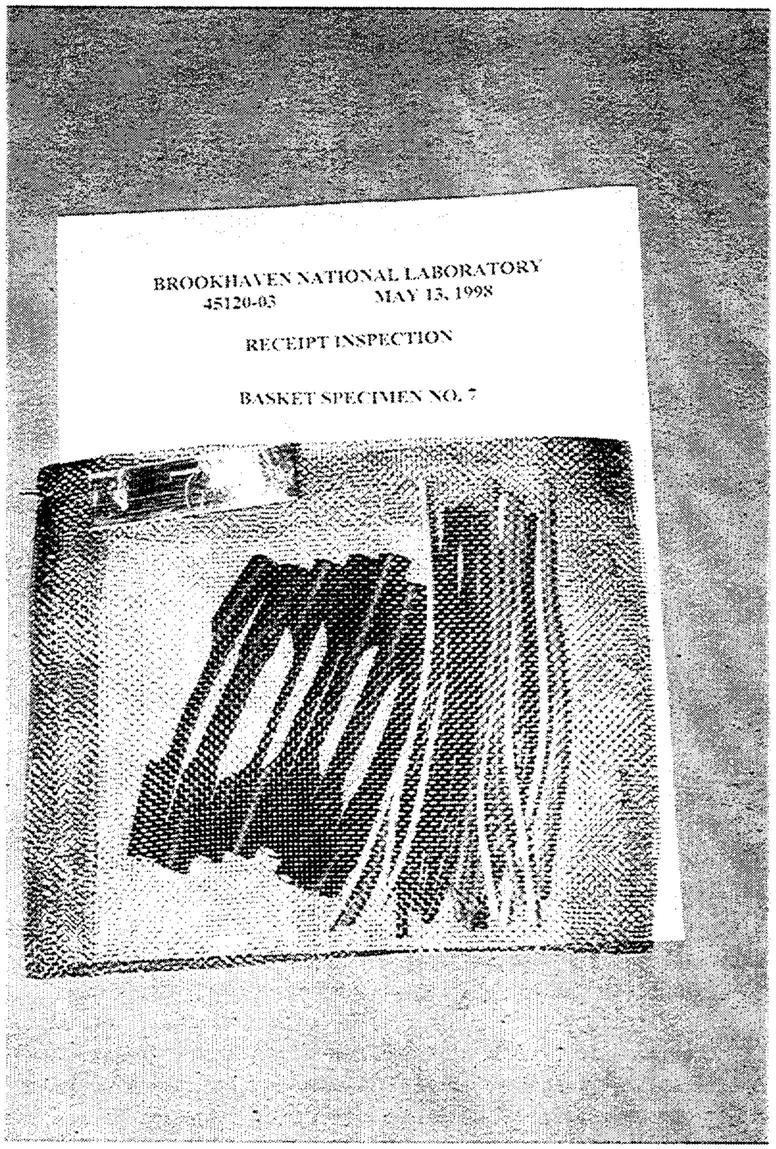

Figure 2.5 Typical basket of short specimens

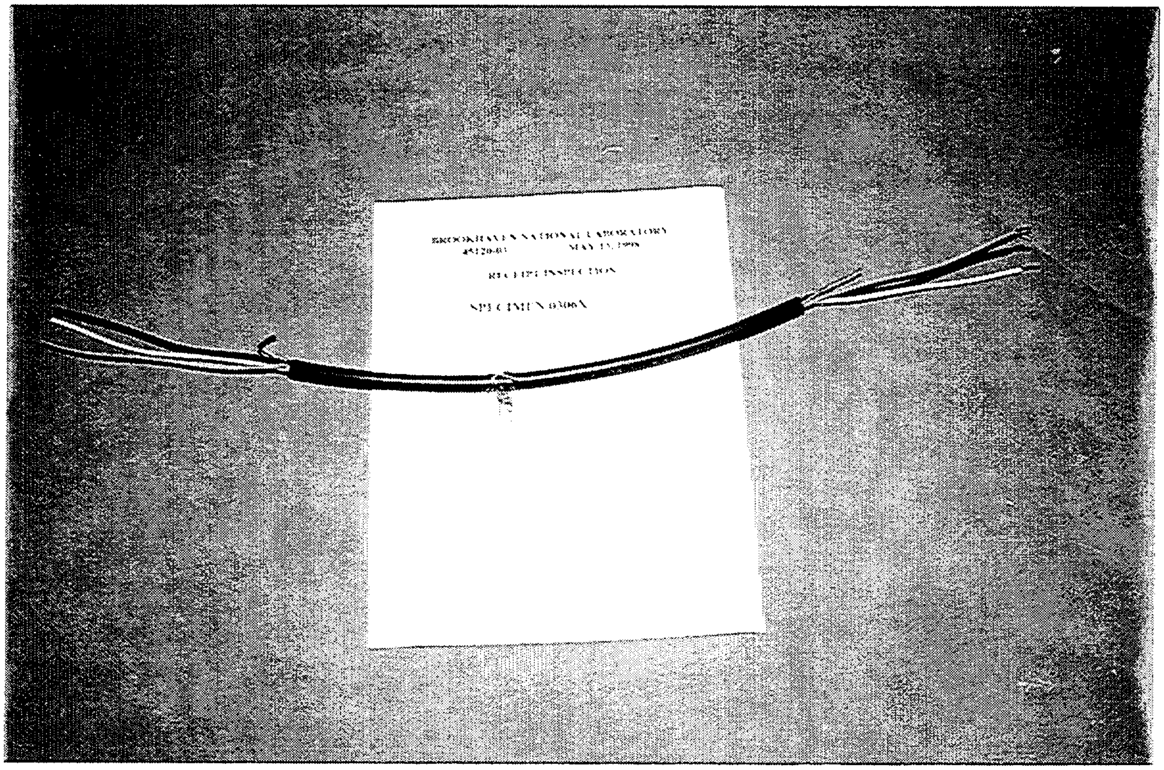

Figure 2.6 Typical 2-foot specimen for indenter testing

2.1.3 Identification of Test Specimens

Throughout this program, hundreds of different cable specimens were prepared and tested. It was critical that each specimen be properly and uniquely identified to allow traceability of test results to the proper specimen, and to draw accurate conclusions. To accomplish this, a procedurally-controlled identification scheme was developed to assign a unique identification number to each specimen. These identification numbers are used throughout this report to identify cable specimens and their test results. The scheme is described in the following paragraphs.

New or unused cables were obtained from nuclear facilities, and were typically long coils or reels of cable from warehouse stock. These are used as the "unaged" cables for this program since they were not in service and the aging degradation from storage is expected to be minimal compared to service in the plant. Naturally aged cables from both mild and harsh environments were also obtained and were typically delivered in their installed configuration. Both the unaged and naturally aged source cables obtained are referred to as cable "samples" and were used as the source cable for preparing the test specimens. The cable test "specimens" are the long (30-foot or 10-foot) and short (2-foot or 6-inch) pieces of cable cut from the source cable samples.

The cable samples are identified by a 10-digit identification number, such as "PNI85RB191." Each digit provides information about the sample, as follows:

Position	Description
1	Code indicating the source of the cables: "P" for PWR, "B" for BWR, "M" for manufacturer, "D" for DOE facility, "L" for National Laboratory.
2	Code indicating the aging of the cable when it was obtained by BNL: "A" for naturally aged, "N" for new or unused, or "U" for used (installed but not energized or not exposed to harsh environments).
3	Code for cable type: "I" for instrumentation, "P" for power, "C" for control.
4 & 5	Year of installation for naturally aged or used cable, or year of manufacture for new or unused cable.
6 & 7	Code indicating the cable manufacturer: "RB" for Rockbestos, "OK" for Okonite, "AI" for American Insulated Wire, "AN" for Anaconda, or "SM" for Samuel Moore.
8, 9 & 10	Sequential number of sample (e.g., 001, 002, etc.).

Each long cable specimen was assigned an identification number consisting of the 10-digit ID code from the parent sample from which it was made, followed by a 4-digit number, such as "0101." The first two digits represent the pre-aging/LOCA sequence in which they were tested. The last two digits are the sequential number of the specimen. Two stainless-steel tags with the specimen's 4-digit number engraved on it were tied to each long specimen using stainless-steel wire to ensure positive identification through all phases of testing. The tag wire was wound loosely around the test specimen to prevent it from damaging the test specimen jacket.

A 2-foot specimen was prepared to accompany each long specimen throughout the pre-aging and LOCA testing process for indenter testing, as previously discussed. These specimens carried the same 4-digit number as the "parent" specimen, but with an "X" suffix; e.g., 0101X. A stainless-steel tag with the specimen's 4-digit number engraved on it was tied to each specimen using stainless-steel wire to ensure positive identification through all phases of testing. The tag wire was wound loosely around the test specimen to prevent it from damaging the test specimen jacket.

The 6-inch specimens were prepared from the same source as the long specimens. Therefore, their identification code is linked to the parent specimen. The small specimen identification consists of the 4-digit code from the long specimen, with one prefix and one or two suffix codes attached, such as "I0101AW." The 4-digit core number (i.e., 0101) indicates it was prepared from the same sample cable used to make the long specimen "0101." The prefix indicates the part of the cable used for the specimen; either "I" for insulation, or "J" for jacket. The first suffix indicates the CM hold point at which the specimen was tested; "A", "B", "C", etc. For insulation specimens, a second suffix indicates the color of the insulation; "B" for black, "R" for red, "G" for green, or "W" for white. Each basket of small specimens was labeled with two stainless-steel tags engraved with the identification number to ensure positive identification throughout all phases of testing.

2.2 Accelerated Aging Protocol

As part of this research program, various new or unused cables were aged using accelerated thermal and radiation aging techniques to simulate actual service conditions. In all cases, sequential thermal aging followed by radiation aging was used. The following sections describe the process used to perform this accelerated aging. The development of this accelerated aging process is described in detail in the Pre-Aging and LOCA Test Plan (Villaran, 1996).

2.2.1 Accelerated Aging Parameters

The accelerated aging parameters (i.e., activation energy, thermal aging temperature, radiation dose rate) were selected to match those used in the original qualification tests of the cables for the plant from which they were obtained. The thermal aging time and total integrated dose were then adjusted using a linear extrapolation to achieve the qualified life being simulated (i.e., 20 years, 40 years, or 60 years). This approach was selected to avoid exposing the cables to any aging stresses in excess of what they were originally designed and qualified to withstand, with the exception of the 60-year tests. Since the parameters used in this test program are the same as those to which the cables were originally qualified, the cables can be expected to perform acceptably with a high level of confidence. Also, using the same aging parameters as those for the original qualification allows comparisons to be made with, and extrapolation of test results to, cables used in the plants.

Table 2.2 lists the qualification test reports obtained and reviewed for the pre-aging information. Table 2.3 presents the pre-aging parameters used in the original qualification tests, along with the accident conditions simulated. Included in Table 2.3 is the equivalent qualified life at an assumed service temperature of 140°F (60°C). This information facilitates comparison of the pre-aging for each of the test specimens and illustrates the differences in pre-aging used by the different cable manufacturers in the qualification tests.

2.2.2 Accelerated Aging Procedure

Prior to thermal aging, the test specimens were prepared and installed on their test fixture (Unistrut® or mandrel), as discussed previously. Accelerated thermal aging was then performed by Wyle Laboratories in Huntsville, Alabama. All specimens with the same specified aging temperature in a particular test sequence were loaded into one oven. The specimens were not energized during the thermal aging exposure. Oven temperature was controlled to +5, -0°F with a thermal trip setting +10°F above the specified aging temperature. Thermal aging duration was controlled to +2, -0 percent of the specified duration. In cases where some specimens in the oven had different required thermal aging durations, the oven was shutdown to remove specimens, then restarted to continue the thermal aging run. The shutdown and startup ramps were typically not credited as aging time for the specimens since they were of relatively short duration (approximately 1 hr.). A continuous circular chart recording was used to monitor the thermal aging process. All work was performed in accordance with Wyle Laboratories' pre-aging procedure under a 10 CFR 50, Appendix B Quality Assurance program.

Table 2.2 Qualification reports used to determine test parameters

Cable Tested	Test Laboratory	Test Report Title	Report Number	Report Date
AIW	Franklin Institute Research Laboratories	Qualification of Electrical Cables for a Loss-of-Coolant Accident	F-C4197-2	12/75
Anaconda	Franklin Institute Research Laboratories	Tests of Electrical Cables Subjected to Thermal Aging, Gamma Radiation and a Loss-of-Coolant Accident Simulation	F-C4350-3	7/76
Okonite	The Okonite Company	Nuclear Environmental Qualification Report for Okonite Insulated Cables	NQRN-1A	Rev. 5 10/24/88
Samuel Moore	Isomedix Inc.	Qualification Test of Electric Cables Under a Simulated LOCA/DBE by Sequential Exposure to Environments of Radiation, Thermal Aging, Steam and Chemical Spray	LOCA XLPO/ EPDM	6/78
Rockbestos	The Rockbestos Company	Report on Qualification Tests for Firewall III Irradiation Cross-Linked Polyethylene Constructions for Class 1E Service in Nuclear Generating Stations	QR-1806[a] QR-5805[a]	5/1/81 5/22/86

[a] Rockbestos report QR-1806 was used to determine the pre-aging parameters for the cables in test sequences 1 and 3, while report QR-5805 was used for test sequence 6.

Table 2.3 Parameters used in original qualification tests

Cable Tested	Qualified Life	Activation Energy (eV)	Service Pre-aging		Accident Simulated	Equivalent Qualified Life at 140°F (60°C) (d)
			Thermal	Radiation		
AIW	40 yr.@122°F (50°C) (a)	1.18 (b)	168hr.@ 250°F (121°C)	25Mrad@ 0.55Mrad/hr.	75 Mrad + 1 Peak Steam Exposure	11 yrs.
Anaconda	40 yr.@156°F (69°C) (a)	1.18 (b)	168hr.@ 302°F (150°C)	50Mrad@ 0.36Mrad/hr.	150 Mrad + 1 Peak Steam Exposure	120 yrs.
Okonite	40 yr.@194°F (90°C)	1.44 (c)	504hr.@ 302°F (150°C)	50Mrad@ 0.65Mrad/hr.	150 Mrad + 2 Peak Steam Exposure	2,495 yrs.
Samuel Moore	40 yr.@136°F (58°C) (a)	1.36 (b)	168hr.@ 250°F (121°C)	25Mrad@ 0.75Mrad/hr.	175 Mrad + 2 Peak Steam Exposure	30 yrs.
Rockbestos (QR#1806)	40 yr.@194°F (90°C)	1.33 (c)	1,300hr.@ 302°F (150°C) (e)	50Mrad@ 0.50Mrad/hr.	150 Mrad + 2 Peak Steam Exposure	2,847 yrs.
Rockbestos (QR#5805)	40 yr.@194°F (90°C)	1.33 (c)	909.5hr.@ 302°F (150°C) (e)	50Mrad@ 0.40Mrad/hr.	150 Mrad + 2 Peak Steam Exposure	1,992 yrs.

(a) Service temperature calculated based on thermal aging performed and activation energy stated.
(b) Activation energy obtained from literature (Holzman and Sliter, 1992).
(c) Activation energy calculated based on thermal aging performed and qualified life simulated.
(d) Equivalent qualified life of the insulating material at a service temperature of 140°F (60°C) calculated using the Arrhenius model and the activation energy stated, based on thermal aging only.
(e) Thermal aging duration includes margin above calculated duration of 850 hr.

After completion of thermal aging at Wyle Laboratories, accelerated service radiation and LOCA radiation exposures were performed at the Neely Nuclear Research Center located at the Georgia Institute of Technology in Atlanta, Georgia. The accelerated service radiation exposure was used to simulate service radiation conditions. This was followed by a LOCA radiation exposure simulating the design basis accident radiation dose used in the original cable qualification tests. Specimens were not energized during either of the radiation exposures.

A photograph of the hot cell in which the specimens were irradiated is shown in Figure 2.7. As shown, the hot cell is large enough to accommodate the long specimens in their Unistrut® support channels. Figure 2.8 presents a schematic of the hot cell with a typical arrangement of long specimens in Unistrut® stacked upon each other, with the open portion of the channels facing the sources. The individual source holders without the sources were first positioned on the test bench at the required distance to provide the desired dose rate. For the mandrel mounted specimens, several mandrels were stacked on top of each other and the source holders were placed at the appropriate distance around the outside circumference of the specimens to irradiate them. The individually identified Cobalt-60 sources are kept in a source storage pool adjacent to the hot cell. After the specimens and source holders were properly placed, the designated sources were transferred from the storage pool into the hot cell by the operator using manipulator arms. The specific sources to be used, and the positions of the sources with respect to the target cable specimens, were calculated and verified by the hot cell engineer prior to the irradiation run. All irradiations were performed in accordance with Georgia Institute of Technology procedures under a 10 CFR 50, Appendix B Quality Assurance program.

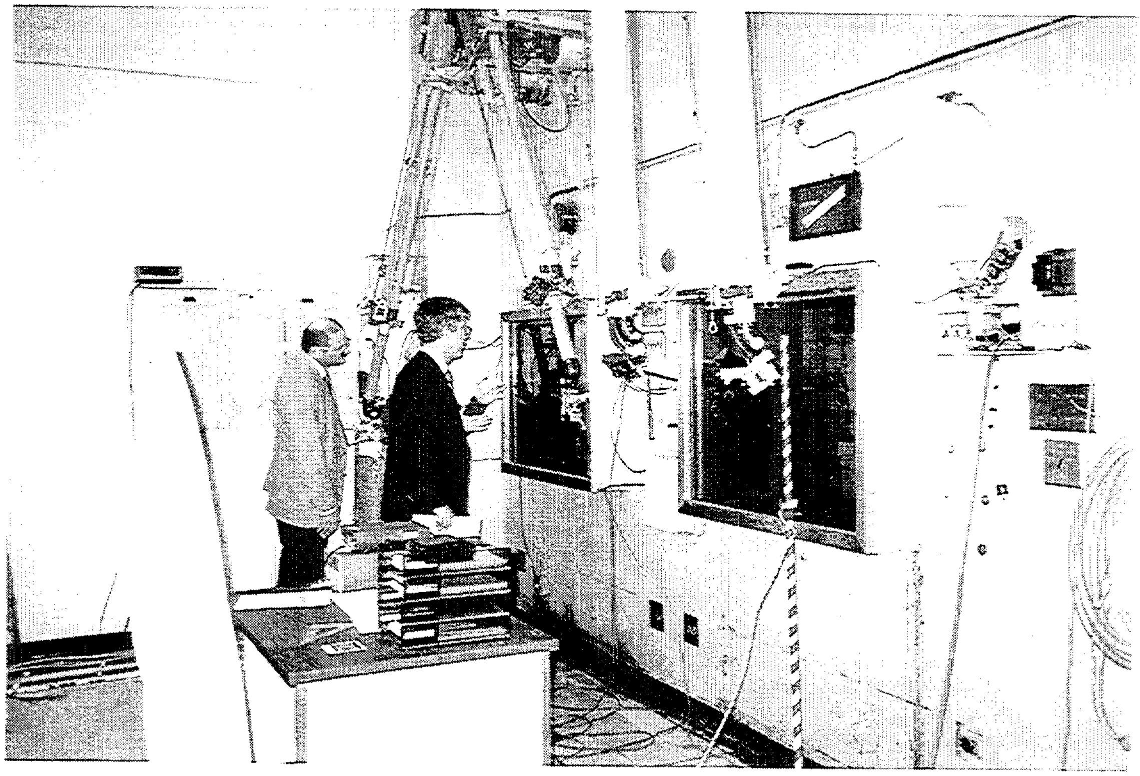

Figure 2.7 Hot cell used for irradiation of specimens at Georgia Institute of Technology

2.3 LOCA Testing Protocol

The LOCA steam/chemical spray exposure testing was performed by Wyle Laboratories in Huntsville, Alabama. All work was performed in accordance with Wyle Laboratories' LOCA test procedure under a 10 CFR 50, Appendix B Quality Assurance program.

2.3.1 LOCA Profile

As for the pre-aging parameters, the LOCA test profile was selected to be consistent with the original qualification test for the cables in performing test sequences 1 through 3, and with the generic BWR/PWR LOCA profile suggested in Appendix A to IEEE Standard 323-1974 in performing test sequences 4 through 6. While the original qualification tests were 30 to over 100 days in duration, the LOCA tests for this program were shortened to simulate only the first 7 to 10 days of the LOCA since post-LOCA duration was not an issue being addressed in this program. The qualification test profiles included either a single or double peak to maximum temperature and pressure, as specified in the qualification report for the cable. In general, a double peak LOCA profile is considered more severe and can cause more degradation to the test cables. Chemical spray was included during the steam exposure for all test sequences. The qualification reports used are listed in Table 2.2.

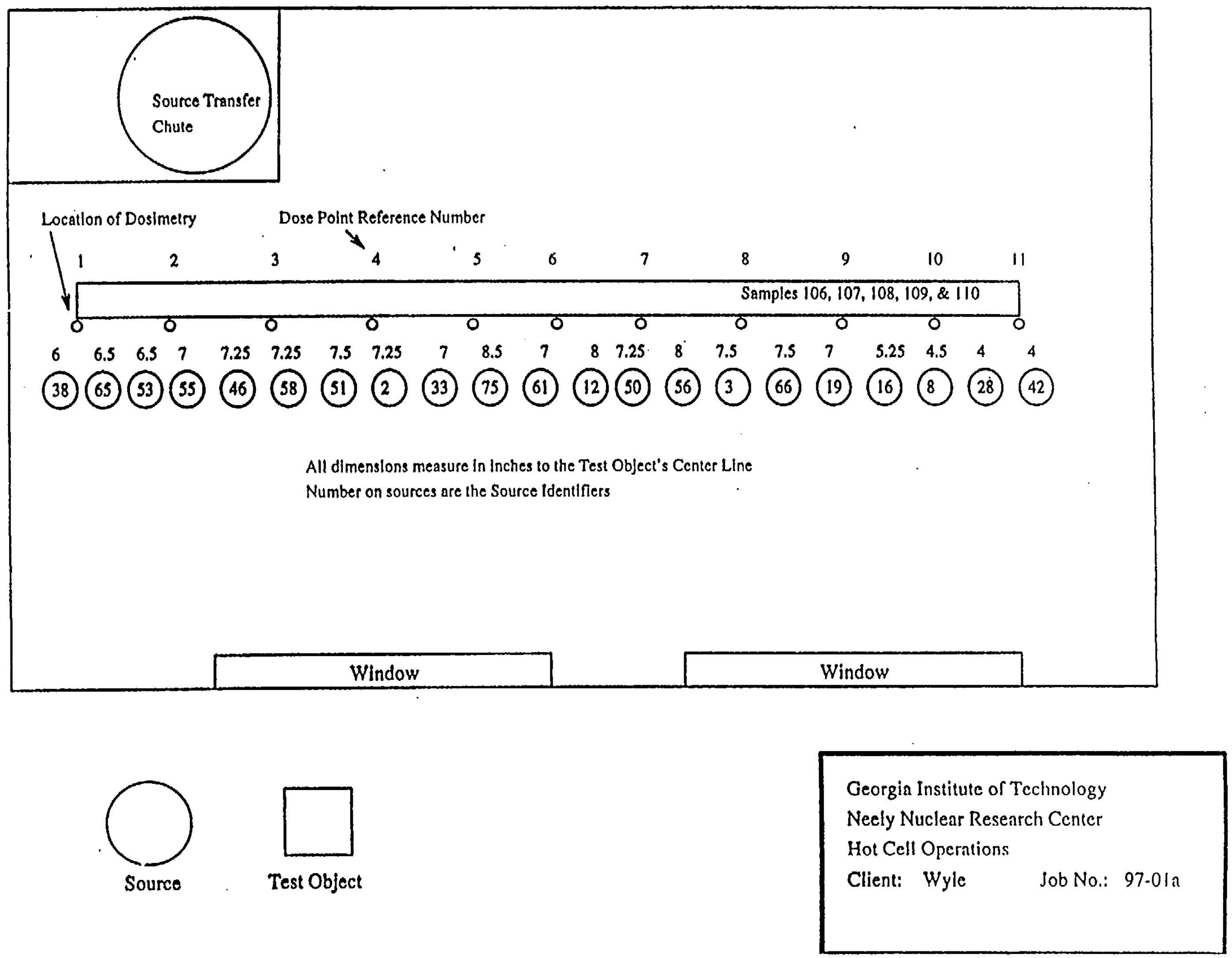

Figure 2.8 Diagram of the Hot Cell at Georgia Institute of Technology with typical arrangement of long specimens

2.3.2 LOCA Test Setup

Two different LOCA test chambers were used in this program. One LOCA test chamber was a 30-inch diameter cylindrical chamber that can accommodate the 10-foot long straight cable specimens mounted in the Unistrut® support channels. Figure 2.9 shows a side view photograph of this chamber with the specimens inside and the end bell unattached, along with a dimensional schematic of the chamber. Figure 2.10 shows the open end of the chamber with specimens loaded. This chamber was used for test sequences 1, 2 and 3. The second chamber, which was used for test sequences 4, 5, and 6, is a 59-inch diameter vessel, which was more suitable for loading mandrel mounted specimens. Figure 2.11 shows a front view of this chamber.

Thermocouples were mounted in the test chambers to monitor chamber temperature distribution in the horizontal direction and the vertical direction. The chamber temperature distribution in the area of the specimens was monitored by placing five thermocouples within one inch of the cable specimens along their length. Two other thermocouples, placed at the top and bottom of the vertical central axis of the chamber, provided the temperature distribution in the vertical direction. The average chamber temperature was calculated and recorded. The pressure in the test chamber was monitored and recorded throughout the test by means of a pressure transducer connected to the chamber.

The boilers used to provide steam to the LOCA test chamber are capable of providing saturated steam at up to 20,000 lbs/hr at 150 psig; superheat capability is also available. A chemical spray system consisting of a 140-gallon tank, recirculating pump, control valves, flow monitoring, and level instrumentation injects a chemical spray to the chamber through one or more full-cone spray nozzles.

The energized cable specimens were connected to Teflon®-insulated facility lead wires prior to being placed in the LOCA simulation chamber. This was accomplished by connecting the lead wires to the un-insulated butt-splices on the test specimens, which were previously attached during the initial specimen preparation for test sequences 1, 2 and 3. For test sequences 4, 5 and 6, the facility lead wires were connected to the pigtails that were installed prior to accelerated aging. Raychem® Nuclear Grade Heat Shrink was finally applied to all of the splice areas. The specimens were then placed in the LOCA test chamber. Typically, the facility lead wires exited the LOCA chamber through fittings that were sealed with 3M® Scotchcast potting compound[1]. The nuclear grade splices attaching the facility lead wire to the test specimen were exposed to the internal environment of the chamber and were not part of the chamber's pressure boundary. Figure 2.12 shows the typical Wyle penetrations on the end of the LOCA chamber with the facility lead wires extending through them.

2.3.3 LOCA Test Procedure

Prior to initiating the LOCA transients, the test chamber was preheated to a temperature of approximately 140°F (60°C) and held for approximately 30 to 60 minutes to allow temperatures to stabilize. Following preheat, saturated steam was admitted to the test chamber and was controlled to simulate the LOCA profile desired. The initial transients were continued until the specified peak conditions were reached, after which conditions were held for approximately 3 hours. After completing the transients, the LOCA chamber temperature and pressure enveloped the LOCA test profile specified. The total duration of the LOCA exposure was 7 to 10 days.

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[1] Several of the energized specimens in test 4 exited directly through the LOCA chamber with no facility lead wire attached, and Swagelock penetration assemblies were installed (see discussion of LOCA test 4).

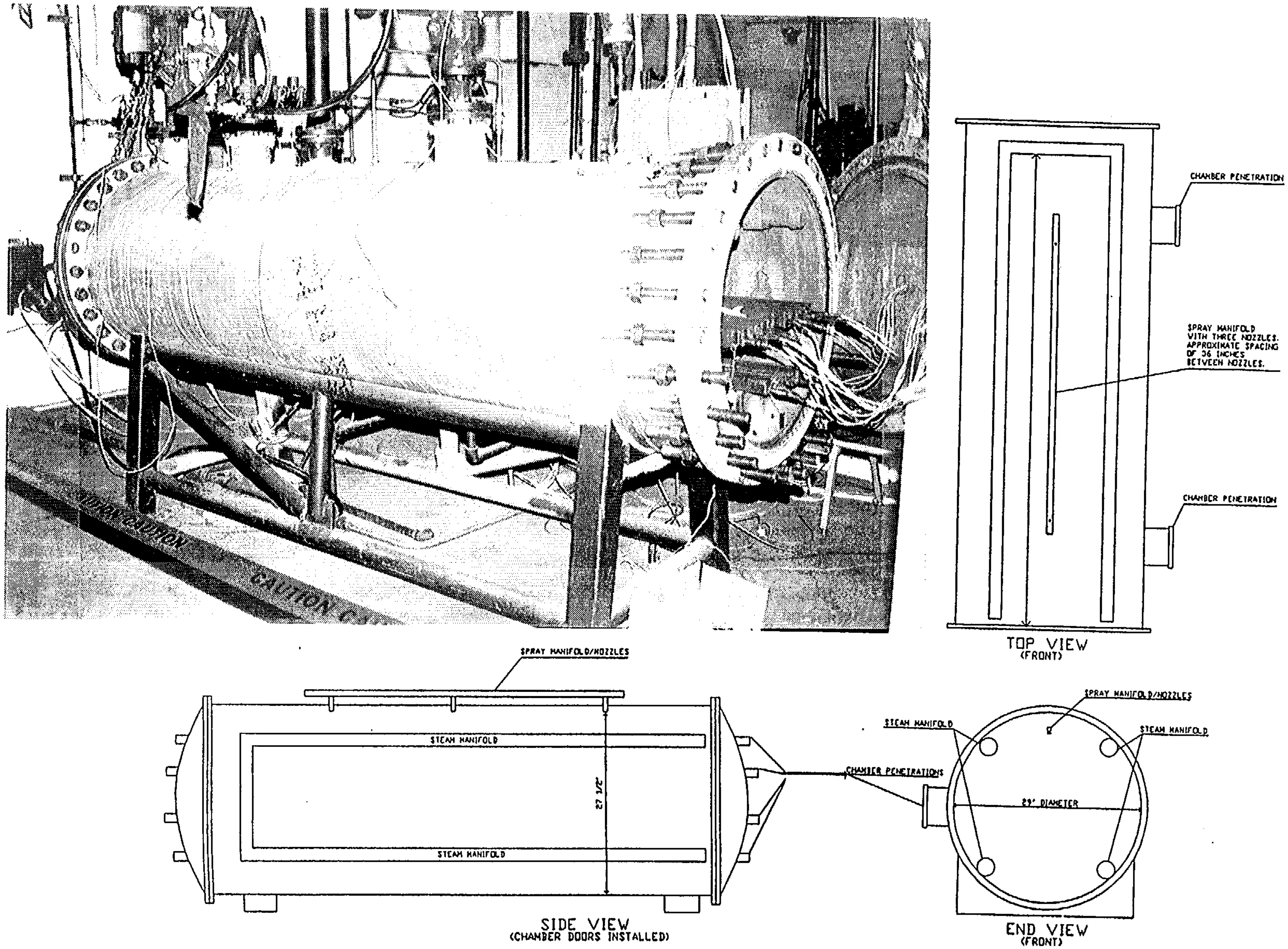

Figure 2.9 Photograph and diagram of the LOCA test chamber at Wyle Laboratories used for Tests 1, 2 and 3

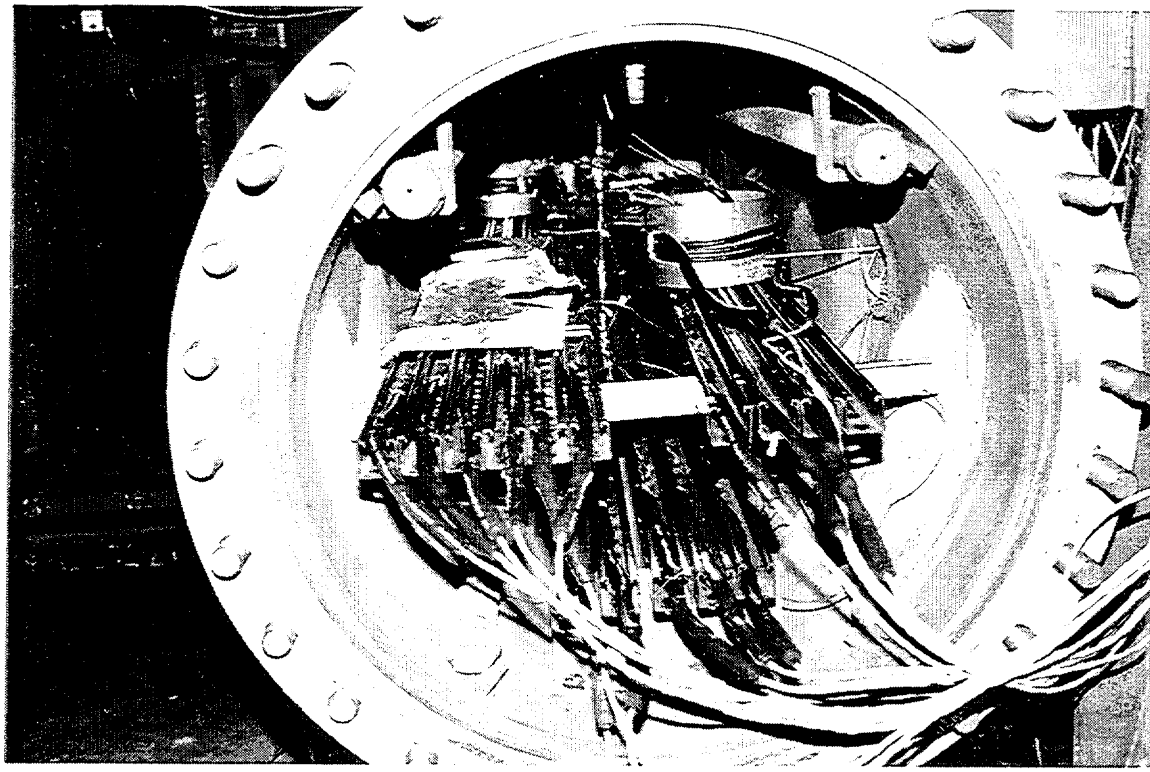

Figure 2.10 End view of the LOCA test chamber with the cable specimens loaded prior to testing

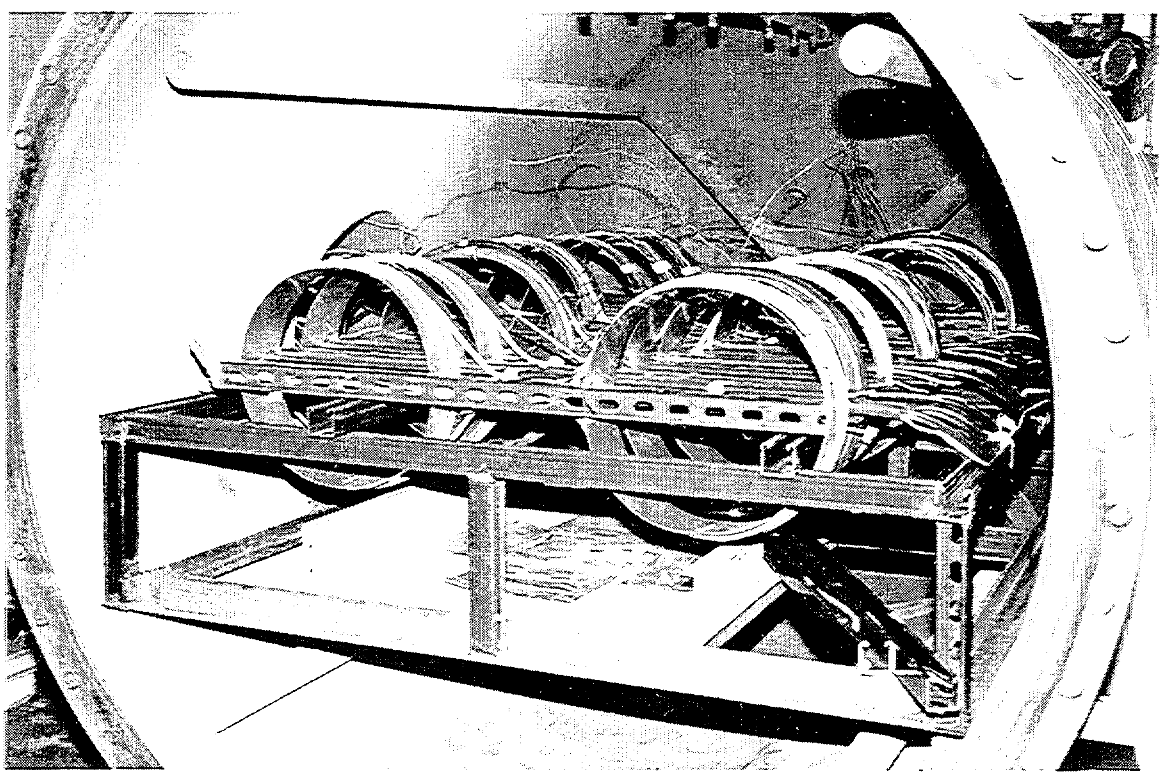

Figure 2.11 End view of large diameter LOCA chamber used for tests 4, 5 and 6

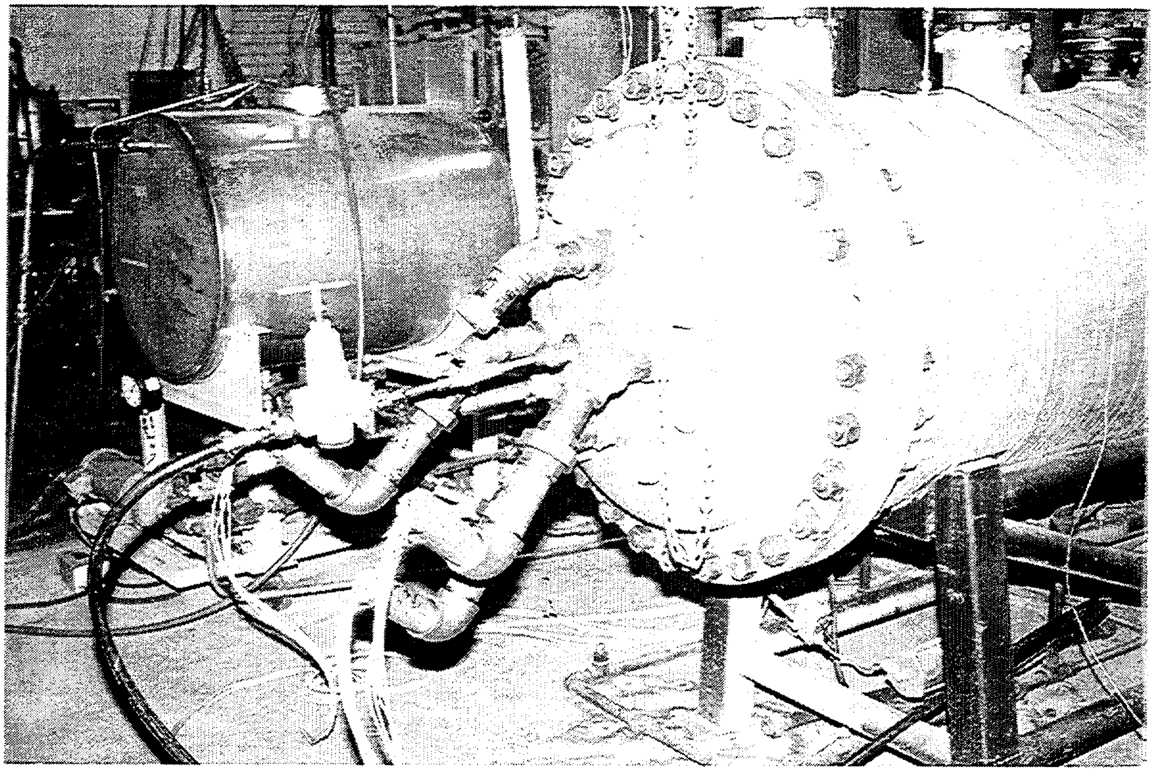

Figure 2.12 Facility lead wires extending through the penetrations on the end of the LOCA test chamber

Once the LOCA chamber pressure had decreased to approximately 32 psig, the chemical spray was initiated. The chemical spray flow rate was approximately 0.15 gpm per ft^2 of projected area[2], as recommended by IEEE Standard 323-1974. Chemical spray solution and steam condensate were captured and recirculated to the spray header for 24 hours, after which the flow was terminated. The chemical spray flow was monitored and recorded during the chemical spray portion of the exposure. The initial chemical spray solution consisted of deionized water with 0.28 molar H_3BO_3 (3000 ppm Boron), 0.064 molar $Na_2S_2O_3$, and NaOH to make a pH of 10.6 at the start of the spray test. Dilution of the recirculated chemical spray solution by condensate lowered the pH to approximately 8.5 by the end of spray test.

2.3.4 Functional Performance Monitoring

The long specimens (except the sacrificial specimens that were cut up for archiving at each hold point) were individually powered and loaded as detailed in Figures 2.13 and 2.14 for the Unistrut® mounted and mandrel mounted specimens, respectively. Each of these specimens was powered separately with 28 Vdc. A pressure transmitter was connected to

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[2] The "projected area" for determination of the chemical spray flow rate is the area projected by the test cables in a plane perpendicular to the spray direction. For the tests reported herein, the projected area was approximately 26.7 ft^2 resulting in a chemical spray flow rate of 4 gpm.

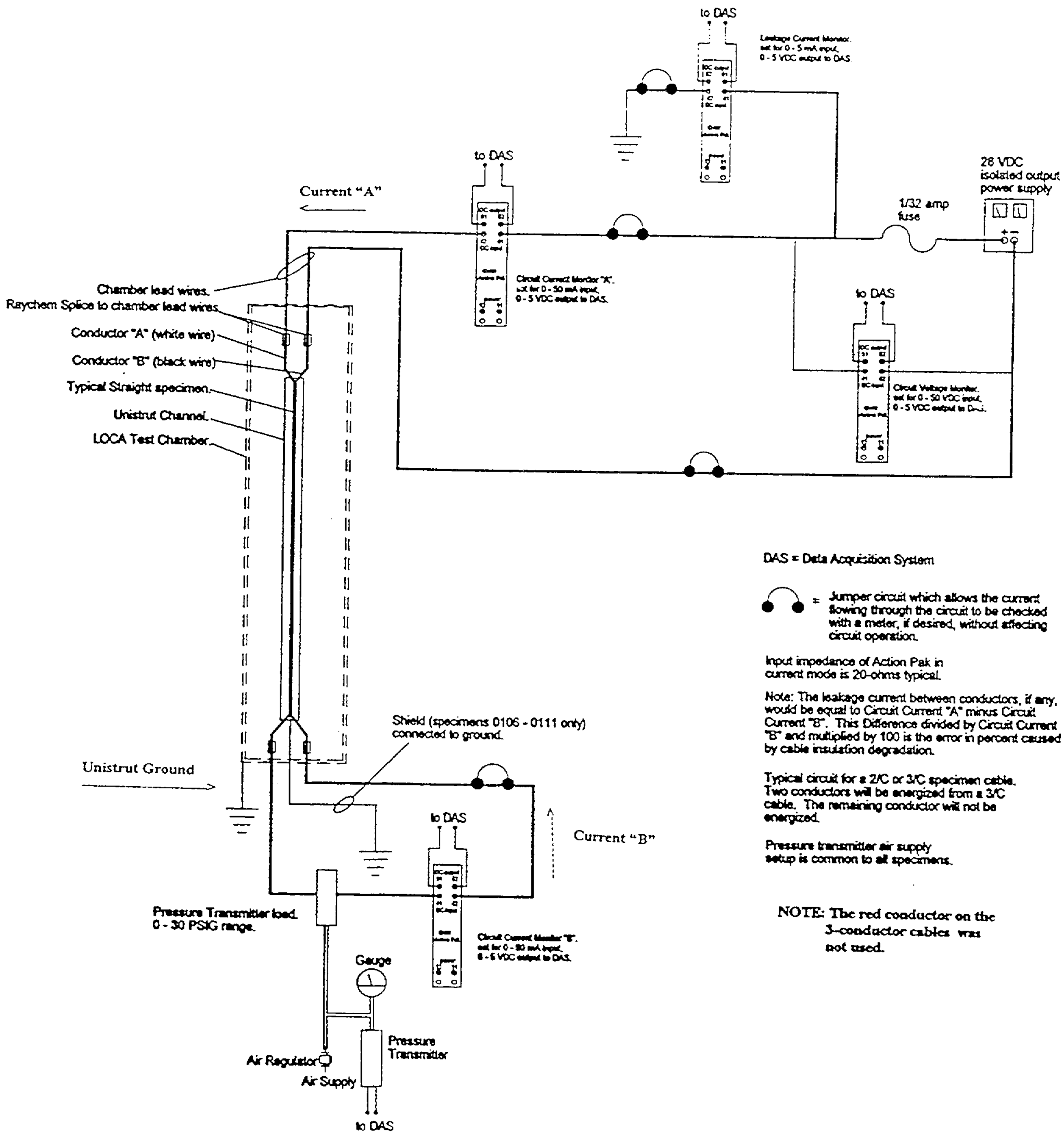

Figure 2.13 Monitoring circuit diagram for straight Unistrut® mounted specimens

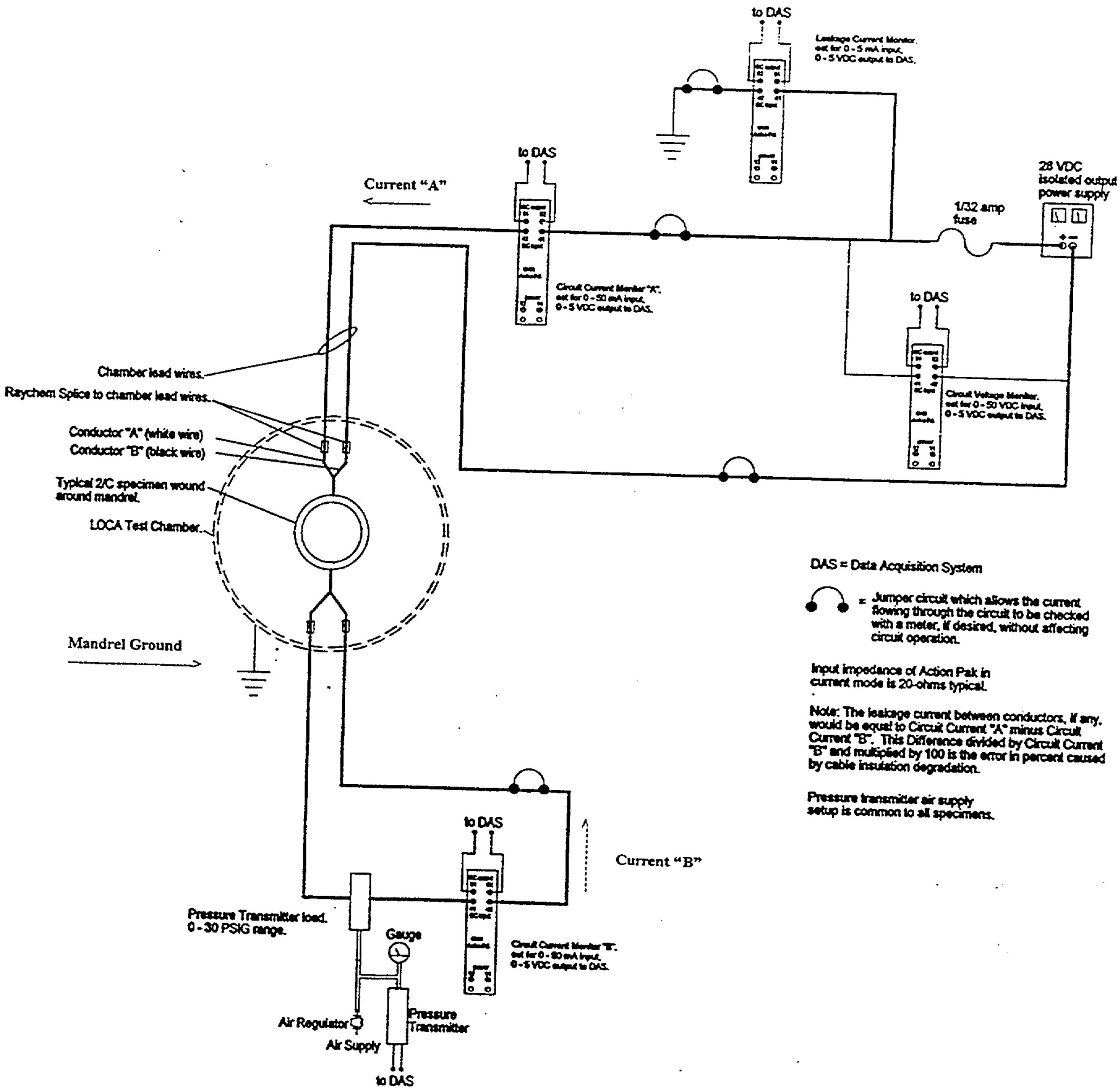

Figure 2.14 Monitoring circuit diagram for mandrel mounted specimens

the chamber leads of each long cable specimen to simulate a 4-20 mA instrumentation loop circuit. The pressure source tank and header with sixteen pressure transmitters can be seen under the test bench in Figure 2.15. The short specimens in the stainless steel baskets were not powered since they were to be used for materials condition monitoring.

Each of the powered specimens was monitored for applied voltage, circuit current, and leakage current throughout the LOCA steam exposure simulation. Circuit current was monitored for each conductor to facilitate troubleshooting. These currents are identified as "A"and "B" on the circuit diagram. Nominal values for the initial healthy circuits are 28 volts dc applied voltage, 12.0 milliamps for "A" and "B" currents, and 0 milliamps for leakage current. These circuit values correspond to the pressure source being maintained at approximately 15 psig. The test specimen powering and monitoring equipment are shown in Figure 2.16.

2.3.5 Post LOCA Inspection and Voltage-Withstand Test

Upon completion of each of the LOCA steam/chemical spray exposures, the test chamber was opened and the specimens were inspected. The specimens were then removed from the test chamber and post-LOCA condition monitoring tests were performed. Following these CM tests, the long cable specimens were submerged in tap water at room temperature while still mounted in their Unistrut® or mandrel, and a voltage withstand test was performed at 80 Vac/mil of insulation thickness, in accordance with IEEE Standard 383-1974. For cables with, as well as without an individual jacket on top of the insulation, only the insulation thickness (30 mils) was considered in determining the test voltage. The one exception was the Samuel Moore cables for which both the thickness of the insulation (20 mils) plus the thickness of the individual jacket (10 mils) were used to be consistent with the original qualification test. Therefore, a test voltage of 2,400 volts was used for all test specimens.

In performing this test, the test voltage was initially set to zero volts, then was gradually increased to 2,400 volts. The acceptance criteria used was for the test specimen to hold 2,400 volts for five minutes without exceeding a leakage current of 10 milliamps, which was the maximum leakage current measurable with the test equipment used. If the leakage current exceeded 10 mA during the rise to 2,400 volts, or during the hold period, the test was terminated and the specimen was considered failed. The test setup for performing the submerged voltage withstand test on the straight specimens is shown in Figure 2.17.

2.4 Condition Monitoring (CM) Protocol

2.4.1 CM Tests Evaluated

As previously mentioned, two of the issues being studied in this program are related to condition monitoring techniques for installed low-voltage instrumentation and control electric cables. To address these issues, several promising CM techniques were selected for evaluation in this program. Each of these techniques was performed at prescribed times throughout the testing to obtain data for evaluation. The selection process and planned CM evaluation approach are described in detail in the BNL Condition Monitoring Research Plan, BNL Technical Report TR-6168/69-03-95 (Lee, 1996). The CM tests evaluated in this program are listed below.

Mechanical CM Tests

- Elongation-at-break
- Indenter (Compressive Modulus)

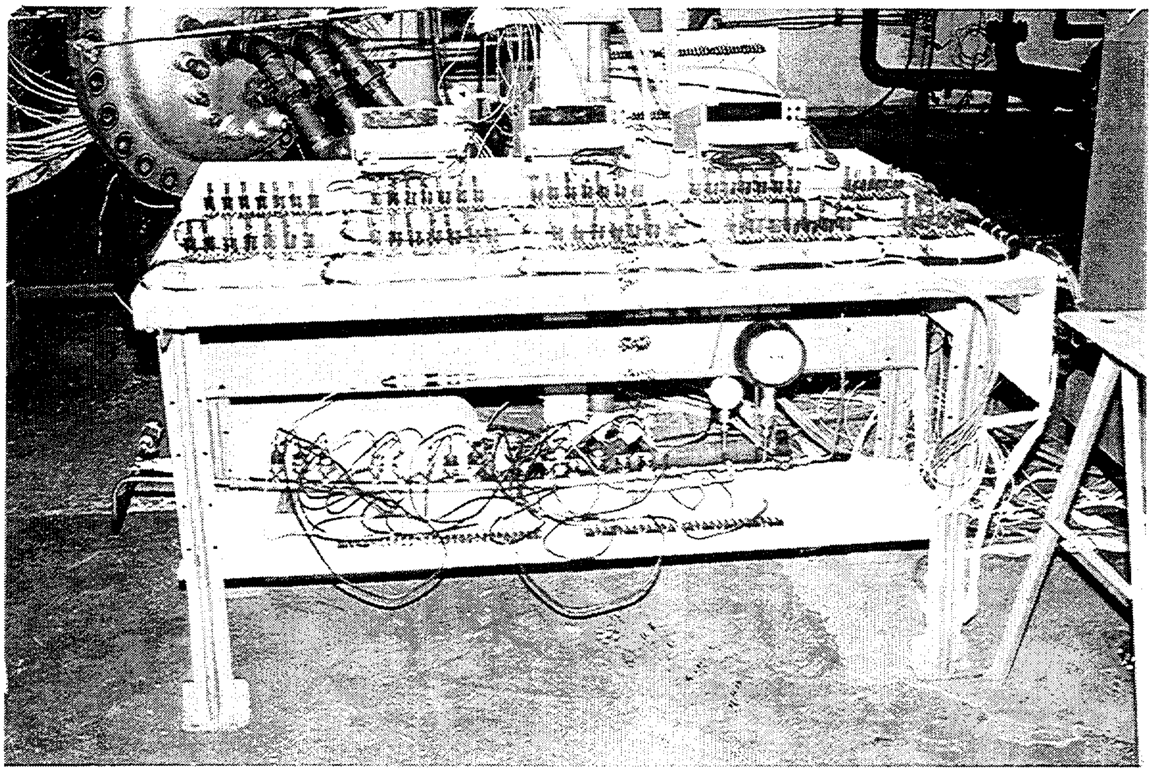

Figure 2.15 Test bench with hard-wired monitoring circuits and simulated pressure instrumentation loops

Chemical CM Tests

- Oxidation Induction Time
- Oxidation Induction Temperature
- Fourier Transform Infrared Spectroscopy

Electrical CM Tests

- AC Impedance/Dielectric Loss
- Insulation Resistance

Simple/Inexpensive CM Tests

- Visual Inspection
- Hardness

2.4.2 Condition Monitoring Points

Periodically throughout the test sequence, testing was halted and condition monitoring data were obtained. These data were used to determine the condition of the test specimens at each stage of the test and to evaluate the effectiveness of the different CM techniques. Each of these hold points, identified by a capital letter, corresponds to a different condition for the cable specimens. The test results reported herein are presented based on these condition monitoring (CM) points, which are defined in Table 2.4.

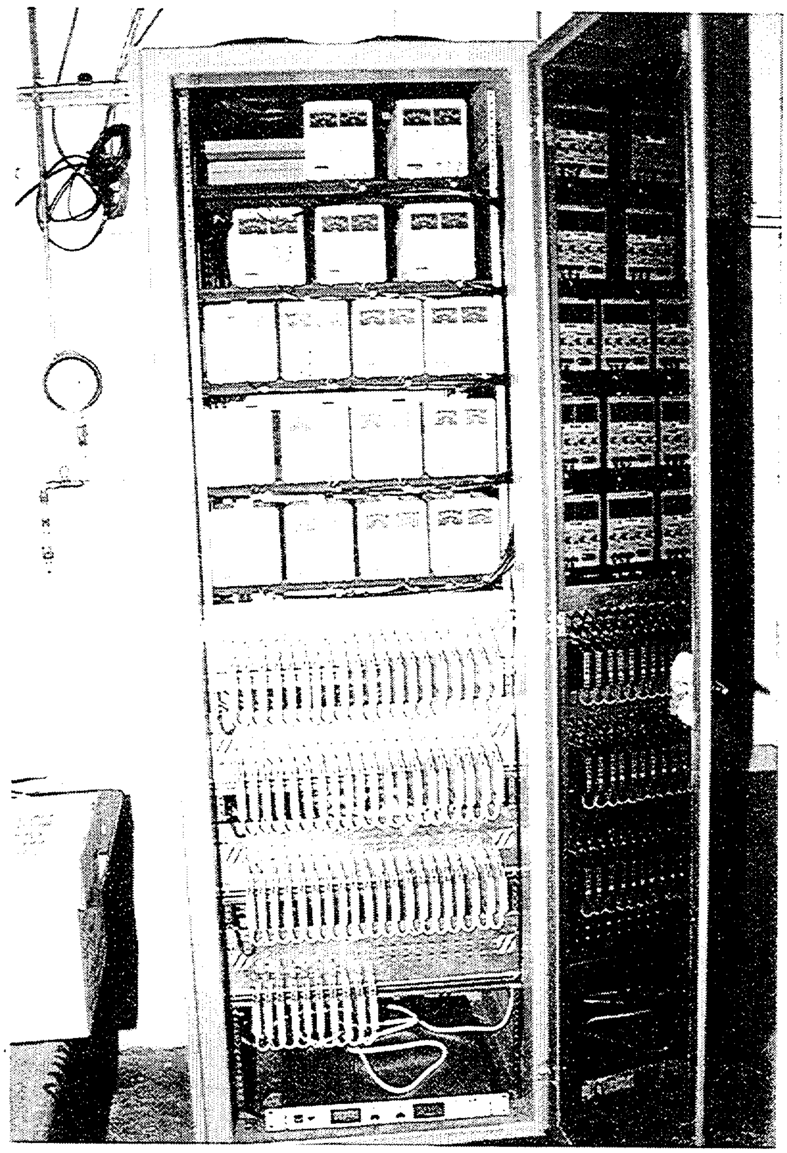

Figure 2.16 Specimen powering and monitoring equipment

Typical specimen CM hold points in test sequences 1, 2, and 3 were A-B-D-F-G-H for specimens that were being tested to match naturally aged cables, or A-C-E-F-G-H for specimens that were being tested to simulate a specific service age. The CM hold points for the control specimens and the naturally aged specimens were A-F-G-H, since no accelerated aging was applied to these specimens.

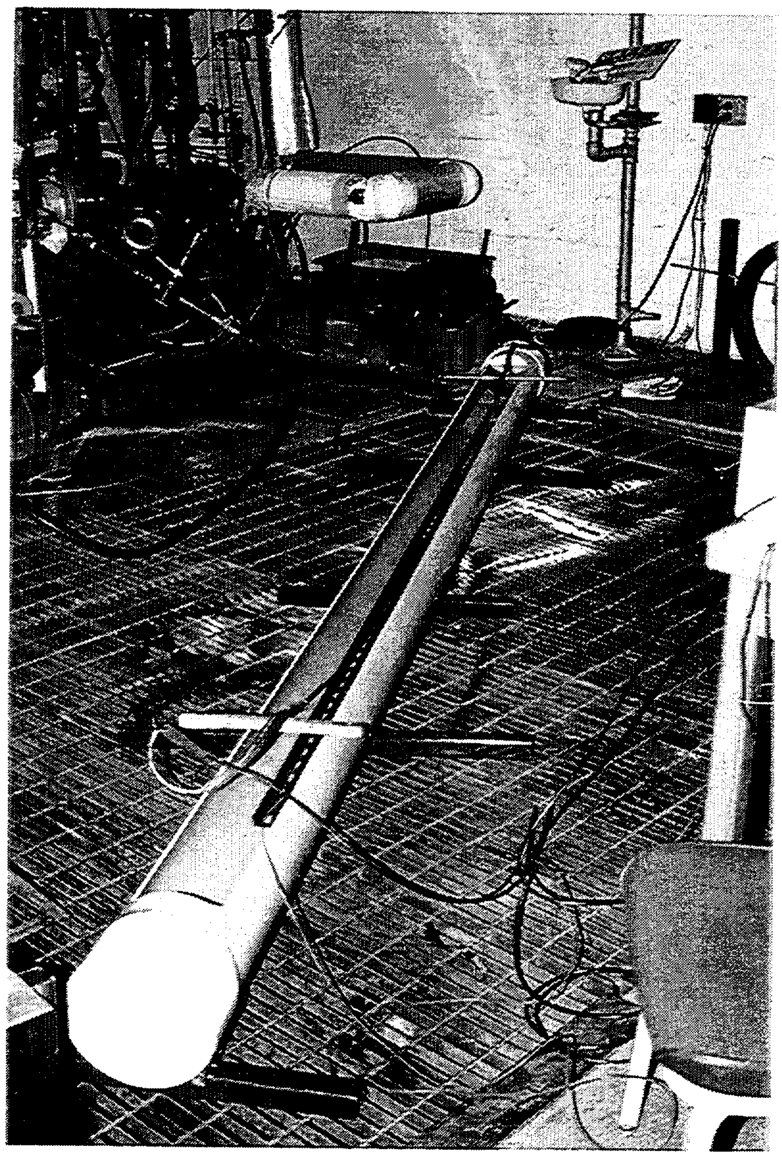

Figure 2.17 Test setup for the submerged voltage withstand test

Table 2.4 Definition of lettered CM hold points

CM Hold Point	Condition of Cable Specimens	Test Sequence
A	Baseline as-received condition	All
B	Completion of thermal aging to match condition of naturally aged cable specimens	1, 2, 3
	Completion of thermal aging to simulate 20 years of qualified life	4, 5
	Completion of thermal aging to simulate 40 years of qualified life	6
C	Completion of thermal aging to simulate 20 years of qualified life	1, 2
	Completion of thermal aging to simulate 40 years of qualified life	3, 4, 5
	Completion of thermal aging to simulate 60 years of qualified life	6
D	Completion of thermal and radiation aging to match condition of naturally aged cable specimens	1, 2, 3
	Completion of thermal and radiation aging to simulate 20 years of qualified life	4, 5
E	Completion of thermal and radiation aging to simulate 20 years of qualified life	1, 2
	Completion of thermal and radiation aging to simulate 40 years of qualified life	3, 4, 5
	Completion of thermal and radiation aging to simulate 60 years of qualified life	6
F	Completion of 75 Mrad of the simulated LOCA accident radiation	All
G	Completion of 150 Mrad of the simulated LOCA accident radiation	All
H	Completion of steam/chemical spray LOCA exposure simulation	All

3. RESULTS OF ACCELERATED AGING AND LOCA TESTING

This section presents the results of the LOCA testing for the cable specimens in all six test sequences. For each test sequence, the specimens are described, along with the results of the accelerated aging and LOCA radiation exposure. Next, specimen performance during the LOCA steam test is discussed. Finally, the post-LOCA inspection and voltage withstand test results are presented. The cable specimens in each test sequence are grouped according to the aging they received prior to LOCA testing. For ease in referencing specific cable samples in this report, the groups are referred to as Group X.Y, where X is the test sequence number and Y is the group in that test. For example, Group 1.2 refers to the Group 2 specimens in test sequence 1.

3.1 Test Sequence 1: Cross-Linked Polyethylene (XLPE) Insulated Cables Aged to 20 Years

3.1.1 Test Objectives

The objectives of this test sequence were the following:

- To validate the accelerated aging, LOCA testing and condition monitoring procedures developed for this program,
- To obtain LOCA performance data on XLPE insulated cables with accelerated aging to an equivalent qualified life of 20 years,
- To obtain LOCA performance data on naturally aged XLPE insulated cables,
- To compare the condition of naturally aged XLPE insulated cable with similar cable subjected to accelerated aging to simulate an equivalent amount of service aging, and
- To obtain data for evaluating condition monitoring techniques on XLPE insulated cable

3.1.2 Description of Test Specimens

The source cable samples used for the unaged specimens in test sequence 1 are PNI85RB191 and PNI79RB188, both of which have irradiation cross-linked polyethylene insulation with a Neoprene® jacket manufactured by Rockbestos, with the trade name "Firewall® III." These cables were obtained from warehouse stock from the same decommissioned plant as the naturally aged cables. The PNI85RB191 source cable contained 3 XLPE insulated #16 AWG stranded copper conductors with a bare, stranded, tinned copper drain wire, while the PNI79RB188 source contained 2 XLPE insulated #14 AWG copper conductors with no drain wire. Both source cables had 30 mils of XLPE insulation on the individual conductors and a 45 mil overall Neoprene® jacket.

The source cable sample for the naturally aged cable specimen was PAP86RB267, which is also a 3-conductor #16 AWG with a drain wire Rockbestos Firewall® III cable with the same jacket and insulation material specifications as described above. This naturally aged cable was approximately 10 years old at the time of testing, and was obtained from a decommissioned PWR plant. It was located in a steam generator compartment during its service, and was used in a temperature detector circuit. The detector was located at the bottom of the steam generator, and the circuit ran vertically up the compartment wall. Historical radiation work permit information was obtained from the plant files to provide the most accurate operational radiological survey information in the area of this cable. In the lower portion of the compartment, the radiation dose rate was approximately 50 rad/hr during operation, and decreased vertically to the top of the compartment. Based on this information, a dose rate of approximately 15 rad/hr near the top of the compartment was calculated. The temperature in the compartment varied from 70°F (21°C) to a maximum of approximately 110°F (43°C) during full power operation. The entire length of cable in the circuit was obtained for this program. A section of cable from the circuit at the top of the compartment was used in test sequence 1. The cable from the lower portion of the circuit, which experienced a higher dose rate, was used in test sequence 3.

Seventeen long (10-foot) cable specimens were prepared for this test sequence, as presented in Table 3.1. Fifteen of the long specimens were mounted in straight Unistrut® channels approximately 10 feet long to simulate a typical plant installation in a cable tray. Two of the long specimens were mounted on stainless steel mandrels approximately 10 inches in diameter to simulate the test configuration during qualification testing. One Unistrut® mounted specimen was used for archiving purposes. The remaining 14 Unistrut® mounted specimens, along with the two mandrel mounted specimens, were energized during the LOCA steam exposure to obtain circuit performance data.

In addition to the long specimens, 16 baskets containing 6-inch specimens of both jacket and insulation materials were prepared for destructive testing at the various hold points. Also, one 2-foot specimen was prepared from the same cable sample for each of the seventeen long specimens, and followed the "parent" long specimen through each phase of aging and testing. These 2-foot specimens were used to perform indenter testing to prevent damaging the long specimen.

3.1.3 Accelerated Aging Parameters

The specimens in test sequence 1 can be grouped according to the accelerated aging they received. Group 1.1 contained five 10-foot specimens, which were tested without any accelerated service aging. Group 1.2 contained five specimens, which were aged to simulate the service conditions experienced by the naturally aged specimen in Group 1.3. Group 1.3 included one specimen, which was prepared from the naturally aged sample, and was tested without any accelerated service aging. Group 1.4 included five specimens, which received accelerated aging to simulate 20 years of qualified life prior to testing. In addition, one specimen was aged to the equivalent of 20 years of qualified life, similar to the specimens in Group 1.4, for use as an archive specimen. After each pre-aging step, a 2-foot section of the archive specimen was cut off, tagged and placed in storage to document the condition of the test specimen at each stage of the test sequence. The four aging groups for test sequence 1 are summarized as follows:

Group 1.1: No accelerated aging (control specimens),
Group 1.2: Accelerated aging to simulate the exposure of the naturally aged cable in Group 1.3,
Group 1.3: Naturally aged 10-year old cable (no accelerated aging), and
Group 1.4: Accelerated aging to simulate 20 years of qualified life

The accelerated aging applied to the cable specimens in test sequence 1 was based on Rockbestos qualification report QR #1806, which was the qualification basis used by the plant from which the cable was obtained. For the original qualification test, as described in report QR #1806, the Rockbestos Firewall® III cables were qualified for 40 years of service at a service temperature of 194°F (90°C). The accelerated aging used in this qualification included thermal aging at 302°F (150°C) for 1300 hours[3]. After thermal aging, the cables were subjected to a radiation exposure of 50 Mrad at a dose rate of 1.0 Mrad per hour to simulate service radiation aging. Following accelerated service aging, the cables were exposed to an additional 150 Mrad of radiation, bringing the total integrated dose to 200 Mrad, followed by a LOCA steam profile while energized with rated voltage and current to simulate service under LOCA conditions. The steam profile was based on that recommended in IEEE Standard 323-1974 for combined PWR/BWR plants. After exposure to LOCA conditions, the cables were straightened and recoiled with a diameter 40 times their outside diameter and immersed in tap water at room temperature. While immersed, the samples were subjected to a voltage withstand test at a potential of 80 volts ac per mil of insulation thickness (2,400 Vac for 30 mil insulation). To further demonstrate serviceability after a LOCA, following the post LOCA submerged voltage withstand test the cables were exposed to an environment of 100 percent relative humidity at 200°F (93°C) and ambient pressure for 365 days. Following this exposure, the cables were again straightened and recoiled with an inside diameter of 40 times their outside diameter, and the submerged voltage withstand test was repeated. The post-LOCA testing for the original qualification was not duplicated in the test program reported herein.

For the test specimens in Group 1.2, the Arrhenius model using an activation energy of 1.33 eV predicted that thermal aging at 302°F (150°C) would have required an aging duration of only several minutes due to the minimal amount of aging required to simulate the conditions experienced by the Group 1.3 naturally aged test specimen. Therefore, the aging temperature was lowered to 248°F (120°C) to provide a more controllable duration. The total integrated radiation dose was calculated to match that to which the naturally aged cable in Group 1.3 was exposed. For the test specimens

[3] The 1300 hour thermal aging time was arrived at using the Arrhenius model with an activation energy of 1.33 eV to calculate an aging duration of 850 hours. A margin of 450 hours was then added to arrive at 1300 hours. No basis for determining the 450 hour margin is provided in the report.

Table 3.1 Description of specimens in Test Sequence 1

Group	Specimen ID No.	Sample ID No.	Configuration [a]	Manufacturer [a]	Insulation Material [a]	Jacket Material [a]	No. of Conductors	Wire Gauge (AWG)	Cable Diameter (in.)	Cable Type [a]	Insulation Thickness (mils)
1.1	0101	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.38	I	30
	0102	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.38	I	30
	0118 [c]	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.38	I	30
	0104	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.38	I	30
	0105	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.38	I	30
1.2	0106	PNI85RB191	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
	0107	PNI85RB191	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
	0108	PNI85RB191	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
	0109	PNI85RB191	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
	0110	PNI85RB191	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
1.3	0111	PAP86RB267	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
1.4	0112	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.38	I	30
	0113	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.38	I	30
	0114	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.38	I	30
	0115	PNI79RB188	10 FT - MAN	RB FW-III	XLPE	NEO	2	14	0.38	I	30
	0116	PNI79RB188	10 FT - MAN	RB FW-III	XLPE	NEO	2	14	0.38	I	30
Archive	0117 [b]	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.38	I	30

(a) STR=Straight, MAN=Mandrel, RB FW-III=Rockbestos Firewall® III, XLPE=Cross-linked Polyethylene, NEO=Neoprene®, I=Instrumentation

(b) This specimen was included for archiving purposes and was not energized during the LOCA steam exposure. A 2-foot section was removed at each hold point and placed in storage.

(c) Specimen 0103 was found to be damaged in the baseline visual inspection and was replaced with specimen 0118 prior to pre-aging and LOCA testing.

in Group 1.4, 20 years of qualified life was simulated using half of the thermal aging duration and total integrated radiation dose used in the original qualification. The actual aging conditions received by the specimens in test sequence 1are summarized in Table 3.2. Calculations for determining the accelerated aging conditions for test sequence 1 are provided in Appendix A.

During the pre-aging of the specimens for test sequence 1, two anomalies occurred. The first occurred during thermal aging of the Group 1.4 specimens, in which the temperature controller on the aging oven failed resulting in the aging temperature rising to 310°F (154°C) for approximately 53 minutes. The specified temperature was 302°F (150°C) (+5/-0°F); therefore, the maximum allowable temperature was 307°F (153°C). It was determined that the over-temperature condition would not cause any significant impact on the test results, therefore, the total thermal aging duration was adjusted to account for this over-temperature period and the testing was resumed. This is documented in notice of Anomaly No. 1 in Appendix B.

The second anomaly occurred during radiation aging of the Group 1.2 long specimens, in which the dose rate achieved was lower than specified due to limitations in the number of sources allowed in the hot cell at one time. The specified dose rate was 0.5 Mrad/hr (+0/-20 percent); however,the maximum achievable dose rate for these specimens was 0.334 Mrad/hr., which is 33 percent lower than the specified nominal dose rate. It was determined that the reduced dose rate would not significantly impact the test results, therefore, the testing was resumed at the lower dose rate. The dose rate achieved for the Group 1.2 baskets was 0.420 Mrad/hr, which was within the acceptable range. This is documented in notice of Anomaly No. 2 in Appendix B.

3.1.4 Results of Accelerated Aging

Visual examination and baseline elongation-at-break measurements confirmed that all cable specimens were initially in excellent condition. No discoloring or cracking was evident in either the jacket or insulation for any of the specimens. Average elongation-at-break values for the unused cables ranged from approximately 454 percent to 535 percent for the Neoprene® jackets, and from 379 percent to 622 percent for the XLPE insulation, as shown in Table 3.3. Similarly, for the naturally aged cable, EAB values were approximately 521 percent for the jacket and 412 percent for the insulation, indicating excellent ductility for both materials. Baseline results for other CM tests are discussed in Volume 2 of this report.

Following thermal aging, the Group 1.2 specimens (aged to match the naturally aged cable) showed a slight change in condition. Some yellowing of the white insulation was noted; however, no cracking was noted in either the jackets or insulation. Average elongation-at-break values for the jackets decreased slightly from a baseline value of 454 percent to a post-thermal aging value of 428 percent; however, they retained excellent ductility. The EAB values for the white insulation showed a slight increase from its baseline value of 379 percent to a post-thermal aging value of 427 percent, indicating an improvement in ductility. Similar results were found for the black and red insulation.

The post-thermal aging appearance of the Group 1.4 cable outer jackets (aged to 20 years) was extremely poor. The Neoprene® jackets were brittle with numerous circumferential cracks noted along the entire length of the specimens. Also, the jackets were discolored with areas of whitish/grey noted, and surface contamination was evident in the form of white powdery spots, possibly from additives that had been driven out of the material by the heat and deposited on the surface. EAB values for the jackets were unobtainable due to the extreme brittleness of the material, indicating no ductility remaining. The insulation also was degraded, however, not as severely as the jackets. The white insulation appeared dark brown, as if burnt. No cracking was noted in the insulation. EAB values for the insulation were less than 5 percent, indicating very little ductility remaining.

The service radiation exposures caused little change in the condition of the Group 1.2 and Group 1.4 specimens. For the Group 1.2 specimens, the jacket and insulation EAB decreased slightly to approximately 421 percent and 377 percent, respectively. The Group 1.4 specimens were already brittle from the thermal aging, as previously described.

Table 3.2 Actual accelerated aging conditions received by the specimens in Test Sequence 1

Group	Thermal Aging		Service Radiation [a]		LOCA Radiation [a, b]	
	Temperature (°F/°C)	Duration (hours)	Total Integrated Dose (Mrad)	Dose Rate (Mrad/hr.)	Total Integrated Dose (Mrad)	Dose Rate (Mrad/hr.)
1.1	-	None	None	-	Phase 1: 78.4 Phase 2: 78.6	Phase 1: 0.87 Phase 2: 0.87
1.2	248°F (120°C)	2.86	0.63	0.38 [d]		
1.3	-	None	None	-		
1.4	302°F (150°C)	648.5 [c]	26.1	0.48		

(a) Radiation exposures for long specimens and/or basket specimens in the same group were performed in multiple runs due to restrictions on the number of sources allowed in the hot cell at one time. Therefore, the radiation doses and dose rates reported are averages for all runs.

(b) The specified LOCA radiation exposure was the same for all groups. It was performed in two separate phases to allow condition monitoring measurements to be taken at the midpoint.

(c) During thermal aging, the temperature controller on the aging oven failed resulting in the aging temperature rising to 310°F (154°C) for approximately 53 minutes. The total thermal aging duration was adjusted to account for this over-temperature period. This is documented in notice of Anomaly No. 1 in Appendix B.

(d) During irradiation of the long specimens in Group 1.2, the maximum dose rate achievable was 0.334 Mrad/hr, which is below the minimum specified dose rate. The basket dose rate was 0.420 Mrad/hr., which was within the acceptable range. This is documented in notice of Anomaly No. 2 in Appendix B.

Table 3.3 Average elongation-at-break values for the specimens in Test Sequence 1

Group	Cable	Average elongation-at-break at each CM Point (%)											
		Baseline No Aging		After Thermal Service Aging		After Radiation Service Aging		After Half LOCA Radiation		After Full LOCA Radiation		After LOCA Steam Exposure	
		Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)
1.1 (0 yr.)	Rockbestos PNI79RB188	535	622	NA	NA	NA	NA	233	294	88	111	31	120
1.2 (match Group 1.3)	Rockbestos PNI85RB191	454	379	428	427	421	377	97	241	53	125	33	160
1.3 (naturally aged 10 yr.)	Rockbestos PAP86RB267	521	412	NA	NA	NA	NA	73	186	44	74	41	166
1.4 (20 yr.)	Rockbestos PNI79RB188	535	622	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5

(a) EAB values are for white insulation.
NA = Not applicable

In summary, after completion of the accelerated aging, all of the Groups 1.1, 1.2 and 1.3 specimens appeared to be in good physical condition with good ductility and no cracking evident in any of the specimens. The Group 1.4 specimens appeared to be severely degraded with extensive cracking in the outer jackets; however, no cracking was evident in the insulation. Insulation resistance measurements indicated that electrically, the insulation on all specimens was in acceptable condition, including the specimens in Group 1.4. Figure 3.1 shows a typical specimen after thermal aging to the equivalent of 20 years of qualified life. Figure 3.2 shows six of the cable specimens in Unistruts® loaded in the LOCA test chamber after service and LOCA radiation exposure.

3.1.5 LOCA Conditions Simulated

The LOCA conditions simulated included exposure to 150 Mrad of accident radiation , followed by exposure to steam at high temperature and pressure. The accident radiation exposure was performed after completion of the service aging and prior to the steam exposure.

Following accident irradiation, the specimens were subjected to a high temperature and pressure steam exposure. The test chamber temperature/pressure profile for the LOCA steam exposure in test sequence 1 was obtained from Rockbestos report QR #1806, as previously discussed. This is a "double-peak" profile, meaning that the rapid increase in test chamber temperature and pressure to peak conditions is performed twice. The specified temperature and pressure were obtained by controlling the amount of steam entering the test chamber. Figure 3.3 presents the profile used in LOCA Test 1.

In the original qualification test documented in Rockbestos report QR #1806, the LOCA steam exposure test duration was 30 days. Since post-LOCA duration was not being examined in this program, the steam exposure was shortened to 7 days to expedite testing.

3.1.6 Results of LOCA Radiation and Steam Exposure

Exposure to the LOCA radiation did cause a noticeable drop in EAB for all of the specimens in Groups 1.1, 1.2 and 1.3. The EAB values for the outer jackets after the full LOCA radiation ranged from 44 percent for Group 1.3 to 88 percent for those in Group 1.1, indicating a significant loss in ductility. Similarly for the insulation, EAB values dropped to approximately 74 percent in Group 1.3 to 111 percent in Group 1.1. Still, no insulation or jacket cracking was evident in any of the Group 1.1, 1.2 or 1.3 specimens, nor in the Group 1.4 insulation.

Prior to initiating the LOCA simulation, the test chamber was preheated to 140°F (60°C) with saturated steam and was held for approximately 30 minutes. Chamber pressure during this hold period was slightly above atmospheric, at approximately 1 psig. At approximately 27 minutes into the preheat period, a leakage current of 2.8 mA was noted for specimen 0113 (Group 1.4; aged to 20 years). Leakage current remained at 0 mA for all other specimens.

Following preheat, the first LOCA transient was initiated, with chamber temperature and pressure being ramped up to approximately 346°F (174°C) and 115 psig. Conditions were then held for approximately 3 hours, after which the temperature and pressure were reduced to preheat conditions. Pressure in the common manifold, to which all pressure transmitters were connected, remained relatively constant at approximately 16 psig throughout the LOCA test. This corresponded to a nominal loop current of 12.8 mA in the pressure transmitter circuits.

Approximately 15 seconds after initiating the first transient, the 1/32 amp (31.25 mA) fuse for specimen 0116 (Group 1.4; aged to 20 years) blew, which caused the voltage in that circuit to drop to 0. Test chamber temperature and pressure were approximately 220°F (104°C) and 20 psig, respectively. The fuse was subsequently replaced twice and blew both times. It was replaced a third time approximately 15 minutes into the first transient and the circuit continued to operate throughout the first transient with a leakage current of 0.2 to 1.3 mA.

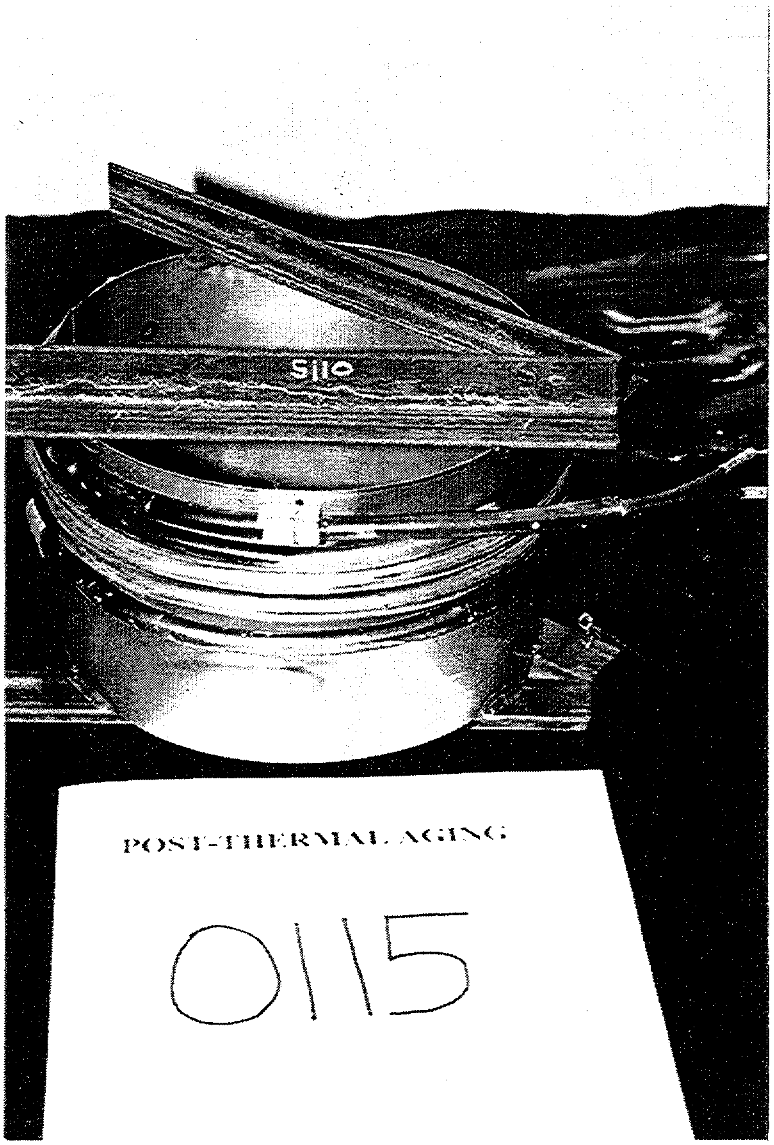

Figure 3.1 Rockbestos specimen 0115 from Group 1.4 (pre-aged to 20 years) after accelerated thermal aging

Figure 3.2 Rockbestos specimens loaded in LOCA chamber after accelerated aging plus LOCA radiation

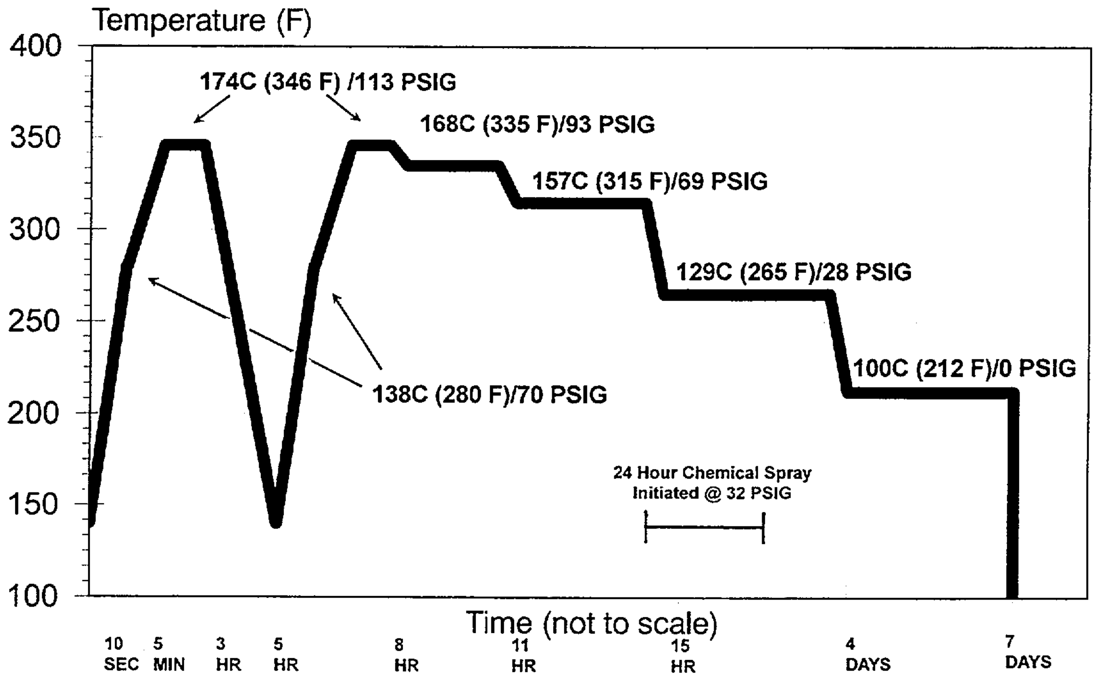

Figure 3.3 Test chamber temperature/pressure profile used in LOCA Tests 1, 3, 4, 5 and 6 (Note: LOCA Tests 4, 5 and 6 were 10 days in duration)

At approximately 26 minutes into the test, the "A" current for specimen 0116 was observed to increase above the "B" current, indicating a short in the circuit. Test chamber temperature and pressure were approximately 349°F (176°C) and 116 psig, respectively. This mismatch continued to increase as the test progressed with the "A" current eventually reaching 19.0 mA at approximately 2 hr. 44 min. into the test, while the "B" current remained relatively constant at 12.3 mA. Test chamber temperature and pressure were approximately 352°F (178°C) and 112 psig, respectively. It was noted that, even with this mismatch of currents, the leakage current for the circuit remained relatively small at approximately 0.5 mA compared to the other Group 1.4 specimens. It should be noted that, for actual plant circuits, which may be considerably longer that these test specimens, a leakage current of 0.5 mA per 10 feet may have a more significant impact on the instrument loop accuracy. This suggests that leakage current may not be the best indicator of circuit performance during LOCA testing since the current mismatch could have caused a significant error in the pressure signal while the small leakage current may have indicated relatively good circuit performance. As the test chamber temperature and pressure were reduced during the down-ramp, the current mismatch for specimen 0116 decreased until both currents were approximately equal.

The leakage current for specimen 0112 (Group 1.4, aged to 20 years) was also noted to increase throughout the test, eventually exceeding 20 mA. At approximately 2 hr. 40 min. into the test, the fuse for specimen 0112 blew, resulting in the circuit voltage dropping to 0. It was subsequently replaced and the circuit continued to operate with a leakage current that exceeded 20 mA. It is interesting to note that the leakage current for specimen 0112 exceeded 20 mA during this portion of the test; however,the "A" and "B" currents in the circuit remained equal and relatively constant at 12.5 mA.

During this portion of the test, leakage currents were also noted for specimens 0113 and 0115, both of which are from Group 1.4 (aged to 20 years). The "A" and "B" currents for these circuits remained relatively constant at 12.3 to 12.4 mA.

Once the test chamber temperature and pressure were reduced to preheat conditions, all leakage currents were below the measuring range of the test equipment, with the exception of specimen 0112, which remained at approximately 0.3 mA. None of the other specimens showed any performance anomalies during this portion of the test.

Immediately upon reaching preheat conditions after completion of the first LOCA peak, at approximately 5 ½ hours into the test, the second transient was initiated. Test chamber temperature and pressure were again ramped up to peak conditions and held for 3 hours. During the up-ramp for the second transient, leakage currents were noted for specimens 0112, 0113, 0115, and 0116, all from Group 1.4 (aged to 20 years). At approximately 7 hrs. 44 min. into the test, when test chamber temperature and pressure reached 350°F (177°C) and 116 psig, respectively, the fuse protecting the power supply to the instrument loop circuit for specimen 0116 blew. It was replaced and immediately blew again. Thereafter, specimen 0116 was left de-energized.

At approximately 7 hrs. 50 min. into the test, the "A" and "B" currents for specimen 0105 (see circuit diagram in Figure 2.13) dropped to approximately 5.7 mA. This was followed by a rise in both currents to over 25 mA approximately 3 min. later. Test chamber temperature and pressure were being held relatively constant at approximately 351°F (177°C) and 116 psig, respectively, at the time. At approximately 8 hrs. 5 min. into the test, the fuse for specimen 0105 blew. It was replaced and the circuit continued to operate with nominal "A" and "B" currents and no leakage. No other anomalies were noted during this portion of the test.

At the completion of the second 3 hour hold at peak conditions (approximately 8 hrs. 38 min. into the test), test chamber temperature and pressure were gradually reduced in four steps to 212°F (100°C) and 0 psig, respectively. At each step, conditions were held and allowed to stabilize. During this cool down, when the test chamber pressure reached 32 psig, the chemical spray was initiated and maintained for 24 hours. The decision to start the chemical spray at 32 psig was based on the head capacity of the test facility chemical spray pump.

During the chemical spray portion of the test, a slight mismatch between "A" and "B" currents was noted for specimen 0113 (Group 1.4, aged to 20 years). The "A" current dropped to approximately 11.7 mA, while the "B" current remained relatively constant at approximately 12.1 mA. Later, specimen 0113 "A" current increased to approximately 13.2 mA while the "B" current continued to remain at approximately 12.1 mA.

Specimen 0116 (Group 1.4, aged to 20 years) remained de-energized until approximately 23½ hours into the test when another fuse was installed and the circuit operated. Once re-energized, a leakage current was noted for specimen 0116, which increased to approximately 3 mA. The circuit continued to operate until approximately 29 hr. 31 min. into the test when the fuse blew again. The circuit remained de-energized for the remainder of the test.

At approximately 39 hours into the test, a level controller on the test chamber failed. This required shutdown of the steam flow to the chamber for repairs. The downtime was approximately 37 minutes, during which the temperature and pressure in the test chamber dropped below the specified profile. Following repairs to the level controller, the temperature and pressure were gradually increased to the conditions prior to the shutdown. It was determined that this downtime would not significantly impact the test results, therefore, testing was continued. To account for this downtime period, 37 minutes were added to the test duration. This event is documented in Notice of Anomaly 3 in Appendix B.

Leakage currents continued throughout this portion of the test for specimens 0112, 0113 and 0115 (all Group 1.4, aged to 20 years). At approximately 65 hrs. 54 min. into the test, a small leakage current was first observed for specimen 0114 (Group 1.4, aged to 20 years). This continued and increased slightly for the remainder of the test. It was noted that as test chamber temperature and pressure were reduced, the leakage currents generally remained constant during this period. However, at approximately 83 hrs. 51 min. into the test, the leakage current for specimen 0112 increased from approximately 2.7 mA to 5.1 mA. Test chamber temperature and pressure were 268°F (131°C) and 25 psig, respectively, at the time. It continued to increase to over 7 mA, after which it decreased. It sporadically increased and decreased for the remainder of the test. No other performance anomalies were noted for the other specimens during this portion of the test.

Table 3.4 presents a summary of the functional performance anomalies observed throughout the steam exposure test. The maximum deviation shown in the table presents the percent of instrument full scale, which for the 4-20 mA pressure transmitters is16 mA, that the signal varied from its nominal value. Therefore, a 10 percent variation would represent a 10 percent error in the pressure reading. The number of blown fuses indicates the number of times during the test the total circuit current exceeded 1/32 amp, which is the capacity of the fuse used in the circuit.

The data in Table 3.4 indicate that the Group 1.1 (no accelerated aging), Group 1.2 (accelerated aging to match the naturally aged cable) and Group 1.3 (naturally aged) specimens showed very few anomalies. Specimens 0118 and 0107 experienced a leakage current of 0.1 mA; however, this is a minimal current which could have been due to instrument inaccuracies. Specimen 0105 experienced a large deviation in circuit current, followed by a blown fuse. However, this anomaly was attributed to a problem with the pressure transmitter since Wyle had noted similar problems with this model transmitter in past tests in which the current behaved similarly. The fuse was replaced and the circuit continued to operate properly for the remainder of the test. All other specimens had signal deviations less than 5 percent with no significant leakage currents.

The Group 1.4 specimens (accelerated aging to 20 years) had the greatest number of performance anomalies. Specimen 0112 experienced a relatively large leakage current up to 23.7 mA, and had 1 blown fuse. Specimens 0113, 0114 and 0115 experienced somewhat smaller leakage currents. Specimen 0116 experienced a leakage current up to 3.7 mA, along with a large deviation in the "A" circuit current (see circuit diagram in Figure 2.14). This specimen also experienced blown fuses at 3 different times during the test[4].

Figures 3.4 and 3.5 show two specimens from Group 1.4 (pre-aged to 20 years) after completion of the LOCA steam/chemical spray exposure. As shown, the outer jackets were cracked in various locations and some pieces had broken off exposing the insulated conductors beneath them. In locations where it was visible, the insulation did not appear damaged. Chemical deposits were noticeable on all specimens.

3.1.7 Results of Post-LOCA Testing

After completing the LOCA test, a special post-LOCA examination of the specimens was performed to determine the cause of the performance anomalies noted during the steam exposure. This special examination was initiated the day after completion of the LOCA test, once the test chamber temperature was sufficiently reduced to allow the chamber to be safely opened. The test specimens were initially examined while they were still moist to help determine if the anomalies were related to moisture induced shorts. The specimens were examined again approximately 2½ weeks later once they had dried to some degree. The examinations involved a visual inspection of each specimen, along with insulation resistance measurements taken from conductor-to-conductor, and conductor-to-ground. Figure 3.6 shows the test specimens in the test chamber after completion of the LOCA test. The Raychem® splices can be seen on the end of the test specimens, along with the Wyle test leads, which extend out of the chamber.

The insulation resistance of each specimen circuit was checked prior to removal from the LOCA chamber, and after removal from the chamber. The IR measurements taken the day after completion of the LOCA test indicated acceptable values for all of the specimens from Groups 1.1, 1.2, and 1.3. However, the IR values for the Group 1.4 specimens indicated short circuits in all of the test specimens, which is consistent with the functional performance anomalies noted during the steam exposure. IR measurements taken after the specimens were allowed to dry for two weeks indicated

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4 It should be noted that for specimen 0116, each time a fuse blew it was replaced and sometimes immediately blew again. Thereafter, the circuit was left de-energized until test conditions changed sufficiently to warrant an attempt to re-energize the circuit. At that time the circuit was re-energized with a new fuse and continued to operated until the next occurrence. Although more than one fuse blew at each occurrence, each of the three occurrences was counted as one blown fuse.

Table 3.4 Summary of functional performance anomalies during LOCA Test 1 steam exposure

Group	Specimen No.	Maximum Deviation (% Full Scale)		Number of Fuses Blown	Maximum Leakage Current (mA)
		Side "A" Current	Side "B" Current		
1.1 (no aging)	0101	4	4	0	0
	0102	3	3	0	0
	0118 [a]	3	3	0	0.1
	0104	3	3	0	0
	0105	96 [b]	96 [b]	1	0
1.2 (aged to match Group 1.3)	0106	3	3	0	0
	0107	4	3	0	0.1
	0108	3	3	0	0
	0109	4	3	0	0
	0110	4	3	0	0
1.3 (naturally aged)	0111	2	2	0	0
1.4 (aged to 20 years)	0112	2	2	1	23.7
	0113	8	3	0	4.3
	0114	2	2	0	0.4
	0115	4	3	0	3.7
	0116	46	3	3	3.7

(a) Specimen 0103 was found to be damaged during baseline visual examination and was replaced with specimen 0118.
(b) The current deviation for specimen 0105 was attributed to a malfunction in the pressure transmitter, and not the specimen.

similar values, indicating the presence of either conductor-to-conductor or conductor-to-ground short circuits, or a moisture leakage path that was still active.

To isolate the location of the short circuits, sections of the test circuits were cut off one piece at a time, starting with the Wyle test lead. IR measurements were taken after each piece was removed. After removing the Wyle test lead, the IR readings showed no change, indicating the problems were still in the circuit. Once the Raychem® splices were removed, the IR readings for all specimens returned to an acceptable value, indicating that the short circuit was within the splice. To investigate this further, a Raychem® representative was called in and one of the splices was dissected to examine it in detail.

Figure 3.7 shows the splice prior to being dissected. One potential problem noted is that, as shown, the overall length of the outer jacket is approximately 6½ inches. According to Raychem®, a longer jacket is recommended and would have provided added protection to the splice. Figure 3.8 shows the splice after removing the outer jacket (top portion of the photograph). The splice is shown beneath the outer jacket, which includes the test specimen (0 to 4 in.), the butt splice (4 in.), an inner sleeve covering the butt splice (2¾ to 5 in.), the Wyle test lead (> 4 in.), and a shim covering the Wyle test lead (5 to 7⅛ in.). A shim was added to the Wyle test lead to more closely match the diameter of the test specimen, since the Wyle test lead is of smaller diameter. A second potential problem noted is that the individual sleeve used to cover the butt splice is approximately 2 inches long. Raychem® indicated that this is insufficient to prevent moisture penetration into the splice, and should be approximately 6 inches long.

Figure 3.4 Post-LOCA condition of Rockbestos specimen 0113 from Group 1.4 (pre-aged to 20 years)

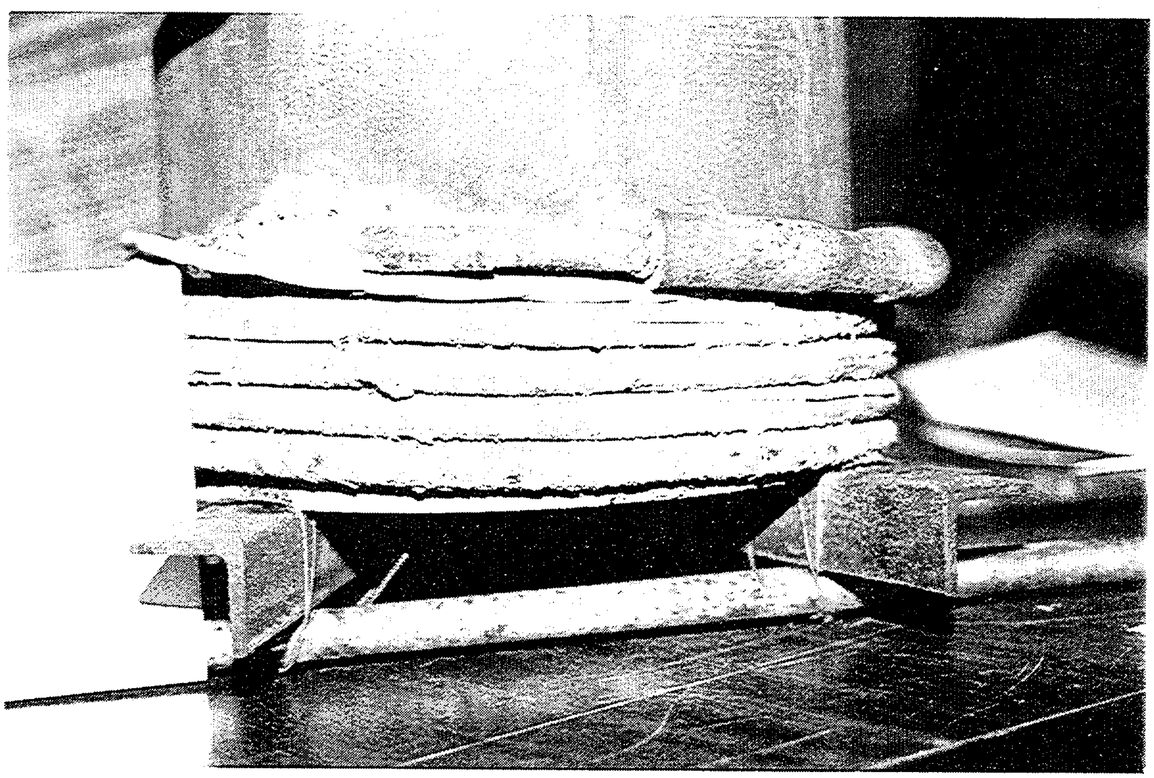

Figure 3.5 Post-LOCA condition of Rockbestos specimen 0115 from Group 1.4 (pre-aged to 20 years)

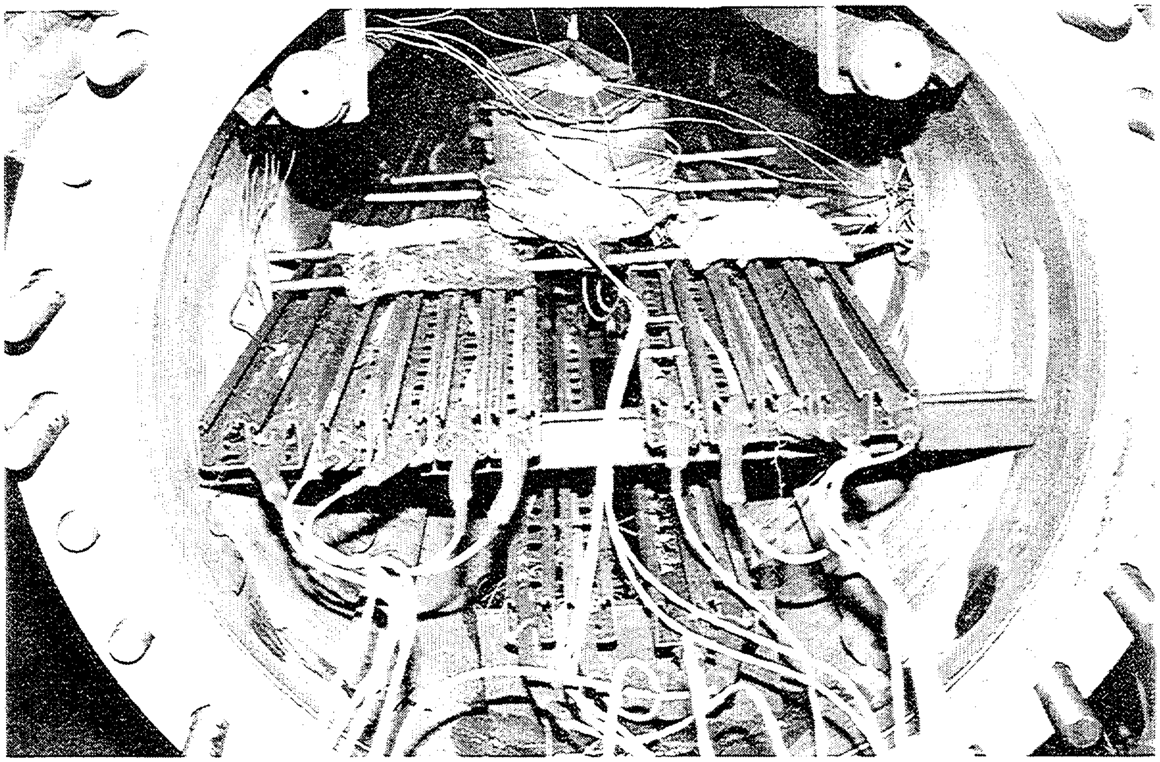

Figure 3.6 Rockbestos specimens in LOCA chamber after steam/chemical spray exposure

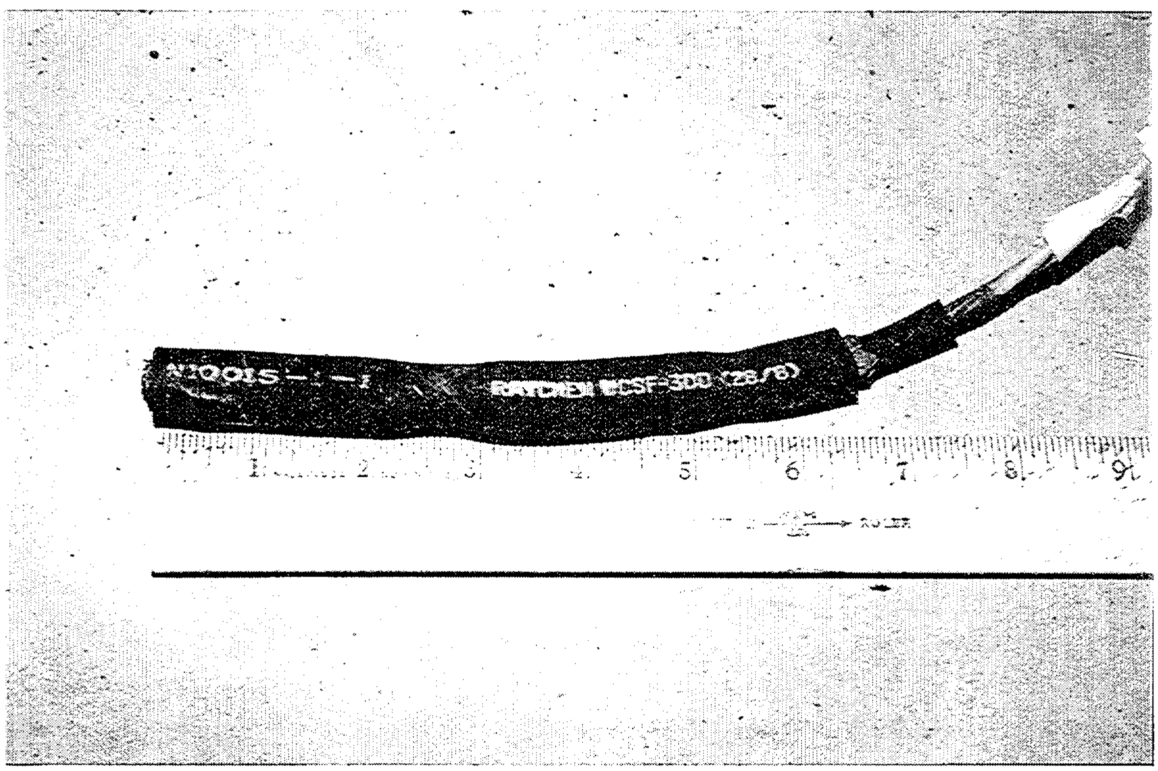

Figure 3.7 Raychem® splice as installed on specimen 0112

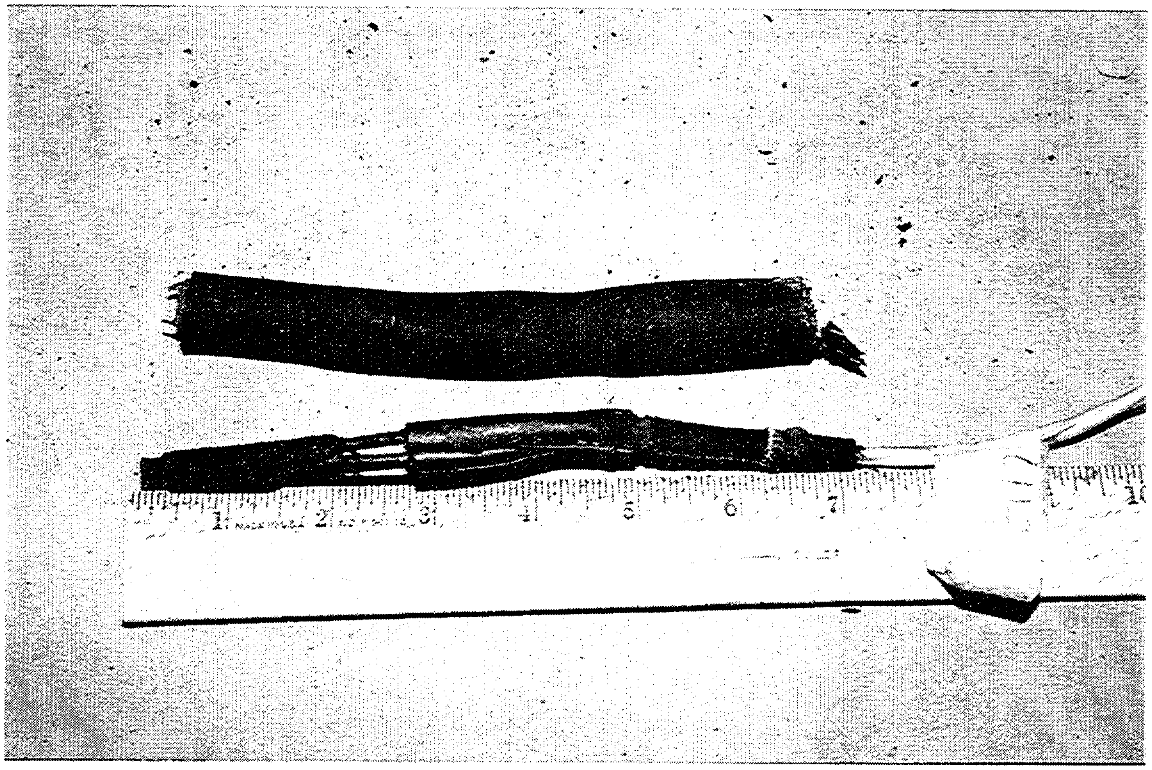

Figure 3.8 Raychem® splice with outer jacket removed

It should be noted that the splice problems are directly related to the severely degraded condition of the cable due to aging. The cables with less aging or no aging did not experience problems with moisture intrusion into the splice. Therefore, the problems experienced are an artifact of the aging received by the cables and are not totally application related.

Figure 3.9 shows a close up of the splice with the shim removed from the Wyle test lead. A third potential problem noted is that the ground/drain wire in the Wyle test lead was left inside the splice in close proximity to the butt splice, and was not capped (location 7/8 to 1 in.). This provided a potential current leakage path to ground should moisture get into the interior of the splice.

From the examination of the splices and the IR readings obtained, it was concluded that the anomalies observed during the LOCA steam exposure were caused by the splices, and not the test specimens. It is believed that, due to the severe degradation of the Group 1.4 specimens, moisture intrusion occurred through the cracks in the jacket, and possibly through micro-cracks in the insulation, after which it traveled along the conductors and into the splice. A leakage path was then set up from conductor-to-conductor, or from a conductor to the ground/shield wire in the test lead, which caused the anomalous current readings observed.

Subsequent to the special post-LOCA examination, condition monitoring measurements were taken on the specimens. The specimens were then subjected to a submerged voltage withstand test, which was part of the original test plan. Since this is a high potential test that is potentially destructive to the specimens, all other condition monitoring tests were performed first.

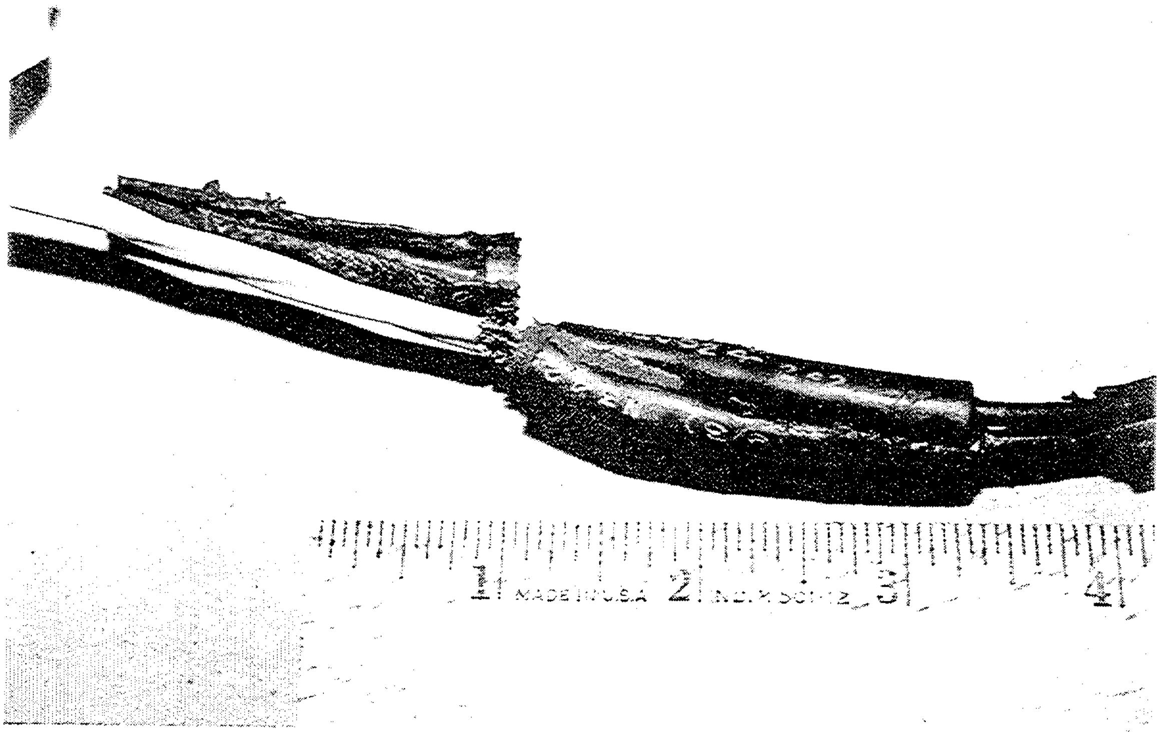

Figure 3.9 Raychem® splice with test lead shim removed

The submerged voltage withstand test was performed by Wyle using a Hipotronics model 760-2HVT high potential test set. Each specimen was submerged in a trough containing tap water at room temperature and subjected to a voltage of 80 Vac per mil of insulation thickness, which was 2,400 volts for the 30-mil insulation on these specimens. All specimens tested remained on their respective test fixture (i.e., Unistrut® or mandrel) for this test. This test is similar to that described in IEEE Std. 383-1974 for cable qualification testing, with the exception that the IEEE standard recommends that the specimens first be removed from their mandrels, straightened and rewound on the mandrels prior to the test. The straightening and recoiling was not performed in this program since it was determined to be an unreasonably harsh test (Lofaro, 1996).

The results of the submerged voltage withstand test are presented in Table 3.5. For purposes of this program, specimens that did not exhibit an off-scale leakage current were considered to have passed the test. As shown, all of the specimens exhibited an acceptable leakage current, therefore, they were considered to have passed this test. In an actual qualification, the leakage currents measured would be analyzed based on the intended application for the specimens to determine if they were acceptable. It is noted that the Group 1.4 specimens had the Raychem® splices removed prior to performing this test as part of the special examination discussed previously. The splices remained in place for all other specimens during this test.

The leakage currents measured during the submerged voltage withstand test may provide some indication of the relative dielectric strength of the insulation in the cable under test; however,they should not be used as an absolute measure of insulation condition. For example, the leakage currents measured for specimens 0114, 0115 and 0116, which did undergo the most severe accelerated aging and appeared to be more damaged than specimens in other groups, were higher than for other specimens. However, specimens 0112 and 0113 in the same group had relatively low leakage currents even though they went through the same aging conditions as specimens 0114, 0115 and 0116.

Table 3.5 Results of submerged voltage withstand test on specimens in Test Sequence 1

Group	Specimen No.	Manufacturer	Applied Voltage (Vac)	Leakage (microamps)		Pass/Fail
				White Conductor	Black Conductor	
1.1 (no aging)	0101	Rockbestos	2,400	640	640	Pass
	0102		2,400	690	660	Pass
	0118 [(a)]		2,400	560	560	Pass
	0104		2,400	690	680	Pass
	0105		2,400	690	680	Pass
1.2 (aged to match Group 1.3)	0106	Rockbestos	2,400	720	740	Pass
	0107		2,400	350	400	Pass
	0108		2,400	690	760	Pass
	0109		2,400	720	740	Pass
	0110		2,400	720	760	Pass
1.3 (naturally aged)	0111	Rockbestos	2,400	680	720	Pass
1.4 (aged to 20 years)	0112	Rockbestos	2,400	480	480	Pass [(b)]
	0113		2,400	550	700	Pass [(b)]
	0114		2,400	920	940	Pass [(b)]
	0115		2,400	820	730	Pass [(b)]
	0116		2,400	740	760	Pass [(b)]

(a) Specimen 0103 was found to be damaged during baseline visual examination and was replaced with specimen 0118.
(b) Specimens in Group 1.4 passed the voltage withstand test after removing the Raychem® splices from the cable ends.

3.2 Test Sequence 2: Ethylene Propylene Rubber (EPR) Insulated Cables Aged to 20 Years

3.2.1 Test Objectives

The objectives of this test sequence were the following:

- To obtain LOCA performance data on EPR insulated cables with accelerated aging to an equivalent qualified life of 20 years,
- To obtain LOCA performance data on naturally aged EPR insulated cables,
- To compare the condition of naturally aged EPR insulated cable with similar cables subjected to accelerated aging to simulate an equivalent amount of service aging, and
- To obtain data for evaluating condition monitoring techniques on EPR insulated cable

3.2.2 Description of Test Specimens

All of the cables used in test sequence 2 were manufactured by American Insulated Wire (AIW). They have an EPR insulation with a chlorosulfonated polyethylene (CSPE), also known as Hypalon®, jacket covering each individual conductor. This jacket covering the insulation on the individual conductors is referred to herein as the "individual" jacket. The individual jacket was not bonded to the insulation as part of the manufacturing process, as it is for some cables. The conductors were covered as a group with an overall outer jacket, which was also made of Hypalon®. This overall jacket is referred to herein as the "outer" jacket. These components are shown schematically in Figure 3.10.

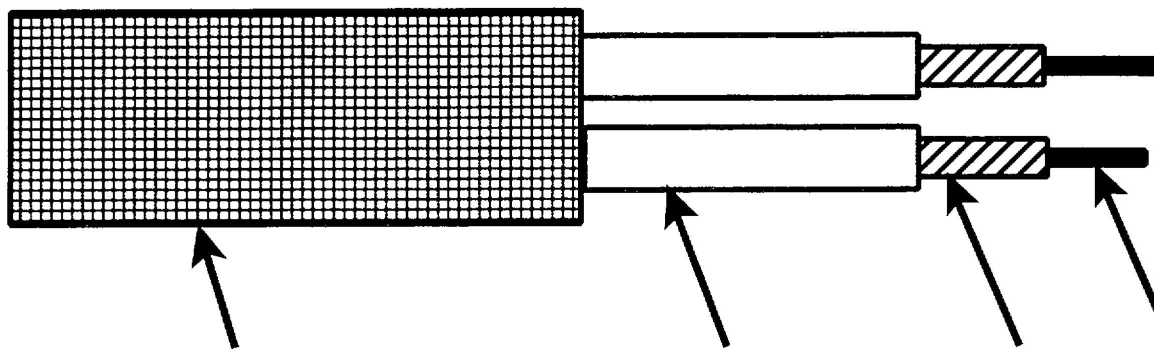

Figure 3.10 Typical sub-components of EPR/Hypalon® cables

The source cable samples used for the unaged specimens are PNI74AI025, 026, 027, 028, 031, 032 and 033. Since warehouse stock was not available, these cables were obtained from the cable spreading room and the computer room of a decommissioned PWR plant, which is considered a mild environment. The temperature in the cable spreading room ranged from 50°F (10°C) to 104°F (40°C). The computer room is a controlled environment with a nominal service temperature of 75°F (24°C). Sources PNI74AI025, 026, 027 and 028 were 4/C #16 AWG, 600 V cables with a ground wire. Sources PNI74AI031, 032 and 033 were 3/C #16 AWG, 600 V cables with a ground wire. For all source samples in this test, the conductors have 30 mils of EPR insulation with a 15-mil CSPE individual jacket and a 45-mil CSPE overall jacket.

The source cable samples used for the naturally aged cable specimens are PAI74AI015, 016, 017, 019 and 020, which were approximately 24 years old at the time of testing. These cables are all 4/C #16 AWG, 1,000 V cables with a ground wire manufactured by AIW. They were obtained from inside the plant containment area in the vicinity of the reactor coolant pumps. All of the naturally aged samples were installed in conduit, and were used for temperature detector circuits. Plant data indicated a service radiation dose rate of approximately 6 rad/hr at 24 percent power for source cables PAI74AI015, 016 and 017. The service radiation dose rate for source cables PAI74AI019 and 020 was approximately 10 rad/hr at 24 percent power. Based on this information, and the plant power history, a total dose of approximately 3 Mrad was calculated for the source cables. The service temperature for the source cables ranged from 70°F (21°C) during plant shutdown, to a maximum of 110°F (43°C) during full power operation.

Eighteen long cable specimens were prepared for test sequence 2, as shown in Table 3.6. Sixteen of the long specimens were mounted in straight Unistrut® channels approximately 10 feet long to simulate a typical plant installation in a cable tray. Two of the Unistrut®-mounted specimens were used for archiving purposes. Two of the long specimens were mounted on stainless steel mandrels approximately 10 inches in diameter to simulate the test configuration during qualification testing.

In addition to the long specimens, 29 baskets containing 6 inch specimens of both jacket and insulation materials were prepared for destructive testing at the various hold points. Also, eighteen 2-foot specimens were prepared for indenter testing, as in test sequence 1.

3.2.3 Accelerated Aging Parameters

The specimens included in test sequence 2 can be grouped according to the pre-aging they received. Group 2.1 contained two 10-foot specimens, which were tested without any accelerated aging. In Group 2.2, four 10-foot specimens were prepared from unaged samples and received accelerated aging to simulate the service conditions experienced by the naturally aged cables in Group 2.3. Group 2.3 included three 10-foot specimens and two 8-foot specimens, which were prepared from naturally aged samples and received no accelerated aging prior to LOCA testing. Eight foot specimens were used instead of the typical 10-foot specimens due to the limited amount of naturally aged cable available. In Group 2.4, five specimens received accelerated aging to simulate 20 years of qualified life prior to LOCA testing. In addition, two specimens were aged to the equivalent of 20 years of qualified life and used as archive specimens. The four aging groups for test sequence 2 are summarized as follows:

Group 2.1: No accelerated aging (control specimens),
Group 2.2: Accelerated aging to simulate the exposure of the naturally aged cables in Group 2.3,
Group 2.3: Naturally aged 24-year old cables (no accelerated aging), and
Group 2.4: Accelerated aging to simulate 20 years of qualified life

The accelerated aging parameters used in test sequence 2 were based on Franklin Institute Research Laboratories (FIRL) qualification report number F-C4197-2, which was the qualification basis used by the plant from which the cables were obtained. In this report, AIW cables were qualified to 40 years of service at a temperature of 122°F (50°C)[5]. The accelerated aging used in this qualification included thermal aging at 250°F (121°C) for 168 hours followed by 100 Mrad of radiation at an average dose rate of 0.55 Mrad per hour. The cables were subsequently exposed to a 100-day LOCA steam profile while energized with rated voltage and current to simulate service under LOCA conditions. After LOCA testing, the cables were straightened and recoiled around a mandrel with a diameter 40 times that of the cables. The mandrels were immersed in tap water and a voltage of 80 volts per mil of insulation was applied (2,400 Vac for the 30-mil thickness of the insulation).

For the Group 2.2 cables, the Arrhenius calculation using an activation energy of 1.18 eV resulted in an aging time of 26.4 hrs at 250°F (121°C) to match the thermal aging received by the naturally aged cables. Also, the total integrated dose was calculated to be approximately 3 Mrad to match the radiation exposure received by the naturally aged cables in Group 1.3. For the Group 1.4 cable specimens, 20 years of qualified life was simulated using half of the thermal aging duration and half of the total integrated dose used in the original qualification. The actual aging conditions received by the test sequence 2 cable specimens is summarized in Table 3.7. Calculations for determining the accelerated aging conditions for the test sequence 2 specimens is provided in Appendix A.

During pre-aging of the specimens, one anomaly occurred. During thermal aging of the specimens, a temperature controller on the thermal aging oven malfunctioned causing the oven to be shutdown. The oven temperature had returned to ambient by the time the problem was noticed. After verifying proper functioning of the controller, the oven temperature was increased to the specified aging temperature and the thermal aging proceeded normally. Total time of the shutdown was approximately 16 hours. The thermal aging duration was adjusted to account for this downtime and testing resumed. This event in documented as Notice of Anomaly 4 in Appendix B.

[5] FIRL report F-C4197-2 does not specifically identify the qualified life or service temperature to which the AIW cables were qualified. However, based on an activation energy of 1.18 eV, an Arrhenius calculation shows that the accelerated aging performed equates to 40 years at 50 °C.

3. Results

Table 3.6 Description of specimens in Test Sequence 2

Group	Specimen ID No.	Sample ID No.	Configuration [a]	Manufacturer [a]	Insulation Material [a]	Jacket Material [a]	No. of Conductors	Wire Gauge (AWG)	Cable Diameter (in.)	Cable Type [a]	Insulation Thickness (mils)
2.1	0201	PNI74AI025	10 FT - STR	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
	0202	PNI74AI031	10 FT - STR	AIW	EPR[c]	CSPE	3 w/gnd	16	0.445	I	30
2.2	0203	PNI74AI026	10 FT - STR	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
	0204	PNI74AI026	10 FT - STR	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
	0205	PNI74AI027	10 FT - STR	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
	0206	PNI74AI027	10 FT - STR	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
2.3	0207	PNI74AI015	10 FT - STR	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
	0208	PNI74AI016	10 FT - STR	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
	0209	PNI74AI017	10 FT - STR	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
	0210	PNI74AI019	10 FT - STR	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
	0211	PNI74AI020	10 FT - STR	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
2.4	0212	PNI74AI028	10 FT - STR	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
	0213	PNI74AI028	10 FT - STR	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
	0214	PNI74AI032	10 FT - STR	AIW	EPR[c]	CSPE	3 w/gnd	16	0.445	I	30
	0215	PNI74AI028	10 FT - MAN	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
	0216	PNI74AI032	10 FT - MAN	AIW	EPR[c]	CSPE	3 w/gnd	16	0.445	I	30
Archive	0217[b]	PNI74AI025	10 FT - STR	AIW	EPR[c]	CSPE	4 w/gnd	16	0.445	I	30
	0218[b]	PNI74AI033	10 FT - STR	AIW	EPR[c]	CSPE	3 w/gnd	16	0.445	I	30

(a) STR=Straight, MAN=Mandrel, AIW=American Insulated Wire, EPR=Ethylene Propylene Rubber, I=Instrumentation
(b) These specimens were included for archiving purposes and were not energized during the LOCA steam exposure. A 2-foot section was removed at each hold point and placed in storage.

Table 3.7 Actual accelerated aging conditions received by the specimens in Test Sequence 2

Group	Thermal Aging		Service Radiation [a]		LOCA Radiation [a, b,c]	
	Temperature (°F/°C)	Duration (hours)	Total Integrated Dose (Mrad)	Dose Rate (Mrad/hr.)	Total Integrated Dose (Mrad)	Dose Rate (Mrad/hr.)
2.1	-	None	None	-	Phase 1: 77.6 Phase 2: 77.2	Phase 1: 0.73 Phase 2: 0.74
2.2	250°F (121°C)	28.5	3.3	0.49		
2.3	-	None	None	-		
2.4	250°F (121°C)	82.2	25.7	0.49		

(a) Radiation exposures for long specimens and/or basket specimens in the same group were performed in multiple runs due to restrictions on the number of sources allowed in the hot cell at one time. Therefore, the radiation doses and dose rates reported are averages for all runs.
(b) The specified LOCA radiation exposure was performed in two separate phases to allow condition monitoring measurements to be taken at the midpoint.
(c) Specimens 0203, 0204, and 0207 to 0212 did not receive the second phase of the radiation.

3.2.4 Results of Accelerated Aging

Visual examination and baseline elongation-at-break measurements confirmed that all cable specimens were initially in excellent condition. No discoloring or cracking was evident in either the jacket or insulation for any of the specimens. Average elongation-at-break values for the unused cables ranged from approximately 563 percent to 649 percent for the Hypalon® jackets, and from 284 percent to 341 percent for the EPR insulation, as shown in Table 3.8. Similarly, for the naturally aged cable, EAB values were 650 percent for the jacket, and 343 percent for the insulation, indicating excellent ductility for both materials. Baseline results for other CM tests are discussed in Volume 2 of this report.

Following thermal aging, the Group 2.2 specimens (aged to match the naturally aged cable) showed a slight discoloring on the outer jackets, with a greyish/white color evident along the length of the cable. No change in insulation color was noted, and no cracking was evident in either the outer or individual jackets, or the insulation. Average elongation-at-break values for the outer jackets decreased slightly from a baseline value of 649 percent to a post-thermal aging value of 634 percent; however,they retained excellent ductility. The EAB values for the insulation showed a slight increase from their baseline value of 284 percent to a post-thermal aging value of 336 percent, indicating an improvement in ductility.

The post-thermal aging condition of the Group 2.4 cables (aged to 20 years) also indicated only a slight change in condition. The outer jackets retained their uniform black color. However, a slight darkening was noted on the white individual jackets, and a slight yellowing of the green individual jackets was also noted. No cracking or surface contamination was noted for any of the specimens. EAB values for the outer jackets showed a decrease from the pre-thermal aging values of 563 percent and 649 percent to post-thermal aging values of 390 percent and 553 percent; however,excellent ductility still was remaining. The insulation also was in excellent condition with EAB remaining relatively constant or decreasing slightly. No cracking was noted in the insulation or jackets.

The service radiation exposures caused additional degradation in the condition of the Group 2.2 and Group 2.4 specimens. For the Group 2.2 specimens, the outer jacket and insulation EAB decreased to 582 percent and 224 percent, respectively. The EAB for the Group 2.4 outer jackets decreased to 369-429 percent, while that for the insulation decreased to 186-196 percent. These values still indicate significant ductility remaining for all specimens.

Table 3.8 Average elongation-at-break values for the specimens in Test Sequence 2

Group	Cable	Average elongation-at-break at each CM Point (%)											
		Baseline No Aging		After Thermal Service Aging		After Radiation Service Aging		After Half LOCA Radiation		After Full LOCA Radiation		After LOCA Steam Exposure	
		Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)
2.1 (0 yr.)	AIW PNI74AI025	649	284	NA	NA	NA	NA	591	215	481	187	162	35
	AIW PNI74AI031	563	341	NA	NA	NA	NA	459	211	359	138	85	32
2.2 (match Group 2.3)	AIW PNI74AI026	649	284	634	336	582	224	546	151	318	127	165	45
2.3 (naturally aged 24 yr.)	AIW PAI74AI015	650	343	NA	NA	NA	NA	NA	NA	426	162	179	86
2.4 (20 yr.)	AIW PNI74AI028	649	284	553	283	429	196	352	141	256	120	132	38
	AIW PNI74AI032	563	341	390	318	369	186	313	140	224	132	81	27

(a) EAB value is for EPR insulation alone; individual CSPE jacket was removed prior to aging.

In summary, after completion of the accelerated aging, all of the specimens appeared to be in relatively good condition with good ductility and no cracking evident in any of the specimens. Insulation resistance measurements indicated that all specimens were in acceptable condition electrically. Figure 3.11 shows the typical condition of a naturally aged specimen after LOCA radiation exposure. The bend shown is the as-installed configuration of the cable, which was maintained for this test. Figure 3.12 shows a typical specimen from Group 2.4 (pre-aged to 20 years) after service aging plus LOCA radiation exposure.

3.2.5 LOCA Conditions Simulated

The LOCA conditions simulated included exposure to 75 or 150 Mrad of accident radiation , followed by exposure to steam at high temperature and pressure. The accident radiation exposure was performed after completion of the service aging and prior to the steam exposure.

Following accident irradiation, the specimens were subjected to a high temperature and pressure steam exposure. The test chamber temperature/pressure profile for the LOCA steam exposure in test sequence 2 was obtained from FIRL report F-C4197-2, as previously discussed. This is a "single-peak" profile, meaning that the rapid increase in test chamber temperature and pressure to peak conditions is performed once. The specified temperature and pressure were obtained by controlling the amount of steam entering the test chamber. Figure 3.13 presents the profile used in LOCA Test 2.

For the original qualification test documented in the FIRL report, the LOCA steam exposure test duration was 100 days. Since post-LOCA duration was not being examined in this program, the steam exposure was shortened to 7 days to expedite testing.

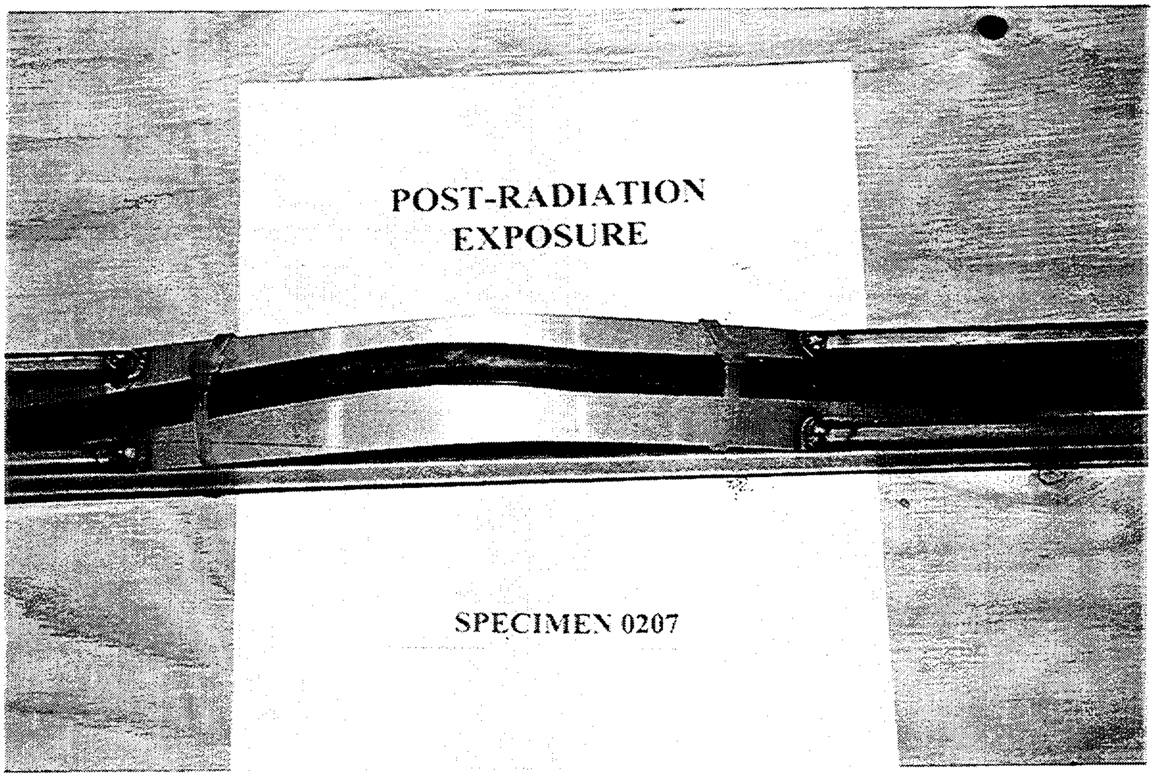

Figure 3.11 AIW specimen 0207 from Group 2.3 (naturally aged 24 years) after LOCA radiation

3.2.6 Results of LOCA Radiation and Steam Exposure

Exposure to the LOCA radiation caused a noticeable drop in EAB for the specimens in all groups. The EAB values for the outer jackets after the LOCA radiation ranged from 224 percent for Group 2.4 to 481 percent for those in Group 2.1. Similarly for the insulation, EAB values dropped to approximately 120 percent in Group 2.4 to 187 percent in Group 2.1. No cracking was evident in any of the specimens.

During the accident irradiation, the dose rates achieved were 21 percent to 33 percent lower than specified, which was below the 20 percent criteria for the minimum dose rate. The lower dose rates were determined not to have caused any significant impact to the test results; therefore, testing was continued. This event in documented as Notice of Anomaly 5 in Appendix B.

Prior to initiating the LOCA simulation, the test chamber was preheated to 140°F (60°C) with saturated steam and was held for approximately 30 minutes. Chamber pressure during this hold period was slightly above atmospheric, at approximately 1 psig. No performance anomalies were noted for any of the specimens during preheat.

Following preheat, the LOCA transient was initiated, with test chamber temperature and pressure being ramped up to approximately 340°F (171°C) and 60 psig. Once peak temperature and pressure were achieved, conditions were held for 3 hours. Subsequently, test chamber temperature and pressure were gradually reduced in three steps. At each step, conditions were held and allowed to stabilize. When the test chamber pressure reached 32 psig, the chemical spray was initiated and maintained for 24 hours. Pressure in the common manifold was relatively constant at approximately 15 psig throughout the LOCA test.

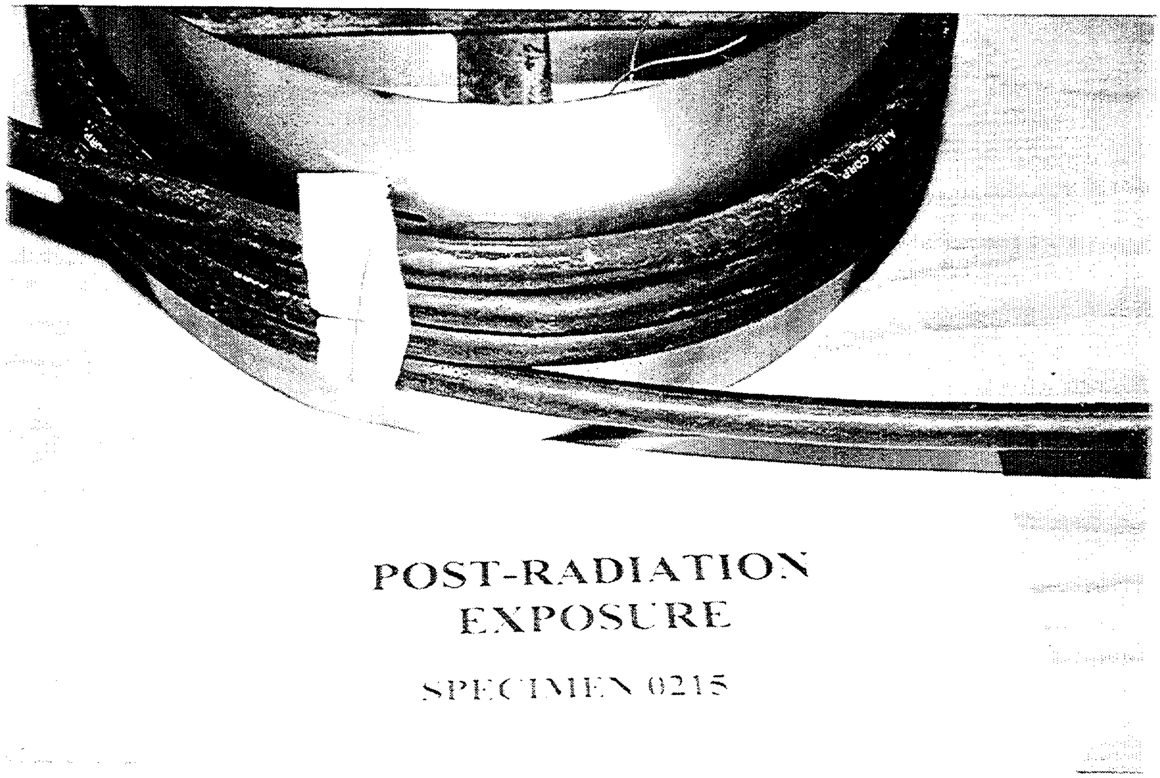

Figure 3.12 AIW specimen 0215 from Group 2.4 (pre-aged to 20 years) after service aging plus LOCA radiation

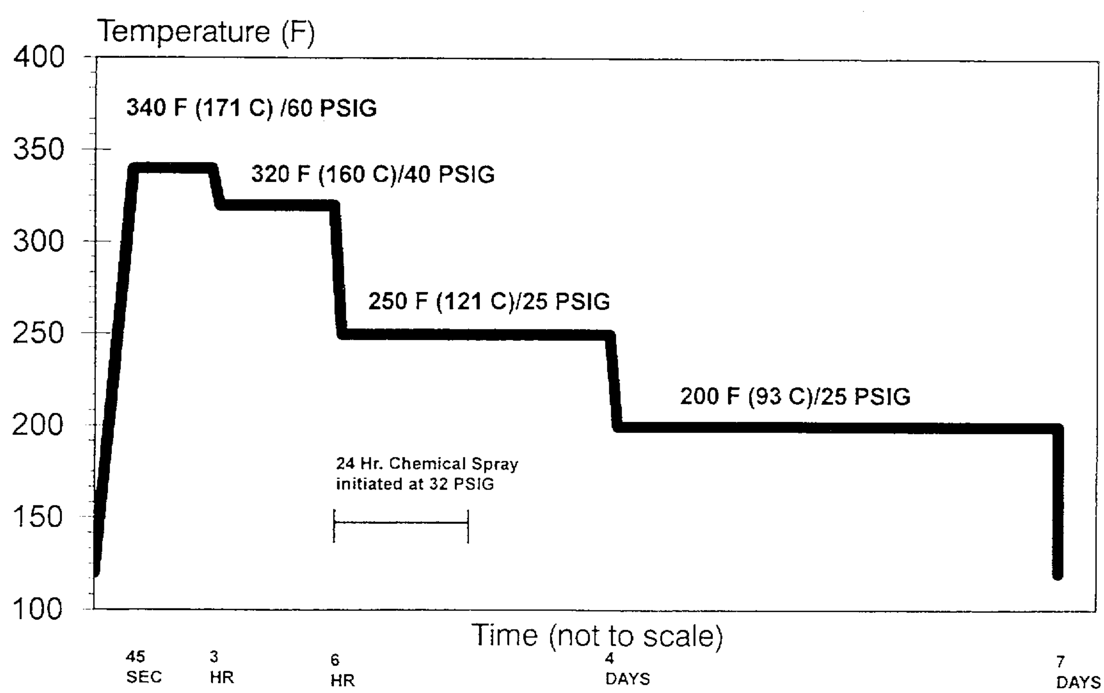

Figure 3.13 Test chamber temperature/pressure profile used in LOCA Test 2

Throughout the LOCA test, no performance anomalies were noted for any of the specimens. Circuit voltages and currents remained at their nominal values.

Figure 3.14 shows the post-LOCA condition of specimen 0207X (naturally aged 24 years) with a section of the outer jacket removed. As shown, the individual CSPE jacket on one of the conductors was shriveled and pulled away from the underlying EPR insulation, which appeared to be in good physical condition. This was observed on several of the insulated conductors that were exposed to the steam environment. Figures 3.15 and 3.16 show the post-LOCA condition of specimens 0208 (naturally aged 24 years) and 0216 (pre-aged to 20 years), respectively. As shown, these specimens appeared to be in good physical condition.

3.2.7 Results of Post-LOCA Testing

Subsequent to LOCA test, condition monitoring measurements were taken on the specimens. The specimens were then subjected to a submerged voltage withstand test, which was part of the original test plan. Since this is a high potential test that is potentially destructive to the specimens, all other condition monitoring tests were performed first. The submerged voltage withstand test was performed by Wyle in the same manner as described for test sequence 1.

The results of the submerged voltage withstand test are presented in Table 3.9. For purposes of this program, specimens that did not exhibit an off-scale leakage current (>10 milliamps) were considered to have passed the test. As shown, all of the specimens exhibited an acceptable leakage current, therefore, they were considered to have passed this test. In an actual qualification, the leakage currents measured would be analyzed based on the intended application for the specimens to determine if they were acceptable.

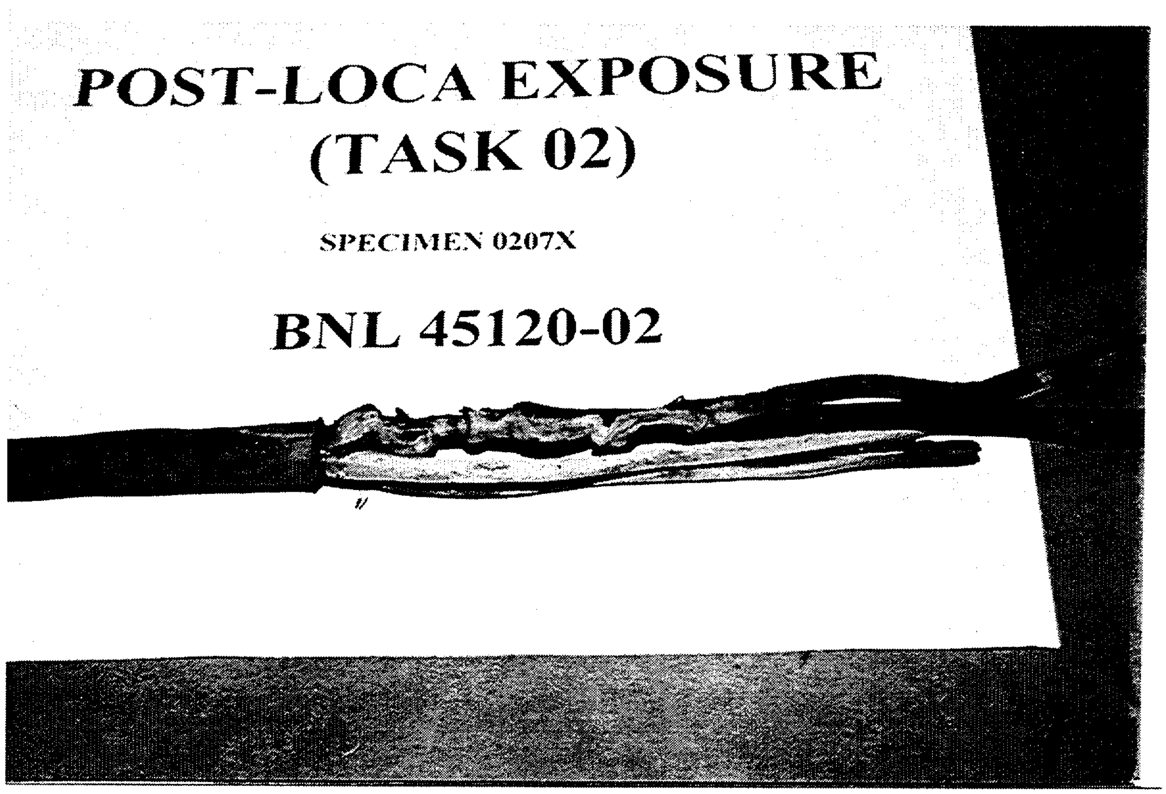

Figure 3.14 Post-LOCA condition of AIW specimen 0207X from Group 2.3 (naturally aged 24 years)

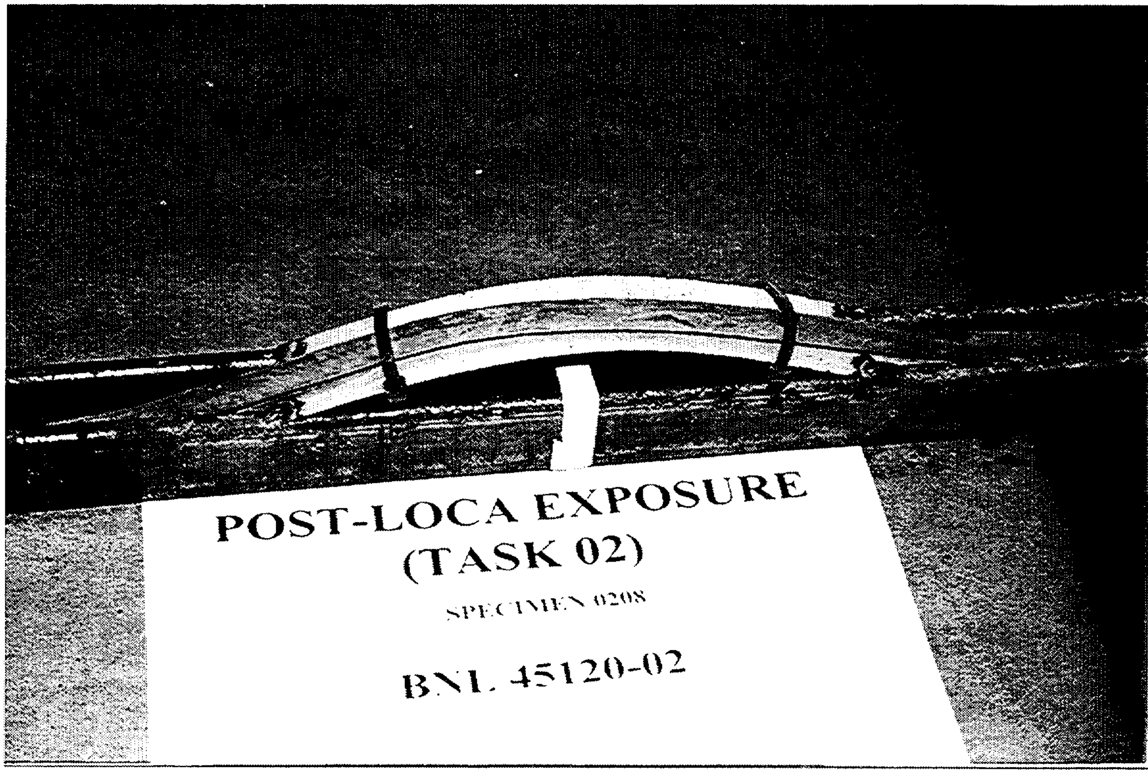

Figure 3.15 Post-LOCA condition of AIW specimen 0208 from Group 2.3 (naturally aged 24 years)

3.3 Test Sequence 3: XLPE Insulated Cables Aged to 40 Years

3.3.1 Test Objectives

The objectives of this test sequence were the following:

- To obtain LOCA performance data on XLPE insulated cables with accelerated aging to an equivalent qualified life of 40 years,
- To obtain LOCA performance data on naturally aged XLPE insulated cables,
- To compare the condition of naturally aged XLPE insulated cable with similar cables subjected to accelerated aging to simulate an equivalent amount of service aging, and
- To obtain data for evaluating condition monitoring techniques on XLPE insulated cable

3.3.2 Description of Test Specimens

The source cable samples used for the unaged specimens in Test Sequence 3 are PNI79RB188 and PNI85RB191, both of which have XLPE insulation with a Neoprene® jacket manufactured by Rockbestos, with the trade name "Firewall® III." These cables were obtained from warehouse stock from the same decommissioned PWR plant as the naturally aged cables. The PNI85RB191 source cable contained 3 XLPE insulated #16 AWG stranded copper conductors with a bare, stranded, tinned copper drain wire, while the PNI79RB188 source contained 2 XLPE insulated #14 AWG copper conductors with no drain wire. Both source cables had 30 mils of XLPE insulation on the individual conductors and a 45-mil overall Neoprene® jacket.

The source samples for the naturally aged cable specimens are PAP86RB229, 244, 245, 246 and 267, which are also 3 conductor #16 AWG with drain wire Rockbestos Firewall® III cables with the same jacket and insulation specifications as described above. The naturally aged cables were approximately 10 years old at the time of testing, and were obtained from the same decommissioned PWR plant as that used in test sequence 1. A section of cable from the circuit at the top of the compartment was used in test sequence 1. The cable from the lower portion of the circuit, which experienced a higher dose rate of approximately 50 rad/hr. during operation was used in this test.

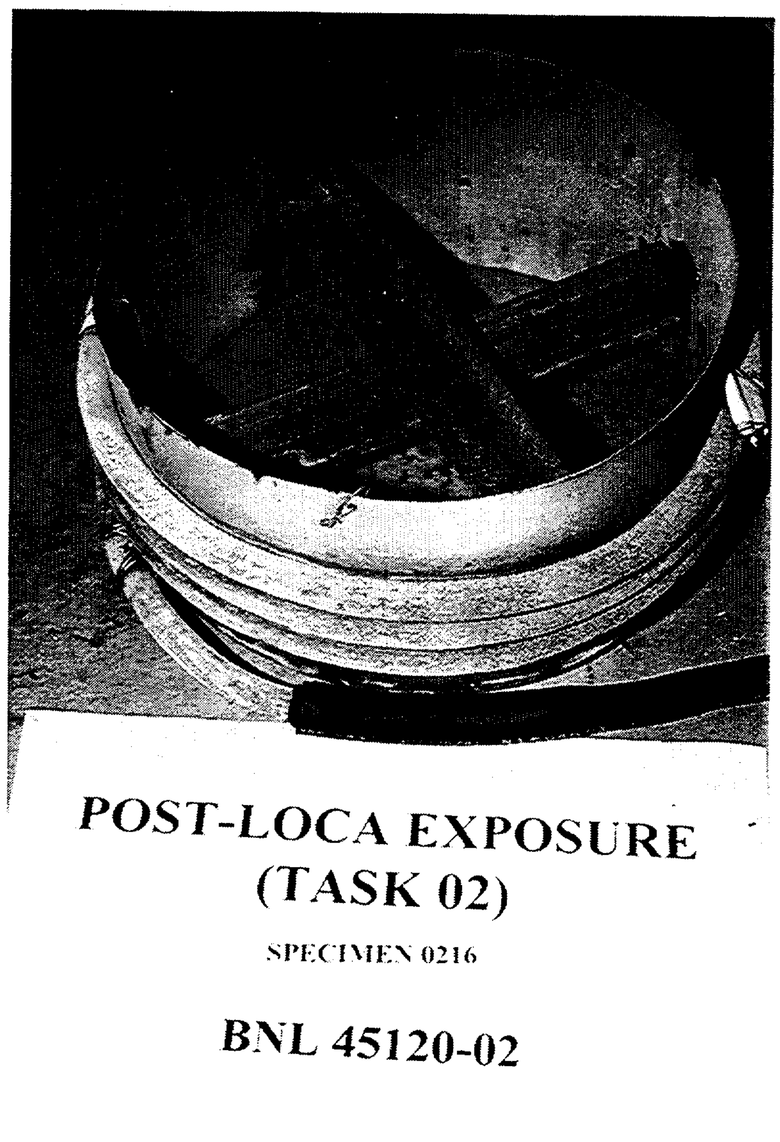

Figure 3.16 Post-LOCA condition of AIW specimen 0216 from Group 2.4 (pre-aged to 20 years)

For test sequence 3, 17 long (10-foot) cable specimens were prepared, as presented in Table 3.10. Fifteen of the long specimens were mounted in straight Unistrut® channels approximately 10-feet long to simulate a typical plant installation in a cable tray. Two of the long specimens were mounted on stainless steel mandrels approximately 10 inches in diameter to simulate the test configuration during qualification testing. One Unistrut® mounted specimen was used for

Table 3.9 Results of submerged voltage withstand test on specimens in Test Sequence 2

Group	Specimen No.	Manufacturer	Applied Voltage (Vac)	Leakage (microamps)		Pass/Fail
				White Conductor	Black Conductor	
2.1 (no aging)	0201	AIW	2,400	780	840	Pass
	0202		2,400	1,000	1,000	Pass
2.2 (aged to match Group 2.3)	0203	AIW	2,400	770	820	Pass
	0204		2,400	900	1,200	Pass
	0205		2,400	780	920	Pass
	0206		2,400	810	900	Pass
2.3 (naturally aged)	0207	AIW	2,400	780	820	Pass
	0208		2,400	740	790	Pass
	0209		2,400	790	770	Pass
	0210		2,400	860	900	Pass
	0211		2,400	730	760	Pass
2.4 (aged to 20 years)	0212	AIW	2,400	870	940	Pass
	0213		2,400	820	930	Pass
	0214		2,400	940	940	Pass
	0215		2,400	800	890	Pass
	0216		2,400	940	930	Pass

archiving purposes. The remaining 14 Unistrut® mounted specimens, along with the two mandrel mounted specimens, were energized during the LOCA steam exposure to obtain circuit performance data.

In addition to the long specimens, 22 baskets containing 6-inch specimens of both jacket and insulation materials were prepared for destructive testing at the prescribed hold points. Also, one 2-foot specimen was prepared from the same cable sample as each of the seventeen long specimens, and followed the "parent" long specimen through each phase of aging and testing. These 2-foot specimens were used to perform indenter testing to prevent damaging the long specimen.

3.3.3 Accelerated Aging Parameters

The specimens in test sequence 3 can be grouped according to the pre-aging they received. Group 3.1 contained two 10-foot specimens, which were prepared and LOCA tested without any pre-aging. Group 3.2 included four 10-foot specimens, which were prepared from unaged samples and received accelerated aging to simulate the equivalent service life of the naturally aged specimens prior to LOCA testing. In Group 3.3, five 10-foot specimens were prepared from naturally aged samples and received no accelerated aging prior to LOCA testing. Group 3.4 included five specimens, which were aged to the equivalent of 40 years of qualified life prior to LOCA testing. Also, one specimen was aged to the equivalent of 40 years of qualified life and used as an archive specimen. The four aging groups for test sequence 3 are summarized as follows:

Group 3.1: No accelerated aging (control specimens),
Group 3.2: Accelerated aging to simulate the exposure of the naturally aged specimens in Group 3.3,
Group 3.3: Naturally aged 10-year old cable (no accelerated aging), and
Group 3.4: Accelerated aging to simulate 40 years of qualified life

Table 3.10 Description of specimens in Test Sequence 3

Group	Specimen ID No.	Sample ID No.	Configuration [a]	Manufacturer [a]	Insulation Material [a]	Jacket Material [a]	No. of Conductors	Wire Gauge (AWG)	Cable Diameter (in.)	Cable Type [a]	Insulation Thickness (mils)
3.1	0301	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.38	I	30
	0302	PNI85RB191	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
3.2	0303	PNI85RB191	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
	0304	PNI85RB191	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
	0305	PNI85RB191	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
	0306	PNI85RB191	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
3.3	0307	PAP86RB229	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
	0308	PAP86RB244	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
	0309	PAP86RB245	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
	0310	PAP86RB246	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
	0311	PAP86RB267	10 FT - STR	RB FW-III	XLPE	NEO	3 w/shield	16	0.386	I	30
3.4	0312	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.38	I	30
	0313	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.38	I	30
	0314	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.38	I	30
	0315	PNI79RB188	10 FT - MAN	RB FW-III	XLPE	NEO	2	14	0.38	I	30
	0316	PNI79RB188	10 FT - MAN	RB FW-III	XLPE	NEO	2	14	0.38	I	30
Archive	0317 [b]	PNI79RB188	10 FT - MAN	RB FW-III	XLPE	NEO	2	14	0.38	I	30

(a) STR=Straight, MAN=Mandrel, RB FW-III=Rockbestos Firewall® III, XLPE=Cross-linked Polyethylene, NEO=Neoprene®, I=Instrumentation

(b) This specimen was included for archiving purposes and were not energized during the LOCA steam exposure. A 2-foot section was removed at each hold point and placed in storage.

Similar to test sequence 1, the accelerated aging applied to the cable specimens in test sequence 3 was based on Rockbestos qualification report QR #1806, which was the qualification basis used by the plant from which the cable was obtained (for details on the qualification process used in that report, see Section 3.1.3).

Based on the qualification parameters specified in Rockbestos report QR #1806, the accelerated aging for the cables in test sequence 3 were determined. For the Group 3.2 cables, the Arrhenius calculation using an activation energy of 1.33 eV indicated that thermal aging at 302°F (150°C) would have required an aging duration of only several minutes due to the minimal amount of aging required to simulate the conditions experienced by the Group 3.3 naturally aged cable. Therefore, the aging temperature was lowered to 248°F (120°C) to provide a more controllable duration. The total integrated radiation dose was calculated to match that to which the naturally aged cable in Group 3.3 was exposed. For the Group 3.4 cables, 40 years of qualified life was simulated using the same thermal aging duration and total integrated radiation dose used in the original qualification. The actual aging conditions received by the test sequence 3 cables are summarized in Table 3.11. Calculations for determining the accelerated aging conditions for test sequence 3 are provided in Appendix A.

During pre-aging of the specimens, one anomaly occurred. During thermal aging of the specimens a facility power failure caused the oven to be shutdown. Oven temperature had returned to ambient by the time the power was restored. After verifying proper functioning of the oven, the oven temperature was increased to the specified aging temperature and the thermal aging proceeded normally. The thermal aging duration was adjusted to account for this downtime and testing resumed. This event in documented as Notice of Anomaly 6 in Appendix B.

3.3.4 Results of Accelerated Aging

Visual examination and baseline elongation-at-break measurements confirmed that all cable specimens were initially in excellent condition. No discoloring or cracking was evident in either the jacket or insulation for any of the specimens. Average elongation-at-break values for the unused cables ranged from 427 percent to 535 percent for the Neoprene® jackets, and from 426 percent to 620 percent for the XLPE insulation, as shown in Table 3.12. Similarly, for the naturally aged cable, EAB values were 598 percent for the jacket and 465 percent for the insulation, indicating excellent ductility for both materials. Baseline results for other CM tests are discussed in Volume 2 of this report.

Following thermal aging, the Group 3.2 specimens (aged to match the naturally aged cable) showed a slight change in condition. Some yellowing of the white insulation was noted; however,no cracking was noted in either the jackets or insulation. Average elongation-at-break values for the jackets decreased slightly from a baseline value of 427 percent to a post-thermal aging value of 362 percent; however,they retained excellent ductility. The EAB values for the white insulation showed a slight decrease from its baseline value of 426 percent to a post-thermal aging value of 391 percent, also indicating excellent ductility.

Neoprene® jackets were brittle with numerous circumferential cracks noted along the entire length of the specimens. Also, the jackets were discolored with areas of whitish/grey noted, and surface contamination was evident in the form of white powdery spots, possibly from additives that had diffused out of the material by the heat and deposited on the surface. EAB values for the jackets were unobtainable due to the extreme brittleness of the material, indicating no ductility remaining. It should be noted that the activation energy of Neoprene® (1.00 eV) is lower than that of XLPE (1.33 eV), therefore, the qualified life simulated would only be approximately 13.5 years for the Neoprene®. The insulation also was degraded, however, not as severely as the jackets. The white insulation appeared dark brown, as if burnt. No cracking was noted in the insulation. EAB values for the insulation were also unobtainable due to the extreme brittleness of the material, indicating no ductility remaining.

The service radiation exposures caused little change in the condition of the Group 3.2 and Group 3.4 specimens. For the Group 3.2 specimens, the jacket and insulation EAB increased slightly to approximately 406 percent and 403 percent, respectively, indicating a slight improvement in ductility. The Group 3.4 specimens were already brittle from the thermal aging, as previously described.

Table 3.11 Actual accelerated aging conditions received by the specimens in Test Sequence 3

Group	Thermal Aging		Service Radiation [a]		LOCA Radiation [a, b]	
	Temperature (°F/°C)	Duration (hours)	Total Integrated Dose (Mrad)	Dose Rate (Mrad/hr.)	Total Integrated Dose (Mrad)	Dose Rate (Mrad/hr.)
3.1	-	None	None	-	Phase 1: 76.61 Phase 2: 76.67	Phase 1: 0.65 Phase 2: 0.64
3.2	248°F (120°C)	9.93	2.27	0.50		
3.3	-	None	None	-		
3.4	302°F (150°C)	1301.16	51.49	0.45		

(a) Radiation exposures for long specimens and/or basket specimens in the same group were performed in multiple runs due to restrictions on the number of sources allowed in the hot cell at one time. Therefore, the radiation doses and dose rates reported are averages for all runs.
(b) The specified LOCA radiation exposure was the same for all groups. It was performed in two separate phases to allow condition monitoring measurements to be taken at the midpoint.

Table 3.12 Average elongation-at-break values for the specimens in Test Sequence 3

Group	Cable	Average elongation-at-break at each CM Point (%)											
		Baseline No Aging		After Thermal Service Aging		After Radiation Service Aging		After Half LOCA Radiation		After Full LOCA Radiation		After LOCA Steam Exposure	
		Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)
3.1 (0 yr.)	Rockbestos PNI79RB188	535	620	NA	NA	NA	NA	184	259	44	65	12	111
	Rockbestos PNI85RB191	443	437	NA	NA	NA	NA	104	208	46	35	16	142
3.2 (match Group 3.3)	Rockbestos PNI85RB191	427	426	362	391	406	403	58	167	37	59	14	125
3.3 (naturally aged 10 yr.)	Rockbestos PAP86RB229	598	465	NA	NA	NA	NA	245	214	93	85	14	120
3.4 (40 yr.)	Rockbestos PNI79RB188	532	620	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5

(a) EAB values are for white insulation.

The post-thermal aging appearance of the Group 3.4 cable jackets (aged to 40 years) was extremely poor. The In summary, after completion of the accelerated aging, all of the Group 3.1, 3.2, and 3.3 specimens appeared to be in good physical condition with good ductility and no cracking evident in any of the specimens. The Group 3.4 specimens appeared to be severely degraded with extensive cracking in the jackets; however, no cracking was evident in the insulation. Insulation resistance measurements indicated that electrically, the insulation in all specimens was in acceptable condition, including the specimens in Group 3.4. The appearance of the cable specimens is similar to those shown in Figures 3.1 and 3.2 for the test sequence 1 specimens.

3.3.5 LOCA Conditions Simulated

The LOCA conditions simulated included exposure to 150 Mrad of accident radiation, followed by exposure to steam at high temperature and pressure. The accident radiation exposure was performed after completion of the service aging and prior to the steam exposure.

Following accident irradiation, the specimens were subjected to a high temperature and pressure steam exposure. The test chamber temperature/pressure profile for the LOCA steam exposure in test sequence 3 was obtained from Rockbestos report QR #1806, as previously discussed, and is the same as that used in test sequence 1. Figure 3.3 presents this profile. As for test sequence 1, the steam exposure was shortened to 7 days to expedite testing.

3.3.6 Results of LOCA Radiation and Steam Exposure

Exposure to the full LOCA radiation did cause a noticeable drop in EAB for all of the specimens in Groups 3.1, 3.2, and 3.3. The EAB values for the jackets after the full LOCA radiation ranged from 37 percent for Group 3.2 to 93 percent for those in Group 3.3, indicating a significant loss in ductility. Similarly for the insulation, EAB values dropped to approximately 35 percent in Group 3.1 to 85 percent in Group 3.3. Still, no insulation or jacket cracking was evident in any of the Group 3.1, 3.2 or 3.3 specimens, or in the Group 3.4 insulation.

During the accident irradiation, the average dose rate achieved for the long Unistrut® mounted specimens was 0.644 Mrad/hr and for the baskets it was 0.791 Mrad/hr. Both of these dose rates were below the specified dose rate of 1.0 Mrad/hr (+0/-20 percent). Also, the dose rate achieved for the mandrel mounted specimens was 1.001 Mrad/hr, which is above the specified dose rate. These deviations were determined not to cause any significant impact on the test results; therefore, testing was resumed. This event is documented as Notice of Anomaly 8 in Appendix B.

Prior to initiating the LOCA simulation, the test chamber was preheated to 140°F (60°C) with saturated steam and was held for approximately 55 minutes. Chamber pressure during this hold period was slightly above atmospheric, at approximately 4 to 5 psig.

Within the first minute of steam introduction into the test chamber, leakage currents were noted for two of the Group 3.4 specimens (pre-aged to simulate 40 years of service), 0313 and 0314. The leakage for specimen 0313 ranged from approximately 3 to 4 mA during the first 25 minutes of preheat, while that for specimen 0314 ranged from 0.2 to 2 mA during this period. At approximately 26 minutes into the preheat, the 1/32 amp (31.25 mA) fuse protecting the power supply to the instrument loop circuit for specimen 0313 blew. Several attempts were made to replace the fuse; however, each new fuse blew almost immediately. Specimen 0313 was left de-energized at this point.

At approximately 55 minutes into preheat, a leakage current was noted for a third Group 3.4 specimen, 0312. The leakage was approximately 1.6 mA. No anomalies were noted for any of the Group 3.1, 3.2 or 3.3 specimens during preheat.

Following preheat, the first LOCA transient was initiated with chamber temperature and pressure being ramped up to approximately 354°F (178.9°C) and 115 psig, respectively, in approximately 5 minutes. Conditions were then held for approximately 3 hours, after which the temperature and pressure were reduced to preheat conditions. Pressure in the common manifold was relatively constant at approximately 15 psig throughout the LOCA test. This corresponded to a nominal loop current of 12.0 mA in the pressure transmitter circuits.

Immediately prior to initiation of the first transient, a new fuse was placed in the circuit for specimen 0313 to re-energize it. A leakage current of approximately 3.5 mA was noted; however,the circuit continued to operate for approximately 2 minutes, after which the fuse blew again.

Throughout the first transient and the subsequent three hour hold period, leakage currents were noted for three of the remaining four Group 3.4 specimens that were still operating. Leakage for specimen 0312 ranged from 0.2 mA to 3.9 mA, while that for specimens 0314 and 0315 was lower, ranging from 0.2 to 0.6 mA. No leakage current was noted for Group 3.4 specimen 0316, nor for any of the Group 3.1, 3.2 or 3.3 specimens.

It was noted that the "A" and "B" circuit current (see circuit diagrams in Figures 2.13 and 2.14) for all of the specimens remained relatively constant and equal at approximately 11.7 mA during this period. This is of interest since leakage currents were noted for the Group 3.4 specimens; however, this did not impact the cable's ability to maintain circuit current. The manifold pressure at this time had dropped to approximately 14.7 psig from the 15.0 psig initial value due to inaccuracies in the pressure controller, which would explain the drop in circuit current from its initial value of 12.0 mA.

During the cool down to preheat conditions following completion of the 3-hour hold, all of the leakage currents dropped below the measuring range of the test equipment.

Following the cool down to preheat conditions, the second LOCA transient was initiated with chamber temperature and pressure being ramped up to approximately 353°F (178.3°C) and 113 psig, respectively, in approximately 4 minutes. Conditions were then held for approximately 3 hours. During the 3-hour hold a power failure occurred at Wyle. This caused circuit voltage to drop temporarily, along with test chamber pressure and temperature; however, power was restored within 1 minute and all test parameters returned to their values prior to the outage. The power outage did not have an impact on test performance. Pressure in the common manifold remained relatively constant at approximately 14.5 to 15.0 psig throughout this period of the LOCA test.

Specimen 0313 remained de-energized for this portion of the LOCA test. As test chamber temperature and pressure increased for the second transient, leakage currents increased for Group 3.4 specimens 0312, 0314 and 0315. Throughout the second transient and the three hour hold period, leakage currents were noted for these three specimens. Leakage for specimen 0312 ranged from 0.2 mA to 1.2 mA, while that for specimens 0314 and 0315 was lower, ranging from 0.2 to 0.7 mA. No leakage current was noted for Group 3.4 specimen 0316, nor for any of the Group 3.1, 3.2 or 3.3 specimens.

As for the first transient, it was noted that the "A" and "B" circuit currents for all of the specimens remained relatively constant and equal at approximately 11.5 to 11.7 mA during this second transient and hold period. Again, while leakage currents were noted for the Group 3.4 specimens, this did not impact the cable's ability to maintain circuit current. The manifold pressure at this time had dropped to approximately 14.6 psig from the 15.0 psig initial value due to inaccuracies in the pressure controller, which would explain the drop in circuit current from its initial value of 12.0 mA.

After completion of the second 3-hour hold period, test chamber temperature and pressure were gradually reduced in four steps to 212°F (100°C) and 0 psig over the next seven days, as indicated in Figure 3.3. At each step, conditions were held and allowed to stabilize.

At approximately 9 hours into the test, a thermocouple used to control LOCA chamber temperature failed causing the chamber temperature and pressure to drop below the specified profile for approximately 18 minutes. The thermocouple was replaced with a spare and testing was resumed. The chamber temperature and pressure were increased to the profile requirements and 18 minutes were added to the test duration to account for the time below the profile. This event is documented as Notice of Anomaly 7 in Appendix B.

During the cool down, when test chamber pressure reached 32 psig, at 15 hours 20 minutes from test initiation, the chemical spray was initiated and maintained for 24 hours. At 15 hours 22 minutes into the test, a leakage current of 1.7 mA was noted for specimen 0316. Test chamber conditions were 270°F (132.2°C) and 27.6 psig. This was the first occurrence of leakage for this specimen. Leakage current for this specimen continued sporadically for the next several days ranging from 0 to 1 mA. Leakage currents also continued for Group 3.4 specimens 0312 and 0315 during the cool down portion of the test, ranging from 0 to 1 mA on the average. Leakage for 0312 showed several spikes to approximately 4 mA during the period from 35 to 55 hours into the test.

At 15 hours 23 minutes from test initiation, specimen 0313 was re-energized by replacing the fuse in the instrument loop circuit and it continued to operate. A leakage current of 2.3 mA was noted for this specimen when it was re-energized. Also, a circuit current mismatch was noted for this specimen with the "A" current at approximately 13.9 mA and the "B" current at 11.9 mA. The manifold pressure being monitored by the circuit was at its nominal value of 15.0 psig at this time. The leakage current for this specimen continued to increase to over 20 mA, and at 23 hours 12 minutes into the test, the fuse blew for the third time. Test chamber conditions were 268°F (131.1°C) and 28.2 psig. The specimen was left de-energized for the remainder of the test.

At 65 hours 20 minutes into the test, the fuse for Group 3.4 specimen 0316 blew. Test chamber conditions were 269°F (131.7°C) and 30 psig.

Table 3.13 presents a summary of the functional performance anomalies noted for each of the specimen groups. The maximum deviation shown in the table represents the percent of instrument full scale, which for the 4-20 mA pressure transmitters is 16 mA, that the signal varied from its nominal value. Therefore, a 10 percent variation would represent a 10 percent error in the pressure reading. It should be noted that the variation in manifold pressure being monitored by the circuits was +4.7 percent to -2.7 percent from its nominal value of 15.0 psig. The number of blown fuses indicates the number of times during the test the total circuit current exceeded 1/32 amp, which is the capacity of the fuse used in the circuit.

The data in Table 3.13 show that the Group 3.1 (no accelerated aging), Group 3.2 (accelerated aging to match the naturally aged cable) and Group 3.3 (naturally aged) specimens showed no anomalies during the LOCA test. Group 3.4 specimens (accelerated aging to simulate 40 years of service) all had anomalies, including circuit current deviations, leakage currents and/or blown fuses.

3.3.7 Results of Post-LOCA Testing

Following the LOCA steam exposure test, a post-LOCA inspection was performed in which in situ insulation resistance measurements were made on all of the specimens before and after opening the test chamber. The results showed generally lower insulation resistance than prior to the LOCA steam exposure, especially in the Group 3.4 specimen circuits.

The Group 3.4 specimens were then removed from the chamber and the nuclear grade Raychem® splices connecting them to the test instrumentation leads were cut off at both ends of each specimen in order to isolate and physically locate the problem areas causing the performance anomalies. Insulation resistance measurements were repeated for each Group 3.4 specimen and for each individual Raychem® splice removed from the Group 3.4 specimens. This series of IR measurements showed acceptable values for four of the five cable specimens thereby indicating that the problem was in the splice. The IR measurements of the splices confirmed this, with each splice showing a low insulation resistance.

Disassembly, inspection, and testing of the Raychem® splices revealed water inside the splices. Cracks were also noted in the insulation inside the splice. A dissected splice is shown in Figure 3.17. Based on these observations, it was concluded that moisture intrusion into the splices, together with the insulation faults within the splices, had contributed to the Group 3.4 insulation resistance anomalies noted in the in situ measurements. The installation of these splices on cables with cracked and embrittled jackets is not a typical application for which this splice configuration was designed. Similar problems were observed in test sequence 1 when splices were applied on cables with damaged jackets. Although custom engineered splice kits were used for test sequence 3, and technicians were given training in the installation of

Table 3.13 Summary of performance anomalies during LOCA Test 3 steam exposure

Group	Specimen No.	Maximum Deviation (% Full Scale)		Number of Fuses Blown	Maximum Leakage Current (mA)
		Side "A" Current	Side "B" Current		
3.1 (No aging)	0301	± 2	± 2	0	0
	0302	± 2	± 2	0	0
3.2 (Aged to match Group 3.3)	0303	± 2	± 2	0	0
	0304	+1 / -2	± 2	0	0
	0305	+1 / -2	± 2	0	0
	0306	+1 / -2	+1 / -2	0	0
3.3 (Naturally aged)	0307	± 2	+1 / -2	0	0
	0308	+1 / -2	± 1	0	0
	0309	+1 / -2	+1 / -2	0	0
	0310	+1 / -3	+1 / -3	0	0
	0311	± 2	± 2	0	0
3.4 (Aged to 40 years)	0312	+1 / -2	± 2	0	3.9
	0313 (a)	+24 (a)	-1 (b)	3	26.7
	0314	+6 / -1	± 2	0	12.4
	0315	+1 / -2	± 2	0	1.1
	0316 (c)	+18 / -2	+1 / -3	1	1.7

(a) Functional test for specimen 0313 abandoned after 18.5 hours.
(b) Circuit current deviation for specimen 0313 measured prior to the fuse blowing for the second time during period when circuit was operational.
(c) Functional test for specimen 0316 abandoned after 65 hours.

these splices, moisture was still observed inside the splices. The high pressure steam in the LOCA chamber environment forced moisture into the cable through cracks in the jacket, where it was driven along the interior of the jacket, directly into the interior of the splice. Once there, cracks in the insulation allowed the moisture to provide a conductive path between cable conductors. Since the insulation was fairly brittle after aging, cracking could have occurred during application of the splices or during condition monitoring of the cables when the conductors were handled, even though special precautions were taken to minimize the potential for handling damage.

Specimen 0313 continued to show an anomaly even after its splices were removed. The white-to-black conductor setup would not hold the full 500 volts; the voltage had to be reduced to 100 volts to obtain a reading. It was noted during the condition monitoring visual inspection that this specimen was cracked at the point where it was fastened by a cable tie to its protective Unistrut® support channel. Cable ties were applied by hand on the test specimens with just enough force to hold them in place. The cable "hinged" at that point when the end was handled. Although great care was taken throughout the test sequence to minimize handling damage, some was unavoidable. Subsequent testing by BNL confirmed a fault at this location by running insulation resistance measurements while tap water was sprayed along the length of the cable. Once the area near the cable tie was sprayed with water, the IR reading dropped to zero, indicating a short circuit. This area of the specimen is shown in Figure 3.18.

The cable specimens are handled numerous times during the testing process: during connection of test instruments at each of the six condition monitoring points, during installation of Raychem® splices to connect instrumentation test leads prior to the LOCA steam exposure, and finally during cutting away of the Raychem® splices for inspection and troubleshooting. The long cable specimens were immobilized and mounted in protective Unistrut® channels or on stainless steel mandrels throughout the pre-aging and LOCA testing process. Extreme care was always used while moving or working on the cables. Nevertheless, the possibility of handling damage could not be totally avoided, especially as the cable materials became more and more embrittled in the latter stages of the process. Investigative experiments at BNL on aged and LOCA-exposed cables confirmed that physical handling of cable ends, even when mounted in a protective channel, could produce damage identical to that observed on specimen 0313. This type of damage was also shown to have affected not only the outer jacket, but the cable insulation as well.

After post-LOCA inspections were completed, a voltage withstand test was conducted on each of the test sequence 3 cable specimens. The cables were submerged in tap water at room temperature and subjected to 2,400 Vac for 5 minutes. All of the cables performed acceptably with the exception of 0313, which could not hold the full 2,400 Vac test voltage (i.e., with 2,400 Vac applied, leakage current exceeded the range of the measuring instrument). The location at which specimen 0313 failed was determined to be just outboard of the last cable tie where it was fastened to the Unistrut® channel. This was the same location identified during the post-LOCA visual inspection as the site of handling damage.

The results of the voltage withstand test are presented in Table 3.14.

3.4 Test Sequence 4: Multiconductor Cables

3.4.1 Test Objectives

The objective of this test sequence was to determine if multiconductor cables have any unique failure mechanisms that are not present in single conductor cables.

3.4.2 Description of Test Specimens

To meet the objective of this test, multiconductor cables from two different manufacturers were tested; Anaconda and Samuel Moore. The source cable sample used for the Anaconda unaged specimens in test sequence 4 was DNP78AN008, which is a 3/C #16 AWG, 1,000 V cable with a shield and ground wire. The conductors were insulated with 30 mils of EPR with a 15-mil CSPE individual jacket, and a 45-mil CSPE overall outer jacket. The source cable sample used for the Samuel Moore unaged specimens in test sequence 4 was PNI82SM008, which is a 2/C #16 AWG, 600 V cable with a shield and ground wire. The conductors were insulated with 20 mils of Dekoron®, which is ethylene propylene diene monomer (EPDM), with a bonded 10-mil Dekorad® (CSPE) individual jacket, and a 45-mil Dekorad® (CSPE) overall outer jacket. Each cable was tested in both the multiconductor and single conductor configuration. Single conductor specimens were made by disassembling a multiconductor length of cable. There were no naturally aged cable specimens in this test.

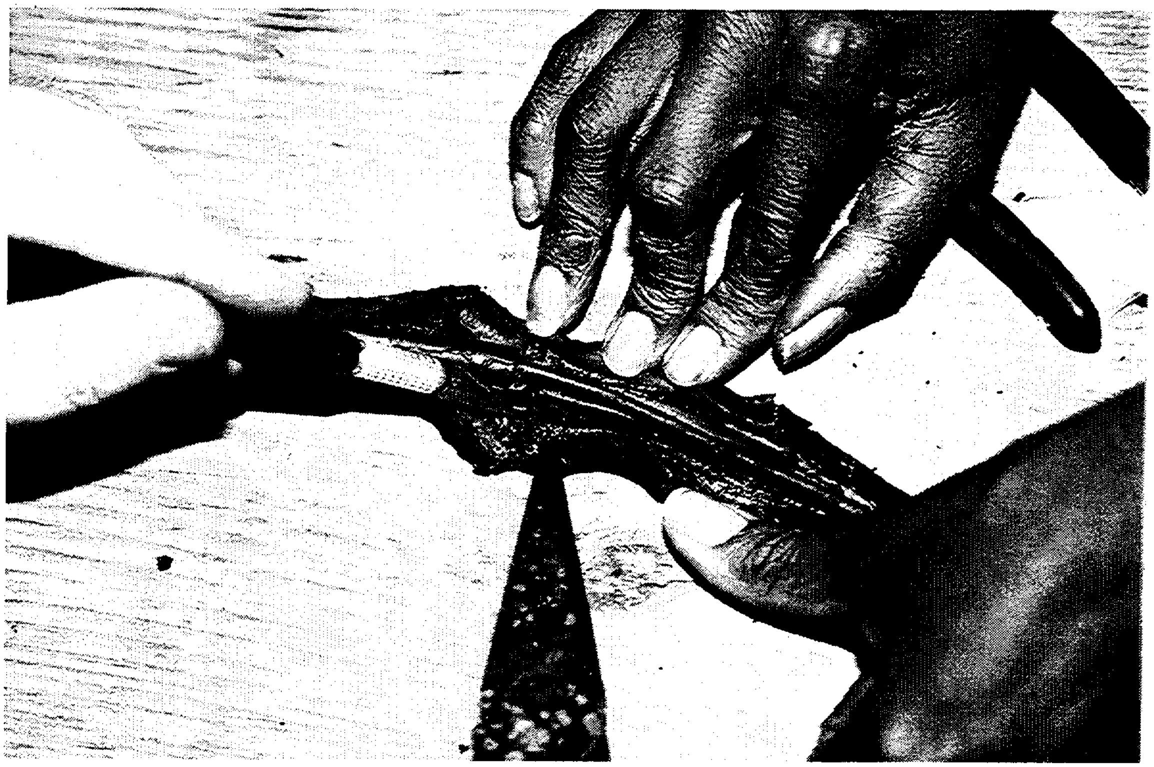

Figure 3.17 Dissected splice from a Group 3.4 specimen after LOCA testing

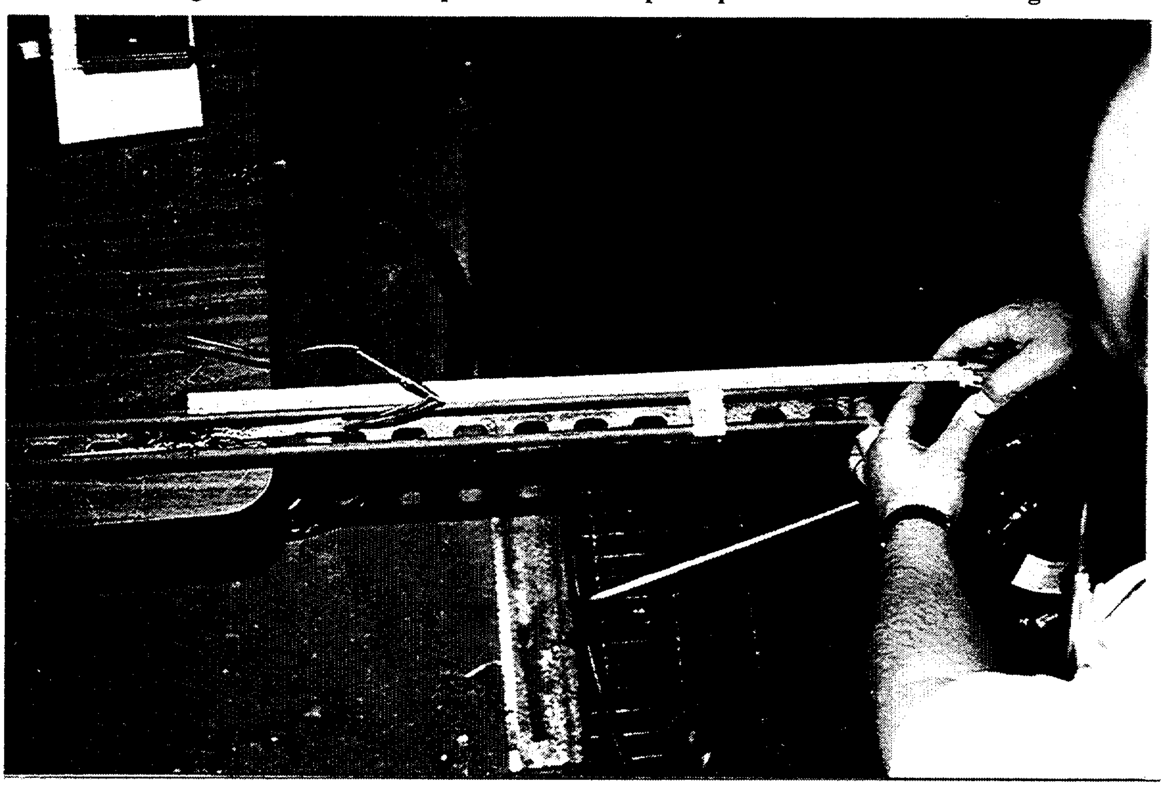

Figure 3.18 Specimen 0313 fault location near outboard cable tie

Table 3.14 Results of submerged voltage withstand test on specimens in Test Sequence 3

Group	Specimen No.	Manufacturer	Applied Voltage (Vac)	Leakage (microamps)		Pass/Fail
				White Conductor	Black Conductor	
3.1 (no aging)	0301	Rockbestos	2,400	590	550	Pass
	0302		2,400	500	520	Pass
3.2 (aged to match Group 3.3)	0303 [(a)]	Rockbestos	2,400	450	590	Pass
	0304		2,400	510	600	Pass
	0305		2,400	510	525	Pass
	0306 [(a)]		2,400	350	375	Pass
3.3 (naturally aged)	0307	Rockbestos	2,400	520	580	Pass
	0308		2,400	550	590	Pass
	0309		2,400	500	520	Pass
	0310		2,400	580	600	Pass
	0311 [(a)]		2,400	350	360	Pass
3.4 (aged to 40 years)	0312 [(a)]	Rockbestos	2,400	1,200	1100	Pass
	0313 [(a)]		200 [(b)]	> 5000	> 5000	**Fail**
	0314 [(a)]		2,400	1300	1150	Pass
	0315 [(a)]		2,400	1,400	1275	Pass
	0316 [(a)]		2,400	950	1050	Pass

(a) Splices were removed from specimen ends prior to voltage withstand testing.
(b) Specimen would not hold 2,400 volts; test performed at lower voltage noted.

The cable samples used in the test were acquired from Sandia National Laboratory. They are the same cables used in past Sandia tests (Bustard, 1983; Jacobus, 1992). Since the cables were originally purchased by Sandia in the early to mid 1980s, they were approximately 15 to 20 years old at the time of testing by BNL. Visual inspection and elongation-at-break testing were performed on the as-received cables to verify they were in excellent condition with no observable signs of degradation. Once received at BNL, the cables were assigned a unique identification number for traceability and maintained in an environmentally controlled storage area and continuously monitored for temperature and humidity to ensure no additional degradation occurred.

For test sequence 4, 18 long cable specimens were prepared, as shown in Table 3.15. As in previous tests, the cable samples were cut into both long and short (6-inch) specimens for testing. However, for this test the long specimens included both 10-foot and 30-foot lengths. The long specimens were installed on stainless steel mandrels to simulate actual qualification testing. A mandrel diameter of approximately 13.5 inches was used. The mandrel design was modified for this, and subsequent tests, to include a 2-foot Unistrut® arm to support the ends of the test specimen as they were routed away from the mandrel to further mitigate potential handling damage to the cables during splice application and CM testing. In addition, short (2-foot to 3-foot) pigtails were spliced to the 10-foot test specimens using Raychem® nuclear grade splices prior to any accelerated aging to avoid handling damage to the test specimens after they had been pre-aged. After pre-aging had been completed, the facility test lead wires were connected to the pigtails on the 10-foot specimens using a second splice, which stayed inside the test chamber, and the test lead wires were extended through the LOCA test chamber wall. The 30-foot specimens were extended through the test chamber wall directly without the use of pigtails or spliced test lead wires within the chamber. Facility test leads were connected to the ends of the 30-foot specimens outside the test chamber. Special Swagelock penetration assemblies, similar to those used by Sandia, were installed outside the test chamber for the 30-foot specimens. The pigtails on the 10-foot specimens, and the ends of the

Table 3.15 Description of specimens in Test Sequence 4

Group	Specimen ID No.	Sample ID No.	Configuration (a)	Manufacturer (a)	Insulation Material (a)	Jacket Material (a)	No. of Conductors	Wire Gauge (AWG)	Cable Diameter (in.)	Cable Type (a)	Insulation Thickness (mils) (c)
4.1	0401	DNP78AN008	10 FT - MAN	AN	EPR(e)	CSPE	3	12	0.475	P	30
	0402	PNI82SM008	10 FT - MAN	SM	EPDM(d)	CSPE	2 w/shld&gnd	16	0.315	I	20
4.2	0403	PNI82SM008	10 FT - MAN	SM	EPDM(d)	CSPE	1	16		I	20
	0404	PNI82SM008	10 FT - MAN	SM	EPDM(d)	CSPE	2 w/shld&gnd	16	0.315	I	20
	0405	PNI82SM008	30 FT - MAN	SM	EPDM(d)	CSPE	1	16		I	20
	0406	PNI82SM008	30 FT - MAN	SM	EPDM(d)	CSPE	2 w/shld&gnd	16	0.315	I	20
4.3	0407	DNP78AN008	10 FT - MAN	AN	EPR(e)	CSPE	1	12		P	30
	0408	DNP78AN008	10 FT - MAN	AN	EPR(e)	CSPE	3	12	0.475	P	30
	0409	DNP78AN008	30 FT - MAN	AN	EPR(e)	CSPE	1	12		P	30
	0410	DNP78AN008	30 FT - MAN	AN	EPR(e)	CSPE	3	12	0.475	P	30
	0411	DNP78AN008	30 FT - MAN	AN	EPR(e)	CSPE	3	12	0.475	P	30
	0412	PNI82SM008	10 FT - MAN	SM	EPDM(d)	CSPE	1	16		I	20
	0413	PNI82SM008	10 FT - MAN	SM	EPDM(d)	CSPE	2 w/shld&gnd	16	0.315	I	20
	0414	PNI82SM008	30 FT - MAN	SM	EPDM(d)	CSPE	1	16		I	20
	0415	PNI82SM008	30 FT - MAN	SM	EPDM(d)	CSPE	2 w/shld&gnd	16	0.315	I	20
	0416	PNI82SM008	30 FT - MAN	SM	EPDM(d)	CSPE	2 w/shld&gnd	16	0.315	I	20
Archive	0417 (b)	DNP78AN008	10 FT - STR	AN	EPR(e)	CSPE	3	12	0.475	P	30
	0418 (b)	PNI82SM008	10 FT - STR	SM	EPDM(d)	CSPE	2 w/shld&gnd	16	0.315	I	20

(a) STR=Straight, MAN=Mandrel, AN=Anaconda, SM=Samuel Moore, EPR=Ethylene Propylene Rubber, EPDM=Ethylene Propylene Diene Monomer, CSPE=Chloro-sulfonated Polyethylene, I=Instrumentation, P=Power

(b) These specimens were included for archiving purposes and were not energized during the LOCA steam exposure. A 2-foot section was removed at each hold point and placed in storage.

(c) Thickness of EPR insulation only; does not include 15 mil CSPE individual jacket for Anaconda cables nor 10 mil CSPE individual jacket for Samuel Moore cables.

(d) Insulation covered with bonded CSPE individual jacket.

(e) Insulation covered with unbonded CSPE individual jacket.

30-foot specimens were shielded from the conditions of thermal and radiation aging, to the extent possible, to keep them from becoming brittle.

Two 10-foot specimens were prepared and mounted in straight Unistrut® supports. These specimens received pre-aging similar to the specimens in Group 4.4, and were used for archiving purposes.

Preparation of the 6-inch short specimens involved removing the cable outer jacket from the individual conductors, and removing the copper conductors from the insulation. Since the individual CSPE jacket was not bonded to the EPR insulation in the Anaconda specimens, it was removed and both were tested independently. In the Samuel Moore specimens, the individual CSPE jacket was bonded to the underlying EPR insulation and could not be removed.

Therefore, the composite EPR insulation with bonded CSPE individual jacket was tested as one specimen. The outer CSPE jackets from the Samuel Moore and Anaconda specimens were punched into a standardized "dog bone" configuration for EAB testing, as in previous tests. The insulation specimens were left in a tubular configuration for testing. The short specimens were placed in stainless steel mesh baskets. Five short cable jacket and insulation specimens were inserted into each basket. The baskets were then designated for removal at specific CM points for materials testing.

3.4.3 Accelerated Aging Parameters

The specimens in test sequence 4 can be grouped according to the pre-aging they received as follows: in Group 4.1, one Anaconda specimen and one Samuel Moore specimen were prepared and LOCA tested without any pre-aging. Group 4.2 included four Samuel Moore specimens, which were pre-aged to the equivalent of 20 years of qualified life prior to LOCA testing. Group 4.3 included five Anaconda specimens and five Samuel Moore specimens, which were pre-aged to the equivalent of 40 years of qualified life prior to LOCA testing. In addition, one Anaconda and one Samuel Moore specimen were pre-aged to the equivalent of 40 years of qualified life and used as archive specimens. The three pre-aging groups for test sequence 4 are summarized as follows:

Group 4.1: Anaconda and Samuel Moore with no accelerated aging (control specimens).
Group 4.2: Samuel Moore with accelerated aging to simulate 20 years of qualified life.
Group 4.3: Anaconda and Samuel Moore with accelerated aging to simulate 40 years of qualified life.

As in previous tests, the accelerated aging parameters were selected to match those used for the original qualification testing of the cables. For the Anaconda cables, Franklin Institute Research Laboratories report F-C4350-3 (FIRL, July 1976) was used, while for the Samuel Moore cables, Isomedix report LOCA XLPO/EPDM (Isomedix, June 1978) was used.

In the FIRL report, Anaconda cables were qualified to 40 years of service at a temperature of 156°F (69°C), as determined by an Arrhenius calculation[6]. The accelerated aging used in this qualification included thermal aging at 302°F (150°C) for 168 hours followed by 200 Mrad of radiation at an average dose rate of 0.35 Mrad per hour. The cables were subsequently exposed to a 30-day LOCA steam profile while energized with rated voltage and current to simulate service under LOCA conditions. The LOCA profile included one peak at 346°F (174 °C) and 113 psig. After LOCA testing, the cables were straightened and recoiled around a mandrel with a diameter 40 times that of the cables. The mandrels were immersed in tap water and a voltage of 80 volts per mil of insulation was applied (2,400 Vac for the 30-mil thickness of the insulation).

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[6] FIRL report F-C4350-3 does not specifically identify the qualified life or service temperature to which the Anaconda cables were qualified. However, based on an activation energy of 1.18 eV, an Arrhenius calculation shows that the accelerated aging performed equates to 40 years at 156°F (69 °C).

In the Isomedix report, Samuel Moore cables were qualified to 40 years of service at a temperature of 122°F (50°C), as determined by an Arrhenius calculation[7]. The accelerated aging used in this qualification included irradiation to 25 Mrad followed by thermal aging at 250°F (121°C) for 168 hours followed by an additional 175 Mrad of radiation at an average dose rate of 0.75 Mrad per hour. The cables were subsequently exposed to a 30-day LOCA steam profile while energized with rated voltage and current to simulate service under LOCA conditions. The LOCA profile included two peaks at 340°F (171°C) and 105 psig. After LOCA testing, the cables were straightened and recoiled around a mandrel with a diameter 40 times that of the cables. The mandrels were immersed in tap water and a voltage of 80 volts per mil of insulation was applied (2,400 Vac for the 30-mil thickness of the combination insulation and individual jacket).

The actual aging conditions received by the test sequence 4 specimens are summarized in Table 3.16.

Table 3.16 Actual accelerated aging conditions received by the specimens in Test Sequence 4

<table>
<tr><th rowspan="2">Group</th><th colspan="2">Thermal Aging</th><th colspan="2">Service Radiation (a)</th><th colspan="2">LOCA Radiation (a)</th></tr>
<tr><th>Temperature (°F/°C)</th><th>Duration (hours)</th><th>Total Integrated Dose (Mrad)</th><th>Dose Rate (Mrad/hr.)</th><th>Total Integrated Dose (Mrad)</th><th>Dose Rate (Mrad/hr.)</th></tr>
<tr><td>4.1</td><td>-</td><td>None</td><td>None</td><td>-</td><td rowspan="4">154.30</td><td rowspan="4">0.60</td></tr>
<tr><td>4.2</td><td>250°F (121°C)</td><td>84.85</td><td>25.99</td><td>0.65</td></tr>
<tr><td>4.3 Anaconda</td><td>302°F (150°C)</td><td>169.20</td><td>53.60</td><td>0.34</td></tr>
<tr><td>4.3 Samuel Moore</td><td>250°F (121°C)</td><td>169.05</td><td>51.57</td><td>0.75</td></tr>
</table>

(a) Radiation exposures for long specimens and/or basket specimens in the same group were performed in multiple runs due to restrictions on the number of sources allowed in the hot cell at one time. Therefore, the radiation doses and dose rates reported are averages for all runs.

During thermal aging of the specimens, two anomalies occurred. In the first, the shutdown time for the ovens was miscalculated. As a result, the Samuel Moore specimens in Group 4.3 were aged for 169 hours 3 minutes instead of the specified 168 hours (+1/-0 hr.). Also, the Anaconda specimens in Group 4.3 were aged for 169 hours 12 minutes instead of the specified 168 hours (+1/-0 hr.). In addition, the thermal aging oven at 302°F (150°C) dropped below the specified temperature to 290°F (143°C) for 1 hour 43 minutes, after which it returned to the specified temperature. The cause of this anomaly is unknown. It was determined that neither of these anomalies would significantly impact the test results, therefore, testing was resumed. These events are documented as Notices of Anomaly 9 and 10 in Appendix B.

3.4.4 Results of Accelerated Aging

Visual examination and baseline elongation-at-break measurements confirmed that all cable specimens were initially in excellent condition. No discoloring or cracking was evident in either the jacket or insulation for any of the specimens. Average elongation-at-break values for the unused Anaconda cables were 356 percent for the EPR insulation and 476 percent for the CSPE outer jackets, as shown in Table 3.17. Similarly, for the unused Samuel Moore cables, average EAB values were 475 percent for the composite EPR insulation with CSPE individual jacket and 696 percent for the CSPE outer jacket. These results confirmed excellent ductility for the materials in both cables.

[7] Isomedix report LOCA XLPO/EPDM does not specifically identify the qualified life or service temperature to which the Samuel Moore cables were qualified. However, based on an activation energy of 1.18 eV, an Arrhenius calculation shows that the accelerated aging performed equates to 40 years at 122 °F (50 °C).

The Group 4.2 Samuel Moore cables were artificially aged to simulate 20 years of qualified life, as determined from the original qualification report. The EAB tests, as well as the visual inspections indicated that the Samuel Moore cables were in acceptable condition throughout the thermal and radiation pre-aging sequence. No cracks were evident and the cables remained relatively flexible with average EAB values after thermal and radiation service aging to the equivalent of 20 years of qualified life of 422 percent for the CSPE outer jacket and 261 percent for the composite insulation. The average EAB values for the Anaconda cables after thermal and radiation service aging to the equivalent of 20 years of qualified life was 87 percent for the CSPE outer jacket and 138 percent for the EPR insulation.

Table 3.17 Average elongation-at-break values for the specimens in Test Sequence 4

Group	Cable	Average elongation-at-break at each CM Point (%)											
		Baseline No Aging		After Thermal Service Aging		After Radiation Service Aging		After Half LOCA Radiation		After Full LOCA Radiation		After LOCA Steam Exposure	
		Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)	Outer Jkt.	Insul. (a)
4.1 (0 yr.)	Anaconda DNP78AN008	476	356	NA	NA	NA	NA	91	187	150	138	81	140
	Sam Moore PNNI82SM008	696	475	NA	NA	NA	NA	231	151	223	130	59	98
4.2 (20 yr.)	Anaconda DNP78AN008	476	356	136	221	87	138	NA	NA	NA	NA	NA	NA
	Sam Moore PNI82SM008	762	467	557	397	422	261	142	131	102	103	27	71
4.3 (40 yr.)	Anaconda DNP78AN008	476	356	24	21	11	13	10	11	9	16	11	< 5
	Sam Moore PNI82SM008	696	475	564	288	312	173	92	90	103	98	28	46

(a) Elongation-at-break value for Samuel Moore insulation is for the composite EPR/CSPE insulation, while the EAB for the Anaconda insulation is for the EPR insulation alone.
NA = not applicable

The Group 4.3 cables were artificially aged to simulate 40 years of qualified life. The EAB tests and visual examinations showed that the Samuel Moore cables were in good condition and remained moderately flexible with no cracking evident. The average EAB values after thermal and radiation service aging to the equivalent of 40 years of qualified life for the Samuel Moore cables was 312 percent for the CSPE outer jacket and 173 percent for the composite insulation. The Anaconda cables appeared degraded and were somewhat stiff; however, no cracking was evident. The average EAB values after thermal and radiation service aging to the equivalent of 40 years of qualified life for the Anaconda cables was 11 percent for the CSPE outer jacket and 13 percent for the EPR insulation. The additional degradation to the Anaconda specimens is due to the more severe aging since the Anaconda cable was qualified to a service temperature of 194°F (90°C), while the Samuel Moore cable was qualified to 122°F (50°C).

The LOCA radiation further reduced the EAB values for all specimens, with the exception of the Group 4.3 Anaconda specimens, which showed a marginal increase for the EPR insulation. The average EAB values after thermal and radiation service aging to the equivalent of 40 years of qualified life plus LOCA radiation for the Samuel Moore cables was 103 percent for the CSPE outer jacket and 98 percent for the composite insulation. The average EAB values after thermal and radiation service aging to the equivalent of 40 years of qualified life plus LOCA radiation for the Anaconda cables was 9 percent for the CSPE outer jacket and 16 percent for the EPR insulation. No cracking was evident in any of the specimens.

Figure 3.19 shows Anaconda single conductor specimen 0409 from Group 4.3 (pre-aged to 40 years) after completion of thermal and radiation service aging. As shown, the specimen appeared in good physical condition with no cracking or discoloring noted. Similarly, Figure 3.20 shows Anaconda multiconductor specimens 0410 and 0411 after accelerated service aging, which also appeared in good physical condition. Figures 3.21 and 3.22 show Samuel Moore single conductor and multiconductor specimens 0412 and 0415 from Group 4.3 (pre-aged to 40 years), respectively, after thermal and radiation service aging. Again, these specimens appeared in good physical condition with no cracking or discoloring evident.

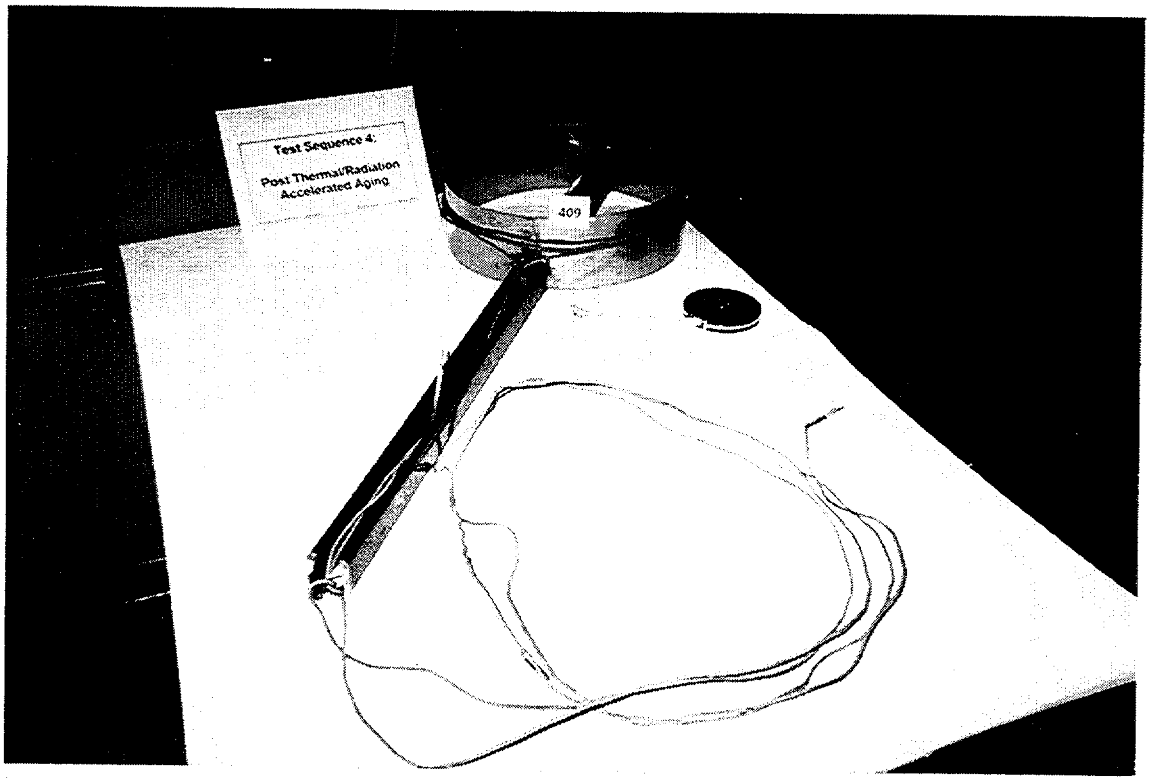

Figure 3.19 Anaconda single conductor specimen 0409 from Group 4.3 (pre-aged to 40 years) after accelerated service aging

3.4.5 LOCA Conditions Simulated

The LOCA conditions simulated included exposure to 150 Mrad of accident radiation , followed by exposure to steam at high temperature and pressure. The accident radiation exposure was performed after completion of the service aging and prior to the steam exposure.

Following accident irradiation, the specimens were subjected to a high temperature and pressure steam exposure. Since cable specimens from two different manufacturers were included in this test, the LOCA test profile was chosen to envelop the original qualification test profiles used for both cables. The original qualification test for the Anaconda cable consisted of a 30-day test with a single peak at 346°F (174°C) and 113 psig, while that for the Samuel Moore cable consisted of a 30-day test with two peaks at 340°F (171°C) and 105 psig. Comparison of these two profiles with that used in Tests 1 and 3 for this program showed that the latter conservatively enveloped both of the LOCA test profiles used for these cables. Therefore, the profile used in this test is the same one used in tests 1 and 3, with the exception that the duration was extended to 10 days to correspond with the duration used in previous testing by Sandia (Jacobus, 1992). The LOCA 4 test profile included a double peak at a maximum temperature of 346°F (174°C) and a pressure

Figure 3.20 Anaconda multiconductor specimens 0410 and 0411 from Group 4.3 (pre-aged to 40 years) after accelerated service aging

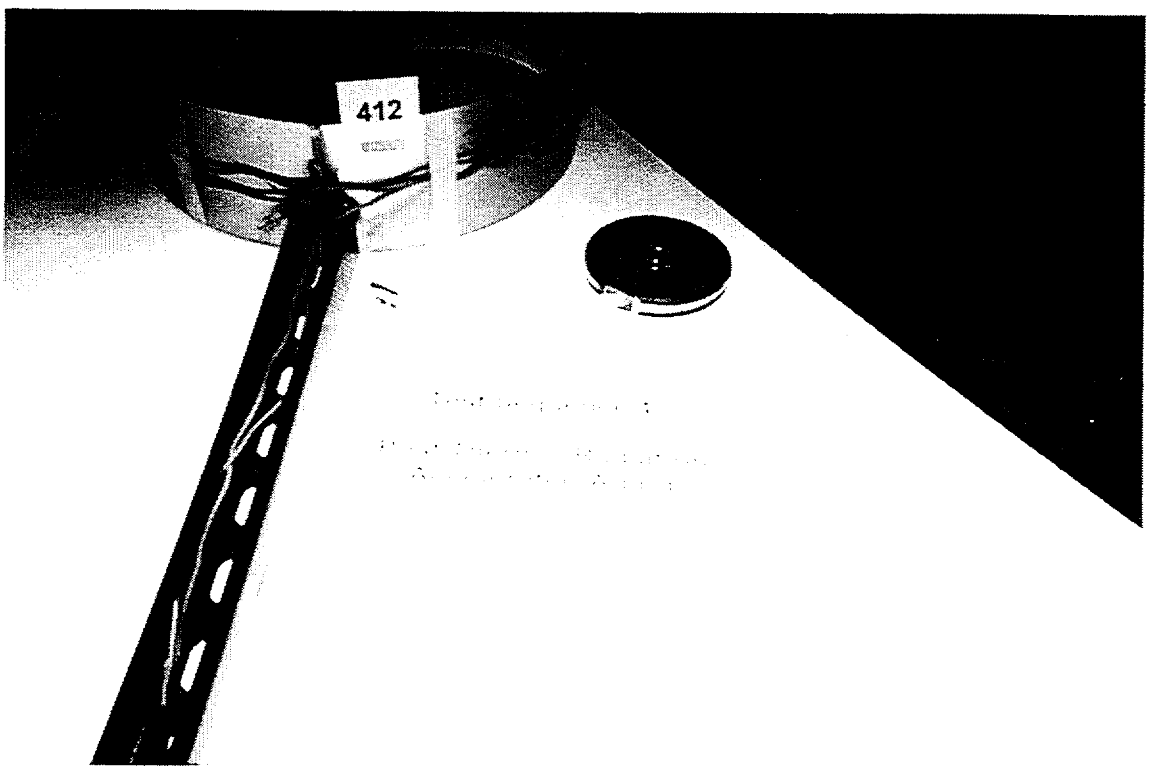

Figure 3.21 Samuel Moore single conductor specimen 0412 from Group 4.3 (pre-aged to 40 years) after accelerated service aging

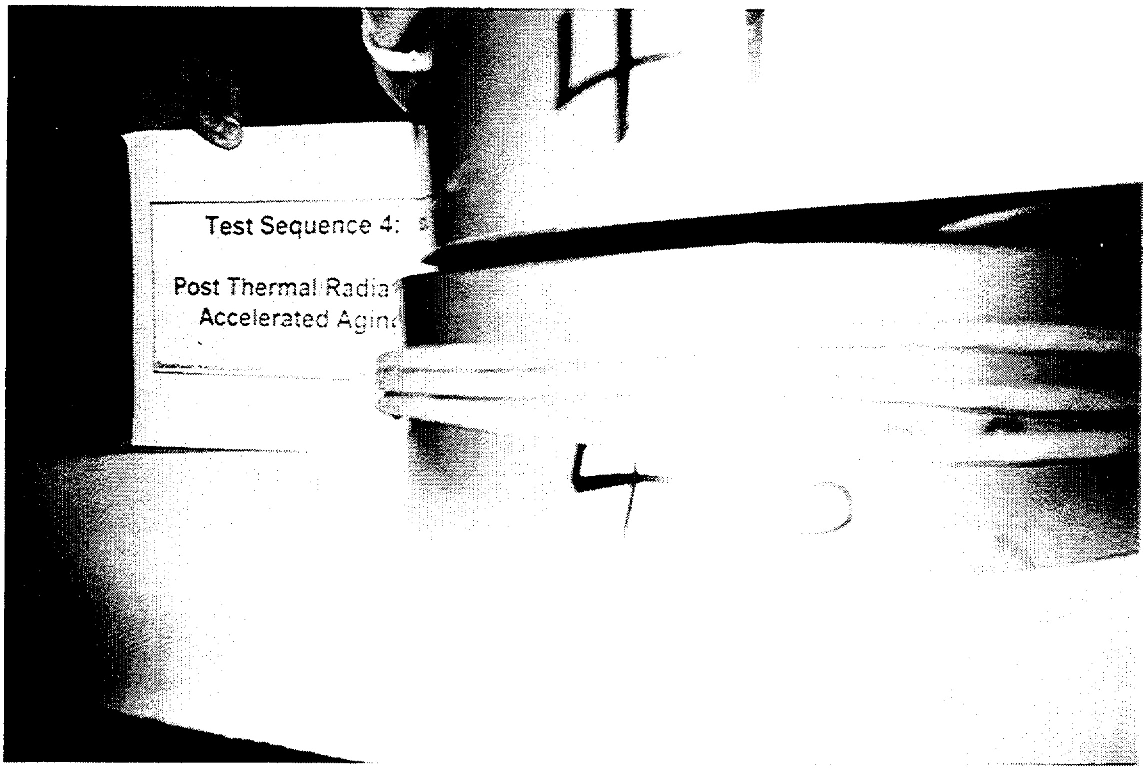

Figure 3.22 Samuel Moore multiconductor specimen 0415 from Group 4.3 (pre-aged to 40 years) after accelerated service aging

of 113 psig, as recommended in Appendix A to IEEE Standard 323-1974. Temperature and pressure were then stepped down to 212°F (100°C) and ambient pressure. Chemical spray was included during the steam exposure starting at approximately 15 hours. The total duration of the LOCA steam exposure was shortened to 10 days as compared to the original qualification test in order to expedite testing since post-LOCA performance was not an objective of this test. The profile is shown in Figure 3.3.

3.4.6 Results of LOCA Radiation and Steam Exposure

Exposure to the accident radiation produced no visible change in the test specimens.

Prior to the initiation of the LOCA steam profile, the test chamber was preheated to approximately 140°F (60°C) with saturated steam and conditions were held for approximately 1 hour. Chamber pressure during this hold period ranged from 4 to 5 psig. No anomalies were noted for any of the test specimens during this period.

Following preheat, the first LOCA transient was initiated with chamber temperature and pressure being ramped up to approximately 346°F (174°C) and 115 psig in approximately 5 minutes. Conditions were then held for approximately 3 hours, after which the temperature and pressure were reduced to preheat conditions. Pressure in the common manifold, to which the pressure transmitters were connected, was relatively constant at approximately 15 psig throughout the LOCA test.

After a cool down to preheat conditions, the second LOCA transient was initiated with chamber temperature and pressure being ramped up to approximately 346°F (174°C) and 113 psig, respectively, in approximately 5 minutes. Conditions were again held for approximately 3 hours.

Throughout both transients, no anomalies were noted for any of the test specimens. Circuit currents and voltages remained at their nominal value and no leakage current was present.

After completion of the second 3-hour hold period, test chamber temperature and pressure were gradually reduced in four steps over the next ten days to 212°F (100°C) and 0 psig, as indicated in Figure 3.3. At each step, conditions were held and allowed to stabilize. During this cool down, when test chamber pressure reached 32 psig, at approximately 5 hours from test initiation, the chemical spray was initiated and maintained for 24 hours. Throughout this portion of the test, no anomalies were noted for any of the test specimens. Circuit currents and voltages remained at their nominal value and no leakage current was present.

3.4.7 Results of Post-LOCA Testing

Following completion of the LOCA steam exposure, the test specimens were removed from the test chamber and a visual inspection was performed. White powdery deposits were noted on the surface of the outer jackets on all of the specimens; however, no cracking was visible on any of the specimens.

The visual inspection of the Group 4.2 cables clearly showed some degree of degradation to all of the specimens. The multiconductor Samuel Moore specimens were still flexible and the outer jackets felt spongy to the touch. Large (5-10 cm) cracks were noted in the jackets; however, the underlying insulation appeared to be in good condition. The single conductor Samuel Moore specimens showed some shriveling and dis-bonding of the CSPE jacket on portions of the cable not attached to the mandrel. The EPR insulation appeared to be in good condition. Swelling was noted for the specimens with the outer jacket diameter increasing approximately 21 percent and the individual jacket diameter increasing approximately 30 percent from the post-service aging condition, as shown in Table 3.18.

Visual inspection of the Group 4.3 cables also showed degradation on each of the specimens. The multiconductor Samuel Moore specimens had multiple large cracks in the outer jacket exposing the individual insulated conductors underneath, as shown in Figure 3.23. The exposed portions of the individual conductor jackets appeared to be in good condition. Small water-filled bubbles were also noted in the outer jacket. The cables were stiff and swelling was noted with the outer jacket diameter increasing approximately 24 percent and the individual jacket diameter increasing approximately 27 percent, as shown in Table 3.18. The single conductor specimens appeared similar to those in Group 4.2 with the CSPE jacket shriveled and dis-bonded on sections that were not attached to the mandrel, as shown in Figure 3.24.

The Group 4.3 Anaconda multiconductor specimens had multiple large cracks and ruptures in the outer jacket, as shown in Figure 3.25. The cable was fairly stiff and swelling was noted with the outer jacket diameter increasing approximately 21 percent and the individual jacket diameter increasing approximately 17 percent from the post-service aging condition, as shown in Table 3.18. It was also noted that the insulation diameter increased approximately 23 percent from the post-service aging condition, which exceeds the increase in the individual jacket diameter. This is probably due to the increased insulation surface area exposed to moisture with the individual jacket removed. The single conductor Anaconda specimens (Figure 3.26) had multiple superficial cracks or crazing in the jacket, but otherwise appeared to be in good physical condition.

Table 3.18 Summary of dimensional measurements for specimens in Test Sequence 4

Group	Mfgr.	Diameter (inches) (% Change from previous point)								
		Baseline			Post Service Aging			Post LOCA Testing		
		Outer Jacket	Individ. Jacket	Ins.	Outer Jacket	Individ. Jacket	Ins.	Outer Jacket	Individ. Jacket	Ins.
4.1 (0 yr.)	Anaconda	0.510	N/A	0.138	-	-	-	0.549 (+8%)	0.185	0.154 (+12%)
	Sam Moore	0.359	0.124	N/A	-	-	-	0.387 (+8%)	0.143 (+15%)	N/A
4.2 (20 yr.)	Sam Moore	0.359	0.124	N/A	0.316 (-12%)	0.105 (-15%)	N/A	0.383 (+21%)	0.137 (+30%)	N/A
4.3 (40 yr.)	Anaconda	0.510	N/A	0.138	0.473 (-7%)	0.153	0.122 (-12%)	0.571 (+21%)	0.179 (+17%)	0.150 (+23%)
	Sam Moore	0.359	0.124	N/A	0.322 (-10%)	0.107 (-14%)	N/A	0.399 (+24%)	0.136 (+27%)	N/A

N/A = Not available

After post-LOCA inspections were completed, a voltage withstand test was conducted on each of the cable specimens. The cables were submerged in tap water at room temperature and subjected to 2,400 Vac for 5 minutes. All of the Anaconda cables performed acceptably. The Samuel Moore specimens aged to simulate 20 years performed acceptably. However, two of the three specimens (0413 and 0416) aged to simulate 40 years could not hold the 2,400V test voltage on one conductor. The results of the submerged voltage withstand test are presented in Table 3.19.

To determine the cause of failure in the submerged voltage withstand test for specimens 0413 and 0416, additional testing was performed. First, the insulation resistance from both conductors to ground was measured while the specimens were dry. These readings ranged from $2.0 \times 10^{10}\ \Omega$ to $2.5 \times 10^{10}\ \Omega$, indicating good dielectric strength. The cables were then sprayed with water starting at one end and proceeding along the entire length of the cable in an attempt to determine if any portion of the specimen was damaged. The red-to-ground IR reading for specimen 0413 dropped to the 10^6 ohm range when a portion of the specimen where the jacket was cracked and degraded was sprayed with water (top coil at approximately 75° on the mandrel moving clockwise from the Unistrut® arm). The IR readings for specimen 0416 did not change with the water spray.

The submerged voltage withstand test was then repeated to isolate the most severely damaged section(s) of the test specimen. It should be noted that each subsequent performance of the high potential test weakens the cable insulation and could result in potential catastrophic failure (breakdown). The mandrel portion of the specimens was submerged in a tank of tap water, and the test voltage was applied. The splices were not submerged. During this test, both the red and black conductors on both specimens reached a leakage current exceeding 10 mA (full scale for the test instrument) before the test voltage of 2,400 Vac was reached. During the test on specimen 0413, bubbles were noted coming from the location at 75° where the jacket was cracked during testing of both the red and black conductors . Similarly, bubbles were noted during the test of specimen 0416 coming from a location at approximately 270° where the jacket was cracked. These bubbles indicated the presence of an electrical discharge. For specimen 0413, the section at 75° was kept out of the water and the test was repeated; however,the specimen still could not sustain the 2,400V test voltage.

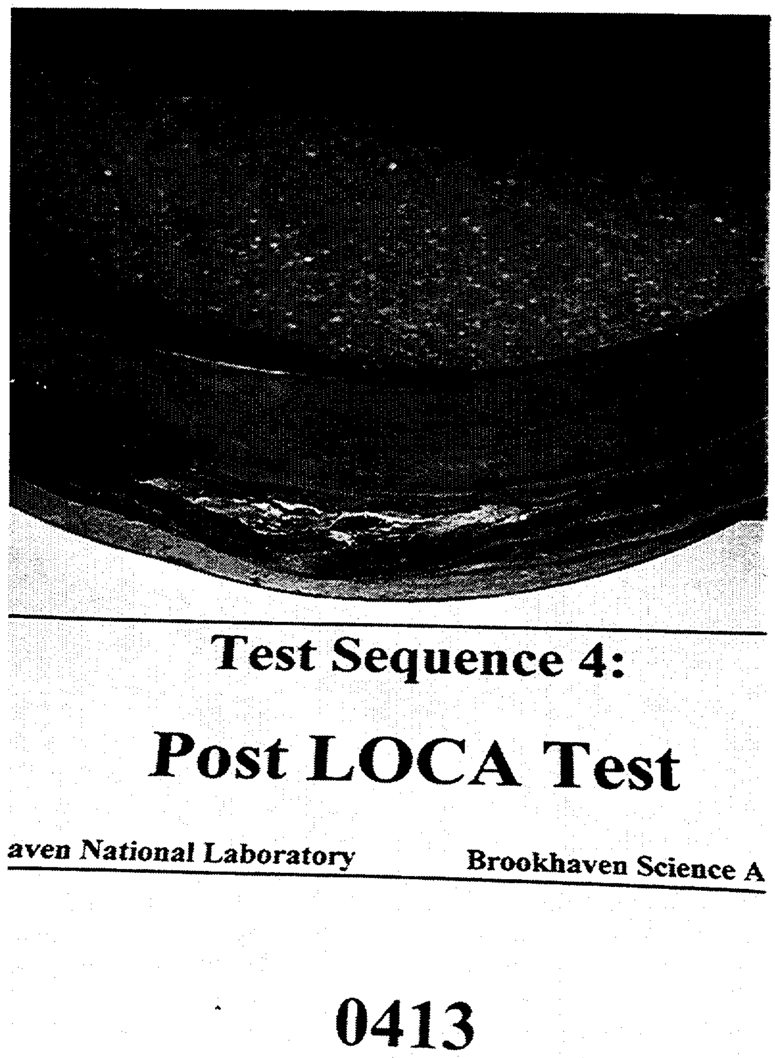

Figure 3.23 Post-LOCA condition of Samuel Moore multiconductor specimen 0413 from Group 4.3 (pre-aged to 40 years)

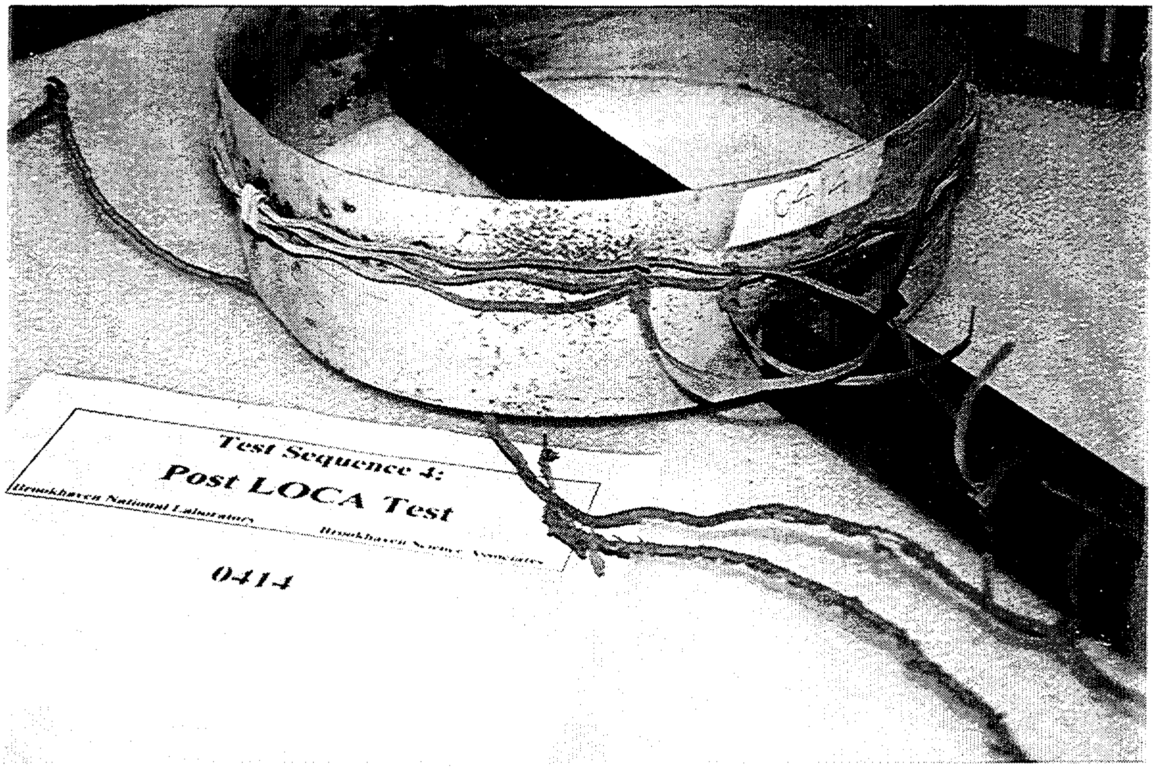

Figure 3.24 Post-LOCA condition of Samuel Moore single conductor specimen 0414 from Group 4.3

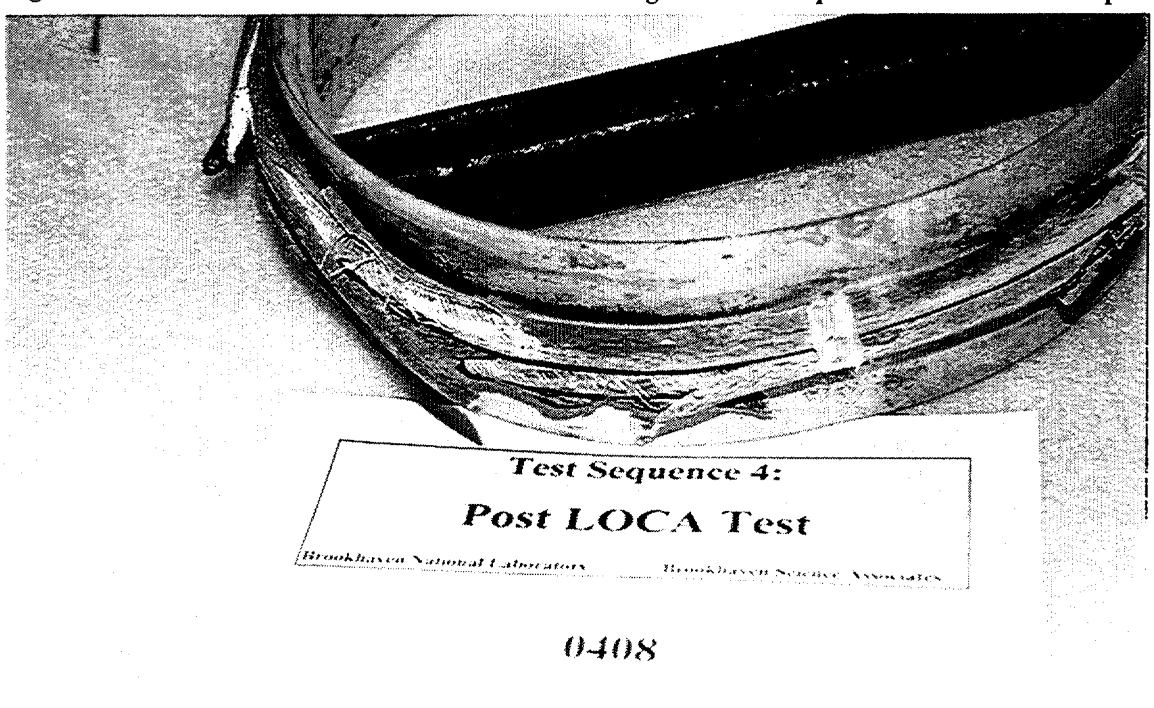

Figure 3.25 Post-LOCA condition of Anaconda multiconductor specimen 0408 from Group 4.3 (pre-aged to 40 years)

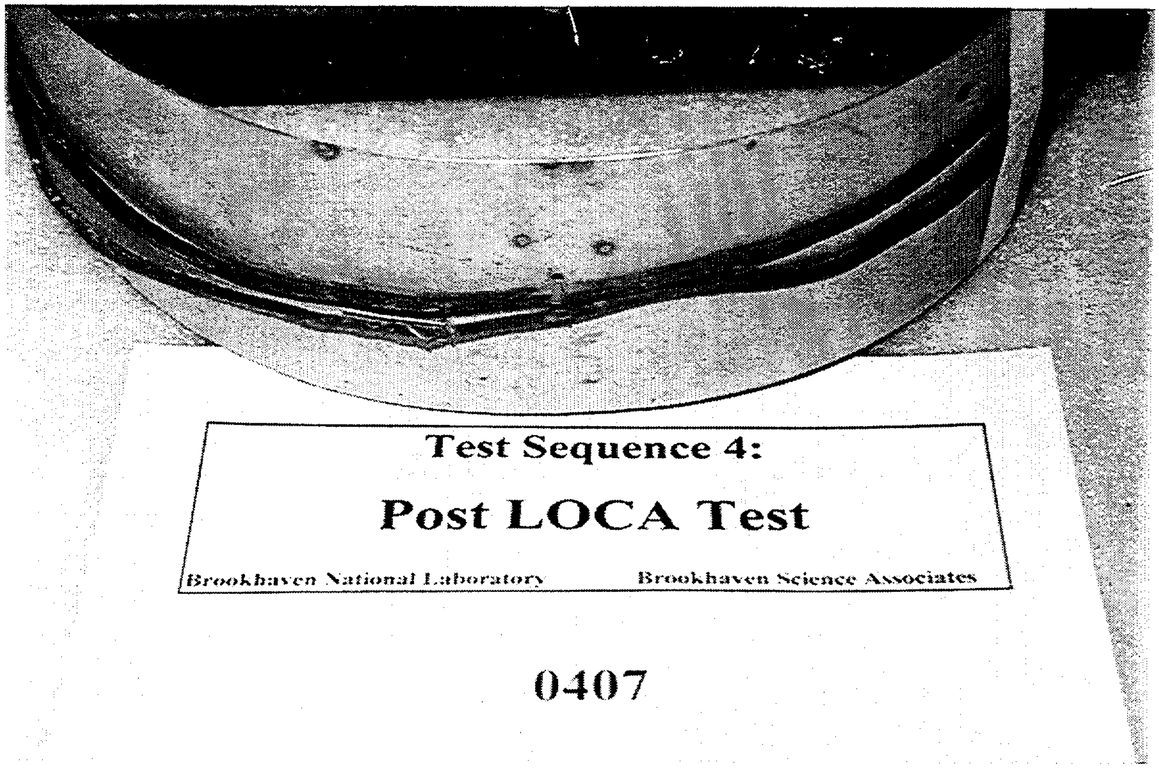

Figure 3.26 Post-LOCA condition of Anaconda single conductor specimen 0407 from Group 4.3 (pre-aged to 40 years)

Specimen 0413 was then removed from the metal mandrel and IR readings from each conductor to the ground wire were taken. These initially ranged from 50k Ω to 60k Ω, indicating low insulation resistance. The splices were then removed from the specimen and the IR was repeated with the same results. IR readings of the splices themselves indicated off-scale resistance (> 200 T Ω), confirming that the splices were not the cause of the low resistance in the specimen. The specimen was covered with wet towels and the voltage withstand test was repeated; the specimen again could not sustain the 2,400V test voltage, indicating the condition still existed.

At three locations on specimen 0413, including the 75° location, approximately 1 to 3 inches of the jacket were cracked and were falling off as a result of the LOCA test. These sections were visually inspected and the remaining pieces of the jacket were carefully removed to examine the underlying insulation. The insulation in all areas appeared to be in good condition, with no cracking evident.

Next, specimen 0413 was cut into three sections. The IR of each section was measured, with two of the sections showing off-scale resistance (> 200 T Ω) red-to-ground wire and black-to-ground wire. The third section had a reading of approximately 700k ohms red-to-ground wire and black-to-ground wire, indicating that the cause of the problem was located in this section. However, no obvious damage could be seen on this section.

Table 3.19 Results of submerged voltage withstand test on specimens in Test Sequence 4

Group	Specimen No.	Manufacturer	Applied Voltage (Vac)	Leakage (microamps)		Pass/Fail
				White Conductor	Black Conductor	
4.1 (no aging)	0401	Anaconda	2,400	800	800	Pass
	0402	Samuel Moore	2,400	800	800	Pass
4.2 (aged to 20 years)	0403	Samuel Moore	2,400	600	NA	Pass
	0404		2,400	1,000	1,000	Pass
	0405		2,400	1,000	NA	Pass
	0406		2,400	1600	1600	Pass
4.3 (aged to 40 years)	0407	Anaconda	2,400	1,000	NA	Pass
	0408		2,400	1,400	1,000	Pass
	0409		2,400	1,000	NA	Pass
	0410		2,400	1600	1600	Pass
	0411		2,400	1600	1600	Pass
	0412	Samuel Moore	2,400	800	NA	Pass
	0413 [(a)]		1,200 [(a)]/2,400	> 10 mA	1,400	**Fail**
	0414		2,400	800	NA	Pass
	0415		2,400	2000	2200	Pass
	0416 [(a)]		2,400/1,000 [(a)]	2000	> 10 mA	**Fail**

(a) Specimen would not hold 2,400 volts; test performed at lower voltage noted.
NA = Not applicable; single conductor cable specimen

The three sections of specimen 0413 were then dissected to enable a thorough visual inspection of the insulation. Upon inspection of the section with low IR readings, a pin-hole was noted in the red insulation at one location. The area around the pin-hole was burnt, indicative of an electrical discharge. This was confirmed by repeating the 2,400V high potential test on the red conductor without submerging the cable, during which a discharge was heard from this location. This section failed the high potential test with a high leakage current. The black conductor passed the 2,400V high potential test un-submerged. Inspection of other areas of the cable showed the presence of moisture and deposits from the chemical spray. The insulation in all other areas appeared to be in good condition, with no degradation noted.

Based on the above findings, the failure of specimen 0413 was determined to be due to localized degradation of the insulation which caused the high potential test to puncture the insulation on the red conductor. The high potential test failure of the black conductor could not be duplicated; therefore, the failure during the second submerged voltage withstand test could not be determined.

Similar testing was performed for specimen 0416 to determine the cause of failure during the submerged voltage withstand test. With the specimen intact, IR readings were taken and the following values were obtained:

Conductor	1-minute reading	10-minute reading	Polarization Index
black-to-ground wire	0.4×10^{12}	1.4×10^{12}	3.5
red-to-ground wire	3.7×10^{7}	5.0×10^{6}	0.1
black-to-red	0.9×10^{12}	1.8×10^{12}	2.0

The low IR readings and the polarization index less than 1 for the red-to-ground wire indicated a problem with the red conductor.

The specimen was then cut into three pieces and the IR repeated to isolate the bad section. A dry 2,400V high potential was performed on each section, and one section failed with excessive leakage current from red-to-ground. This section was determined to contain the fault and was dissected.

Similar to specimen 0413, a hole was found in the red insulation of specimen 0416 in one location. The hole was burnt around the edges indicative of an electrical discharge. This hole was not located in an area where the overall jacket had been damaged. Also, the hole was on the opposite side of the cable from the ground wire.

Inspection of other areas of the cable showed that the insulation appeared to be in good condition. Moisture was present under the overall jacket, along with deposits of the chemical spray; however, no degradation of the insulation was apparent.

Based on the above findings, the failure of specimen 0416 was determined to be due to localized degradation of the insulation which caused the high potential test to puncture the insulation on the red conductor. The failure of the black conductor could not be duplicated; therefore, the failure during the first and second submerged voltage withstand test could not be determined and is attributed to a test anomaly. It is possible that the leads on the test apparatus were reversed (i.e., red conductor failed instead of black) since, after LOCA testing, the insulation is severely blackened on the ends of the specimens and it is difficult to distinguish the original color of the insulation until it is cut, as it was during the dissection.

3.5 Test Sequence 5: Bonded Jacket Cables

3.5.1 Test Objectives

The objective of this test was to determine if cables with individual jackets bonded to the underlying conductor insulation have any unique failure mechanisms that are not present in cables with an unbonded individual jacket.

3.5.2 Description of Test Specimens

To meet the objective of this test, cables from three different manufacturers were tested; Anaconda, Samuel Moore and Okonite. The source cable sample used for the Anaconda specimens in test sequence 5 was DNP78AN008, which is a 3/C #16 AWG, 1,000 V cable with a shield and ground wire. The conductors were insulated with 30 mils of EPR with a 15-mil CSPE individual jacket, and a 45-mil CSPE overall outer jacket. The source cable sample used for the Samuel Moore specimens in test sequence 5 was DNI80SM010, which is a 2/C #16 AWG, 600 V cable with a shield and ground wire. The conductors were insulated with 20 mils of Dekoron® (EPDM) with a bonded 10-mil Dekorad® (CSPE) individual jacket and a 45-mil Dekorad® (CSPE) overall outer jacket. The source cable samples used for the Okonite specimens in test sequence 5 was LNI81OK020, which is a 1/C #12 AWG, 600 V cable. The conductor was insulated with 30 mils of Okonite® (EPR) with a bonded 15-mil Okolon® (CSPE) individual jacket. Single conductor Anaconda and Samuel Moore specimens were not included in this test. Also, there were no naturally aged cable specimens in this test.

The cable samples used in the test were acquired from Sandia National Laboratory. They are the same cables used in past Sandia tests (Bustard, 1983; Jacobus, 1992; Vigil, 1994). Since the cables were originally purchased by Sandia in the early to mid 1980s, they were approximately 15 to 20 years old at the time of testing by BNL. Visual inspection and elongation-at-break testing were performed on the as-received cables to verify they were in excellent condition with no observable signs of degradation. Once received at BNL, the cables were assigned a unique identification number and maintained in an environmentally controlled storage area and continuously monitored for temperature and humidity to ensure no additional degradation occurred.

For test sequence 5, 19 long cable specimens were prepared, as shown in Table 3.20. As in test sequences 1, 2 and 3, the cable samples were cut into both long (10-foot) and short (6-inch) specimens for testing. The long specimens were installed on stainless steel mandrels to simulate actual qualification testing. A mandrel diameter of approximately 13.5 inches was used. The modified mandrel design developed for test sequence 4 was used for this test, which included a 2-foot Unistrut® arm to support the ends of the test specimens as they were routed away from the mandrel to further mitigate potential handling damage to the cables during splice application and CM testing. As in test sequence 4, short (2-foot to 3-foot) pigtails were spliced to the 10-foot test specimens using Raychem® nuclear grade splices prior to any accelerated aging to avoid handling damage to the test specimens. The pigtails on the 10-foot specimens were shielded from the conditions of thermal and radiation aging, to the extent possible, to keep them from becoming brittle. After pre-aging had been completed, the facility test lead wires were connected to the pigtails on the 10-foot specimens using a second splice, which stayed inside the test chamber.

Preparation of the 6-inch short specimens involved removing the cable outer jacket from the individual conductors, and removing the copper conductors from the insulation. Since the individual CSPE jacket was not bonded to the EPR insulation in the Anaconda specimens, it was removed and both were tested independently. The individual CSPE jacket was bonded to the underlying EPR insulation for the Samuel Moore and Okonite specimens, and could not be removed. Consequently, the composite EPR insulation with bonded CSPE individual jacket was tested as a single specimen for these cables. The outer CSPE jackets from the Samuel Moore and Anaconda specimens were punched into a standardized "dog bone" configuration for EAB testing, as in previous tests. The insulation specimens were left in a tubular configuration for testing. The short specimens were placed in stainless steel mesh baskets. Five short cable jacket and insulation specimens were inserted into each basket. The baskets were then designated for removal at specific CM points for materials testing.

3.5.3 Accelerated Aging Parameters

The specimens in test sequence 5 can be grouped according to the pre-aging they received as follows: in Group 5.1, one Anaconda specimen, one Okonite specimen and one Samuel Moore specimen were prepared and LOCA tested without any pre-aging. Group 5.2 included two Anaconda, two Samuel Moore, and two Okonite specimens, which were pre-aged to the equivalent of 20 years of qualified life prior to LOCA testing. Group 5.3 included three Okonite, two Anaconda and two Samuel Moore specimens, which were pre-aged to the equivalent of 40 years of qualified life prior to LOCA testing. In addition, one Okonite, one Anaconda and one Samuel Moore specimen were pre-aged to the equivalent of 40 years of qualified life and used as archive specimens. The three pre-aging groups for test sequence 5 are summarized as follows:

Group 5.1: Okonite, Anaconda and Samuel Moore with no accelerated aging (control specimens).
Group 5.2: Okonite, Anaconda and Samuel Moore with accelerated aging to simulate 20 years of qualified life.
Group 5.3: Okonite, Anaconda and Samuel Moore with accelerated aging to simulate 40 years of qualified life.

As in previous tests, the accelerated aging parameters were selected to match those used for the original qualification testing of the cables. For the Anaconda cables, Franklin Institute Research Laboratories Report F-C4350-3 (FIRL, July 1976) was used, while for the Samuel Moore cables, Isomedix report LOCA XLPO/EPDM (Isomedix, June 1978) was used. The testing documented in these reports is described in Section 3.4.3.

The Okonite cables were tested in accordance with Okonite report NQRN-1A. In this qualification test, Okonite cables of similar materials but different configuration were qualified to 40 years of service at a temperature of 194°F (90°C). The accelerated aging used in this qualification included thermal aging at 302°F (150°C) for 504 hours followed by 200 Mrad of radiation at an average dose rate of 0.75 Mrad per hour. The cables were subsequently exposed to a 130-day LOCA steam profile while energized with rated voltage and current to simulate service under LOCA conditions. The LOCA profile included two peaks at 345°F (174°C) and 114 psig. After LOCA testing, the cables were straightened and recoiled around a mandrel with a diameter 40 times that of the cables. The mandrels were immersed in tap water and a voltage of 80 volts per mil of insulation was applied (2,400 Vac for the 30-mil thickness of the insulation).

Table 3.20 Description of specimens in Test Sequence 5

Group	Specimen ID No.	Sample ID No.	Configuration [a]	Manufacturer [a]	Insulation Material [a]	Jacket Material [a]	No. of Conductors	Wire Gauge (AWG)	Cable Diameter (in.)	Cable Type [a]	Insulation Thickness (mils) [c]
5.1	0501	LNI81OK020	10 FT - MAN	OK	EPR [d]	CSPE	1	12	0.175	I	30
	0502	DNI80SM010	10 FT - MAN	SM	EPDM [d]	CSPE	2 w/shld&gnd	16	0.327	I	20
	0503	DNP78AN008	10 FT - MAN	AN	EPR[e]	CSPE	3	12	0.475	P	30
5.2	0504	LNI81OK020	10 FT - MAN	OK	EPR [d]	CSPE	1	12	0.175	I	30
	0505	LNI81OK020	10 FT - MAN	OK	EPR [d]	CSPE	1	12	0.175	I	30
	0506	DNI80SM010	10 FT - MAN	SM	EPDM [d]	CSPE	2 w/shld&gnd	16	0.327	I	20
	0507	DNI80SM010	10 FT - MAN	SM	EPDM [d]	CSPE	2 w/shld&gnd	16	0.327	I	20
	0508	DNP78AN008	10 FT - MAN	AN	EPR[e]	CSPE	3	12	0.475	P	30
	0509	DNP78AN008	10 FT - MAN	AN	EPR[e]	CSPE	3	12	0.475	P	30
5.3	0510	LNI81OK020	10 FT - MAN	OK	EPR [d]	CSPE	1	12	0.175	I	30
	0511	LNI81OK020	10 FT - MAN	OK	EPR [d]	CSPE	1	12	0.175	I	30
	0512	LNI81OK020	10 FT - MAN	OK	EPR [d]	CSPE	1	12	0.175	I	30
	0513	DNI80SM010	10 FT - MAN	SM	EPDM [d]	CSPE	2 w/shld&gnd	16	0.327	I	20
	0514	DNI80SM010	10 FT - MAN	SM	EPDM [d]	CSPE	2 w/shld&gnd	16	0.327	I	20
	0515	DNP78AN008	10 FT - MAN	AN	EPR[e]	CSPE	3	12	0.475	P	30
	0516	DNP78AN008	10 FT - MAN	AN	EPR[e]	CSPE	3	12	0.475	P	30
Archive	0517 [b]	LNI81OK020	10 FT - STR	OK	EPR [d]	CSPE	1	12	0.175	I	30
	0518 [b]	DNI80SM010	10 FT - STR	SM	EPDM [d]	CSPE	2 w/shld&gnd	16	0.327	I	20
	0519 [b]	DNP78AN008	10 FT - STR	AN	EPR[e]	CSPE	3	12	0.475	P	30

(a) MAN=Mandrel, OK= Okonite, SM = Samuel Moore, AN = Anaconda, EPR = Ethylene Propylene Rubber, EPDM = Ethylene Propylene Diene Monomer, CSPE = Chloro-sulfonated Polyethylene, I=Instrumentation, P = Power

(b) These specimens were included for archiving purposes and were not energized during the LOCA steam exposure. A 2-foot section was removed at each hold point and placed in storage.

(c) Thickness of insulation only; does not include 15 mil CSPE individual jacket for Anaconda and Okonite cables nor 10 mil CSPE individual jacket for Samuel Moore cables.

(d) Insulation covered with bonded CSPE individual jacket.

(e) Insulation covered with unbonded CSPE individual jacket.

3.5.4 Results of Accelerated Aging

Visual examination and baseline elongation-at-break measurements confirmed that all cable specimens were initially in excellent condition. No discoloring or cracking was evident in either the jacket or insulation for any of the specimens. As shown in Table 3.22, average elongation-at-break values for the unused Anaconda cables were 356 percent for the EPR insulation and 476 percent for the CSPE outer jackets. Similarly, for the unused Samuel Moore cables, average EAB values were 418 percent for the composite EPR insulation with CSPE individual jacket and 613 percent for the CSPE outer jacket. The baseline EAB value for the Okonite specimens was 471 percent. These results confirmed excellent ductility for the materials in all of the cable specimens.

The Group 5.2 cables were artificially aged to simulate 20 years of qualified life, as determined from their original qualification report. The EAB tests, as well as the visual inspections indicated that the Samuel Moore and Anaconda cables were in acceptable condition throughout the thermal and radiation pre-aging sequence. For the Samuel Moore specimens, no cracks were evident and the cables remained relatively flexible with average EAB values of 338 percent for the CSPE outer jacket and 147 percent for the composite insulation, as shown in Table 3.22. The Anaconda specimens also had no cracking evident, with average EAB values of 94 percent and 166 percent for the CSPE outer jacket and EPR insulation, respectively. The Okonite cables in Group 5.2 appeared to be in good physical condition with no significant discoloration noted, nor was there any evidence of cracking. The Okonite cables were relatively stiff, as confirmed by the low EAB value of 8 percent for the composite EPR/CSPE insulation.

The accelerated aging received by the test specimens is presented in Table 3.21.

Table 3.21 Actual accelerated aging conditions received by the specimens in Test Sequence 5

Group	Cable	Thermal Aging		Service Radiation [a]		LOCA Radiation [a]	
		Temperature (°F/°C)	Duration (hours)	Total Integrated Dose (Mrad)	Dose Rate (Mrad/hr.)	Total Integrated Dose (Mrad)	Dose Rate (Mrad/hr.)
5.1	All	-	None	None	-	154.40	0.60
5.2	Okonite	302°F (150°C)	252.11	25.79	0.62		
	Anaconda	302°F (150°C)	84.33	25.69	0.35		
	Sam Moore	250°F (121°C)	84.85	25.99	0.65		
5.3	Okonite	302°F (150°C)	504.03	51.49	0.59		
	Anaconda	302°F (150°C)	169.20	51.35	0.35		
	Sam Moore	250°F (121°C)	169.05	51.57	0.75		

(a) Radiation exposures for long specimens and/or basket specimens in the same group were performed in multiple runs due to restrictions on the number of sources allowed in the hot cell at one time. Therefore, the radiation doses and dose rates reported are averages for all runs.

The Group 5.3 cables were artificially aged to simulate 40 years of qualified life. The EAB tests and visual examinations showed that the Samuel Moore cables were in good condition and remained moderately flexible with no cracking evident, similar to test sequence 4. The average EAB values for the Samuel Moore cables were 283 percent for the CSPE outer jacket and 94 percent for the composite insulation. The Anaconda cables appeared degraded and were somewhat stiff; however, no cracking was evident. The average EAB values for the Anaconda cables were 22 percent for both the CSPE outer jacket and the EPR insulation. The Okonite specimens in Group 5.3 displayed only minimal discoloring; however, they had become very brittle, as evidenced by the EAB values of less than 5 percent. Figure 3.27 shows Okonite specimens 0510 and 0511 after accelerated thermal and radiation service aging.

3.5.5 LOCA Conditions Simulated

The LOCA conditions simulated included exposure to 150 Mrad of accident radiation, followed by exposure to steam at high temperature and pressure. The accident radiation exposure was performed after completion of the service aging and prior to the steam exposure.

Following accident irradiation, the specimens were subjected to a high temperature and pressure steam exposure. Since cable specimens from three different manufacturers were included in this test, the LOCA test profile was chosen to envelop the original qualification test profiles used for all three cables. The original qualification test for the Anaconda cable consisted of a 30-day test with a single peak at 346°F (174°C) and 113 psig, while that for the Samuel Moore cable consisted of a 30-day test with two peaks at 340°F (171°C) and 105 psig. The LOCA profile for the Okonite cables included a double peak at 345°F (174°C) and 114 psig. Comparison of these profiles with the profile used in both tests 1 and 3 for this program showed that the test 1/3 profile conservatively enveloped the LOCA test profiles used for these cables. Therefore, the profile used in this test is the same one used in tests 1 and 3 with the exception that the total duration was extended to 10 days to correspond with previous testing performed by Sandia (Jacobus, 1992). The LOCA 5 test profile included a double peak at a maximum temperature of 346°F (174°C) and a pressure of 113 psig, as recommended in Appendix A to IEEE Standard 323-1974. Temperature and pressure were then stepped down to 212°F (100°C) and ambient pressure. Chemical spray was included during the steam exposure starting at approximately 15 hours. The total duration of the LOCA steam exposure was shortened to 10 days as compared to the original qualification tests in order to expedite testing since post-LOCA performance was not an objective of this test. The profile is shown in Figure 3.3.

3.5.6 Results of LOCA Radiation and Steam Exposure

The LOCA radiation further reduced the EAB values for all specimens, as shown in Table 3.22. No cracking was evident in any of the Samuel Moore or Anaconda specimens. The Okonite specimens in Group 5.3 did have several circumferential cracks in the CSPE jacket.

Prior to the initiation of the LOCA steam profile, the test chamber was preheated to approximately 140°F (60°C) with saturated steam and conditions were held for approximately 1 hour. Chamber pressure during this hold period ranged from 4 to 5 psig. No anomalies were noted for any of the test specimens during this period.

Following preheat, the first LOCA transient was initiated with chamber temperature and pressure being ramped up to approximately 346°F (174°C) and 115 psig in approximately 5 minutes. At approximately 8.6 minutes into the test, a pressure regulator on the test chamber failed causing the temperature and pressure to drop to approximately 200°F (100°C) and ambient pressure, respectively, over a period of approximately 25.7 minutes. At that point, replacement of the regulator was completed and the test chamber conditions were returned to peak conditions. Conditions were then held for approximately 3 hours, after which the temperature and pressure were reduced to preheat conditions. Pressure in the common manifold was relatively constant at approximately 15 psig throughout the LOCA test.

Following the cool down to preheat conditions, the second LOCA transient was initiated with chamber temperature and pressure being ramped up to approximately 346°F (174°C) and 113 psig, respectively, in approximately 5 minutes. Conditions were then held for approximately 3 hours.

Throughout both transients, no anomalies were noted for any of the test specimens. Circuit currents and voltages remained at their nominal value and no leakage current was present.

After completion of the second 3-hour hold period, test chamber temperature and pressure were gradually reduced in four steps over the next ten days to 212°F (100°C) and 0 psig as indicated in Figure 3.3. At each step, conditions were held and allowed to stabilize. During this cooldown, when test chamber pressure reached 32 psig, at approximately 15 hours from test initiation, the chemical spray was initiated and maintained for 24 hours.

Table 3.22 Average elongation-at-break values for the specimens in Test Sequence 5

Group	Cable	Average elongation-at-break at each CM Point (%)											
		Baseline No Aging		After Thermal Service Aging		After Radiation Service Aging		After Half LOCA Radiation		After Full LOCA Radiation		After LOCA Steam Exposure	
		Outer Jkt. (b)	Insul. (a)	Outer Jkt. (b)	Insul. (a)	Outer Jkt. (b)	Insul. (a)	Outer Jkt. (b)	Insul. (a)	Outer Jkt. (b)	Insul. (a)	Outer Jkt. (b)	Insul. (a)
5.1 (0 yrs.)	Okonite LNI81OK020	NA	471	NA	NA	NA	NA	NA	172	NA	232	NA	134
	Anaconda DNP78AN008	476	356	NA	NA	NA	NA	154	137	153	140	135	(c)
	Sam Moore DNI80SM010	613	418	NA	NA	NA	NA	154	119	239	163	68	74
5.2 (20 yrs.)	Okonite LNI81OK020	NA	471	NA	12	NA	8	NA	< 5	NA	< 5	NA	< 5
	Anaconda DNP78AN008	476	356	155	287	94	166	39	95	29	84	40	(c)
	Sam Moore DNI80SM010	613	418	453	233	338	147	89	75	95	74	53	59
5.3 (40 yrs.)	Okonite LNI81OK020	NA	471	NA	6	NA	< 5	NA	< 5	NA	< 5	NA	< 5
	Anaconda DNP78AN008	476	356	31	20	22	22	6	10	8	14	10	(c)
	Sam Moore DNI80SM010	613	418	406	186	283	94	79	53	73	58	33	36

(a) Elongation-at-break value for Okonite and Samuel Moore insulation is for the composite EPR/CSPE insulation, while the EAB for the Anaconda insulation is for the EPR insulation alone.
(b) The Okonite specimens are single conductor and do not have an outer jacket.
(c) The specimens were badly distorted and could not be tested.
NA = not applicable

Immediately upon chemical spray initiation, leakage currents were noted for the Group 5.3 Okonite specimens (0510, 0511 and 0512). The leakage currents ranged from 0.2 mA to 0.6 mA. Upon completion of the chemical spray, the leakage currents ceased. No other anomalies were noted for any of the other specimens.

Subsequent to completion of the steam exposure, a check of the test specimen wiring revealed that the single conductor Okonite specimens had inadvertently been wired into the positive side of test circuit. Since this side of the circuit was referenced to ground, this configuration minimized the difference of potential between the conductors and ground, which impaired the capability to monitor leakage current for the test specimens, as was required in the test specification. This event is documented in Notice of Anomaly 11 in Appendix B.

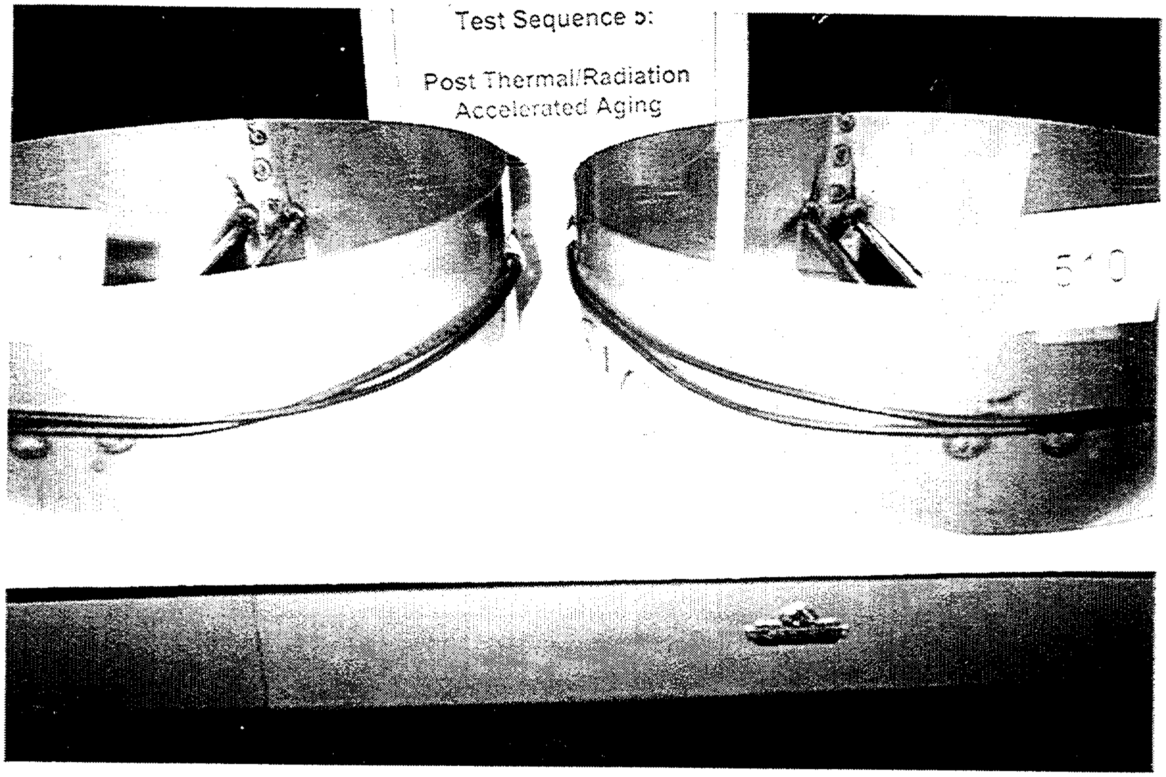

Figure 3.27 Okonite specimens 0510 and 0511 from Group 5.3 (pre-aged to 40 years) after accelerated service aging

3.5.7 Results of Post-LOCA Testing

Following completion of the LOCA steam exposure, the test specimens were removed from the test chamber and a visual inspection was performed. All of the Group 5.1 cables appeared to be in good condition with no cracking evident. Small (1-2 mm diameter) water-filled bubbles were noted on the surface of the outer jackets on all of the specimens; however, no cracking was visible on any of the specimens.

The visual inspection of the Group 5.2 cables clearly showed some degree of degradation to all of the specimens. The Samuel Moore specimens were still flexible and the outer jackets felt spongy to the touch. Small (2-5 cm) longitudinal cracks were noted in the jackets. The Anaconda specimens had multiple longitudinal cracks in the outer jacket; none were through-wall. The cracks appeared to be due to swelling of the jacket. Also, one circumferential cracks was noted in the outer jacket of one of the Anaconda specimens exposing the individual insulated conductor jackets underneath. Each of the Okonite specimens was found to have a longitudinal crack running along the length of the jacket. On one of the Okonite cables, a 12-cm section had split open exposing the bare conductor underneath.

Visual inspection of the Group 5.3 cables also showed degradation on each of the specimens. The Samuel Moore specimens were still flexible and the outer jackets felt spongy. Both of the Samuel Moore specimens had a 5-cm crack in the outer jacket exposing the individual insulated conductor jackets underneath, as shown in Figure 3.28. The exposed individual jackets appeared to be in good condition. The Anaconda specimens had multiple longitudinal cracks in the outer jacket similar to the Group 5.2 specimens. In addition, a large circumferential crack was noted in the overall jacket of one cable exposing the individual insulated conductor jackets underneath, as shown in Figure 3.29.

The Okonite specimens in Group 5.3 all had longitudinal cracking of the composite jacket and underlying insulation that split open along the length of the cable exposing the bare copper conductor. Figures 3.30 to 3.32 show the post-LOCA condition of Okonite specimens 0510, 0511 and 0512.

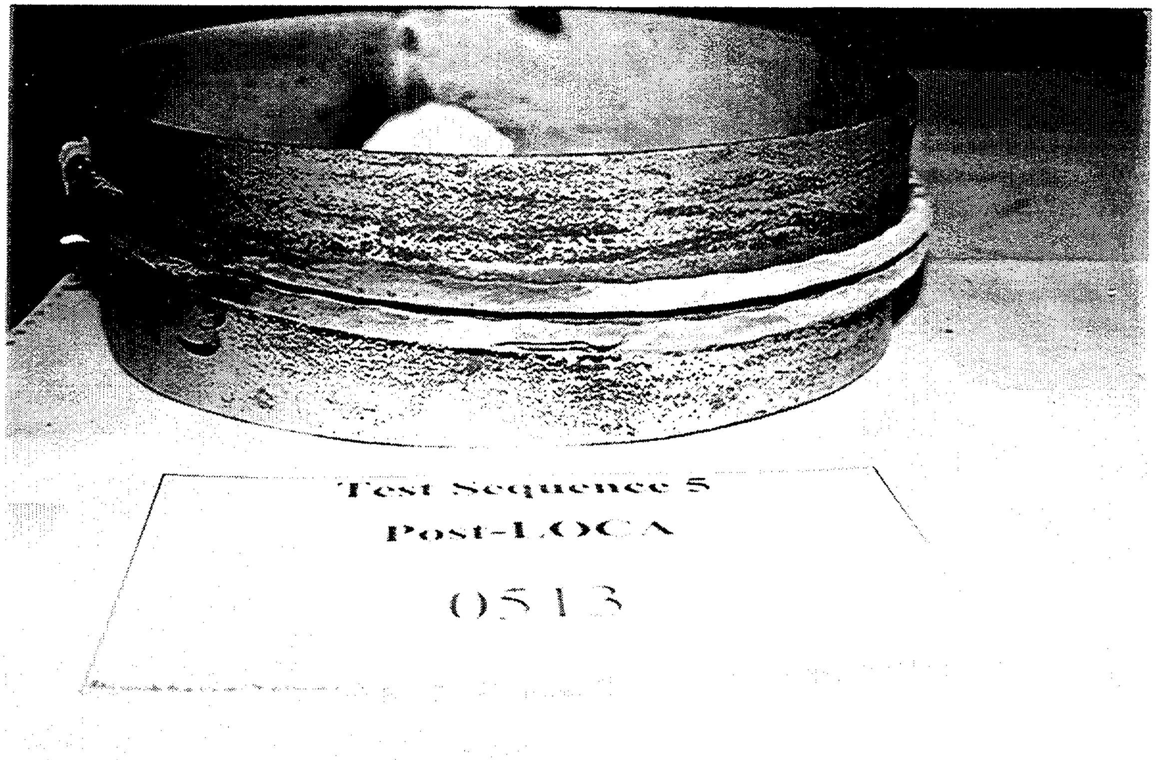

Figure 3.28 Post-LOCA condition of Samuel Moore specimen 0513 from Group 5.3 (pre-aged to 40 years)

After post-LOCA inspections were completed, a voltage withstand test was conducted on each of the cable specimens. The cables were submerged in tap water at room temperature and subjected to 2,400 volts ac for 5 minutes. All of the Samuel Moore and Anaconda cables performed acceptably. For the Okonite cables, 1 of the 2 specimens in Group 5.2 (aged to simulate 20 years), and all 3 specimens in Group 5.3 (aged to simulate 40 years) could not hold the 2,400V test voltage. These cables were judged to have failed the test. The results of the submerged voltage withstand test are summarized in Table 3.23.

3.6 Test Sequence 6: EPR and XLPE Insulated Cables Aged to 60 Years

3.6.1 Test Objectives

The objectives of this test sequence were the following:

- To obtain LOCA performance data on XLPE and EPR insulated cables with accelerated aging to an equivalent qualified life of 60 years, and
- To obtain data for evaluating condition monitoring techniques on XLPE and EPR insulated cables

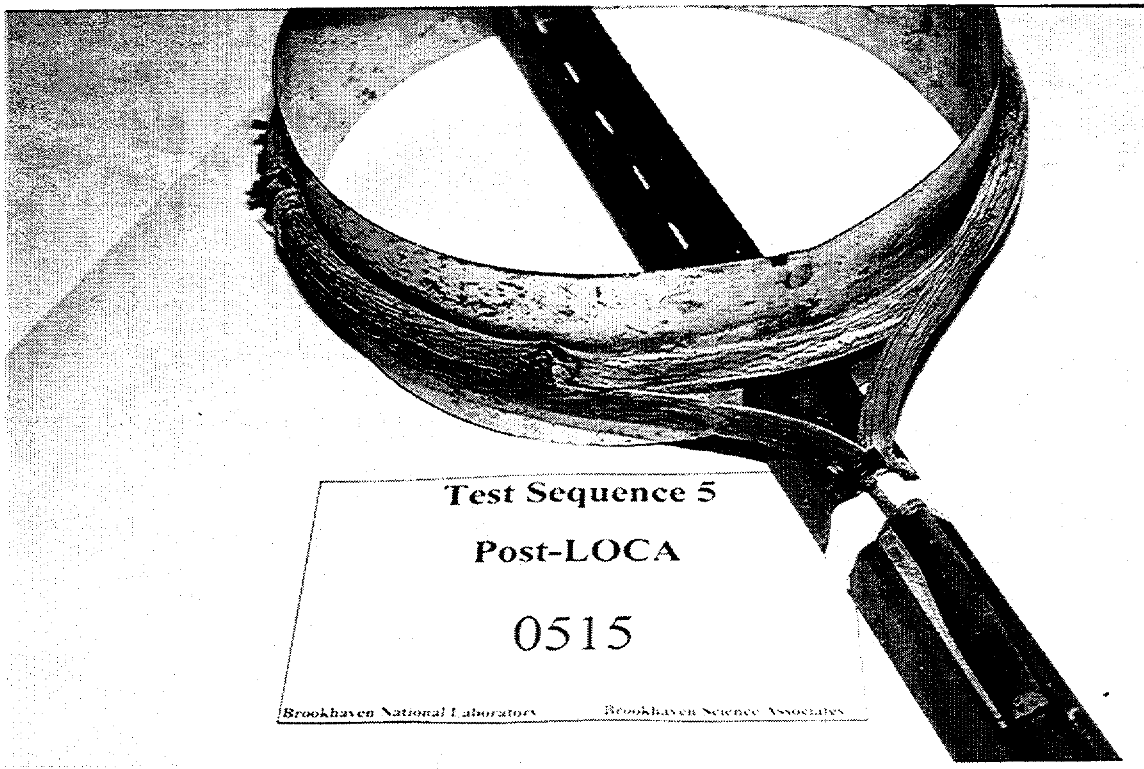

Figure 3.29 Post-LOCA condition of Anaconda specimen 0515 from Group 5.3 (pre-aged to 40 years)

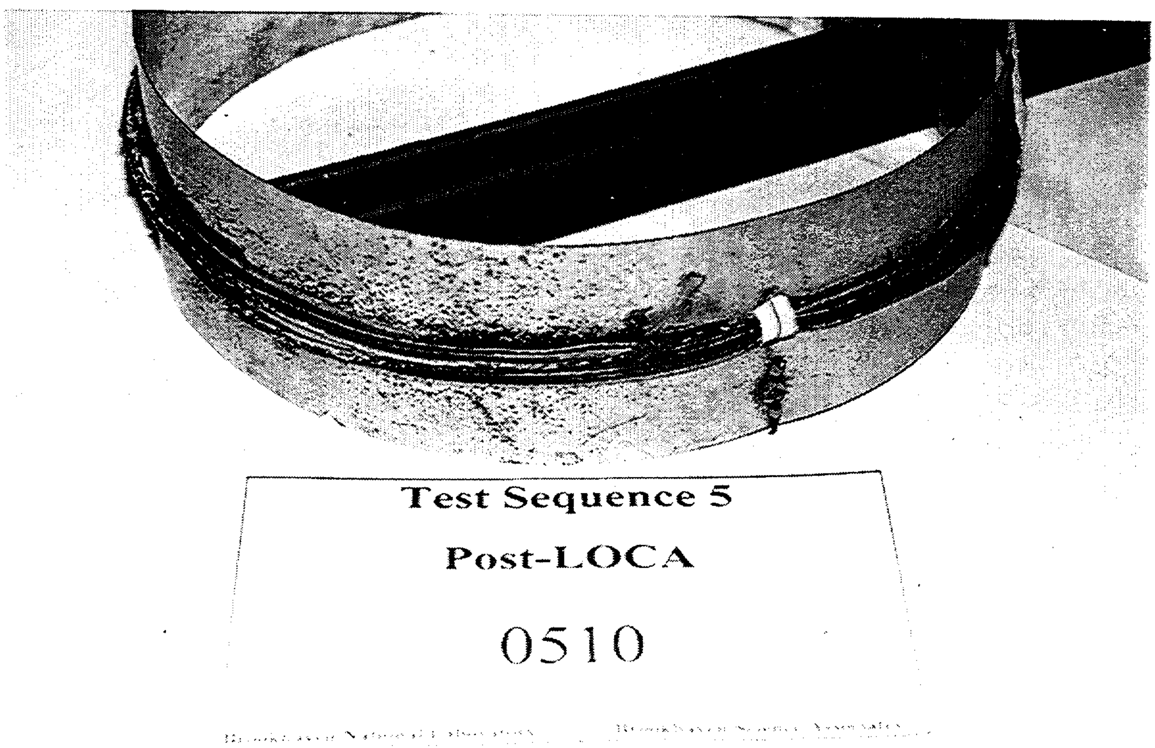

Figure 3.30 Post-LOCA condition of Okonite specimen 0510 in Group 5.3 (pre-aged to 40 years)

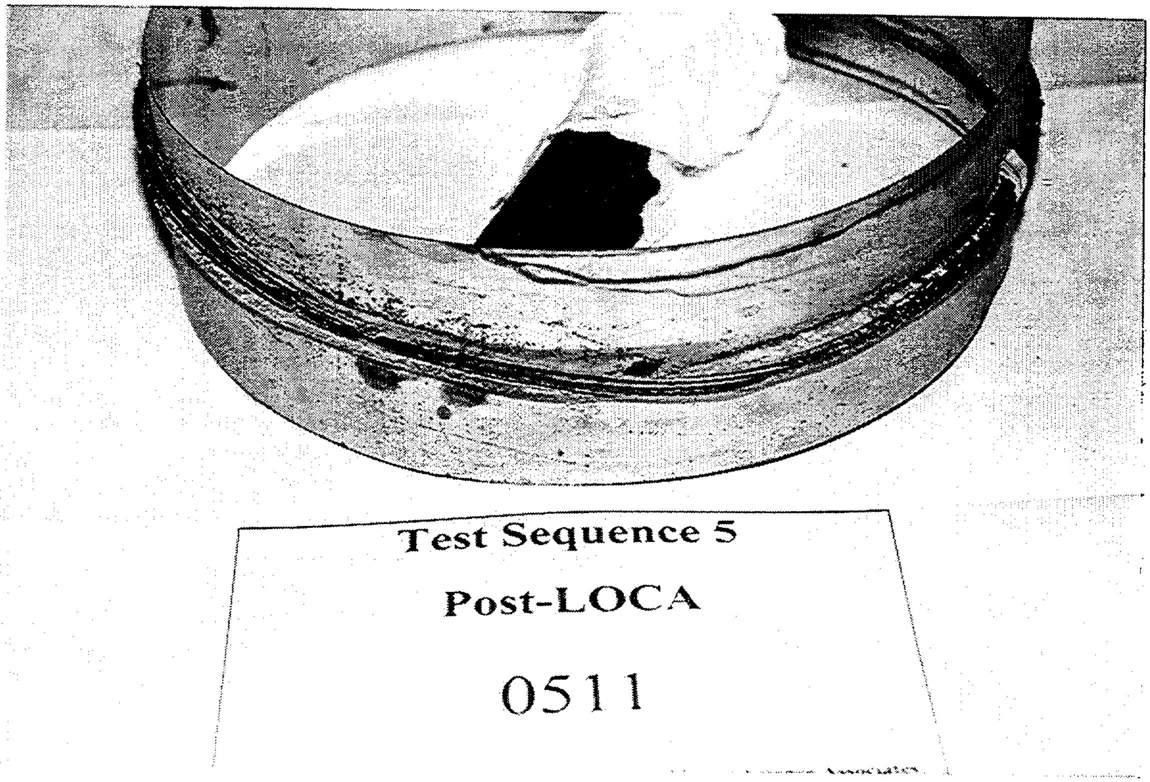

Figure 3.31 Post-LOCA condition of Okonite specimen 0511 in Group 5.3 (pre-aged to 40 years)

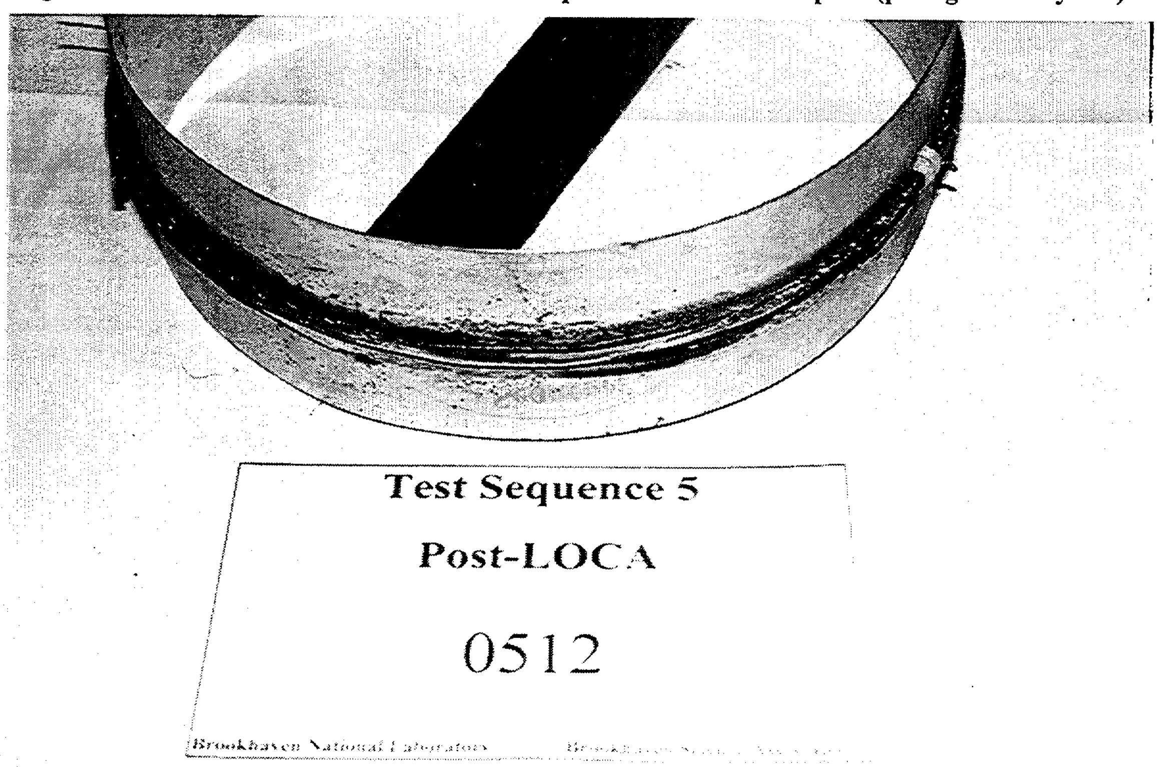

Figure 3.32 Post-LOCA condition of Okonite specimen 0512 in Group 5.3 (pre-aged to 40 years)

3.6.2 Description of Test Specimens

To meet the objective of this test, cables from four different manufacturers were tested; Rockbestos, AIW, Samuel Moore and Okonite. The source cable sample used for the unaged Rockbestos specimens was PNI79RB188, which has XLPE insulation with a Neoprene® jacket, with the trade name "Firewall® III." This cable is the same as that used in tests 1 and 3, and contained 2 XLPE insulated #14 AWG copper conductors with no drain wire. It was insulated with 30 mils of XLPE on the individual conductors and included a 45 mil overall Neoprene® jacket.

The 600V 3/C #16 AWG with ground source cable sample used for AIW specimens 0603 and 0611 was PNI74AI035, and for AIW specimens 0612 and 0619 was PNI74AI036. The 600V 4/C #16 AWG with ground source cable sample used for AIW specimen 0613 was PNI74AI030. The conductors were insulated with 30 mils of EPR with a 15-mil unbonded CSPE individual jacket, and a 45-mil CSPE overall outer jacket. These samples were obtained from the same plant and locations as those used in test sequence 2. The source cable sample used for the Samuel Moore specimens in test sequence 5 was DNI80SM010, which is a 2/C #16 AWG, 600 V cable with a shield and ground wire, and is the same sample used in test sequence 5. The conductors were insulated with 20 mils of Dekoron® (EPDM) with a bonded 10-mil Dekorad® (CSPE) individual jacket, and a 45-mil Dekorad® (CSPE) overall outer jacket. The source cable sample used for the Okonite unaged specimens was LNI81OK020, which is a 1/C #12 AWG, 600 V cable, and is the same sample used in test sequence 5. The conductor was insulated with 30 mils of Okonite® (EPR) with a bonded 15-mil Okolon® (CSPE) individual jacket. There were no naturally aged cable specimens in this test.

For this test, 20 long cable specimens were prepared, as shown in Table 3.24. As in tests 1, 2 and 3, the cable samples were cut into both long (10-foot) and short (6-inch) specimens for testing. The long specimens were installed on stainless steel mandrels to simulate actual qualification testing. A mandrel diameter of approximately 13.5 inches was used. The modified mandrel design developed for test sequence 4 was used for this test, which included a 2-foot Unistrut® arm to support the ends of the test specimens as they were routed away from the mandrel to further mitigate potential handling damage to the cables during splice application and CM testing. As in test sequence 4, short (2-foot to 3-foot) pigtails were spliced to the 10-foot test specimens using Raychem® nuclear grade splices prior to any accelerated aging to avoid handling damage to the test specimens. The pigtails on the 10-foot specimens were shielded from the conditions of thermal and radiation aging, to the extent possible, to keep them from becoming brittle. After pre-aging had been completed, the facility test lead wires were connected to the pigtails on the 10-foot specimens using a second splice, which stayed inside the test chamber.

Preparation of the 6-inch short specimens involved removing the cable outer jacket from the individual conductors, and removing the copper conductors from the insulation. Since the individual CSPE jacket was not bonded to the EPR insulation in the AIW specimens, it was removed and both were tested independently. The individual CSPE jacket was bonded to the underlying EPR insulation for both the Samuel Moore and Okonite specimens and could not be removed.

Consequently, the composite EPR insulation with bonded CSPE individual jacket was tested as a single specimen for these cables. The Rockbestos specimens did not have an individual jacket. The outer jackets from the Rockbestos, Samuel Moore and AIW specimens were punched into a standardized "dog bone" configuration for EAB testing, as in previous tests. The insulation specimens were left in a tubular configuration for testing. The short specimens were placed in stainless steel mesh baskets. Five short cable jacket and insulation specimens were inserted into each basket. The baskets were then designated for removal at specific CM points for materials testing.

Table 3.23 Results of submerged voltage withstand test on specimens in Test Sequence 5

Group	Specimen No.	Manufacturer	Applied Voltage (Vac)	Leakage (microamps)		Pass/Fail
				White Conductor	Black Conductor	
5.1 (no aging)	0501	Okonite	2,400	780	NA	Pass
	0502	Samuel Moore	2,400	790	710	Pass
	0503	Anaconda	2,400	780	720	Pass
5.2 (aged to 20 years)	0504	Okonite	2,400	1,000	NA	Pass
	0505 (a)		< 200	> 10mA	NA	**Fail**
	0506	Samuel Moore	2,400	1,000	1,000	Pass
	0507		2,400	1,200	1,400	Pass
	0508	Anaconda	2,400	780	1,000	Pass
	0509		2,400	790	850	Pass
5.3 (aged to 40 years)	0510 (a)	Okonite	< 200	> 10mA	NA	**Fail**
	0511 (a)		< 200	> 10mA	NA	**Fail**
	0512 (a)		< 200	> 10mA	NA	**Fail**
	0513	Samuel Moore	2,400	1,800	1,000	Pass
	0514		2,400	1,200	1,000	Pass
	0515	Anaconda	2,400	790	850	Pass
	0516		2,400	820	780	Pass

(a) Specimen would not hold 2,400 volts; test performed at lower voltage noted.
NA = Not applicable; single conductor cable specimen

3.6.3 Accelerated Aging Parameters

The specimens in test sequence 6 can be grouped according to the pre-aging they received as follows: in Group 6.1, one cable specimen from each manufacturer was prepared and LOCA tested without any pre-aging; these are the control specimens. Group 6.2 includes three specimens from each manufacturer, which were pre-aged to the equivalent of 60 years of qualified life prior to LOCA testing. The two pre-aging groups are summarized as follows:

Group 6.1: Rockbestos, Okonite, AIW and Samuel Moore with no accelerated aging (control specimens).
Group 6.2: Rockbestos, Okonite, AIW and Samuel Moore with accelerated aging to simulate 60 years of qualified life.

As in previous tests, the accelerated aging parameters were selected to match those used for the original qualification testing of the cables. The test reports cited in Table 2.2 were used to determine the original qualification pre-aging parameters. For the Rockbestos cables in this test, the newer qualification report QR #5805 was used instead of the original qualification report QR #1806. Comparing the two reports, the testing was the same with the exception that the thermal aging duration was reduced to 909 hours at 302°F (150°C) to represent 40 years in the newer qualification test instead of the 1,350 hours at 302°F (150°C) used in the original qualification test. Details of the testing performed in the respective qualification reports are presented in previous sections of this report.

Table 3.24 Description of specimens in Test Sequence 6

Group	Specimen ID No.	Sample ID No.	Configuration [a]	Manufacturer [a]	Insulation Material [a]	Jacket Material [a]	No. of Conductors	Wire Gauge (AWG)	Cable Diameter (in.)	Cable Type [a]	Insulation Thickness (mils) [c]
6.1	0601	LNI81OK020	10 FT - MAN	OK	EPR[d]	CSPE	1	12	0.175	I	30
	0602	DNI80SM010	10 FT - MAN	SM	EPDM[d]	CSPE	2 w/shld&gnd	16	0.327	I	20
	0603	PNI74AI035	10 FT - MAN	AIW	EPR[e]	CSPE	3 w/gnd	16	0.445	I	30
	0604	PNI79RB188	10 FT - MAN	RB FW-III	XLPE	NEO	2	14	0.380	I	30
6.2	0605	LNI81OK020	10 FT - MAN	OK	EPR[d]	CSPE	1	12	0.175	I	30
	0606	LNI81OK020	10 FT - MAN	OK	EPR[d]	CSPE	1	12	0.175	I	30
	0607	LNI81OK020	10 FT - MAN	OK	EPR[d]	CSPE	1	12	0.175	I	30
	0608	DNI80SM010	10 FT - MAN	SM	EPDM[d]	CSPE	2 w/shld&gnd	16	0.327	I	20
	0609	DNI80SM010	10 FT - MAN	SM	EPDM[d]	CSPE	2 w/shld&gnd	16	0.327	I	20
	0610	DNI80SM010	10 FT - MAN	SM	EPDM[d]	CSPE	2 w/shld&gnd	16	0.327	I	20
	0611	PNI74AI035	10 FT - MAN	AIW	EPR[e]	CSPE	3 w/gnd	16	0.445	I	30
	0612	PNI74AI036	10 FT - MAN	AIW	EPR[e]	CSPE	3 w/gnd	16	0.445	I	30
	0613	PNI74AI030	10 FT - MAN	AIW	EPR[e]	CSPE	3 w/gnd	16	0.445	I	30
	0621[b]	PNI79RB188	10 FT - MAN	RB FW-III	XLPE	NEO	2	14	0.380	I	30
	0622[b]	PNI79RB188	10 FT - MAN	RB FW-III	XLPE	NEO	2	14	0.380	I	30
	0623[b]	PNI79RB188	10 FT - MAN	RB FW-III	XLPE	NEO	2	14	0.380	I	30
Archive	0617[f]	LNI81OK020	10 FT - STR	OK	EPR[d]	CSPE	1	12	0.175	I	30
	0618[f]	DNI80SM010	10 FT - STR	SM	EPDM[d]	CSPE	2 w/shld&gnd	16	0.327	I	20
	0619[f]	PNI74AI035	10 FT - STR	AIW	EPR[e]	CSPE	3 w/gnd	16	0.445	I	30
	0624[f]	PNI79RB188	10 FT - STR	RB FW-III	XLPE	NEO	2	14	0.380	I	30

(a) MAN=Mandrel, AIW=American Insulated Wire, OK=Okonite,RB FW-III=Rockbestos Firewall® III, SM=Samuel Moore, XLPE=Cross-linked Polyethylene, EPR = Ethylene Propylene Rubber, EPDM = Ethylene Propylene Diene Monomer, CSPE = Chloro-sulfonated Polyethylene, NEO=Neoprene®, I=Instrumentation

(b) Specimens 0614-0616, which were thermally aged prior to attaching splices, were replaced with specimens 0621-0623 to allow splices to be applied prior to pre-aging.

(c) Thickness of insulation only; does not include 15 mil CSPE individual jacket for AIW and Okonite cables nor 10 mil CSPE individual jacket for Samuel Moore cables.

(d) Insulation covered with bonded CSPE individual jacket. (e) Insulation covered with unbonded CSPE individual jacket.

(f) These specimens were included for archiving purposes and were not energized during the LOCA steam exposure. A 2-foot section was removed at each hold point and placed in storage.

To simulate 60 years of qualified life, the thermal aging time and radiation total integrated dose used to simulate 40 years of qualified life in the qualification reports were multiplied by 1.5. The thermal aging temperature and radiation dose rate were kept the same as in the original qualification test. The accelerated aging received by the test specimens is presented in Table 3.25.

Table 3.25 Actual accelerated aging conditions received by the specimens in Test Sequence 6

Group	Cable	Thermal Aging		Service Radiation (a)		LOCA Radiation (a)	
		Temperature (°F/°C)	Duration (hours)	Total Integrated Dose (Mrad)	Dose Rate (Mrad/hr.)	Total Integrated Dose (Mrad)	Dose Rate (Mrad/hr.)
6.1	All	-	None	None	-	Phase 1: 78.99 Phase 2: 77.64	Phase 1: 0.58 Phase 2: 0.69
6.2	Okonite	302°F (150°C)	756.0	77.28	0.590		
	AIW	302°F (150°C)	252.1	38.65	0.599		
	Sam Moore	250°F (121°C)	252.1	77.28	0.590		
	Rockbestos	302°F (150°C)	1,363.8	77.02	0.390		

(a) Radiation exposures for long specimens and/or basket specimens in the same group were performed in multiple runs due to restrictions on the number of sources allowed in the hot cell at one time. Therefore, the radiation doses and dose rates reported are averages for all runs.

(b) The specified LOCA radiation exposure was the same for all groups. It was performed in two separate phases to allow condition monitoring measurements to be taken at the midpoint.

(c) AIW specimens were not exposed to Phase 2 accident radiation.

3.6.4 Results of Accelerated Aging

Visual examination and baseline elongation-at-break measurements confirmed that all cable specimens were initially in excellent condition. No discoloring or cracking was evident in either the jacket or insulation for any of the specimens. As shown in Table 3.26, average elongation-at-break values for the insulation on the unused specimens ranged from 391 percent to 574 percent, indicating excellent ductility for all of the cable specimens.

The Group 6.2 cables were artificially aged to simulate 60 years of equivalent qualified life. The EAB tests, as well as the visual inspections indicated that the Samuel Moore and AIW cables were in acceptable condition throughout the thermal and radiation pre-aging sequence. For the Samuel Moore specimens (Figure 3.33), no cracks were evident and the cables remained relatively flexible with average EAB values of 145 percent for the CSPE outer jacket and 68 percent for the composite insulation, as shown in Table 3.26. The AIW specimens (Figure 3.34) also had no cracking evident, and average EAB values were 191 percent and 218 percent for the CSPE outer jacket and EPR insulation, respectively.

The Neoprene® outer jackets on the Rockbestos specimens in Group 6.2 were brittle and appeared severely degraded with cracking and discoloration noticeable, as shown in Figure 3.35. The XLPE insulation on the Rockbestos specimens was stiff, as evidenced by the low EAB values; however,no cracking was evident. The CSPE jacket on the Okonite specimens in Group 6.2 appeared to be in good physical condition with no significant discoloring noted (Figure 3.36); however, circumferential hairline cracks were found in the jackets of all three of the pre-aged specimens; the worst being specimen 0605 with 9 cracks noted during the visual inspection. Since the cracks were very thin, it was impossible to determine if they went completely through the jacket wall using visual inspection. The Okonite cables were relatively stiff, as confirmed by the low EAB value of < 5 percent for the composite EPR/CSPE insulation.

Table 3.26 Average elongation-at-break values for the specimens in Test Sequence 6

Group	Cable	Average elongation-at-break at each CM Point (%)											
		Baseline No Aging		After Thermal Service Aging		After Radiation Service Aging		After Half LOCA Radiation		After Full LOCA Radiation		After LOCA Steam Exposure	
		Outer Jkt. (b)	Insul. (a)	Outer Jkt. (b)	Insul. (a)	Outer Jkt. (b)	Insul. (a)	Outer Jkt. (b)	Insul. (a)	Outer Jkt. (b)	Insul. (a)	Outer Jkt. (b)	Insul. (a)
6.1 (0 yrs.)	Rockbestos PNI79RB188	557	574	NA	NA	NA	NA	174	340	143	152	Not Tested	Not Tested
	Okonite LNI81OK020	NA	471	NA	NA	NA	NA	NA	360	NA	234	Not Tested	Not Tested
	AIW PNI74AI030, 035, 036	429	391	NA	NA	NA	NA	373	466	270	161	Not Tested	Not Tested
	Samuel Moore DNI80SM010	613	418	NA	NA	NA	NA	361	300	240	171	Not Tested	Not Tested
6.2 (60 yrs.)	Rockbestos PNI79RB188	557	574	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	Not Tested	Not Tested
	Okonite LNI81OK020	NA	471	NA	< 5	NA	< 5	NA	< 5	NA	< 5	Not Tested	Not Tested
	AIW PNI74AI035	429	391	303	300	191	218	140	131	154	112	Not Tested	Not Tested
	Samuel Moore DNI80SM010	613	418	387	168	145	68	70	42	54	37	Not Tested	Not Tested

(a) Elongation-at-break value for Okonite and Samuel Moore insulation is for the composite EPR/CSPE insulation, while the EAB for the AIW insulation is for the EPR insulation alone.
(b) The Okonite specimens are single conductor and do not have an outer jacket
NA = not applicable

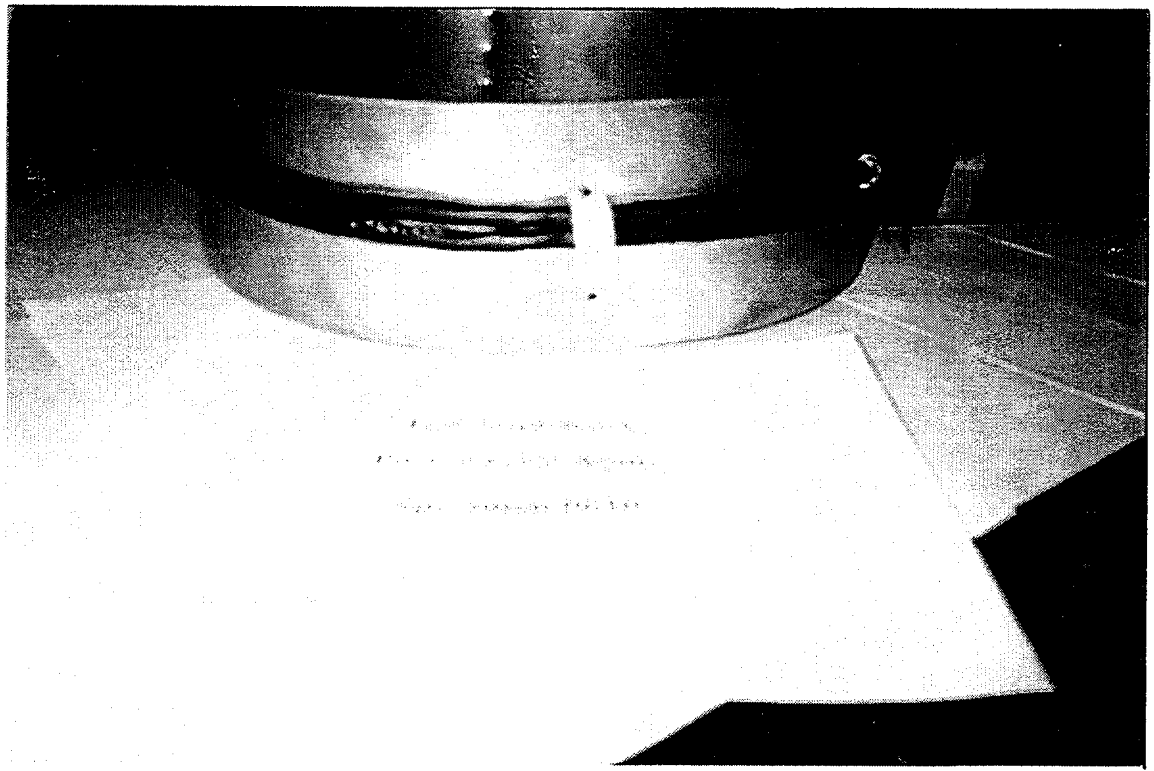

Figure 3.33 Samuel Moore specimen 0610 from Group 6.2 (pre-aged to 60 years) after accelerated service aging

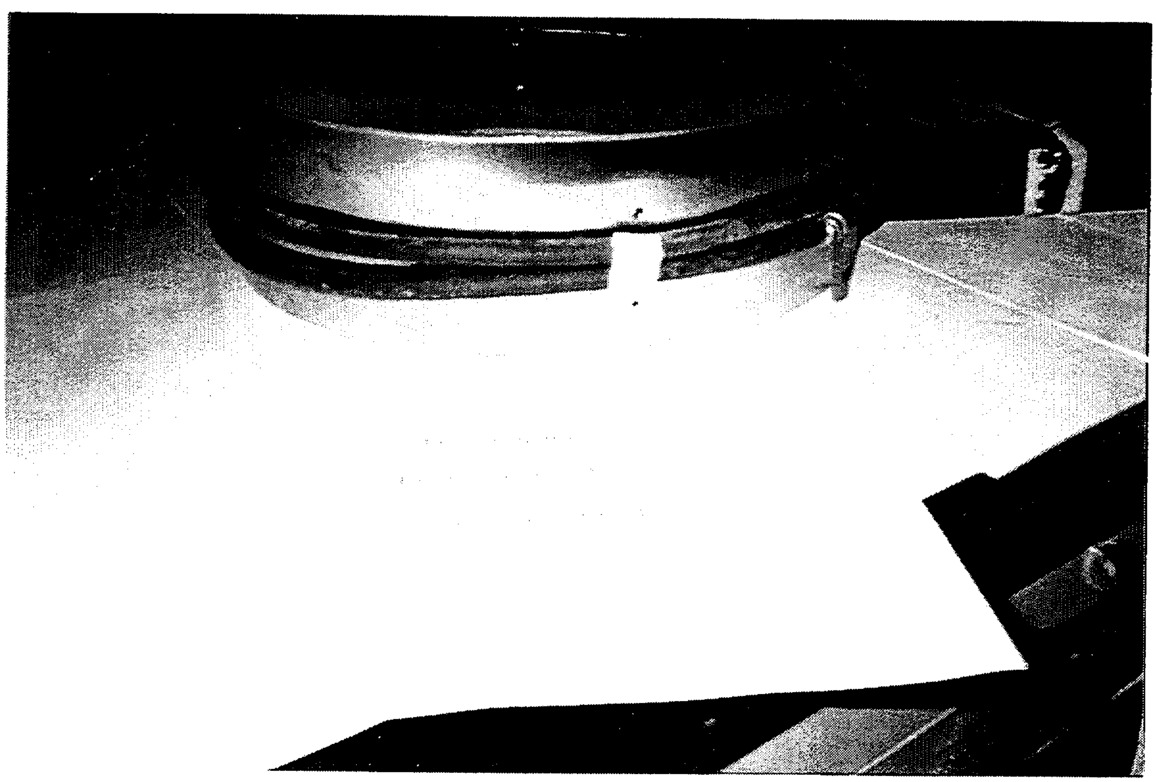

Figure 3.34 AIW specimen 0611 from Group 6.2 (pre-aged to 60 years) after accelerated service aging

3.6.5 LOCA Conditions Simulated

The LOCA conditions simulated included exposure to either 75 or 150 Mrad of accident radiation, followed by exposure to steam at high temperature and pressure. The accident radiation exposure was performed after completion of the service aging and prior to the steam exposure.

Following accident irradiation, the specimens were subjected to a high temperature and pressure steam exposure. Since cable specimens from four different manufacturers were included in this test, the LOCA test profile was chosen to envelop the original qualification test profiles used for all four cables. The original qualification test for the AIW cable consisted of a 100-day test with a single peak at 340°F (171°C) and > 60 psig, while that for the Samuel Moore cable consisted of a 30-day test with two peaks at 340°F (171°C) and 105 psig. The LOCA profile for the Okonite cables included a double peak at 345°F (174°C) and 114 psig, while that for the Rockbestos cables included a double peak at 340°F (171°C) and 104 psig. Comparison of these profiles with the profile used in both LOCA Tests 1 and 3 for this program showed that the Test 1/3 profile conservatively enveloped the LOCA test profiles used for these cables. Therefore, the profile used in this test is the same one used in tests 1 and 3 with the exception of the total duration, which was extended to 10 days to correspond with previous testing by Sandia (Jacobus, 1992). The LOCA 6 test profile included a double peak at a maximum temperature of 346°F (174°C) and a pressure of 113 psig, as recommended in Appendix A to IEEE Standard 323-1974. Temperature and pressure were then stepped down to 212°F (100°C) and ambient pressure. Chemical spray was included during the steam exposure starting at approximately 15 hours. The total duration of the LOCA steam exposure was shortened to 10 days as compared to the original qualification tests in order to expedite testing since post-LOCA performance was not an objective of this test. The profile is shown in Figure 3.3.

3.6.6 Results of LOCA Radiation and Steam Exposure

The LOCA radiation further reduced the EAB values for the AIW and Samuel Moore specimens, as shown in Table 3.26. No cracking was evident in any of the Samuel Moore or AIW specimens prior to the LOCA steam exposure.

Prior to the initiation of the LOCA steam profile, the test chamber was preheated to approximately 140°F (60°C) with saturated steam and conditions were held for approximately 1 hour. Chamber pressure during this hold period ranged from 4 to 5 psig. No anomalies were noted for any of the test specimens during this period.

During the first 3-hour hold at peak conditions, minimal leakage currents ranging from 0.3 to 0.7 mA were noted for the three Rockbestos specimens 0621, 0622 and 0623. For one of the Okonite specimens, 0605, a minimal leakage current of 0.2 mA was measured. All of these leakage currents returned to 0 mA as pressure was reduced during the cooldown period. No leakage current was measured for any of the other specimens. Also, no fuses were blown during this phase of the test for any of the specimens.

During the first minute of the second ramp, at approximately 5 hours into the test, the 1/32-amp (31.25 mA) fuse in the instrument loop circuits in each of the three pre-aged Okonite specimens (0605, 0606 and 0607) blew due to excessive circuit currents. New fuses were installed in each circuit and specimens 0606 and 0605 then continued to function although high leakage currents (6.0 to 27.0 mA) were observed. Okonite specimen 0607 would not operate at that time, immediately blowing the new fuse. At approximately 5 hours 15 minutes into the test, the fuse for the specimen 0607 instrument loop circuit was replaced and the circuit successfully continued to operate.

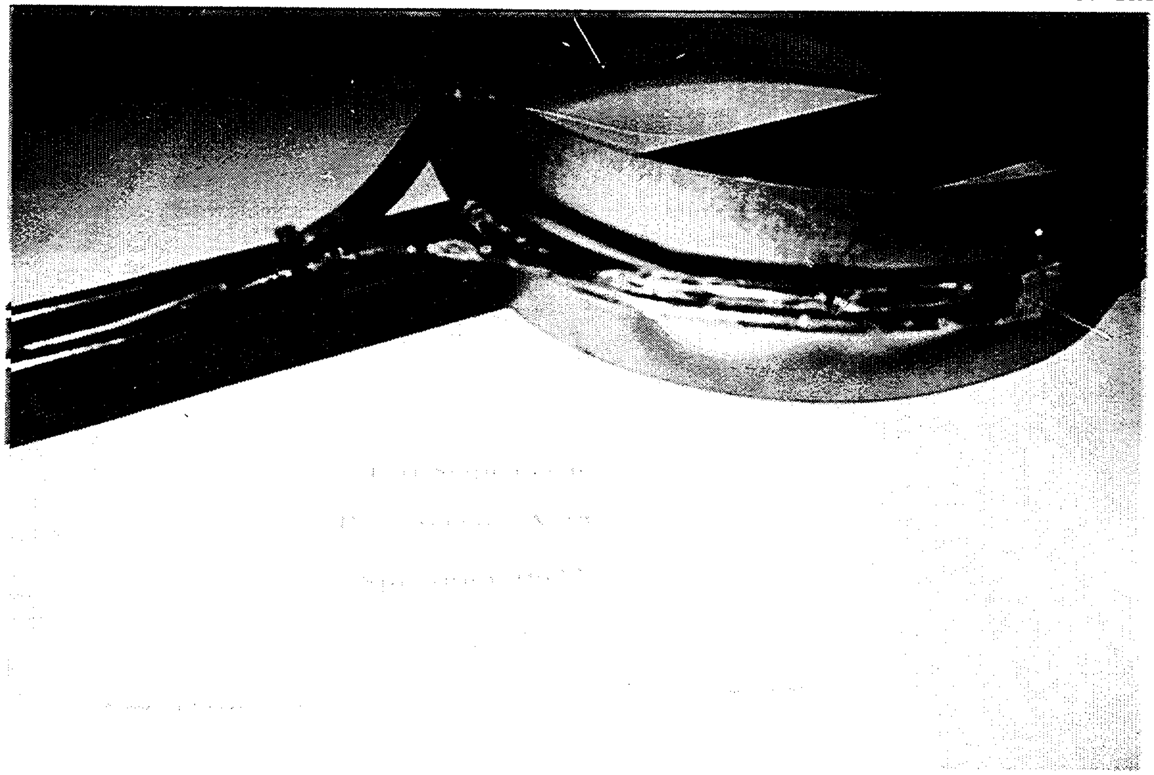

Figure 3.35 Rockbestos specimen 0622 from Group 6.2 (pre-aged to 60 years) after accelerated service aging

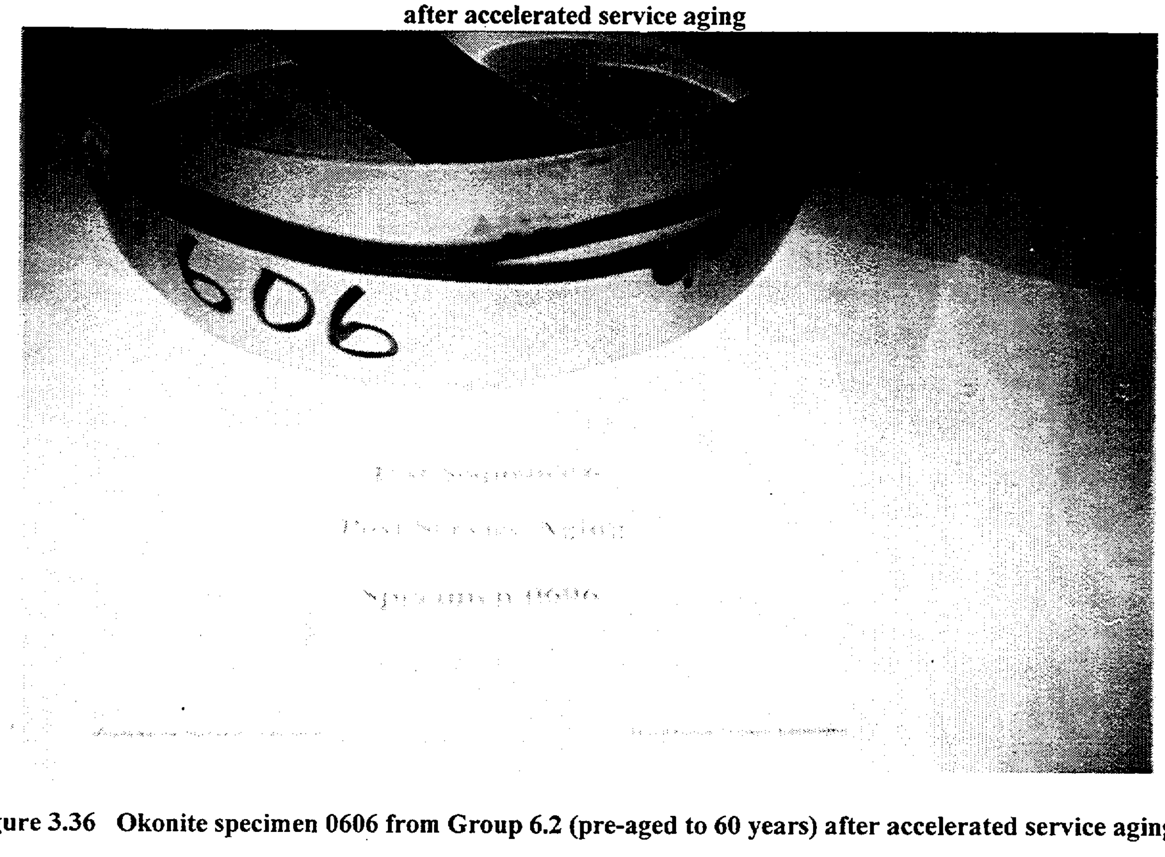

Figure 3.36 Okonite specimen 0606 from Group 6.2 (pre-aged to 60 years) after accelerated service aging

After reaching peak conditions, during the second hold period, the leakage current for the three Okonite specimens gradually decreased to less than 1 mA. Leakage current for the three Rockbestos specimens (0621, 0622, 0623) gradually increased to approximately 0.3 to 0.6 mA, as observed in the first hold period.

At approximately 10 hours into the test, the 1/32-amp (31.25 mA) fuses in the circuits for Okonite specimens 0605 and 0606 blew for the second time. Using a hand-held multi-meter across the fuse terminals in the circuit, currents ranging from 200 to 300 mA were measured. At approximately 11 hours into the test, the 1/32-amp fuse for the third Okonite specimen 0607 blew again. A circuit current of approximately 273 mA was measured across the fuse terminals. All three pre-aged Okonite specimens were left de-energized at this point. The unaged Okonite specimen, as well as all of the AIW, Samuel Moore, and Rockbestos specimens, continued to perform acceptably.

At approximately 15 hours into the test, chemical spray was initiated. No additional performance anomalies were noted as a result of the chemical spray.

No further anomalies were noted for the specimens for the remainder of the test.

3.6.7 Results of Post-LOCA Testing

Following completion of the LOCA steam exposure, the test specimens were removed from the test chamber and a visual inspection was performed.

On the Okonite control specimen 0601 small blisters (0.5mm-1.0mm in diameter) covered the surface of the jacket; however, the bonded jacket was intact. On Okonite specimens 0605, 0606 and 0607 (pre-aged to 60 years), the bonded jacket and insulation were split open in major sections of the cables completely exposing the copper conductor inside, as shown in Figures 3.37 to 3.39. The split was generally facing outward from the center of the test mandrel so the conductor did not come in contact with the metal mandrel.

Visual inspection of the AIW control specimen (0603) found that the outer jacket was cracked and pulled away from the rest of the cable in a series of folds resembling a sawtooth appearance at the support arm and along many sections of the cable on the mandrel. This appeared to be due to dimensional swelling of the jacket in length and diameter. Jacket degradation was also noted on the AIW specimens pre-aged to 60 years. On AIW specimen 0611 the outer jacket was cracked and pulled away from the rest of the cable at the support arm and two sections of the upper cable coil on the mandrel. Four deep cracks were evident with the jacket pulling away or slipping one piece over the other on the lower cable coil on the mandrel. This appeared to be due to dimensional swelling of the jacket in length and diameter.

On AIW specimen 0612, one deep crack was evident with the outer jacket slipping one piece over the other on the upper cable coil on the mandrel. Similarly, on AIW specimen 0613, the outer jacket was cracked and pulled away from the rest of the cable at the support arm and two sections of the upper cable coil on the mandrel; individual conductor jackets were visible in some locations but did not have a damaged appearance. A cracked and charred appearance of the outer jacket in one section on the lower cable coil on the mandrel was also noted. Figure 3.40 shows the typical post-LOCA condition of the AIW specimens.

For Rockbestos specimens 0621-0623 pre-aged to 60 years, numerous radial and longitudinal cracks in the outer jacket over the entire length of the specimens were evident; the individual conductor insulation was not visible. The outer jackets were extremely brittle. Figure 3.41 shows the typical post-LOCA condition of the Rockbestos specimens.

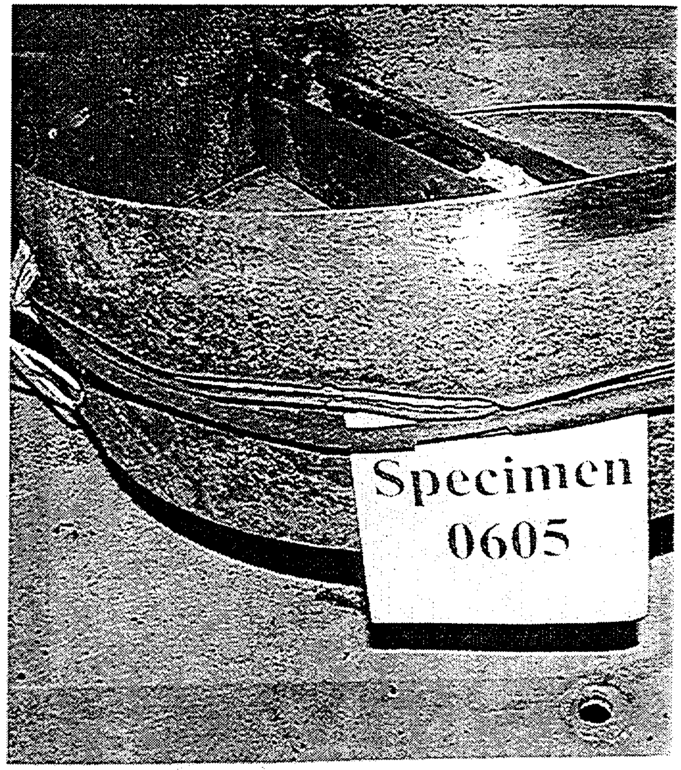

Figure 3.37 Post-LOCA condition of Okonite specimen 0605 from Group 6.2 (pre-aged to 60 years)

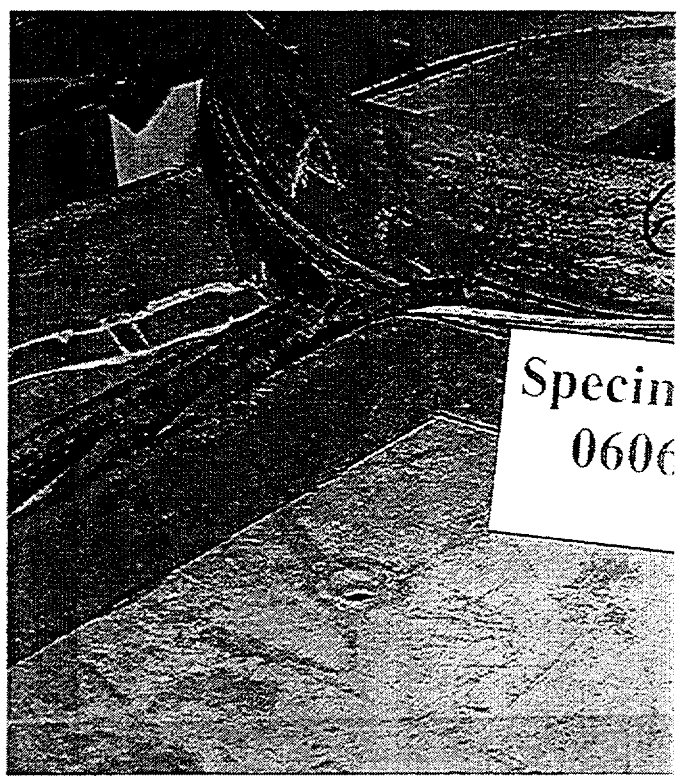

Figure 3.38 Post-LOCA condition of Okonite specimen 0606 from Group 6.2 (pre-aged to 60 years)

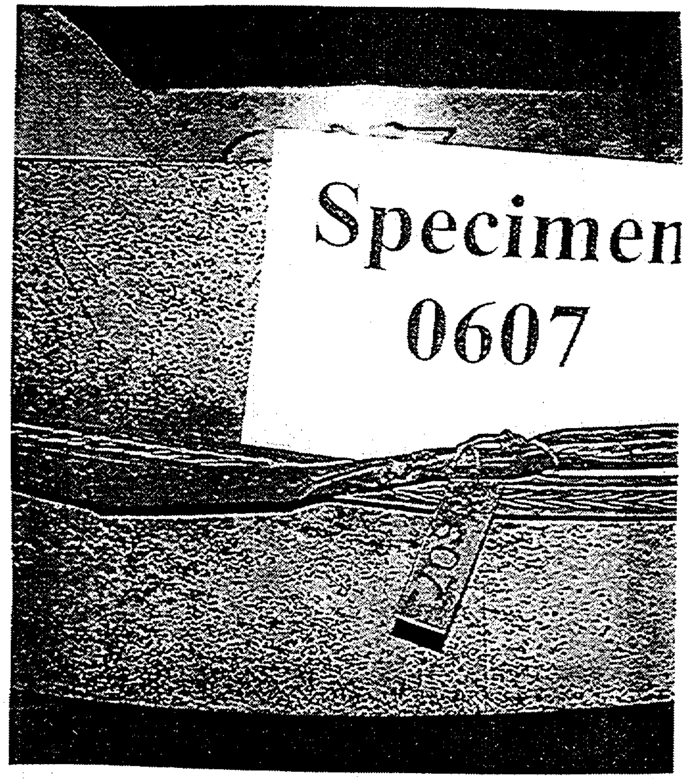

Figure 3.39 Post-LOCA condition of Okonite specimen 0607 from Group 6.2 (pre-aged to 60 years)

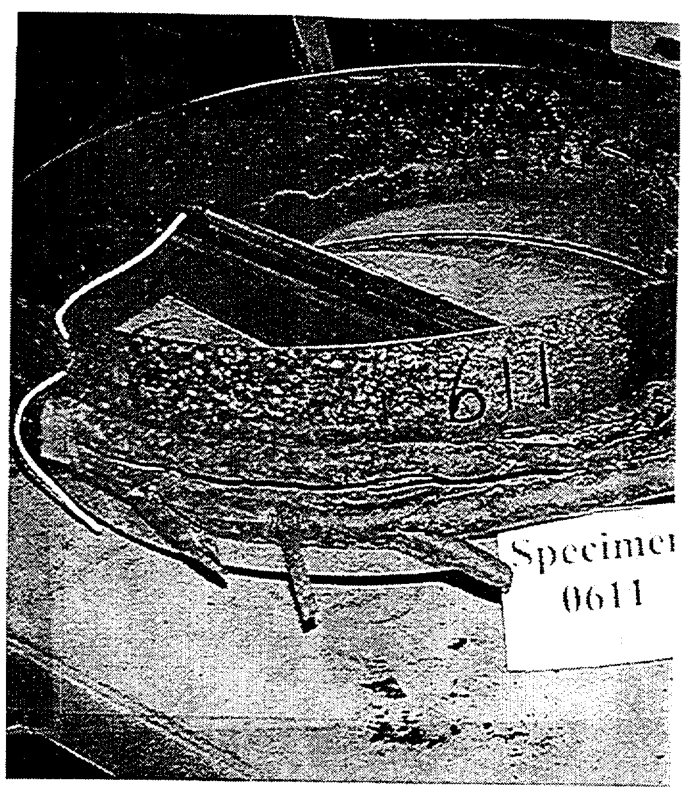

Figure 3.40 Post-LOCA condition of AIW specimen 0611 from Group 6.2 (pre-aged to 60 years)

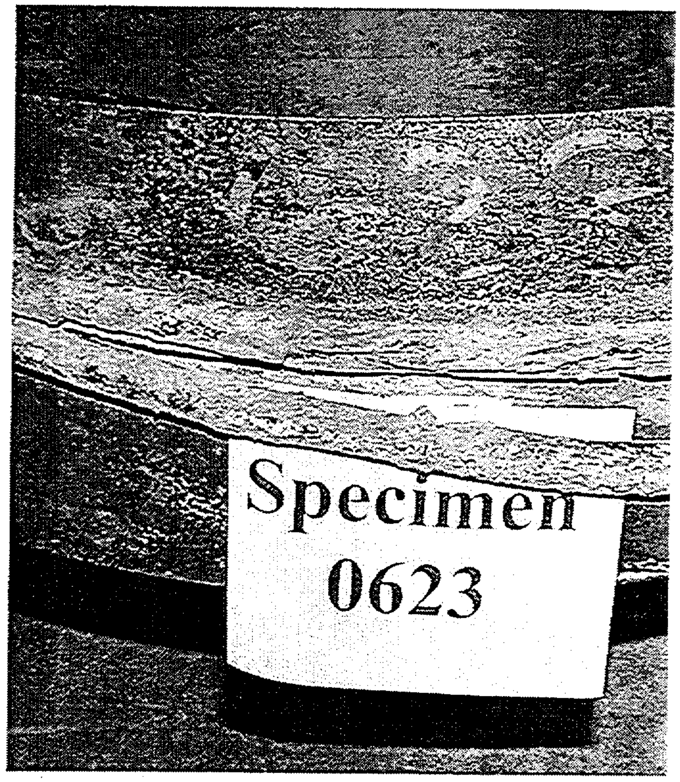

Figure 3.41 Post-LOCA condition of Rockbestos specimen 0623 from Group 6.2 (pre-aged to 60 years)

The Samuel Moore specimens appeared to be in good physical condition. No cracking was evident in the outer jackets, as shown in Figure 3.42.

Insulation resistance (IR)readings were taken using a General Radio Model 1864 megohmmeter capable of measuring insulation resistance up to 200 Teraohm. Polarization index was estimated by dividing the 10 minute IR reading by the 1-minute IR reading. Some of the significant measurements noted are as follows:

The following test specimens exhibited a Polarization Index below 1.0:

- Okonite specimen 0601;
- Samuel Moore specimens 0602 black-ground and 0609 all conductors;
- AIW specimens 0603 black-white and black-ground, 0612 black-white and black-ground, and 0613 white-ground;

The following test specimens exhibited Insulation Resistance below 10^6 Ω range at 500Vdc:

- AIW specimen 0603 white-ground (100Vdc),
- AIW specimen 0611 white-ground (1 min only), and
- AIW specimen 0612 white-ground (1 min only)

Figure 3.42 Post-LOCA condition of Samuel Moore specimen 0608 from Group 6.2 (pre-aged to 60 years)

Following the post-LOCA electrical tests, the test specimens were subjected to a submerged voltage withstand test. The specimens were submerged in tap water at room temperature (approximately 82°F/28 °C) and a test voltage of 2,400Vac was applied for a duration of 5 minutes. The results are presented in Table 3.27.

As shown in Table 3.27, the following specimen conductors exceeded the 10mA leakage current limit of High potential Tester:

- Okonite specimens 0605, 0606, and 0607;
- Samuel Moore specimen 0609 white;
- AIW specimens 0603 white, 0611 white, 0612 white, and 0613 black;
- Rockbestos specimen 0622 black.

Additionally, the following specimen conductors exceeded 1,000μA leakage current at 2,400Vac:

- Samuel Moore specimens 0608 white (4000μA) and black (2200μA),
- Samuel Moore specimen 0609 black (1400μA),
- Samuel Moore specimen 0610 white (3200μA) and black (4400μA),
- AIW specimen 0603 black (1500μA),
- AIW specimen 0611 black (1400μA),
- AIW specimen 0612 black (1400μA),
- AIW specimen 0613 white (4200μA),
- Rockbestos specimen 0621 white (2000μA) and black (1800μA),
- Rockbestos specimen 0622 black (2000μA), and
- Rockbestos specimen 0623 white (3000μA) and black (3600μA).

Table 3.27 Results of submerged voltage withstand test on specimens in Test Sequence 6

Group	Specimen No.	Manufacturer	Applied Voltage (Vac)	Leakage (microamps)		Pass/Fail
				White Conductor	Black Conductor	
6.1 (no aging)	0601	Okonite	2,400	< 1,000	NA	Pass
	0602	Samuel Moore	2,400	< 1,000	< 1,000	Pass
	0603	AIW	2,400/500	1,500	> 10mA	**Fail**
	0604	Rockbestos	2,400	< 1,000	< 1,000	Pass
6.2 (aged to 60 years)	0605 (a)	Okonite	< 200	> 10mA	NA	**Fail**
	0606 (a)		< 200	> 10mA	NA	**Fail**
	0607 (a)		< 200	> 10mA	NA	**Fail**
	0608	Samuel Moore	2,400	4,000	2,200	Pass
	0609 (a)		500/2,400	> 10mA	1,400	**Fail**
	0610		2,400	3,200	4,400	Pass
	0611 (a)	AIW	1,000/2,400	> 10mA	1,400	**Fail**
	0612 (a)		2,400/1,500	1,400	> 10mA	**Fail**
	0613 (a)		500/2,400	> 10mA	4,200	**Fail**
	0621 (b)	Rockbestos	2,400	2,000	1,800	Pass
	0622 (a,b)		2,400/500	2,000	> 10mA	**Fail**
	0623 (b)		2,400	3,000	3,600	Pass

(a) Specimen would not hold 2,400 volts; test performed at lower voltage noted.
(b) Specimens 0614, 0615 and 0616 were replaced with 0621, 0622 and 0623 to allow splice application prior to pre-aging.
NA = Not applicable; single conductor cable specimen

Following the submerged voltage withstand test, the cables that exceeded the leakage current limit of the High potential Tester were inspected further to verify that the problems were in the cable rather than the splices to the test leads. The three pre-aged Okonite specimens 0605, 0606, and 0607 were not included since the condition of the cable insulation was obvious from the visual inspection.

AIW specimens 0603, 0611, 0612, 0613, Samuel Moore specimen 0609, and Rockbestos specimen 0622 were individually IR tested for 1 minute at 500Vdc while tap water was applied from a squirt bottle along the length of the specimens. The IR readings were generally lower than those obtained in the post-LOCA IR tests, since the voltage withstand test is a destructive test that can weaken or fail the insulation. The application of water did not have any significant effect on these specimens.

The splices were then cut from the aforementioned specimens and the individual 1-minute IR tests at 500Vdc were repeated to verify that the splices had acceptable IR readings. All splices were found to be acceptable.

The individual cable conductors were then IR tested at 500Vdc to find lower IR readings that would verify that the cable insulation was the problem. Specimens Samuel Moore specimen 0609, AIW specimens 0611, 0612, 0613, and Rockbestos specimen 0622 all had one or more IR readings lower than $10^6\ \Omega$ range confirming that the cable insulation was degraded in these specimens. AIW specimen 0603 had a conductor-to-conductor IR of $5.8\times10^{10}\ \Omega$, and conductor-to-ground IR readings of $5.3\times10^{10}\ \Omega$, $7.0\times10^{9}\ \Omega$, and $1.06\times10^{9}\ \Omega$. These IR readings were judged not to be indicative of insulation degradation for this specimen.

The submerged voltage withstand test was repeated on AIW specimens 0603 and 0613 after the splices were removed to provide additional verification that the problem was in the cable insulation. These tests were inconclusive since none of the cables could be brought up to the test voltage of 2,400 Vac. The most likely reason for the test being inconclusive is the configuration of the connection to the cables under test. Boric acid and other contaminants on the wet surface of the cable under test, which was now in close proximity to the surface of the water in the test vessel once the splices had been removed, caused immediate tracking of voltage from the High potential tester leads across the surface of the cable under test to ground.

3.7 Measurement of Activation Energies

One of the issues addressed in the current research program is related to the activation energy values used for modeling the thermal aging of cable insulation materials in qualification tests. Specifically, it was desired to determine if the activation energies used were reasonable.

Since measuring and cataloguing activation energies for all materials currently in use would be extremely burdensome, and outside the scope of this program, the approach taken was to focus on the two insulation materials most commonly used--namely, XLPE and EPR. Verification of the activation energies for these two materials would provide confidence that the values used for other materials are also reasonable.

The activation energy values are important since they are used in the qualification process to carry out the accelerated thermal aging of the cable insulation in simulating the long-term aging under plant service conditions. This is achieved by aging at elevated temperatures, and using the Arrhenius equation to extrapolate to plant service temperatures. An incorrect choice of activation energy will lead to inaccurate simulation of actual aging and prevent accurate estimates from being made of the in-service properties of the cables. Note that aging caused by gamma radiation is not considered in this work.

Typically, to determine activation energy values, large numbers of cable samples are aged at different temperatures in air for different lengths of time. At a given temperature, the aging of the material is monitored by secondary techniques such as EAB. From a comparison of the time to reach a given amount of degradation in EAB at different temperatures, it is possible to verify Arrhenius behavior and measure the activation energy. The main drawback in such work lies in the large numbers of samples to be tested, and the cost for additional tensile testing.

In this program, an alternate methodology for determining activation energy was used based on oxidation of the materials under controlled conditions in a differential scanning calorimeter (DSC). The goal was to verify Arrhenius behavior for oxidative degradation of XLPE and EPR, and, if so, to estimate their activation energy. The technique is very useful since materials may actually be aged in the DSC at temperatures that can be controlled to within tenths of a degree Celsius. Also, only small amounts of material (about 10 mg) are needed per test.

The oxidative induction time tests (OITM tests) conducted herein involve the measurement of the time to reach the point where the base polymeric material is oxidized under isothermal conditions in flowing oxygen. When plastics are initially exposed to oxidizing environments, the antioxidants in the material retard the propagation of an oxidative chain reaction and, thereby, protect the base structure. When the antioxidants are exhausted, the polymer structure is rapidly attacked, and a large exothermic reaction is observed.

Figure 3.43 shows a typical DSC thermogram for XLPE. One curve shows the temperature profile throughout the run. The other gives the thermal energy absorbed by the specimen, and includes the exothermic peak, which signifies rapid oxidation. In the DSC tests, the temperature of the specimen is raised to a predetermined set temperature, in this case 410°F (210°C), in nitrogen. When the temperature approaches the set temperature, the nitrogen is replaced by flowing oxygen at atmospheric pressure. A small spike is usually observed when the oxygen begins to react with the specimen. The energy supplied to the specimen remains small and constant during the period when the antioxidant is present. This is shown by the flat line for energy input. When the antioxidant is depleted, the large exothermic peak appears.

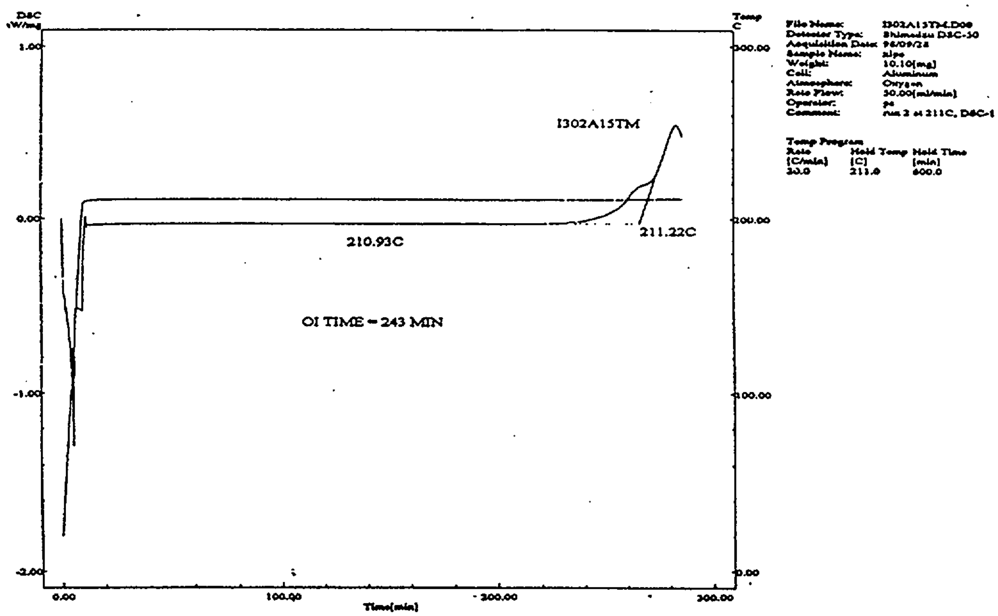

Figure 3.43 Typical DSC Thermogram for XLPE Insulation Oxidized in Oxygen at 410°F (210°C)

The OITM is obtained by the tangent-intercept method. One tangent is drawn along the horizontal portion of the thermogram and the other is drawn along the slope of the major exothermic peak. The initial small exothermic peak was ignored because, in the overall series of tests, it was found to become quite small in most cases. The point of intersection of the two tangents gives the time at which rapid oxidation begins. Zero time is the time at which oxygen is introduced into the system.

By carrying out a series of tests at different temperatures for the XLPE and EPR, oxidation induction times were obtained as a function of the oxidation temperature. By plotting the natural log of the time (t) versus inverse temperature (1/T), the gradient will yield the activation energy, provided that a straight line, indicative of an Arrhenius relationship, is obtained.

For each XLPE specimen, two oxidation induction times were measured. One is the time to reach the onset of oxidation, which is measured by software using a tangent-intercept method. The tangents are shown in Figure 3.43 along with the oxidation-induction time. Note that the start time is the time at which oxygen is introduced, and not the start of the test when the temperature is raised to the test temperature. The second oxidation induction time is the time to reach the top of the oxidation peak. It can be shown that on the standard Arrhenius plot, the activation energies (proportional to the gradients of the lines) for the two oxidation induction times are virtually identical. Therefore, either oxidation induction time may be used to obtain the activation energy.

Table 3.28 shows OITM data for as-received white XLPE insulation from Rockbestos Firewall® III cable.

Figure 3.44 shows the Arrhenius plot for white XLPE insulation material. Note that two different oxidation mechanisms are operating, each over a different temperature range. Based on extrapolation, the mechanism changes at approximately 392°F (200°C). From a linear regression analysis it was found that the low-temperature process has an activation energy of 30.26 kcal/mole (1.31 eV/molecule), while that for the high-temperature is 42.09 kcal/mole (1.83 eV/molecule). The value of 1.31 eV/molecule is in excellent agreement with the value 1.34 eV/molecule used in the qualification of the Rockbestos XLPE cables. Other experimental determinations of the activation energy for XLPE range from 1.10 to 1.62 eV/molecule (Holzman, 1992).

Since the results for XLPE showed that the activation energy could be derived from either the time to reach the onset of the exothermic peak, or the time to reach the maximum exothermic peak value, the onset of oxidation was arbitrarily selected in this analysis. The small early exothermic reaction was ignored since it is greatly overshadowed by the following dominant peak.

In a plant environment, the results presented in Table 3.28 are not applicable since they represent oxidation in a pure oxygen environment instead of in air. Theoretically, the oxidation rate is proportional to the square root of the oxygen concentration. Therefore, since oxygen compresses 21 percent of the pressure of air, the oxidation induction time in air should be longer than that for oxygen by a factor of $(1.00/0.21)^{0.5}$, or 2.18. To verify this, a limited number of in-air oxidations were performed. The results in Table 3.29 show that oxidation induction times in air are approximately 2.02 times as long as those performed in oxygen. This is slightly smaller than the theoretical value. Therefore, for XLPE, the oxidation induction time in air is taken to be approximately double those measured in oxygen.

Table 3.30 gives the OITM results for EPR insulation, and the Arrhenius plot is shown in Figure 3.45. In common with the behavior for XLPE, the Arrhenius plot for EPR displays two separate oxidation mechanisms that transition at approximately 320°F (160°C). The low-temperature mechanism has an activation energy of 28.38 kcal/mole (1.23 eV/molecule) and the high-temperature mechanism has an activation energy of 32.97 kcal/mole (1.43 eV/molecule). The aging temperature of 302°F (150°C) for the AIW cables falls within the range for the low-temperature mechanism, and the value of 1.23 eV is consistent with the 1.18 eV value used in the qualification testing of the AIW cable.

OITM measurements in air were not performed for the EPR material; however, it is assumed that oxidation times at a given temperature in air are approximately double those performed in oxygen, as was determined for XLPE.

The data obtained from the DSC tests may be used to estimate the useful service lives of these materials as a function of service temperature. The following assumptions are made in the analysis:

- The low-temperature oxidation process observed in the current work may be extrapolated to service temperature conditions in a reactor power plants,
- The oxidation-induction time calculated from the equations may be simply doubled to obtain the oxidation-induction time for air environments,
- Irradiation effects are ignored even though they are likely to cause decreases in the OITM, and
- No credit is taken for the presence of the jacket during in-service aging, even though it will likely restrict the flow of air to the insulation. This will tend to increase the OI Times compared to insulation that has unrestricted access to air, such as for the current specimens.

The last two assumptions act in opposite directions with respect to changes in OITM and would tend to balance out to some extent.

Table 3.28 Oxidation Induction Time results for Rockbestos white XLPE material oxidized in oxygen

Specimen Number [(a)]	Test Temperature (^0C)	t_{peak} (min)	t_{onset} (min)
1	240.7	22	18
2	239.5	24	19
3	235.9	35	28
4	235.7	37	34
5	230.7	56	50
6	229.7	55	47
7	224.9	79	75
8	224.9	80	67
9	220.0	116	101
10	220.0	121	106
11	215.9	188	178
12	215.1	171	157
13	210.9	270	243
14	210.0	268	252
15	204.2	450	409
16	199.9	600	553
17	195.0	870	806
18	190.9	1178	1070
19	186.0	1687	1571
20	180.9	2255	2015

(a) Specimens prepared from Rockbestos sample PNI85RB191.

Table 3.29 Comparison of oxidation induction time data for white XLPE oxidized in air and oxygen

Test Temperature	OITM (min.)		Difference Factor
	In Oxygen	In Air	
383°F (195°C)	806	1,650	2.05
392°F (200°C)	553	1,120	2.03
419°F (215°C)	168	336	2.00
428°F (220°C)	103	204	1.98

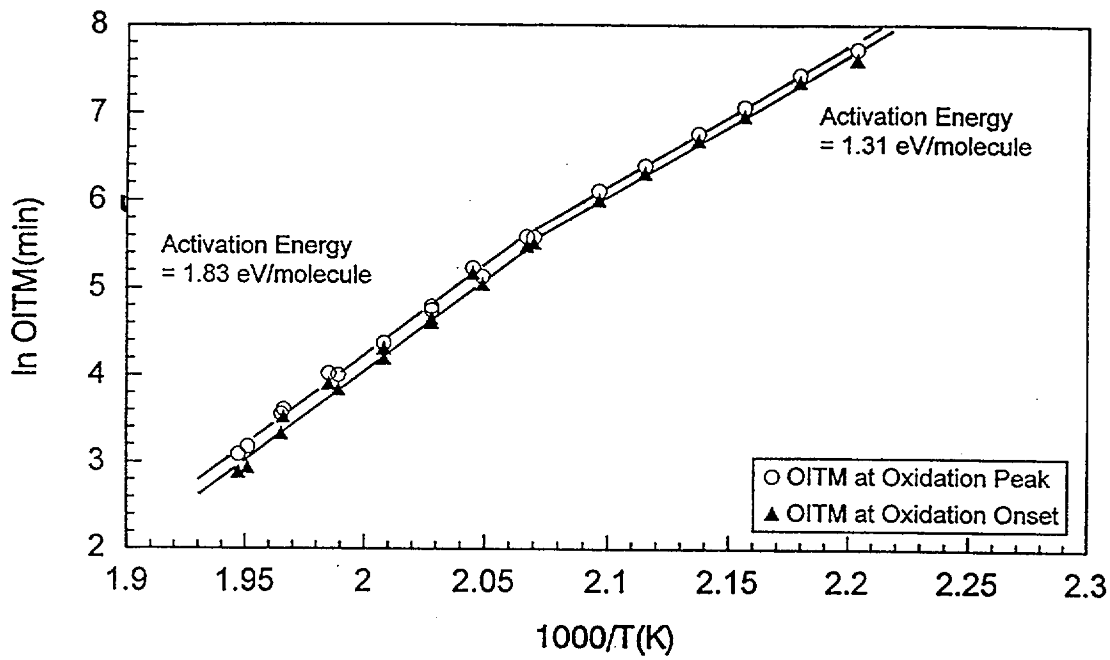

Figure 3.44 Arrhenius plot for white XLPE insulation

Table 3.30 Oxidation induction times for AIW EPR insulation

Specimen Number [a]	Test Temperature (°C)	OITM (min)
1	139.7	2,858
2	149.5	1,252
3	154.9	760
4	160.0	583
5	169.8	240
6	174.9	137
7	180.1	92
8	184.7	77
9	190.0	41
10	199.7	20

(a) Specimens were prepared from cable sample PNI74AI025.

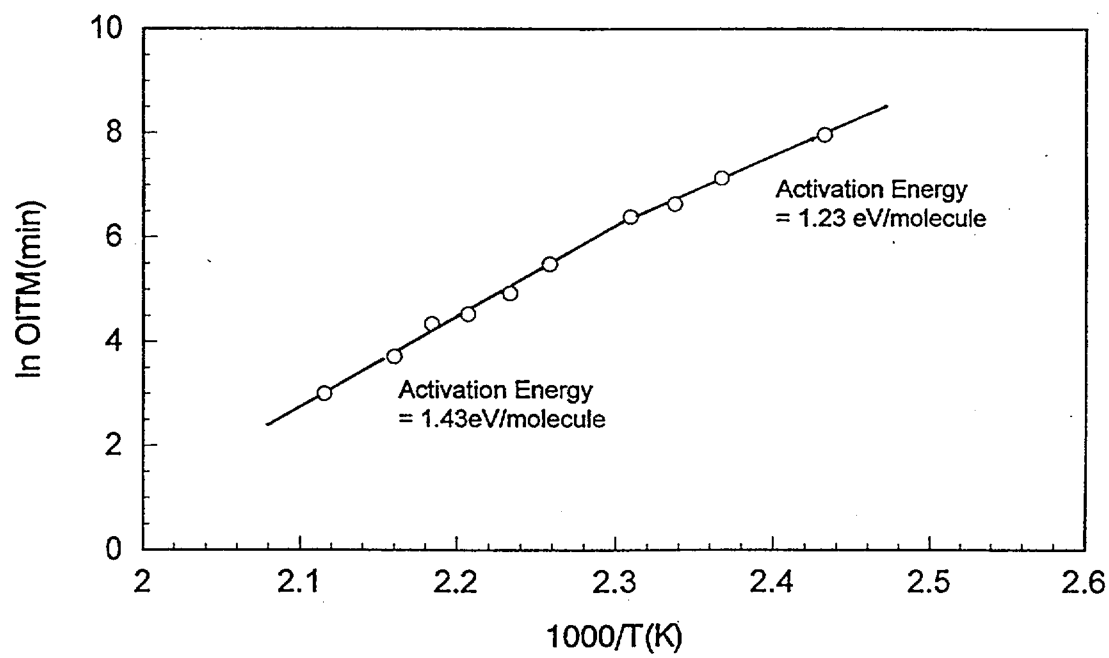

Figure 3.45 Arrhenius plot for EPR insulation

Figures 3.46 and 3.47 show the effect of service temperature on the OITM for XLPE and EPR, respectively. The points on the curves represent calculated values corrected by a factor of 2 for oxidation in air as opposed to pure oxygen. For XLPE at a service temperature of 122°F (50°C), Figure 3.46 shows that it will take approximately 7,000 years to deplete the antioxidants. At a service temperature of 212°F (100°C), they will be depleted in approximately 12 years. Figure 3.47 shows that the EPR material tested is less resistant to oxidation. All antioxidants will be depleted in approximately 200 years at a service temperature of 122°F (50°C), while at a service temperature of 212°F (100°C), it will take only 0.434 years (5.2 months) for them to be lost. Clearly, these results indicate that hot spots in the plant have the potential to cause rapid degradation of cables. It should be noted that these results apply only to the specific materials tested and may not apply in general to all XLPE and EPR materials.

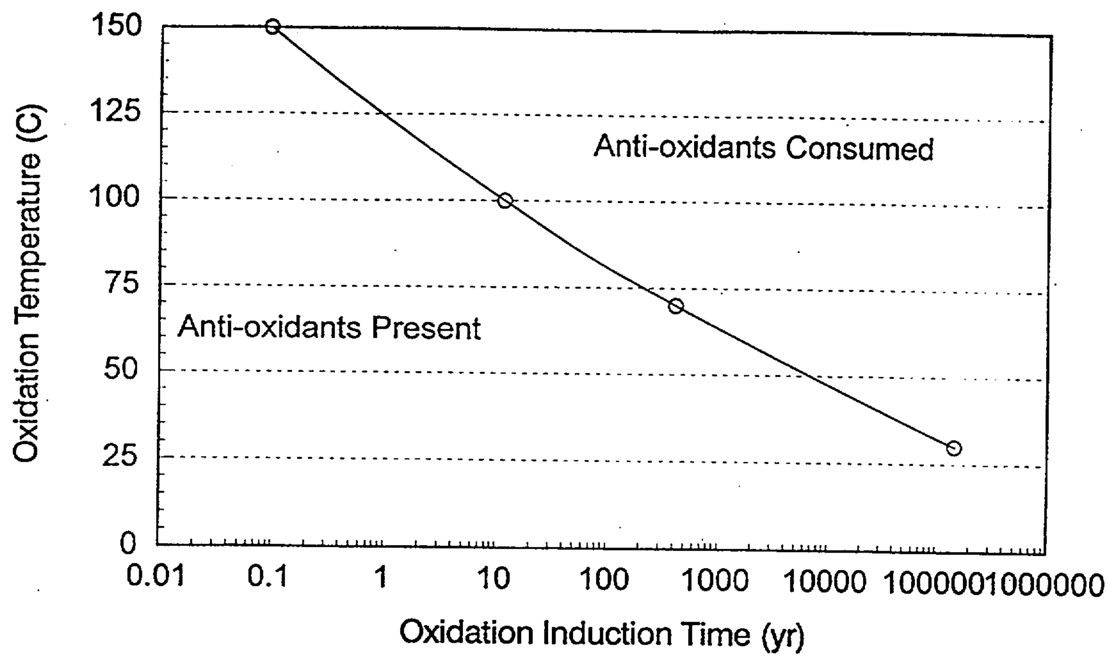

Figure 3.46 Estimated times for depletion of antioxidants in XLPE as a function of aging temperature in an air environment

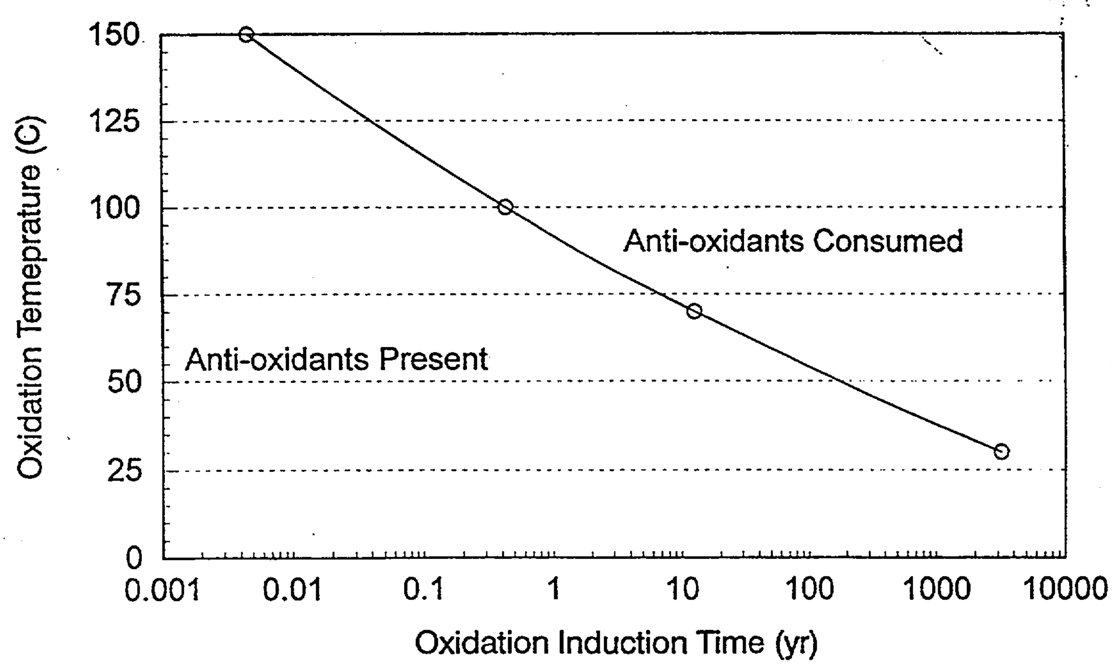

Figure 3.47 Estimated times for depletion of antioxidants in EPR as a function of aging temperature in an air environment

4. ANALYSIS OF LOCA TEST RESULTS

This section presents the analysis of the LOCA test results for the cable specimens in all six test sequences as it relates to the issues being addressed in this program. As discussed in Section 2, of those issues that were unresolved by the literature review, six issues were identified that were felt to be resolvable with additional cable testing. Four of these issues are addressed in this section in terms of the LOCA test results. The two issues related to condition monitoring are addressed in Volume 2 of this report. In addition, several issues were identified for which the test results from this program may provide insights. These are also discussed herein.

4.1 Issue 1: Accelerated Aging Techniques

The following is a statement of the issue being addressed:

How do the properties of cables subjected to accelerated aging techniques used in the original qualification compare with the properties of naturally aged cables of equivalent age?

To address this issue, naturally aged cable samples were obtained from two plants along with unused cable of the same type. The unused cable received accelerated aging to simulate an amount of service aging equivalent to that received by the naturally aged cable. The accelerated aging parameters were calculated using the Arrhenius model for thermal aging, and the equal-dose/equal-damage model for radiation aging. These are the models typically used and accepted for current qualification testing. The naturally aged and accelerated aged cables were then subjected to various condition monitoring tests, as well as LOCA tests to provide a comparison of their material condition and performance under accident conditions. The relevant test sequences in which these comparisons were made are shown in Table 4.1.

Table 4.1 Test Sequences comparing naturally aged and accelerated aged cables

Test Sequence	Cable Tested		Accelerated Aged Cable		Naturally Aged Cable	
	Manufacturer	Configuration	Group	Aging	Group	Aging (a)
1	Rockbestos Firewall® III	3/C #16 AWG XLPE/Neoprene®	1.2	2.9 hrs @ 248°F (120°C) 0.63 Mrad @ 0.38 Mrad/hr.	1.3	10 yrs. @ 70-110°F (21-43°C) 0.63 Mrad @ 0 to 15 rad/hr.
2	AIW	4/C #16 AWG EPR/CSPE	2.2	28.5 hrs @ 250°F (121°C) 3.3 Mrad @ 0.49 Mrad/hr.	2.3	24 yrs. @ 70-110°F (21-43°C) 3 Mrad @ 0 to 40 rad/hr.
3	Rockbestos Firewall® III	3/C #16 AWG XLPE/Neoprene®	3.2	9.9 hrs @ 248°F (120°C) 2.3 Mrad @ 0.50 Mrad/hr.	3.3	10 yrs. @ 70-110°F (21-43°C) 2.3 Mrad @ 0 to 50 rad/hr.

(a) Aging conditions varied with plant power level. Total aging exposure was determined using plant power level history.

Figures 4.1 and 4.2 compare the elongation-at-break (EAB) values for both naturally aged and artificially aged Neoprene® jackets and XLPE insulation from the Rockbestos cable specimens in test sequences 1 and 3, respectively.

As shown in these figures, in all cases, the specimens receiving accelerated aging showed a lower EAB compared to the naturally aged specimen. The lower EAB values indicate more severe aging degradation. For the specimens in test sequences 1 and 3, the accelerated aging over predicted the degradation of the XLPE insulation that was naturally aged for 10 years by approximately 8.5 percent and 13 percent, respectively.

Figure 4.3 provides a comparison of naturally aged and accelerated aged CSPE outer jackets and EPR insulation materials from the AIW cable specimens in test sequence 2. Again, the EAB values for the materials that received accelerated aging were lower than the naturally aged materials, indicating more severe degradation for the accelerated aging. In this test sequence, the accelerated aging over predicted the degradation of the EPR insulation that was naturally aged for 24 years by 35 percent.

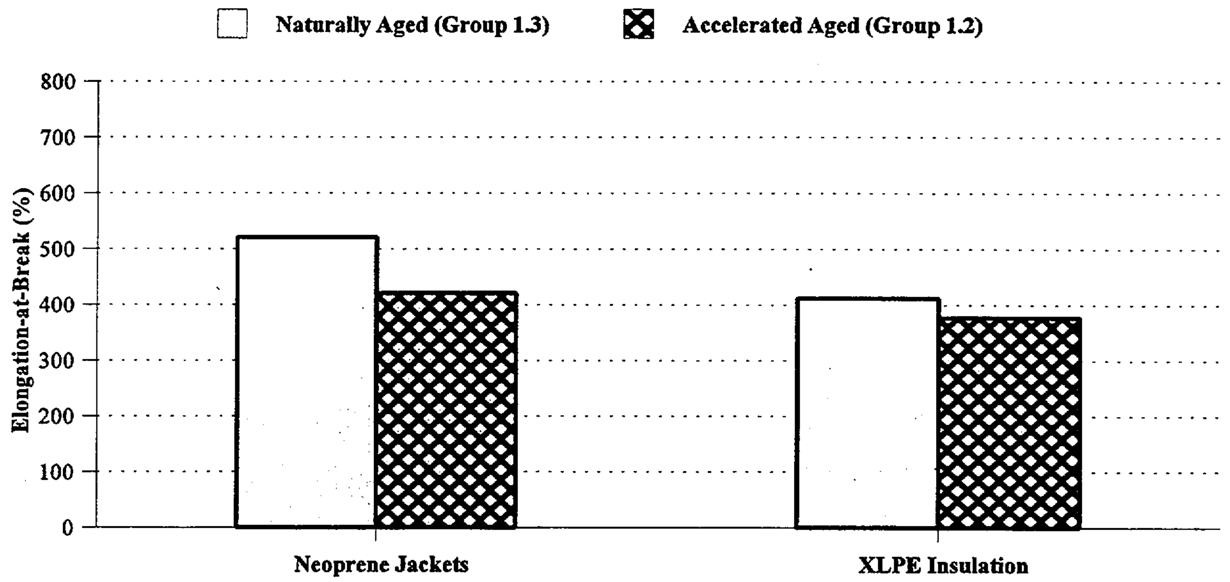

Figure 4.1 EAB values for naturally aged and accelerated aged Neoprene®/XLPE specimens from Test Sequence 1

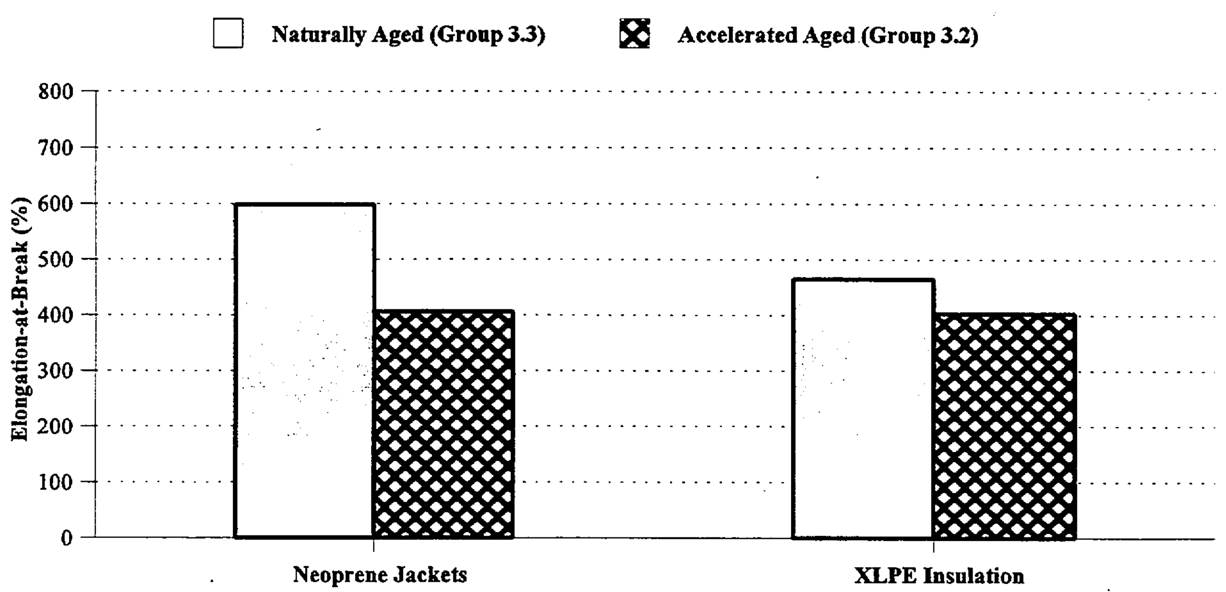

Figure 4.2 EAB values for naturally aged and accelerated aged Neoprene®/XLPE specimens from Test Sequence 3

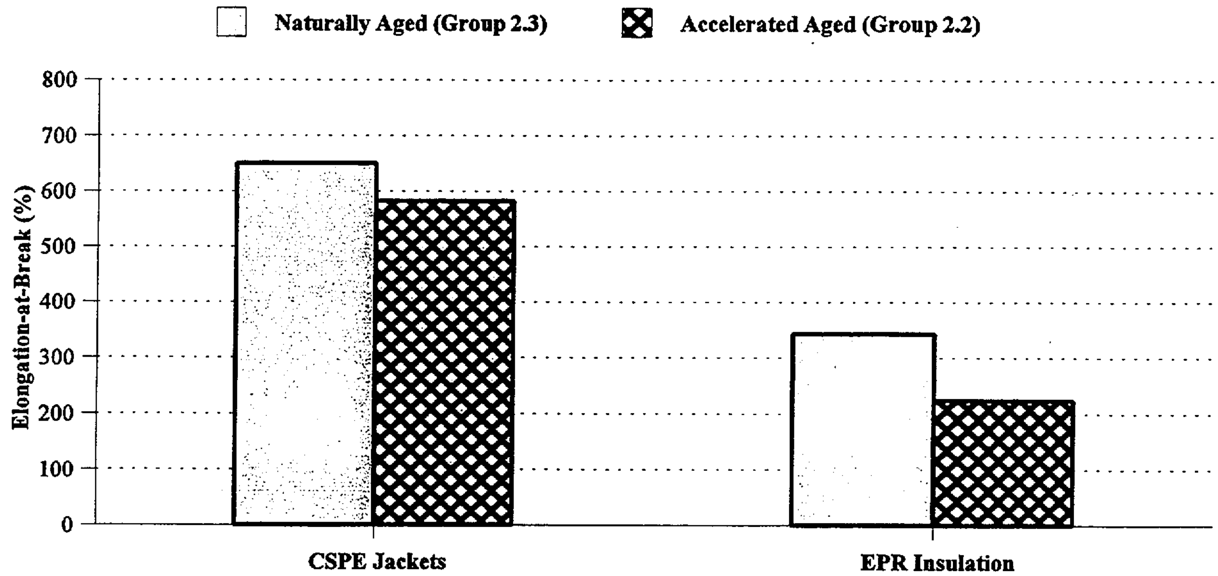

Figure 4.3 EAB values for naturally aged and accelerated aging CSPE/EPR specimens from Test Sequence 2

While there are a number of limitations and uncertainties in the data available for this study, the results suggest that accelerated aging predictions using the Arrhenius model for thermal aging, and the equal-dose/equal-damage model for radiation aging provide adequate estimates of the degradation due to the service aging being simulated; however, the error appears to increase with the amount of aging being simulated. In all cases, the accelerated aging over predicted the degradation caused by the natural aging, and it appears that, as the amount of natural aging increases, the degree to which the accelerated aging models over predict the degradation increases. It is also observed that the amount of aging degradation simulated using these models in the past qualification of electric cables might be conservative in some cases. In qualification tests that simulated 40 years at 194°F (90°C), the pre-aging resulted in cables with brittle insulation and jacket material.

In evaluating the above results the limitations of the data available must be considered. First, the amount of aging experienced by the naturally aged cable specimens was relatively mild. Therefore, the change from their original condition was small. Simulating this small amount of degradation may not provide a representative estimate of the expected error in accelerated aging protocols for larger amounts of service aging, such as might be experienced in 40 years.

Second, the materials used in the comparison were from different manufacturing batches. As can be shown from other EAB measurements, seemingly identical materials can have different property measurements from batch-to-batch. Therefore, the implicit assumption in the above analysis that the "original" EAB values for the materials were the same may not be completely accurate. All of the EPR and CSPE for these cables were manufactured at approximately the same time. The XLPE and Neoprene® cables were produced within 5 or 6 years of each other. Therefore, for this study it was reasonable to assume that the materials might have similar properties prior to aging. However, comparison of the baseline EAB values for the naturally aged material in the third group of specimens and the "new"material in the second group of specimens for test sequences 1, 2 and 3, as shown in Tables 3.3, 3.8, and 3.12, respectively, shows that, in all cases, the new material had a lower EAB value prior to any pre-aging than the naturally aged material. This raises the question of how "new" the new material was, since it was obtained from mild environments in the plant. One possible explanation is that the mild aging received by the naturally aged cables actually increased the EAB slightly.

In tests performed as part of this study, insulation material thermally aged under controlled conditions for relatively short periods of time actually showed an increase in EAB initially, followed by a decrease as the thermal aging time increased. These results are presented in Volume 2, Section 4.2, of this report.

A third potential source of error is the accuracy of in-plant environmental data that were used to determine the level of service aging to which the naturally aged cables had been exposed. Because the accuracy of environmental data was so important for this study, careful measures were taken to ensure that this information was the most accurate available for each cable specimen. Aging calculations were based on many sources of information including: the dates of manufacture, dates of cable installation and removal, the historical operating cycle of the plant, the thermal and radiation environment for the specific cable at power, shutdown, and extended outage from in plant surveys and instrumentation, and historic maintenance work documentation. Inputs from plant operating, maintenance, and health physics personnel were also used to further refine the environmental data.

Finally, the pre-aging parameters used to calculate the quantity of thermal and radiation aging required to match the condition of a naturally aged cable are very important. The Arrhenius calculations for thermal aging are very sensitive to the thermal conditions and activation energy (see discussion in Section 4.2). In addition, thermal aging at too high a temperature can cause other reactions in the cable materials that are different from those that dominate at the lower temperatures found in even the most severe plant environments. Dose rate effects can also have an impact on the severity of radiation damage. To address the aforementioned concerns, the pre-aging parameters found in the original qualification test reports were used in the calculations for this program.

Considering the uncertainties and limitations in the data available, a definitive conclusion regarding the accuracy of the Arrhenius and equal-dose/equal-damage models cannot be drawn. However, the data obtained in this program provide evidence that the accelerated aging protocol used in current qualification testing is conservative.

4.2 Issue 2: Activation Energy

The following is a statement of the issue being addressed:

What are the limitations in using an estimated value of the activation energy to predict the chemical degradation during thermal aging?

The issue of activation energies was addressed by separate laboratory testing, as discussed in Section 3.7. In these tests, XLPE and EPR insulation material samples were taken from the Rockbestos cables and the AIW cables, respectively. A series of oxidation tests were then performed on these samples at different temperatures. From the results of these tests, the activation energy of the material was estimated.

These tests showed that, for both XLPE and EPR insulating materials, oxidative degradation is governed by different and distinct activation energies, depending on the temperature range in which the oxidation occurs. For the XLPE insulating material, oxidation at temperatures below approximately 400°F (204°C) was governed by an activation energy of approximately 1.31 eV. This is in good agreement with the activation energy of 1.34 eV used in the original qualification test by Rockbestos for thermal aging at 302°F (150°C). For the EPR material, oxidation at temperatures below approximately 320°F (160°C) was governed by an activation energy of approximately 1.23 eV. This is also in good agreement with the activation energy of 1.18 eV for the AIW insulation material in the original qualification test for those EPR insulated cables.

The data from these tests demonstrate that, for the two cables tested, the activation energies used in the original qualification tests were representative of the materials being tested. While this does not confirm that accurate activation energies were used for all qualified cables, it does provide evidence that the activation energies used in past qualification tests were reasonable.

The most significant limitation of using estimated activation energies is that the qualified life predicted by the Arrhenius model is very sensitive to the value of activation energy chosen. For example, the thermal aging parameters used in the original qualification test for the AIW cable specimens in test sequence 2 represent 40 years of service at 122°F (50°C) based on an activation energy of 1.18 eV. If the activation energy were increased to 1.23 eV, the same thermal aging would represent 56 years of service at 122°F (50°C). Therefore, a 4 percent increase in activation energy would produce a 40 percent increase in predicted qualified life.

From the results of the testing performed in this program, the activation energies used in the original qualification for two of the materials tested were determined to be reasonable. However, differences in activation energies between manufacturers of the same material, or between batches of material from the same manufacturer were not studied in detail. Since the Arrhenius model is very sensitive to the value of activation energy chosen, a prudent approach in modeling thermal aging using Arrhenius would be to first determine the activation energy for the specific material being studied. This can be done using oxidation tests, as performed herein. Additionally, in cases where qualified life might be re-analyzed, such as for license renewal, caution should be used in modifying the activation energy to achieve a revised qualified life. This approach should only be taken if sufficient technical justification is available to demonstrate that the revised activation energy is more appropriate for the specific material being analyzed. It would also be prudent to monitor cable condition in later years of qualified life due to the uncertainties in, and the sensitivity of the Arrhenius model to variations in activation energy.

4.3 Issue 3: Multiconductor Cables

The following is a statement of the issue being addressed:

Do multiconductor cables have different failure mechanisms than single conductor cables, and, if so, are these unique failure mechanisms properly accounted for in the qualification process?

Test sequence 4 was performed to investigate the issue of multiconductor cables. In that test, EPR insulated cable specimens from both Anaconda and Samuel Moore were tested in the single conductor and multiconductor configuration. The specimens received accelerated aging to simulate 40 years of qualified life, based on their original qualification test report, and were then exposed to LOCA conditions. As presented in Section 3.4, all of the specimens performed acceptably during the pre-aging and LOCA testing.

During the post-LOCA submerged voltage withstand testing, two of the Samuel Moore specimens failed to hold the 2,400 Vac test voltage, as shown in Table 3.19. Both specimens were of the multiconductor configuration. It was determined that the high voltage punctured the insulation at one point on each of the specimens causing the failure. Global degradation of the insulation was not found; however, it is theorized that the insulation was degraded due to the pre-aging and LOCA testing to sufficiently weaken it at specific locations, thus allowing the high voltage to puncture it.

Measurements of the specimen outer jacket and insulation diameters prior to and after the LOCA steam exposure showed that swelling of the materials occurred during the steam exposure (Table 3.18). For the unaged specimens, the swelling ranged from 8 percent to 15 percent. However, for the pre-aged specimens, a higher degree of swelling was noted, ranging from 17 percent to 30 percent. This is believed to be due to the fact that the materials shrank during the pre-aging, as shown from the data, thus resulting in a larger dimensional change due to moisture absorption during the steam exposure. This suggests that, in actual service, shrinkage due to gradual aging could increase the probability of insulation or jacket failure, such as rupture or splitting, during sudden steam exposure due to the more pronounced increase in dimensions under high moisture conditions.

Although it was not the cause of failure for the two specimens in this test, the data obtained in test sequence 4 related to swelling of the jacket and insulation materials provide evidence that this phenomenon can contribute to rupture or cracking of the materials during a steam exposure. If the insulation on the conductors in a multiconductor cable expands faster that the overall outer jacket, the resulting stresses imparted on the outer jacket may be significant enough to cause it to rupture. This is a potential cause of the failures experienced in past Sandia tests on multiconductor cables (Bustard, 1983; Bennet, 1986; Jacobus, 1992) and is consistent with the explanation proposed during those tests.

A review of IEEE Standard 323-1974, which is the qualification standard currently endorsed by the NRC, indicates no specific requirement for type testing to include cables in a multiconductor configuration. It was commonly believed that testing a cable in the single conductor configuration was more conservative since the insulation would not be protected from the harsh testing environment, as it would if covered with an outer jacket in a multiconductor cable. Therefore, multiconductor cables were sometimes qualified by type testing a single conductor cable of the same materials. Based on the results of this test program, consideration should be given to the configuration for which a cable is being qualified. If the cable type will be used in applications requiring a multiconductor configuration, the effect that the configuration will have on the performance of the cable must be determined by analysis or type testing of the proposed multiconductor configuration.

4.4 Issue 4: Bonded Jacket Cables

The following is a statement of the issue being addressed:

Do bonded jacket cables have different failure mechanisms than unbonded jacket cables, and, if so, are these unique failure mechanisms properly accounted for in the qualification process?

Test sequence 5 was performed to investigate the issue of bonded jacket cables. In that test, cables with bonded individual jackets from both Samuel Moore and Okonite were pre-aged to simulate 40 years of qualified life, then LOCA tested. In addition, Anaconda cable specimens, which have an unbonded individual jacket, were included in the test for comparison. As presented in Section 3.5, the Samuel Moore and Anaconda specimens performed acceptably during the pre-aging and LOCA testing. However, the Okonite specimens experienced problems with the composite insulation and individual jacket cracking and splitting open on four of the five pre-aged specimens. The fifth pre-aged specimen was also cracked but did not split open.

From a comparison of the pre-aging received by the different specimens (Table 3.21), it is clear that the Okonite specimens received significantly more severe aging than the other specimens. As seen from the results of test sequence 4, dimensional swelling can be a significant factor in causing damage to the cables, particularly when the cable materials have experienced embrittlement and shrinking due to aging prior to a sudden steam exposure. For the Okonite specimens, the severe aging would have caused the composite insulation and individual jackets to embrittle and shrink considerably, thus, increasing the susceptibility to swelling damage during the steam exposure. During the pre-aging, shrinkage of the CSPE individual jackets induced cracking, which propagated into the insulation since the individual jacket was bonded to the underlying insulation. Upon exposure to steam in the LOCA test, swelling caused the cracking to intensify and propagate further leading to splitting of the insulation. This is believed to be the cause of the splitting in the Okonite specimens. Discussions with Okonite representatives confirm that the CSPE used in the individual jackets has a high propensity for hardening and shrinking under severe aging (Lofaro, 2000C).

The results of this test demonstrate that the bonded jacket insulating system has a potential for catastrophic failure under accident conditions. From the data obtained, it appears that this catastrophic failure can occur if the composite bonded jacket insulation is first exposed to severe aging conditions, causing it to embrittle and shrink significantly prior to being exposed to sudden steam conditions. This is supported by the fact that the Samuel Moore specimens in test sequence 5, which also have bonded individual jackets but received less severe aging, and thus, less embrittlement and shrinkage, did not experience catastrophic failure with the insulation splitting open.

It should be noted that the manufacturer did not test the specific configuration of cable that failed in this program. Instead, this cable was qualified using similarity arguments based on qualification testing of cables with similar construction. The acceleration aging parameters used by the manufacturer in those qualification tests, on which the testing reported herein was based, were among the most severe of all the qualification tests reviewed for this program. Therefore, the degradation simulated, and the amount of shrinkage experienced by the test specimens leading up to the catastrophic failure were also judged to be severe. This suggests that applications using this type of cable in areas of localized adverse environments, where the conditions might approach those simulated in this study, should be closely monitored for signs of degradation.

4.5 Other Qualification Issues

In addition to the six issues for which new testing was performed, the literature review identified seven issues which the information gained from the new testing might help to resolve. These issues relate to addressing hot spots, impingement, physical damage and improper installation in the qualification process. Also, the information gained from the new testing might help resolve issues related to extending the qualified life of I&C cables. These issues are discussed in the following paragraphs.

4.5.1 Hot Spots

It is known that areas exist in nuclear plants in which extreme operating environments are encountered. These are commonly referred to as "hot-spots," and they can significantly accelerate the aging degradation of components located within them. The results of the tests performed in this program demonstrate that aging degradation of cables can impact their performance. In particular, EPR insulated cables that were exposed to severe aging in test sequence 5 split open during a simulated LOCA steam exposure. This suggests that cables located in hot-spots may not be suitable for continued service for their entire qualified life. Identification, surveillance, training and awareness, mitigation and review for potential "hot-spot" locations within a nuclear power plant are, therefore, important activities in an environmental qualification program. Monitoring the condition of cables located in hot-spots is necessary and is recommended as a periodic activity.

4.5.2 Impingement

Impingement was identified as a potential degradation mechanism that can impact the performance of an electric cable. This would be of particular concern for cables that were aged and potentially brittle since impingement on the cable could crack the outer jacket and, possibly, the insulation. The data obtained from the tests in this program show that embrittlement of cable jacket and insulation materials is possible, if sufficient aging exposure is encountered. However, none of the naturally aged cables tested were embrittled. While no 40-year old cables were available to be tested, the naturally aged cables obtained for this program were in good condition with relatively high EAB values, suggesting that cracking due to impingement would typically not be a concern. Cables located in hot-spots that do have the potential of becoming brittle would be susceptible to impingement damage, and it is recommended that they be monitored periodically for signs of degradation.

4.5.3 Physical Damage and Improper Installation

Physical damage and improper installation are both human errors that can affect the performance of electric cables. The test results obtained in this program demonstrate the consequences on cable performance that can result from aging degradation, which can weaken the insulation. Physical damage or improper installation can inflict damage to the cable that will similarly weaken it, such as cutting or chafing of the insulation. Even when following good construction and maintenance practices, it is difficult to completely prevent this type of damage. Plants must depend on a strong program of inspection, surveillance, training and awareness to detect and mitigate the impact of this type of damage wherever possible. Currently, there are no feasible actions that can be recommended to include in the qualification process to account for this type of degradation since it is unlikely that any accurate quantitative estimate can be made of the damage to be expected during the qualified life of a cable.

4.5.4 Extending Qualified Life

The data obtained from test sequence 6 are of particular interest for the issues related to extending qualified life. In that test, cables from four different manufacturers were pre-aged to the equivalent of 60 years of qualified life and were then exposed to simulated LOCA conditions. As discussed in Section 3.6, a number of the specimens experienced degradation related failures during a submerged voltage withstand test in which they were unable to hold the test voltage. These results indicate that the degradation due to aging beyond the qualified life of the cables may be too severe for the insulation material to withstand and still be able to perform during an accident. For life extension purposes, the qualified life of the cables should be reviewed and compared to actual plant service environments. A determination can then be made as to whether the additional exposure to aging stressors during the period of extended operation will be acceptable for the cable materials.

5. CONCLUSIONS AND OBSERVATIONS

5.1 Conclusions Regarding EQ Issues

Based on the results of the testing performed in this program, the following conclusions may be drawn:

Accelerated Aging Techniques:

1. The data obtained suggest that the accelerated aging predictions using the Arrhenius model for thermal aging, and the equal-dose/equal-damage model for radiation aging provide adequate estimates of the degradation experienced due to actual service aging. In six-out-of-six cases, material that received accelerated aging had a lower EAB, indicating more degradation than naturally aged material of equivalent age. Also, as the duration and severity of the natural aging simulated increased, the difference in degradation simulated by the models also increased. However, while these results suggest that currently accepted artificial aging techniques provide conservative estimates of service aging, the limitations in the assumptions made, along with uncertainties in the data available, prevent a definitive conclusion from being drawn regarding the accuracy of the aging models.

Activation Energies:

2. The data from these tests demonstrate that, for the two cable materials tested, the activation energies used in the original qualification tests were representative of the materials being tested. While this does not confirm that accurate activation energies were used for all cables, it does provide evidence that the activation energies used in past qualification tests were reasonable.

Multiconductor Cables:

3. Test results show that differential swelling of jacket and insulation materials due to moisture absorption can occur during a LOCA. This phenomenon can contribute to rupture or cracking of the materials during steam exposure. If the insulation on the conductors of a multiconductor cable expands faster and to a greater degree than the outer jacket, the resulting stresses imparted on the outer jacket may be significant enough to cause it to rupture. While these results might suggest a potential common cause failure for multiconductor cables, it must be noted that, of the 15 cables pre-aged to 40 years and LOCA tested, 3 experienced performance anomalies that could impact their safety function.

Bonded Jacket Cables:

4. The results of this study demonstrate that the bonded jacket/insulation configuration has a potential for catastrophic failure under LOCA conditions. This catastrophic failure can occur if the composite bonded jacket/insulation is first exposed to severe aging conditions, causing it to embrittle and shrink significantly, prior to its sudden exposure to steam. The steam causes swelling stresses that can initiate failure. While this phenomenon was observed for single conductor bonded jacket cables from one manufacturer in this program, it could be problematic for similar cables from other manufacturers.

Extending Qualified Life:

5. The results indicate that degradation due to aging beyond the qualified life of the cables, based on extrapolation of the aging used in the original qualification tests, may be too severe for the insulation material to withstand and still be able to perform adequately during a LOCA. For life extension purposes, the aging protocols used to establish the qualified life of the cables should be reviewed and compared to actual service environments

in a plant. A determination then can be made as to whether the additional exposure to aging stressors during a period of extended operation will be acceptable for the cable materials.

5.2 Observations Regarding the Qualification Process

From the results of the tests reported herein, the following observations are made regarding the qualification process for electric cables:

1. Currently accepted standards permit the qualification of various configurations of electric cables based on their similarity to cables of the same materials or construction that have already passed environmental qualification type tests. The results of this test program have shown that additional factors affecting the performance of a particular cable configuration may be revealed during type testing that would otherwise not have been considered during qualification by simple analysis or similarity of materials. Therefore, the similarity argument may not be appropriate in all cases. Specifically, cables that are to be qualified for use in applications requiring a multiconductor configuration may best be qualified by type testing the cable in that multiconductor configuration. Similarly, electric cables with bonded individual jackets may best be qualified by type testing in the configuration (and conductor diameter) and combination of insulation and jacket materials that will be used in the plant.

2. Consideration should be given to developing more definitive acceptance criteria for determining if a cable passes a qualification type test. Currently, the qualification test results are analyzed to determine if the cable is qualified for its particular application. Typically, as long as one cable specimen passes the mandrel bend/submerged voltage withstand test at the end of the type test, and all other anomalies are determined not to be caused by global degradation of the insulation, the cable can be considered qualified. Guidance should be provided in current qualification standards for the number of data points required, the number of permissible cable failures during the qualification test and how they should be addressed, and the required statistical confidence level to consider a cable qualified.

3. The results of test sequence 5 indicate that cables with a composite EPR insulation with bonded CSPE individual jackets may exhibit catastrophic failure under LOCA conditions, if they have previously been exposed to severe aging causing them to shrink. Additional research is recommended to quantify the degree to which this type of cable can be aged before its ability to function during accident conditions is compromised. The research should determine if this observation is specific to the materials and construction of the one manufacturer for which it was observed, or if the phenomenon is generic to all cables of this construction.

4. In thermally aging cables with a bonded CSPE individual jacket, consideration should be given to using an activation energy representative of the CSPE since it appears to dominate the failure mechanism for this type of cable.

5. For safety-related cables, the electrical performance during accident peak conditions is a critical criteria for establishing qualification. However, current qualification standards do not provide any guidance on what electrical characteristics should be monitored or the frequency at which data should be obtained. Consideration should be given to including this information in the qualification standards (e.g., IEEE Std. 383).

6. During the testing performed in this program, problems were observed on multiple occasions with moisture intrusion into splices applied to cables that had undergone preaging. In all cases, the cable jackets were degraded and cracked due to the preaging, and the moisture intrusion lead to a deterioration of cable performance. On the basis of these results, consideration should be given to evaluating the condition of a cable and developing an acceptance criterion prior to allowing the application of splices.

7. For the Samuel Moore bonded jacket cables tested in this program, localized failures were observed on several of the test specimens after preaging to simulate 40 and 60 years of service, followed by simulated accident testing. While global degradation was not noted for these cables, the localized failures do raise uncertainties related to the accident performance of these cables after being in service for extended periods. On the basis of these results, consideration should be given to identifying and closely monitoring localized adverse environments in plants, and performing condition monitoring of electric cables located in those areas.

6. REFERENCES

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6. References

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APPENDIX A: DETERMINATION OF PRE-AGING PARAMETERS

Table A.1 Calculation of aging parameters for specimens in Test Sequence 1, Group 1.2

Plant A Operating Conditions for Sample PAP86RB267

Start Date	End Date	Days	Dose Rate	Dose	Cumulative Dose	Amb Temp
10/20/85	07/06/86	259	0	0	0	70
07/06/86	05/02/87	300	15	108000	108000	110
05/02/87	07/03/87	62	1	1488	109488	80
07/03/87	11/12/88	498	15	179280	288768	110
11/12/88	01/05/89	54	1	1296	290064	80
01/05/89	06/23/90	534	15	192240	482304	110
06/23/90	11/11/90	141	1	3384	485688	80
11/11/90	10/01/91	324	15	116640	602328	110
10/01/91	03/01/92	152	1	3648	605976	80
03/01/92	12/15/95	1384	0	0	605976	70
		========				
		3708	Days Total			
		10.1589	Years Total			

	ta (dys)	
1643 Days at 70 Deg F	0.002779	at Ta=248 Deg F
1656 Days at 110 Deg F	0.114409	at Ta=248 Deg F
409 Days at 80 Deg F	0.001841	at Ta=248 Deg F
======================	========	
3708 Days Total	0.119029	Days Total ta at Ta=248 Deg F
	2.856681	Hours Total ta at Ta=248 Deg F

Assume: Ea=1.34 eV per QR #1806

Arrhenius Calculation

ts	Ea	Ts (F)	Ta (F)	Ts (K)	Ta (K)	ta (dys)	ta (hrs)
1643	1.34	70	248	294.2911	393.18	0.002779	0.066687
1656	1.34	110	248	316.5133	393.18	0.114409	2.745804
409	1.34	80	248	299.8467	393.18	0.001841	0.044189
========						========	========
3708						0.119028	2.856601

Table A.2 Calculation of aging parameters for specimens in Test Sequence 2, Group 2.2

Plant B Operating Conditions for Samples PAI74AI019 & 20 (12-1 & 12-2)

Start Date	End Date	Days	Dose Rate (rad/hr)	Dose (rads)	Cumulative Dose (rads)	Amb Temp (F)
07/01/72	07/01/74	730	0	0	0	70
07/01/74	12/23/75	540	0	0	0	80
12/23/75	05/20/76	149	1	3576	3576	100
05/20/76	01/04/93	6073	10	3130278	3133854 *	110
01/04/93	07/05/93	182	1	4368	3138222	100
07/05/93	03/01/97	1335	0	0	3138222	80
		========				
		9009 Days Total				
		24.6653 Years Total				

* Calculation based on Plant B power ops charts

	ta (dys)
730 Days at 70 Deg F	0.005471 at Ta=250 Deg F
1875 Days at 80 Deg F	0.033278 at Ta=250 Deg F
331 Days at 100 Deg F	0.03004 at Ta=250 Deg F
6073 Days at 110 Deg F	1.193892 at Ta=250 Deg F
=====================	========
9009 Days Total	1.262681 Days Total ta at Ta=250 Deg F
	30.30434 Hours Total ta at Ta=250 Deg F

Assume: Ea=1.18 per AIW Arrhenius plot

Arrhenius Calculation

ts (dys)	Ea	Ts (F)	Ta (F)	Ts (K)	Ta (K)	ta (dys)	ta (hrs)
730	1.18	70	250	294.2911	394.2911	0.005471	0.131302
1875	1.18	80	250	299.8467	394.2911	0.033278	0.798679
331	1.18	100	250	310.9578	394.2911	0.03004	0.720952
6073	1.18	110	250	316.5133	394.2911	1.193892	28.65341
========						========	========
9009						1.262681	30.30435

Arrhenius Calculation for Franklin Report F-C4197-2 & Trojan Cable Spec 6478-E-23A (7/16/97) (BNL LOCA Test No 2)

ta (dys)	Ea	Ts (F)	Ta (F)	Ts (K)	Ta (K)	ts (dys)	ts (yrs)
7	1.18	122	250	323.18	394.2911	14586.04	39.96175
3.5	1.18	122	250	323.18	394.2911	7293.019	19.98087

Table A.3 Calculation of aging parameters for specimens in Test Sequence 3, Group 3.2

Operating Conditions for Sample PAP86RB244

Start Date	End Date	Days	Dose Rate	Dose	Cumulative Dose	Amb Temp
10/20/85	07/06/86	259	0	0	0	70
07/06/86	05/02/87	300	55	396000	396000	125
05/02/87	07/03/87	62	1	1488	397488	80
07/03/87	11/12/88	498	55	657360	1054848	125
11/12/88	01/05/89	54	1	1296	1056144	80
01/05/89	06/23/90	534	55	704880	1761024	125
06/23/90	11/11/90	141	1	3384	1764408	80
11/11/90	10/01/91	324	55	427680	2192088	125
10/01/91	03/01/92	152	1	3648	2195736	80
03/01/92	12/15/95	1384	0	0	2195736	70
		========				
		3708	Days Total			
		10.1589	Years Total			

	ta (dys)	
1643 Days at 70 Deg F	0.002779	at Ta=248 Deg F
1656 Days at 125 Deg F	0.403486	at Ta=248 Deg F
409 Days at 80 Deg F	0.001841	at Ta=248 Deg F
======================	========	
3708 Days Total	0.408106	Days Total ta at Ta=248 Deg F
	9.794548	Hours Total ta at Ta=248 Deg F

Assume: Ea=1.34 eV per QR #1806

Arrhenius Calculation

ts	Ea	Ts (F)	Ta (F)	Ts (K)	Ta (K)	ta (dys)	ta (hrs)
1643	1.34	70	248	294.2911	393.18	0.002779	0.066687
1656	1.34	125	248	324.8467	393.18	0.403486	9.683672
409	1.34	80	248	299.8467	393.18	0.001841	0.044189
========						========	========
3708						0.408106	9.794548

APPENDIX B: TEST PERFORMANCE ANOMALIES

wyle laboratories

ORIGINAL **NOTICE OF ANOMALY**

DATE: January 10, 1997

NOTICE NO.:	1	P.O. NUMBER:	N/A	CONTRACT NO.:	750945
CUSTOMER:	Brookhaven National Laboratory			WYLE JOB NO.:	45120
NOTIFICATION MADE TO:	Robert Lofaro/Bom Soon Lee			NOTIFICATION DATE:	12/26/96
NOTIFICATION MADE BY:	Bobby Hardy			VIA:	overnight mail

CATEGORY: ☐ SPECIMEN ☐ PROCEDURE ☒ TEST EQUIPMENT DATE OF ANOMALY: 12/24/96

PART NAME:	Cable Samples	PART NO.	N/A
TEST:	Thermal Aging	I.D. NO.	See below
SPECIFICATION:	WLTP 45120-PA-1, Rev. B	PARA. NO.	2.3

REQUIREMENTS:

The specimens that are to be thermally-aged shall be placed in a Wyle Thermal Aging Chamber and thermally aged in air at the temperature (+5/-0°F) and duration specified in Table II of the above noted specification.

Each aging chamber shall have a redundant controller that is capable or terminating the chamber heat should the primary controller malfunction. The redundant controllers shall be set no higher than 10°F above the required aging temperature.

DESCRIPTION OF ANOMALY:

This anomaly applies to the specimens which are being aged for 650 hours at 150°C (302°F).

On December 24, 1996, the primary chamber controller malfunctioned at approximately 14:59 allowing the chamber temperature to exceed the specified temperature until the redundant controller terminated the heat to the chamber. The primary controller was reset at approximately 17:00 in an attempt to troubleshoot the problem. The chamber ran until approximately 18:14 when again the primary controller malfunctioned allowing the chamber temperature to exceed the specified temperature. The redundant controller again terminated heat to the aging chamber. The chamber was left off from this point until December 26 when the Calibration Lab staff returned from the holiday vacation.

RESPONSIBILITY TO ANALYZE ANOMALIES AND COMPLY WITH 10 CFR PART 21: ■ CUSTOMER ☐ WYLE

VERIFICATION:		PROJECT ENGINEER:	Robert Hardy 1/10/97 Robert Hardy
TEST WITNESS:	N/A	PROJECT MANAGER:	Don Smith 1/10/97 Don E. Smith
REPRESENTING:	N/A	INTERDEPARTMENTAL COORDINATION:	
QUALITY ASSURANCE:	TR Hamilton 1/10/97		

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wyle laboratories

NOTICE OF ANOMALY

DISPOSITION - COMMENTS - RECOMMENDATIONS:

The primary controller was taken to the Calibration Lab for repair on the morning of the 26th. The primary controller was not repaired but was replaced with another calibrated controller of the same type. The chamber was restarted at approximately 10:55 with the specimen mounted thermocouples reaching the required aging temperature at approximately 11:55.

The over temperatures and time at over temperature are as follows:

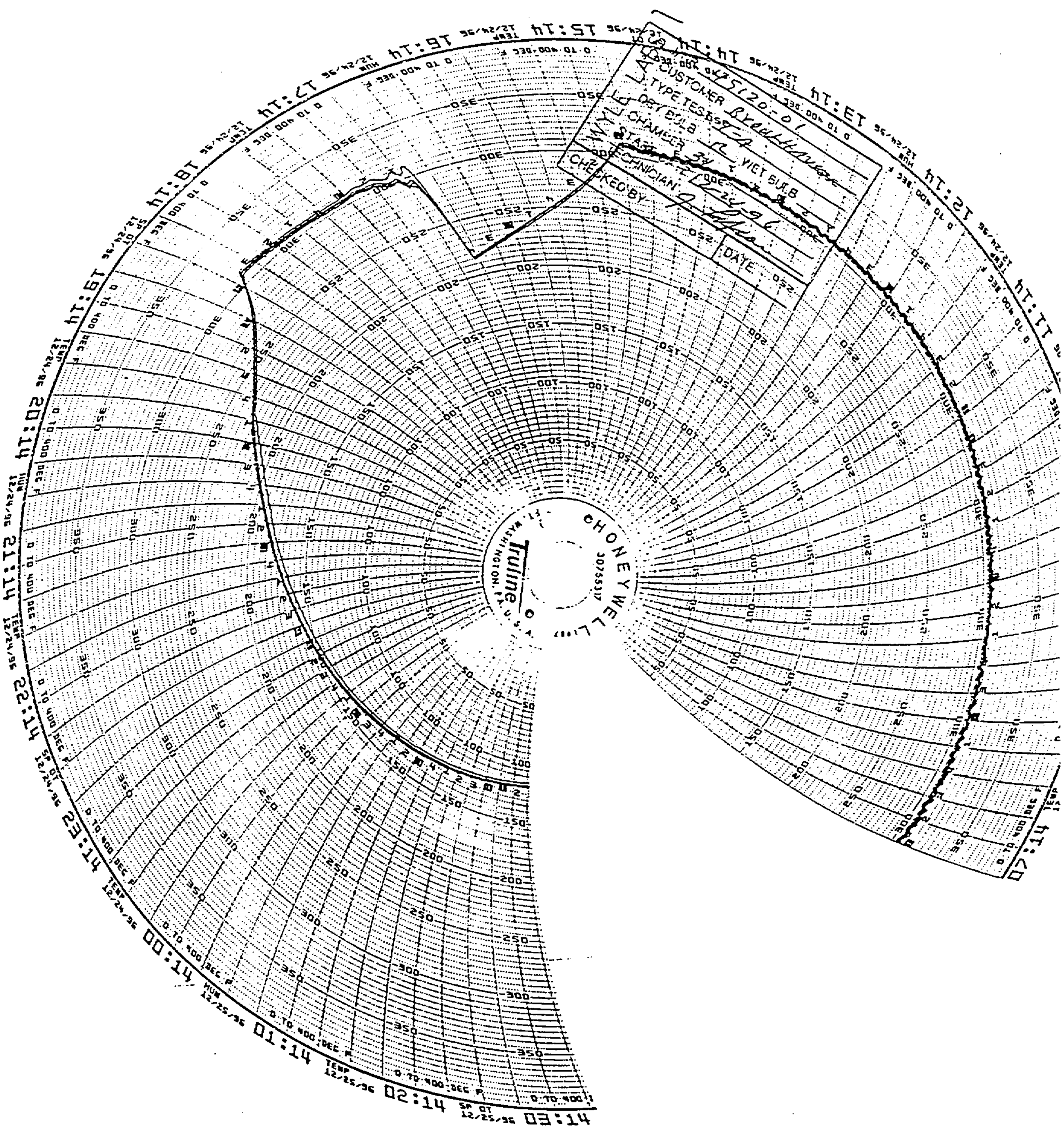
- Approximately 14:59 until approximately 15:15, the chamber ramped up from approximately 307°F to approximately 310°F (3°F over the maximum allowed). 16 minutes at elevated temperature.
- Approximately 18:14 until approximately 18:51, the chamber ramped up from approximately 307°F to approximately 310°F (3°F over the maximum allowed). 37 minutes at elevated temperature.

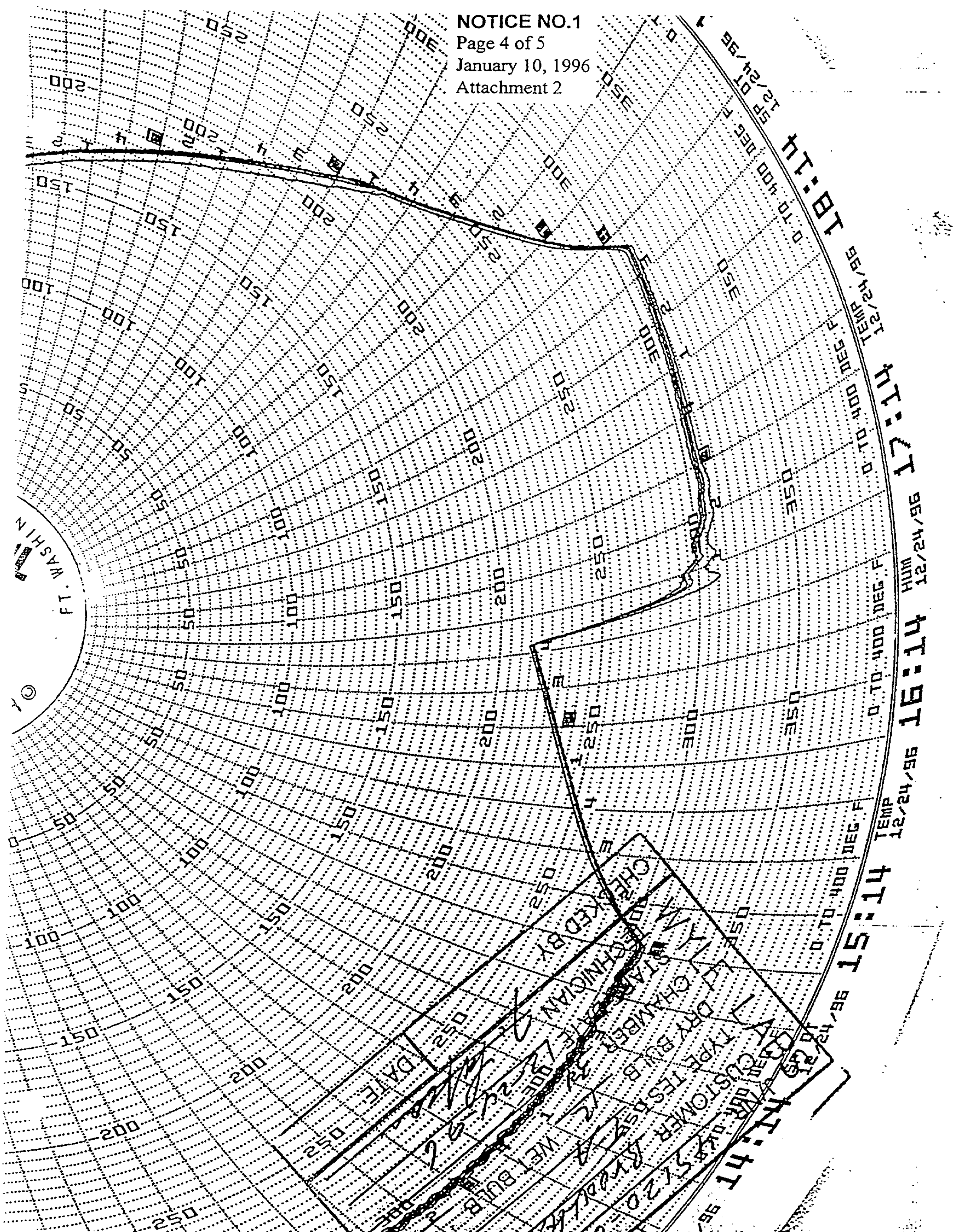
Attachment 1 is a copy of the temperature chart for December 24. Attachment 2 is an expanded copy of the time and temperature which led to this Notice of Anomaly from Attachment 1. Attachment 3 is a copy of the temperature chart for December 26.

It should be noted that the highest thermocouple shown in Attachment 2 is the chamber mounted thermocouple and not a specimen mounted thermocouple. This thermocouple is not the chamber controlling thermocouple. A specimen mounted thermocouple is connected to the primary controller to control the temperature of the chamber. The temperatures documented in this Notice of Anomaly represent the specimen mounted thermocouples and not the chamber mounted thermocouple. It should be noted that the three specimen mounted thermocouples were within 1.2°F of each other.

Should any further malfunctions occur with the thermal aging equipment, Brookhaven National Laboratory shall be notified prior to restarting the aging process. After evaluation of this anomaly, Brookhaven National Laboratory will notify Wyle Laboratories of the date and time when thermal aging is to be terminated.

NOTICE NO.1
Page 3 of 5
January 10, 1996
Attachment 1




CUSTOMER
TYPE TEST
DRY BULB
WET BULB
CHAMBER
START DATE
TECHNICIAN
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16:14
17:14
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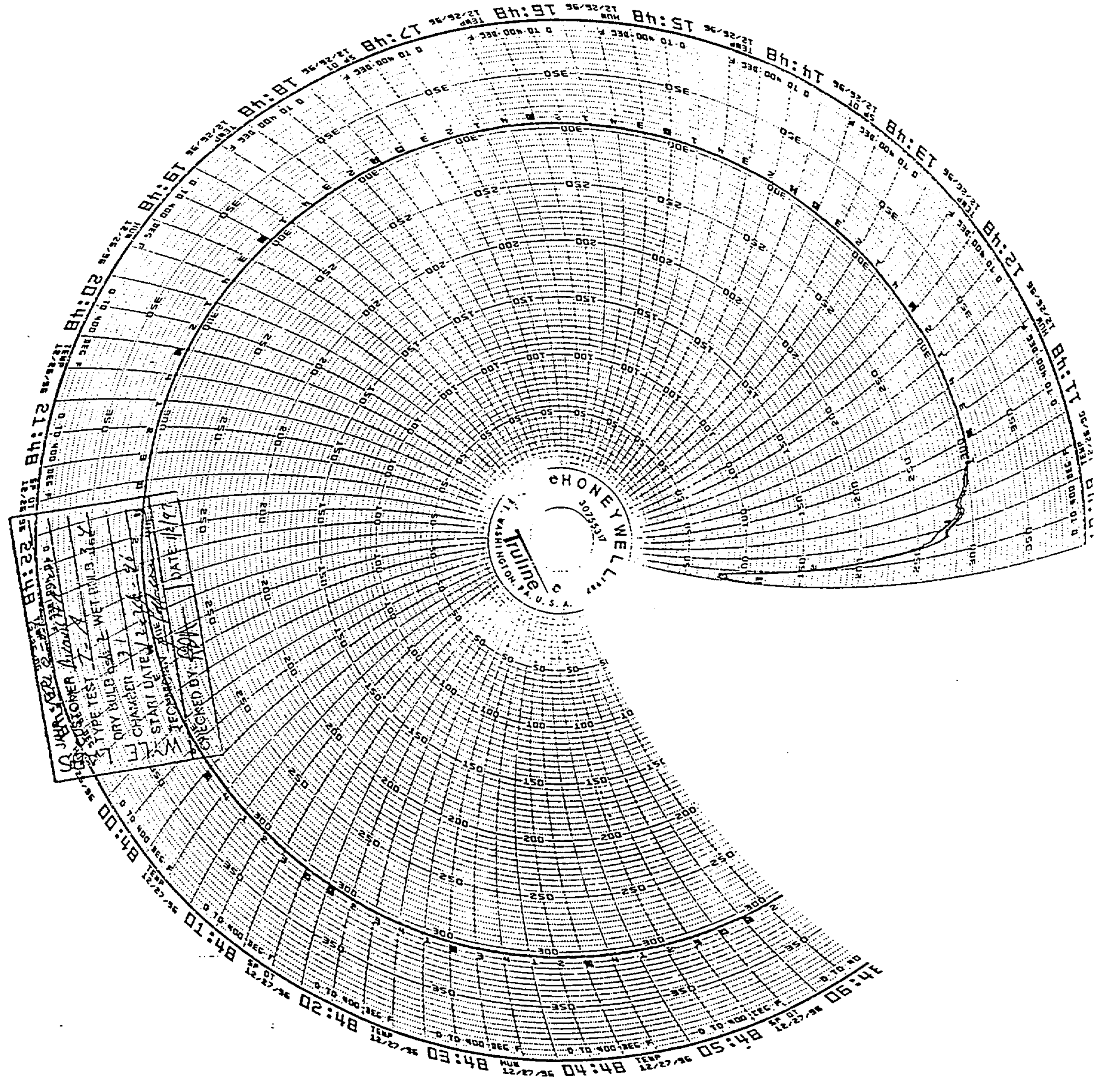
0 TO 400 DEG F



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ORIGINAL NOTICE OF ANOMALY

DATE: March 12, 1997

NOTICE NO.: 2 P.O. NUMBER: N/A CONTRACT NO.: 750945

CUSTOMER: Brookhaven National Laboratory WYLE JOB NO.: 45120

NOTIFICATION MADE TO: Robert Lofaro NOTIFICATION DATE: 3/11/97

NOTIFICATION MADE BY: Bobby Hardy VIA: in person

CATEGORY: ☐ SPECIMEN ☒ PROCEDURE ☐ TEST EQUIPMENT DATE OF ANOMALY: 3/10/97

PART NAME: Cable Samples PART NO. N/A

TEST: Radiation Aging I.D. NO. See below

SPECIFICATION: WLTP 45120-PA-1, Rev. C PARA. NO. 2.4

REQUIREMENTS:

The specified dose rate shall be controlled to the specified value within +0/-20%.

DESCRIPTION OF ANOMALY:

This anomaly applies to the following specimens: 0106, 0107, 0108, 0109, and 0110.

The required dose rate of 0.5 Mrads/hr (+0/-20%) could not be attained. The overall average dose rate was 0.334Mrads/hr as reported by Georgia Tech.

DISPOSITION - COMMENTS - RECOMMENDATIONS:

The dose rate could not be corrected due to the short time duration (1.2 hours) of the exposure for these specimens. If more sources had been placed in an attempt to increase the dose rate, the time required to do so would have over exposed the cable specimens. Adjustments have been made to the source placement procedure so that all subsequent exposures should be at the specified rate. Georgia Tech's final report of the exposures for this task will detail the specific exposures along the length of the samples.

RESPONSIBILITY TO ANALYZE ANOMALIES AND COMPLY WITH 10 CFR PART 21: ■ CUSTOMER ☐ WYLE

VERIFICATION:

PROJECT ENGINEER: Bobby Hardy 3/12/97
Robert Hardy

TEST WITNESS: N/A

PROJECT MANAGER: Don Smith 3/12/97
Don E. Smith

REPRESENTING: N/A

INTERDEPARTMENTAL COORDINATION:

QUALITY ASSURANCE: R Hamilton 3/12/97

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ORIGINAL

NOTICE OF ANOMALY

DATE: May 19, 1997

NOTICE NO.: 3	P.O. NUMBER: N/A	CONTRACT NO.:	750945
CUSTOMER:	Brookhaven National Laboratory	WYLE JOB NO.:	45120
NOTIFICATION MADE TO:	Robert Lofaro	NOTIFICATION DATE:	5/16/97
NOTIFICATION MADE BY:	Bobby Hardy	VIA:	in person

CATEGORY: ☐ SPECIMEN ☐ PROCEDURE ☒ TEST EQUIPMENT — DATE OF ANOMALY: 5/16/97

PART NAME:	Cable Samples	PART NO.	N/A
TEST:	LOCA Simulation	I.D. NO.	N/A
SPECIFICATION:	WLTP 45120-LOCA-1, Rev. A	PARA. NO.	2.3

REQUIREMENTS:

The specimens detailed in the above referenced specification shall be subjected to a 7-day LOCA Simulation Test.

DESCRIPTION OF ANOMALY:

At the 39-hour point of the 7-day test, the test chamber was shut down to allow for repair of a malfunctioning level controller.

The test chamber temperature and pressure were below requirements for 37 minutes while the repair was made.

DISPOSITION - COMMENTS - RECOMMENDATIONS:

The repair was made following the completion of chemical spray so that chemical spray would not be interrupted. The chamber temperature and pressure were gradually raised back to the requirements once repairs were complete so that the specimens would not be exposed to a rapid temperature/pressure transient. The Brookhaven representative on site was informed prior to the repair and directed Wyle to perform the repair. The test was extended 37 minutes such that the specimens wee subjected to the required temperature and pressure for the specified duration.

RESPONSIBILITY TO ANALYZE ANOMALIES AND COMPLY WITH 10 CFR PART 21: ■ CUSTOMER ☐ WYLE

VERIFICATION:		PROJECT ENGINEER:	Robert Hardy 5/19/97 Robert Hardy
TEST WITNESS:	Robert Lofaro	PROJECT MANAGER:	Don Smith 5/19/97 Don E. Smith
REPRESENTING:	Brookhaven National Lab.	INTERDEPARTMENTAL COORDINATION:	
QUALITY ASSURANCE:	R D [illegible] 5-20-97		

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ORIGINAL NOTICE OF ANOMALY

DATE: January 23, 1998

NOTICE NO.: 4 **P.O. NUMBER:** N/A **CONTRACT NO.:** 750945

CUSTOMER: Brookhaven National Laboratory **WYLE JOB NO.:** 45120

NOTIFICATION MADE TO: Robert Lofaro **NOTIFICATION DATE:** 1/22/98

NOTIFICATION MADE BY: Bobby Hardy **VIA:** phone & fax

CATEGORY: ☐ SPECIMEN ☐ PROCEDURE ☒ TEST EQUIPMENT **DATE OF ANOMALY:** 1/21/98

PART NAME: Cable Samples **PART NO.** N/A

TEST: Thermal Aging **I.D. NO.** N/A

SPECIFICATION: WLTP 45120-PA-2, Rev. A **PARA. NO.** 2.3

REQUIREMENTS:

The specimens that are to be thermally-aged shall be placed in a Wyle Thermal Aging Chamber and thermally aged in air at the temperature (+5/-0°F) and duration specified in Table II of the above noted specification.

Each aging chamber shall have a redundant controller that is capable or terminating the chamber heat should the primary controller malfunction. The redundant controllers shall be set no higher than 10°F above the required aging temperature.

DESCRIPTION OF ANOMALY:

This anomaly applies to all of the specimens which are being aged at 250°F.

On 1/21/98 at 16:35, the redundant controller terminated the heat to the chamber.

DISPOSITION - COMMENTS - RECOMMENDATIONS:

The exact cause of the termination is unknown but it is believed that a power glitch may have caused the redundant controller to trip off line which shut down heat to the chamber. The chamber slowly returned to laboratory ambient temperature. Brookhaven personnel were notified the morning of the 22nd. A copy of the temperature chart was sent to Brookhaven via fax. Brookhaven directed Wyle to re-start the heat in the chamber while calculations were made to determine the end time for thermal aging. Brookhaven was made aware of the exact time the chamber reached temperature stabilization following the re-start. With this information, Brookhaven directed that Wyle was to stop thermal aging of the 30.3-hour specimens at 05:06 on 1/23/98. Additionally, Brookhaven directed Wyle to add 53 hours and 42 minutes to the remaining specimens (84-hour specimens) to commence when the chamber had reached temperature stabilization. The 30.3-hour specimens were removed at appropriate time and thermal aging was continued on the remaining specimens.

RESPONSIBILITY TO ANALYZE ANOMALIES AND COMPLY WITH 10 CFR PART 21: ■ CUSTOMER ☐ WYLE

VERIFICATION:

PROJECT ENGINEER: Robert Hardy 1/23/98
Robert Hardy

TEST WITNESS: N/A

PROJECT MANAGER: Rod Thornberry 1-23-98
Rod Thornberry

REPRESENTING: N/A

INTERDEPARTMENTAL COORDINATION:

QUALITY ASSURANCE: TR Hamilton 1-23-98

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ORIGINAL **NOTICE OF ANOMALY** DATE: March 26, 1998

NOTICE NO.: 5 P.O. NUMBER: N/A CONTRACT NO.: 750945

CUSTOMER: Brookhaven National Laboratory WYLE JOB NO.: 45120

NOTIFICATION MADE TO: Robert Lofaro NOTIFICATION DATE: 2/22/98

NOTIFICATION MADE BY: Bobby Hardy VIA: phone

CATEGORY: ☐ SPECIMEN ☒ PROCEDURE ☐ TEST EQUIPMENT DATE OF ANOMALY: 2/21/98

PART NAME: Cable Samples PART NO. N/A

TEST: Accident Radiation Exposure I.D. NO. N/A

SPECIFICATION: WLTP 45120-LOCA-2, Rev. B PARA. NO. 2.2

REQUIREMENTS:

The specified Accident Radiation Exposure dose rate shall be controlled to the specified value within +0/-20%.

DESCRIPTION OF ANOMALY:

This anomaly applies to all specimens which were exposed to Accident Radiation.

The required dose rates were below the -20% margin of the specified value of 1.0E6 rads/hour.

DISPOSITION - COMMENTS - RECOMMENDATIONS:

Wyle was directed by BNL to continue with the irradiation exposure until the specimens received their required total dose. Following the completion of the radiation exposure, BNL performed Condition Monitoring Tests on the specimens per the directions of the above referenced test procedure. Copies of the radiation facilities report are attached to this notice of anomaly. The following is a summary of the conditions which lead to the generation of this notice of anomaly:

NRC Reference	Required Dose Rate	Average Dose Rate	% Deviation
9805d	1.0E6 rads/hr +0-20%	0.6644E6 rads/hr	-33.56
9805e	1.0E6 rads/hr +0-20%	0.7899E6 rads/hr	-21.01
9805f	1.0E6 rads/hr +0-20%	0.6806E6 rads/hr	-31.94
9805g	1.0E6 rads/hr +0-20%	0.7904E6 rads/hr	-20.96

RESPONSIBILITY TO ANALYZE ANOMALIES AND COMPLY WITH 10 CFR PART 21: ■ CUSTOMER ☐ WYLE

VERIFICATION:

PROJECT ENGINEER: Bobby Hardy 3/26/98
Robert Hardy

TEST WITNESS: N/A

PROJECT MANAGER: Rod Thornberry 3-26-98
Rod Thornberry

REPRESENTING: N/A

INTERDEPARTMENTAL COORDINATION:

QUALITY ASSURANCE: T R Hamilton 3-26-98

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ORIGINAL NOTICE OF ANOMALY

DATE: September 21, 1998

NOTICE NO.: 6 P.O. NUMBER: N/A CONTRACT NO.: 750945

CUSTOMER: Brookhaven National Laboratory WYLE JOB NO.: 45120

NOTIFICATION MADE TO: Robert Lofaro NOTIFICATION DATE: 6/5/98

NOTIFICATION MADE BY: Bobby Hardy VIA: phone & fax

CATEGORY: ☐ SPECIMEN ☐ PROCEDURE ☒ TEST EQUIPMENT DATE OF ANOMALY: 6/4/98

PART NAME: Cable Samples PART NO. N/A

TEST: Thermal Aging I.D. NO. N/A

SPECIFICATION: WLTP 45120-PA-3 PARA. NO. 2.3

REQUIREMENTS:

The specimens that are to be thermally-aged shall be placed in a Wyle Thermal Aging Chamber and thermally aged in air at the temperature (+5/-0°F) and duration specified in Table II of the above noted specification.

Each aging chamber shall have a redundant controller that is capable or terminating the chamber heat should the primary controller malfunction. The redundant controllers shall be set no higher than 10°F above the required aging temperature.

DESCRIPTION OF ANOMALY:

This anomaly applies to all of the specimens which are being aged at 302°F.

On 6/4/98 at approximately 13:14, the facility power went off momentarily causing the controller to terminate the heat to the chamber.

On 6/5/98 at approximately 05:14, the facility power went off and stayed off until approximately 08:19.

DISPOSITION - COMMENTS - RECOMMENDATIONS:

The chamber slowly returned to laboratory ambient temperature. Brookhaven personnel were notified of both occurrences immediately. A copy of the temperature charts were sent to Brookhaven via fax. Brookhaven directed Wyle to restart the heat in the chamber while calculations were made to determine the end time for thermal aging. Brookhaven was made aware of the exact time the chamber reached temperature stabilization following the restarts.

RESPONSIBILITY TO ANALYZE ANOMALIES AND COMPLY WITH 10 CFR PART 21: ■ CUSTOMER ☐ WYLE

VERIFICATION:

PROJECT ENGINEER: Robert Hardy 9/21/98
Robert Hardy

TEST WITNESS: N/A

PROJECT MANAGER: Don Smith 9/21/98
Don Smith

REPRESENTING: N/A

INTERDEPARTMENTAL COORDINATION:

QUALITY ASSURANCE: [illegible] 9/21/98

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ORIGINAL NOTICE OF ANOMALY

DATE: October 9, 1998

NOTICE NO.: 7	P.O. NUMBER: N/A	CONTRACT NO.:	750945
CUSTOMER:	Brookhaven National Laboratory	WYLE JOB NO.:	40047.03
NOTIFICATION MADE TO:	Robert Lofaro	NOTIFICATION DATE:	10/7/98
NOTIFICATION MADE BY:	Bobby Hardy	VIA:	In person
CATEGORY:	☐ SPECIMEN ☐ PROCEDURE ☒ TEST EQUIPMENT	DATE OF ANOMALY:	10/7/98
PART NAME:	Cable Samples	PART NO.	N/A
TEST:	LOCA Simulation	I.D. NO.	N/A
SPECIFICATION:	WLTP 45120-LOCA-3, Rev. A	PARA. NO.	2.3

REQUIREMENTS:

The specimens shall be subjected the Accident Profile as shown in the above referenced specification.

DESCRIPTION OF ANOMALY:

During the 335°F/93 psig plateau, a thermocouple used by the chamber controller ceased functioning causing the temperature and pressure of the chamber to drop below the requirements for 18 minutes.

DISPOSITION - COMMENTS - RECOMMENDATIONS:

The thermocouple was replaced with a spare. 18 minutes were to be added to the plateau to make up for the lost time, but only six minutes were added to the plateau due to human error. Approximately ten minutes were added to the following plateau (315°F/69 psig) at the direction of the Brookhaven representative on site for testing.

RESPONSIBILITY TO ANALYZE ANOMALIES AND COMPLY WITH 10 CFR PART 21: ■ CUSTOMER ☐ WYLE

VERIFICATION:		PROJECT ENGINEER:	Robert Hardy 10/9/98 Robert Hardy
TEST WITNESS:	Robert Lofaro	PROJECT MANAGER:	Don Smith 10/9/98 Don Smith
REPRESENTING:	Brookhaven National Lab.	INTERDEPARTMENTAL COORDINATION:	
QUALITY ASSURANCE:	R Hamilton 10/9/98		

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ORIGINAL NOTICE OF ANOMALY

DATE: October 16, 1998

NOTICE NO.: 8 P.O. NUMBER: N/A CONTRACT NO.: 750945

CUSTOMER: Brookhaven National Laboratory WYLE JOB NO.: 40047.03

NOTIFICATION MADE TO: Robert Lofaro NOTIFICATION DATE: 10/16/98

NOTIFICATION MADE BY: Bobby Hardy VIA: phone

CATEGORY: ☐ SPECIMEN ☒ PROCEDURE ☐ TEST EQUIPMENT DATE OF ANOMALY: 8/26/98

PART NAME: Cable Samples PART NO. N/A

TEST: Accident Radiation Exposure I.D. NO. N/A

SPECIFICATION: WLTP 45120-LOCA-3, Rev. A PARA. NO. 2.2

REQUIREMENTS:

The specified Accident Radiation Exposure dose rate shall be controlled to the specified value within +0/-20%.

DESCRIPTION OF ANOMALY:

The required dose rates, as detailed below, were below the -20% margin of the specified value of 1.0E6 rads/hour with the exception of NRC Reference No. 9819d which was above the +0% margin of the specified value.

DISPOSITION - COMMENTS - RECOMMENDATIONS:

Wyle was not aware of the anomaly until the irradiation report was received. Every specimen received its required total dose. Copies of the radiation facility's report sheets pertaining to this notice of anomaly are attached. The following is a summary of the conditions which lead to the generation of this notice of anomaly:

NRC Reference	Required Dose Rate	Average Dose Rate	% Deviation
9819c	1.0E6 rads/hr +0-20%	0.6465E6 rads/hr	-35.35
9819e	1.0E6 rads/hr +0-20%	0.6422E6 rads/hr	-35.78
9819d	1.0E6 rads/hr +0-20%	1.001E6 rads/hr	+0.1
9819f	1.0E6 rads/hr +0-20%	0.7910E6 rads/hr	-20.90

RESPONSIBILITY TO ANALYZE ANOMALIES AND COMPLY WITH 10 CFR PART 21: ■ CUSTOMER ☐ WYLE

VERIFICATION:

PROJECT ENGINEER: Robert Hardy 10/16/98
Robert Hardy

TEST WITNESS: N/A

PROJECT MANAGER: Don Smith 10/20/98
Don Smith

REPRESENTING: N/A

INTERDEPARTMENTAL COORDINATION:

QUALITY ASSURANCE: R Hamilton 10/20/98

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ORIGINAL **NOTICE OF ANOMALY**

DATE: July 2, 1999

NOTICE NO.: 9	P.O. NUMBER: N/A	CONTRACT NO.:	750945
CUSTOMER:	Brookhaven National Laboratory	WYLE JOB NO.:	40047.04
NOTIFICATION MADE TO:	Robert Lofaro	NOTIFICATION DATE:	7/1/99
NOTIFICATION MADE BY:	Bobby Hardy	VIA:	phone

CATEGORY:	☐ SPECIMEN ☒ PROCEDURE ☐ TEST EQUIPMENT	DATE OF ANOMALY:	6/29/99
PART NAME:	Cable Samples	PART NO.	N/A
TEST:	Thermal Aging	I.D. NO.	N/A
SPECIFICATION:	WLTP 45120-PA-4, Rev. C	PARA. NO.	2.3

REQUIREMENTS:

The specimens that are to be thermally-aged shall be placed in a Wyle Thermal Aging Chamber and thermally aged in air at the temperature (+5/-0°F) and duration specified in Table II of the above referenced specification. The specified thermal aging duration shall be kept within +2, -0% of the specified value not to exceed one hour.

DESCRIPTION OF ANOMALY:

The 250°F specimens which were to be thermally aged for 168 hours (-0, +1 hour) were aged for 169 hours and 3 minutes. The 302°F specimens which were to be thermally aged for 168 hours (-0, +1 hour) were aged for 169 hours and 12 minutes.

DISPOSITION - COMMENTS - RECOMMENDATIONS:

The specimens were removed from the thermal aging chamber and stored under controlled conditions. The customer will make the decision as to the final disposition.

RESPONSIBILITY TO ANALYZE ANOMALIES AND COMPLY WITH 10 CFR PART 21: ■ CUSTOMER ☐ WYLE

VERIFICATION:		PROJECT ENGINEER:	Robert Hardy 7/2/99
TEST WITNESS:	N/A	PROJECT MANAGER:	Don Smith 7/2/99
REPRESENTING:	N/A	INTERDEPARTMENTAL COORDINATION:	
QUALITY ASSURANCE:	7/2/99		

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ORIGINAL

NOTICE OF ANOMALY

DATE: July 28, 1999

NOTICE NO.: 10	P.O. NUMBER: N/A	CONTRACT NO.:	750945
CUSTOMER:	Brookhaven National Laboratory	WYLE JOB NO.:	40047.04
NOTIFICATION MADE TO:	Mike Villirain	NOTIFICATION DATE:	7/27/99
NOTIFICATION MADE BY:	Bobby Hardy	VIA:	phone
CATEGORY:	☐ SPECIMEN ☐ PROCEDURE ☒ TEST EQUIPMENT	DATE OF ANOMALY:	7/27/99
PART NAME:	Cable Samples	PART NO.	N/A
TEST:	Thermal Aging	I.D. NO.	N/A
SPECIFICATION:	WLTP 45120-PA-4, Rev. C	PARA. NO.	2.3

REQUIREMENTS:

The specimens that are to be thermally-aged shall be placed in a Wyle Thermal Aging Chamber and thermally aged in air at the temperature (+5/-0°F) and duration specified in Table II of the above referenced specification.

DESCRIPTION OF ANOMALY:

The temperature of the thermal aging chamber dropped below the required 302°F for a duration of approximately one hour and 43 minutes. The temperature dropped to a low of approximately 290°F.

DISPOSITION - COMMENTS - RECOMMENDATIONS:

The temperature of the chamber returned to the required setting without intervention of Wyle personnel. The reason for the temperature drop is unknown. BNL personnel were notified during the temperature drop. Once the chamber had returned to the required temperature and stabilized, a copy of the temperature chart was faxed to BNL. BNL determined that the temperature drop would not effect the outcome of the thermal aging process and directed that the cut-off point for the chamber should remain the same. The customer will make the decision as to the final disposition.

RESPONSIBILITY TO ANALYZE ANOMALIES AND COMPLY WITH 10 CFR PART 21: ■ CUSTOMER ☐ WYLE

VERIFICATION:		PROJECT ENGINEER:	Robert Hardy 7/28/99 Robert Hardy
TEST WITNESS:	N/A	PROJECT MANAGER:	For Thornberry 7-28-99 For Don Smith
REPRESENTING:	N/A	INTERDEPARTMENTAL COORDINATION:	
QUALITY ASSURANCE:	7-28-99		

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wyle laboratories

NOTICE OF ANOMALY

DATE: April 25, 2000

NOTICE NO.: 11 P.O. NUMBER: N/A CONTRACT NO.: 750945

CUSTOMER: Brookhaven National Laboratory WYLE JOB NO.: 40047.05

NOTIFICATION MADE TO: Bob Lofaro NOTIFICATION DATE: 1/14/00

NOTIFICATION MADE BY: Bobby Hardy VIA: In person

CATEGORY: ☐ SPECIMEN ☐ PROCEDURE ☒ TEST EQUIPMENT DATE OF ANOMALY: 1/14/00

PART NAME: Cable Samples PART NO. N/A

TEST: LOCA Simulation I.D. NO. N/A

SPECIFICATION: WLTP 45120-LOCA-5, Rev. A PARA. NO. 2.2.3

REQUIREMENTS:

Each of the powered specimens shall be monitored for applied voltage, circuit current, and leakage current throughout the duration of the LOCA Simulation test.

DESCRIPTION OF ANOMALY:

The single-conductor specimens (0501, 0504, 0505, 0510, 0511, and 0512) were not monitored for leakage current as required due to incorrect wiring.

DISPOSITION - COMMENTS - RECOMMENDATIONS:

A review of the test circuit following the Accident Simulation revealed that these specimens (all single conductor) had been connected to the positive side of the test circuit which prevented a difference of potential between the conductor(s) and ground. The customer will make the decision as to the final disposition.

RESPONSIBILITY TO ANALYZE ANOMALIES AND COMPLY WITH 10 CFR PART 21: ■ CUSTOMER ☐ WYLE

VERIFICATION:

PROJECT ENGINEER: Robert Hardy 4/25/00
Robert Hardy

TEST WITNESS: N/A

PROJECT MANAGER: Don Smith 4/25/00
Don Smith

REPRESENTING: N/A

INTERDEPARTMENTAL COORDINATION:

QUALITY ASSURANCE: R Hamilton 4/25/00

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(See instructions on the reverse)

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

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BNL-NUREG-52610

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3. DATE REPORT PUBLISHED

MONTH	YEAR
February	2001

4. FIN OR GRANT NUMBER

W-6465

5. AUTHOR(S)

R. Lofaro, E. Grove, M. Villaran, P. Soo, and F. Hsu

6. TYPE OF REPORT

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Energy Sciences and Technology Department
Brookhaven National Laboratory
Upton, NY 11973-5000

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

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

10. SUPPLEMENTARY NOTES

S.K. Aggarwal, Project Manager

11. ABSTRACT *(200 words or less)*

This report documents the results of a research program addressing issues related to the qualification process for low-voltage instrumentation and control (I&C) electric cables used in commercial nuclear power plants. Three commonly used types of I&C cable were tested: Cross-Linked Polyethylene (XLPE) insulation with a Neoprene® jacket, Ethylene Propylene Rubber (EPR) insulation with an unbonded Hypalon® jacket, and EPR with a bonded Hypalon® jacket. Each cable type received accelerated aging to simulate 20, 40, and 60 years of qualified life. In addition, naturally aged cables of the same types were obtained from decommissioned nuclear power plants and tested. The cables were subjected to simulated loss-of-coolant-accident (LOCA) conditions, which included the sequential application of LOCA radiation followed by exposure to steam at high temperature and pressure, as well as to chemical spray. Periodic condition monitoring (CM) was performed using nine different techniques to obtain data on the condition of the cable, as well as to evaluate the effectiveness of those CM techniques for in situ monitoring of cables.

Volume 1 of this report presents the results of the LOCA tests, and Volume 2 discusses the results of the condition monitoring tests.

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

electric cables, aging, performance testing, environmental effects, nuclear power plants, electrical equipment, electrical insulation, loss of coolant, materials testing, monitoring, radiation effects, service life

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