June 28, 2002

MEMORANDUM TO: Samuel J. Collins, Director
Office of Nuclear Reactor Regulation

FROM: Ashok C. Thadani, Director **/RA/**
Office of Nuclear Regulatory Research

SUBJECT: TECHNICAL ASSESSMENT OF GENERIC SAFETY ISSUE (GSI) 168, "ENVIRONMENTAL QUALIFICATION OF LOW-VOLTAGE INSTRUMENTATION AND CONTROL (I&C) CABLES"

The RES staff has completed the technical assessment of Generic Safety Issue GSI-168, "Environmental Qualification of Low-Voltage Instrumentation and Control (I&C) Cables" (Attachment 1). I am transmitting this assessment to you to implement Stage 4, "Regulation and Guidance Development," according to Management Directive 6.4, "Generic Issues Program."

The technical assessment is based on reviews and analyses of the research results of six LOCA tests, condition-monitoring tests on I&C cables, and information provided by the nuclear industry. The staff concluded that typical cable qualification test programs include numerous conservative practices that collectively provide a high level of confidence that the installed plant cables will adequately perform during the accident events. These conservative practices support the use of a single prototype (or a small number of test specimens) during the qualification test program. Licensee knowledge of the environment is essential to assure that the operating conditions in nuclear power plants do not exceed the qualification parameters assumed during the test. In this regard, licensee walkdowns to look for any visible signs of anomalies attributable to cable aging, coupled with the knowledge of operating environments, have proven to be effective and useful.

Interaction with the industry was an important aspect of the technical assessment of this issue. The staff had numerous public meetings on this subject during 2000-2001. During these meetings the staff raised several technical issues for discussion based on the research results. The industry (Nuclear Energy Institute and the Institute of Electrical and Electronics Engineers) provided their written responses. The industry stated that the aging evaluations are ongoing throughout the plant life. When unexpected adverse conditions are identified, the condition of the affected cables is evaluated and appropriate corrective actions are taken. The industry response was generic and not plant-specific. The RES assessment, therefore, did not address plant specific implementation and the industry did not provide plant specific information to confirm that these good practices are implemented uniformly by all licensees.

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In the final analysis, the staff recommends dissemination of research results and other information, as discussed in Section 6.3 of Attachment 1, consistent with the generic communication process.

The technical assessment of this issue and its recommended disposition have been closely conducted with the Division of Engineering in NRR and cooperation of the DE staff in this effort is greatly appreciated.

On June 6, 2002, the staff met with the Advisory Committee on Reactor Safeguards (ACRS), and presented the technical assessment of GSI-168. The Committee endorsed the staff's conclusions and recommendations (see Attachment 2).

Attachments: 1. Technical Assessment of GSI-168
2. ACRS letter dated June 17, 2002

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Technical Assessment of Generic Safety Issue GSI-168, “Environmental Qualification of Low-Voltage Instrumentation and Control Cables”

1. BACKGROUND

Safety-related electric cables are used in a wide variety of applications in a nuclear power plant. Some of these cables are medium-voltage cables used to transmit electric power to safety-related electrical equipment; others are low-voltage cables used to transmit signals between instrumentation and control (I&C) devices (e.g., data and control signals) for performing safety functions.

Environmental qualification (EQ) requirements were developed to provide reasonable assurance that safety-related electric cables will perform their safety functions during their service life in the environment in which they operate during normal operation, transient conditions, and accidents. These requirements have evolved as operating experience accumulated and the aging process was better understood. Initially, qualification was based on the "high industrial quality" of electrical components. For plants constructed after 1971, a more formal approach was adopted: qualification was judged on the basis of Institute of Electrical and Electronics Engineers (IEEE) Standard 323-1971, "IEEE Trial-Use Standard: General Guide for Qualifying Class 1E Electrical Equipment for Nuclear Power Generating Stations." Although IEEE Std. 323-1971 did not address aging or life determination issues, the standard did call for a systematic program of analysis, testing, and quality assurance. It specified that qualification may be achieved through type testing, analysis, operating experience, or a combination of these methods.

For plants with NRC construction permits dated July 1, 1974, or later, the Commission endorsed the 1974 version of IEEE Std. 323 as an acceptable standard for demonstrating EQ. At that time, the NRC considered backfitting older plants to meet IEEE Std. 323-1974, "IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations," but recommended against it because the incremental improvements provided by the new standard were not considered cost effective.

During the EQ rule-making process in 1982, the Commission again had the opportunity to require older plants to meet the latest standards. When the rule (10 CFR 50.49) was finalized, the Commission deemed older qualification methods acceptable (i.e., grandfathered them). The Commission stated that the new rule allowed older plants to use the Division of Operating Reactor (DOR) guidelines and NUREG-0588 ("Interim Staff Position on Environmental Qualification of Safety-Related Electrical Equipment," 1981) Category II to qualify electric equipment. The Commission also recognized that the industry had just invested significant human resources and millions of dollars in conforming plants to the requirements of the DOR guidelines and NUREG-0588 Category II. Requiring the older plants to meet the newer EQ requirements (NUREG-0588 Category I) would invalidate the industry's efforts to comply with the staff's previous directions (to meet the requirements of the DOR guidelines and NUREG-0588 Category II).

Since older plants were not required to upgrade to the latest EQ requirements, the staff in effect sanctioned the use of three different sets of EQ requirements: (1) the DOR guidelines, which generally apply to equipment installed in plants that became operational before 1980, (2) the Category II criteria of NUREG-0588, which apply primarily to plants that became operational after 1980 and had originally committed to the requirements of IEEE Std. 323-1971, and (3) the Category I criteria of NUREG-0588 and Regulatory Guide 1.89, "Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants" (Revision 1, 1984), which apply to plants committed to meeting the requirements of IEEE Std. 323-1974 and to replacement equipment.

During license renewal activities in the late 1980s and early 1990s, the staff revisited the issue of EQ of safety-related electrical equipment, particularly the issue of whether EQ requirements for older plants were adequate for license renewal.

In SECY-93-049, "Implementation of 10 CFR 54 Requirements for Renewal of Operating Licenses for Nuclear Power Plants, March 1, 1993," the staff informed the Commission that, in evaluating the technical adequacy of the EQ requirements for license renewal, the staff had identified generic issues that might require backfits even for plants that were not renewing their licenses. Subsequently, in a June 28, 1993, memorandum from Samuel J. Chilk to James M. Taylor, the Commission directed the staff to treat EQ of electrical equipment in operating reactors as a potential safety issue and to periodically inform the Commission of the staff's progress in assessing the issue. On July 1, 1993, the staff submitted its EQ task action plan (EQ-TAP) as Enclosure 3 of the third quarterly report on fire protection issues. The purpose of the EQ-TAP was to evaluate and resolve existing environmental qualification concerns and to identify and resolve any other EQ concerns.

The EQ-TAP involved reviewing EQ-related information and conducting EQ-related research to enable the staff to (1) assess existing differences in the EQ requirements for older and newer plants, (2) assess the adequacy of accelerated aging practices for demonstrating equipment qualification, and (3) identify and resolve any other EQ issues. The plan included meetings with the industry, an EQ program review, data collection and analysis, a refined PRA, research on aging and condition monitoring, and options for resolving EQ concerns. These activities were modified as more information became available through research and a review of industry operating experience.

The Commission was informed of the status of the EQ-TAP by memoranda dated April 8, 1994; November 16, 1994; June 27, 1995; August 22, 1996; November 15, 1996; and February 5, 1998. In summary, the staff developed an EQ research program plan in 1995 to test cables, assess cable condition-monitoring methods, and develop and update an EQ database. The program was limited to low-voltage I&C cables since they were judged to be the most susceptible to aging degradation resulting in misleading information to control room operators. The information from the program was to be used to determine whether research should be done on other electric equipment. One of the initial steps in the program plan was to review information already available to avoid duplications and unnecessary research. In a memorandum to the Commission on November 15, 1996, the staff concluded, in part, that it would be prudent to have some form of condition monitoring and feedback mechanism during the current licensing period and the license renewal period.

In April 1996, the NRC issued a two-volume technical report, NUREG/CR-6384, "Literature Review of Environmental Qualification of Safety-Related Cables," which documented past and ongoing EQ research on safety-related cables. This report identified 7 major issues related to EQ. These 7 major issues were subdivided into 43 sub-issues; of which, 19 were considered unresolved and warranted further research. Public meetings to discuss the results of this review yielded additional data and industry reports on EQ to supplement the information already obtained. This supplemental information was subsequently reviewed in the research program and, as a result, additional sub-issues were determined to be resolved. Based on the various public meetings (including a public workshop held in November 1993 -- see NUREG/CP-0135), the literature review results documented in NUREG/CR-6384, the review of the supplemental information, and the availability of funding, six issues were identified to be addressed through new testing of cables. These issues are (1) the acceptability of using the Arrhenius methodology to simulate natural aging of cables, (2) the acceptability of activation energy estimates used in past qualification tests, (3) whether multi-conductor cables have any unique failure mechanisms compared to single conductor cables, and whether these failure mechanisms are adequately addressed in EQ practices, (4) whether bonded-jacket cables have any unique failure mechanisms compared to non-bonded jacket cables and whether these failure mechanisms are adequately addressed in EQ practices, (5) whether condition-monitoring methods exist that could be used to monitor the condition of cables in situ, and (6) whether condition monitoring could be used to predict the accident survivability of cables. Note that the issue concerning differences in EQ requirements between older and newer plants was addressed as part of the literature review and site visits and did not require additional cable testing. Subsequently, a test program was developed and implemented that focused on three of the most popular types of in-containment cables currently used in U.S. nuclear power plants.

Since the concerns identified in the EQ-TAP were either resolved by reviewing EQ-related literature or were being addressed by the cable research program, and since the cable research program was a long-term effort, the staff decided to close the EQ-TAP in 1998 and transfer the long-term research activities to Generic Safety Issue (GSI) 168, “Environmental Qualification of Low-Voltage Instrumentation and Control Cables.” The staff would then inform the Commission of its progress on this issue through updates to NUREG-0933, “Prioritization of Generic Safety Issues.”

2. SCOPE OF GSI-168, "ENVIRONMENTAL QUALIFICATION OF LOW-VOLTAGE INSTRUMENTATION AND CONTROL CABLES"

While preparing the EQ-TAP in 1993, the staff initiated GSI-168 to address any EQ-related generic safety issues identified during the EQ-TAP reviews. NUREG-0933 describes GSI-168 as follows:

> As discussed in SECY-93-049, the staff reviewed significant license renewal issues and found that several related to environmental qualification (EQ). A key aspect of these issues was whether the licensing bases, particularly for older plants whose licensing bases differ from newer plants, should be reassessed or enhanced in connection with license renewal or whether they should be reassessed for the current license term. The staff concluded that differences in EQ requirements constituted a potential generic issue, which should be evaluated for backfit independent of license renewal.
>
> In the staff's development of an interoffice action plan to address upgrading EQ requirements for older plants during the current licensing term, the staff evaluated the technical adequacy of EQ requirements. As part of this evaluation, the staff reviewed tests of qualified cables performed by SNL, under contract with the NRC. The purpose of these tests was to determine the effects of aging on cable products used in nuclear power plants. After accelerated aging, some of the environmentally qualified cables either failed or exhibited marginal insulation resistance during accident testing, indicating that qualification of some electric cables may have been non-conservative. Although the SNL tests may have been more severe than required by NRC regulations, the test results raised questions with respect to the EQ and accident performance capability of certain artificially aged cables. Depending on the application, failure of these cables during or following design basis events could affect the performance of safety functions in nuclear power plants.

Although none of the EQ issues remaining after the EQ-TAP was closed in 1998 were identified as generic safety issues, GSI-168 was considered the most appropriate management tool for tracking and reporting progress in resolving them.

3. RESEARCH PROGRAM

In 1995, a research program was implemented with the following goals:

> To establish a database on operational performance, test performance, and environmental testing of cable in domestic and foreign operating plants and to determine which EQ- related technical issues can be resolved with existing information and which need further research.
>
> To develop and implement testing of low-voltage I&C cables to (a) assess the validity of current qualification methods, (b) evaluate the adequacy of accelerated aging methods, (c) evaluate methods for in situ cable inspection and condition monitoring, and (d) provide a technical basis for revising current rules and guidance on environmental qualification of cables, as needed.

As stated earlier, a thorough literature review and analysis was done to resolve as many issues as possible without resorting to extensive cable testing. The literature review and analysis, which is documented in Volumes 1 and 2 of NUREG/CR-6384, and Brookhaven National Laboratory (BNL) technical report TR-6169-9/97 sorted the 43 technical issues into four categories:

Category 1 issues were resolved by past work, new research was not needed: 24 issues.

Category 2 issues were unresolved by past work, but new research was not recommended: 6 issues.

Category 3 issues were unresolved by past work and new research was recommended: 6 issues.

Category 4 issues were unresolved by past work. No new research was recommended but the issues may be elucidated by the research on the Category 3 issues: 7 issues.

The Category 3 issues were:

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

> Prolonged thermal exposure of cables inside nuclear power plants can cause significant degradation of their insulating polymers. These changes in the elastic properties of cable insulation and jacket materials can be considered a precursor to eventual cable failure. To account for this in the qualification process, cable samples are thermally pre-aged prior to loss-of-coolant accident (LOCA) testing to simulate their expected condition at the end of their service life. To simulate thermal aging for a 40-year service life, cable specimens are typically subjected to elevated temperature conditions in ovens. The aging oven temperatures are calculated based on the Arrhenius methodology using an estimated activation energy. Only limited work has been done to evaluate the application of Arrhenius, which was of interest in the research program. Comparisons of Arrhenius predictions to naturally aged materials have been limited. Therefore, the staff decided to study a comparison of naturally aged cables with cables aged under accelerated conditions.

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

The estimated qualified life of a polymer is very sensitive to the value used for activation energy in the Arrhenius equation. For example, a change in activation energy from 1.0 to 1.3 eV increases the predicted qualified life from 12 to 87 years. The issue of activation energies is not resolved since there is uncertainty in the process used and the values obtained. It would be extremely cost- and time-intensive to embark on a comprehensive research program to accurately determine activation energies. It was, therefore, decided to use activation energies in our research program as used in the original qualification. However, the staff decided to include tests in our research program to verify activation energies for the cable materials being tested.

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

Control cables typically contain # 12-14 American Wire Gauge (AWG) conductors and may be single or multi-conductor cables. The number of conductors may influence the failure mechanism of the cable because of interaction between conductors. In Sandia's previous work, ethylene propylene rubber (EPR) multiconductor cables were found to have a higher propensity to failure during a LOCA compared to identical single conductor cables. This was attributed to severe dimensional swelling, specifically under simultaneous radiation and steam exposure, and raised a question of whether this is a generic problem with multiconductor cables. Several hypotheses were provided to explain why the multiconductor cables failed. It is possible that penetrations used in the Sandia's LOCA test chamber could have caused differential pressure to develop between the inside and the outside of the cable during LOCA testing. Sufficient information was not available to draw a definitive conclusion. Therefore, the staff decided to include testing of single conductor and multiconductor cables in the research program.

(4) *Do cables with bonded jackets have different failure mechanisms than cables with unbonded jackets, and if so, are these failure mechanisms accounted for in the qualification process?*

Another variation in cable construction involves the insulating system used on the conductors. One popular cable design uses a single layer of polymer insulating material on each of the conductors. However, in some cable designs a second layer of insulating material is applied over the primary insulation. This second layer forms an individual jacket on each conductor and can be bonded directly to the underlying insulation forming a composite insulating system. The individual jacket is used to provide specific properties to the cable, such as increased fire resistance. Past research has suggested that this bonded-jacket construction may have unique failure mechanisms because of the bonding between the individual jacket and the underlying insulation. In testing performed by Sandia, cables with bonded CSPE jackets cracked through to the conductor and subsequently failed during a post-LOCA voltage withstand test. The cause of the cracking was believed to be due to surface cracks that developed in the individual Hypalon jackets and, due to its integral bonding to the insulation, propagated into the insulation material. Since the cause of the bonded-jacket cable failures in the Sandia tests could not be determined decisively, the staff decided to perform additional research to further investigate this phenomenon. In the new research program, the Sandia tests were repeated using the same source of cable, but with various controls designed into the test to isolate the cause of failure.

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

As discussed earlier, there is a wide variation in the construction of cables; including the materials used, the number of conductors, the thickness of insulation and jackets, and the configuration. These variations, together with the environment in which the cables are installed, will affect the rate and degree to which cables will degrade. To ensure the cable will perform its safety function when needed, it is desirable to monitor its condition. There are many promising condition-monitoring techniques. The staff decided to evaluate several of these techniques and their effectiveness.

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

Since cables have a qualified life of 40 years and are not routinely replaced in a nuclear power plant, as noted earlier, it is desirable to determine the condition of the safety-related cables, with the ultimate goal of condition monitoring being to provide a means of predicting accident survivability for the cable.

3.1 Research Approach

The research approach consisted of:

1. Identification of the most popular types of in-containment cables currently used in U.S. nuclear power plants: Approximately 89% of the currently operating plants had cables with cross-linked polyethylene (XLPE) insulation in containment, and approximately 73% had cables with EPR insulation.

2. Acquisition of cable samples: Naturally aged cables from two nuclear power plants were obtained. Unaged cables of the same type as the naturally aged cables were also obtained. Some cables were also obtained from Sandia, which had been tested in previous tests.

3. Baseline Information: Unaged cables with no pre-aging were included in the tests as “control specimens.” 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 techniques were used at each hold point to obtain data on cables, as well as to evaluate those CM techniques for monitoring cable condition.

4. Pre-aging and LOCA testing: Three types of cables were selected for inclusion in the program: (1) cables insulated with EPR and covered with a bonded Hypalon (chlorosulfonated polyethylene) individual jacket and a Hypalon outer jacket, (2) cables insulated with EPR covered with a non-bonded Hypalon individual jacket and a Hypalon outer jacket, and (3) cables insulated with cross-linked polyethylene (XLPE) with no individual jacket and a Neoprene outer jacket.

As part of the test protocol, unaged cables received accelerated aging, using currently accepted accelerated aging techniques, to simulate 20, 40, and 60 years of qualified life. The accelerated aging parameters were chosen to match those used in the original qualification tests for those cables. Note that the staff was unsuccessful in obtaining typical environmental conditions (temperature and radiation) from operating nuclear power plants to more accurately simulate pre-aging. In addition, naturally aged cables from two nuclear power plants were included in the test. For comparison, unaged cables of similar material and design that received accelerated aging to match the service conditions to which the naturally aged cables were exposed were included in the test.

Following accelerated aging, the cables were exposed to high-temperature and high pressure steam and chemical spray, simulating a design basis LOCA. Unaged control specimens and the naturally aged cables were also exposed to the same LOCA simulations. The testing was performed in accordance with IEEE Standard 323-1974, IEEE Standard 383-1974, and Regulatory Guide 1.89.

The cables went through six sequences of accelerated aging followed by LOCA simulation testing to address the EQ issues of interest. In each sequence, one or more of the three cable types being studied were tested. When more than one type of cable was tested, the cables were pre-aged separately, using the original qualification parameters. The LOCA test profile was selected to envelop the profiles used in the original qualification of all the cables in the test. The accelerated aging consisted of sequential thermal aging followed by radiation aging to be consistent with the original qualification protocol. In the LOCA simulations, radiation exposure preceded steam exposure.

Periodically during the accelerated aging, as well as prior to and after LOCA simulation, the physical, chemical, and electrical properties of the cables were measured. These data were used to monitor the condition of the cables as the testing progressed, as well as to evaluate the effectiveness of the condition-monitoring techniques being studied.

During the LOCA simulations, the specimens were individually powered with 28 Vdc. Facility lead wires were spliced to each cable using nuclear grade splices for this purpose. The lead wires were then passed through penetrations on the test chamber. A pressure transmitter was connected to the leads for each cable specimen to simulate a typical instrumentation circuit. Short specimens in stainless-steel baskets, which were included for destructive materials testing at various hold points, were not powered. 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 of any performance anomalies. Each circuit was protected by a 1/32 amp fuse.

Following LOCA simulation, each cable was subjected to a submerged voltage withstand test, in accordance with IEEE Standard 383-1974. In this test, the cable is submerged in tap water and a voltage equal to 80 volts per mil of insulation thickness is applied to the cable. Since the cables in this program had 30 mils of insulation, a test voltage of 2,400 volts was used. Leakage current was then monitored while the cable remained energized for five minutes. For this program, a leakage current less than 10 mA was used as the acceptance criteria for passing the voltage withstand test. In actual applications, the leakage currents would be analyzed to determine whether they are acceptable for the intended application of the cable.

3.2 Documents on Research Program

The following documents on this research program were made publicly available for review and comment.

"Acquisition Plan for Non-Aged and Naturally Aged Cable Samples From Nuclear Facilities," BNL Technical Report TR-6168/69-01-9/95. This plan describes the process used to obtain representative new and naturally aged low-voltage electric cables from operating and decommissioned nuclear power plants, DOE facilities, and cable manufacturers for testing. The plan specifies the criteria for selecting samples and the background data to be obtained with the samples. It also gives special handling instructions to ensure that the selected cable samples were not damaged and did not experience abnormal environmental conditions during and after removal from a facility.

"Quality Assurance Plan," BNL Technical Report TR-6169-05-95. This quality assurance (QA) plan ensured that the research results are traceable. The QA plan is based on the requirements in Appendix B to 10 CFR Part 50. All work, including the work of subcontractors, was done under this QA plan, which specified the development and approval of detailed test procedures for all testing activities and periodic audits.

"Pre-Aging and LOCA Test Plan," BNL Technical Report TR-6168/69-04-95. This report describes the basis for the pre-aging and LOCA testing of low-voltage safety-related cables. The preliminary five-phase approach and test matrixes are described in this report. Throughout the test program, the test plan was modified to incorporate public input and recommendations, as well as lessons learned from previously completed tests. Specimens of each type and manufacturer were prepared according to the established procedures. Some of the new or unused long specimens were wound on mandrels during testing; others were tested in straight lengths mounted in Unistrut® channels to simulate a typical installation in a cable tray. Each group of specimens was pre-aged by currently accepted accelerated thermal and radiation aging techniques to simulate the service age of the naturally aged cable samples and 20, 40, and 60 years of qualified life.

"Condition-Monitoring Research Plan for Low-Voltage Electric Cables," BNL Technical Report TR 6168/69-03-95. This report describes the goals of the condition-monitoring research, the approach taken and the condition-monitoring techniques studied. The techniques studied were visual examination, elongation-at-break, oxidation induction time, oxidation induction temperature, Fourier transform infrared spectroscopy, indenter, hardness, dielectric loss, insulation resistance, functional tests, and voltage withstand tests.

4. RESULTS OF ACCELERATED AGING AND LOCA TESTING

This section summarizes the results of the six test sequences. Details on the performance of these tests are provided in NUREG/CR-6704.

4.1 Test Sequence 1: XLPE Insulated Cables Aged to 20 Years

The samples tested in this sequence were #14 and #16 AWG XLPE-insulated cables with a Neoprene® overall outer jacket manufactured by Rockbestos, with the trade name "Firewall® III." These cables had 30 mils of XLPE insulation on the individual conductors and a 45-mil overall Neoprene® jacket. The pre-aging parameters for the four groups of specimens in this test sequence were:

Group 1: No pre-aging (control specimens)
Group 2: Pre-aging to match naturally aged cable (2.86 hrs @ 248 °F + 0.63 Mrad)
Group 3: Naturally aged cable (10 years old)
Group 4: Pre-aging to 20 years (648.5 hrs @ 302 °F + 26.1 Mrad)

After completion of the accelerated aging, all the specimens in the first three groups appeared to be in good physical condition with good ductility, and no cracking was evident in any of the specimens. However, the Group 4 specimens were severely degraded with excessive cracking in the outer jackets, but no cracking in the conductor insulation. Insulation resistance measurements indicated that, electrically, the insulation on all specimens was in acceptable condition.

The LOCA conditions simulated included exposure to 150 Mrad of accident radiation, followed by exposure to steam at high temperature and pressure (346 °F and 113 psig peak conditions; double peak profile), as well as chemical spray. The test duration was 7 days.

Specimens in Groups 1, 2, and 3 exhibited acceptable performance during the accident steam exposure. However, all five test specimens in Group 4 experienced performance anomalies. All specimens experienced leakage currents and fuses were blown when the total current exceeded the fuse rating. In actual plant conditions, the leakage currents measured would be analyzed based on the intended safety application for the specimens to determine if the leakage currents were acceptable.

Post-LOCA insulation resistance (IR) measurements indicated acceptable values for specimens in Groups 1, 2, and 3. However, the Group 4 measurements indicated short circuits in all the test specimens. Because of severe degradation of the outer jackets on the Group 4 specimens, moisture intrusion occurred through the cracks in the jacket and through micro-cracks in the insulation, after which it traveled along the conductor 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 high current readings observed. All cables passed the post-LOCA voltage withstand test once the splices were removed from Group 4 specimens prior to this test.

In the final analysis, it was concluded that all specimens passed the LOCA test.

4.2 Test Sequence 2: EPR-Insulated Cables Aged to 20 Years

The samples used in this sequence were #16 AWG, 3/C and 4/C 600V cables with 30 mils of EPR insulation and a 15-mil unbonded chlorosulfonated polyethylene (CSPE) (also known as Hypalon®) individual jacket covering the insulation on each conductor. The 45-mil overall outer jacket covering the conductor bundle was also made of Hypalon®. The cables were manufactured by American Insulated Wire (AIW). The pre-aging parameters for the four groups of specimens in this test sequence were:

Group 1: No pre-aging (control specimens)
Group 2: Pre-aging to match naturally aged cable (28.5 hrs @ 250 °F + 3.3 Mrad)
Group 3: Naturally aged cable (24 years old)
Group 4: Pre-aging to 20 years (82.2 hrs @ 250 °F + 25.7 Mrad).

After completion of accelerated aging, all the specimens appeared to be in relatively good condition with good ductility, and no cracking was evident in any of the specimens. Insulation resistance measurements indicated that all specimens were in acceptable condition electrically.

The LOCA conditions simulated included exposure to 150 Mrad of radiation followed by exposure to steam (340 °F and 60 psig, peak conditions, single peak profile) and chemical spray. The test duration was 7 days.

Throughout the LOCA steam exposure, no performance anomalies were noted for any of the specimens. All cable specimens performed acceptably in the post-LOCA voltage withstand test.

In the final analysis, it was concluded that all specimens passed the LOCA test.

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

The test specimens were XLPE-insulated cables with a Neoprene® overall outer jacket manufactured by Rockbestos, with the trade name "Firewall® III." (These cables were from the same sources as those used in test sequence 1.) The pre-aging parameters for the four aging groups in this test sequence were:

Group 1: No accelerated aging (control specimens)
Group 2: Accelerated aging to simulate the exposure of the naturally aged specimens (9.93 hrs @ 248 °F + 2.27 Mrads)
Group 3: Naturally aged 10-year-old cable
Group 4: Accelerated aging to simulate 40 years of qualified life (1301.16 hrs @ 302 °F + 51.49 Mrads)

After completion of the accelerated aging, all the specimens in the first three groups appeared to be in good physical condition with good ductility, and no cracking was evident in any of the specimens. The Group 4 specimens appeared to be severely degraded with extensive cracking in the jackets; however, no cracking was evident in the conductor insulation. IR measurements indicated that, electrically, the insulation in all specimens was in acceptable condition.

The LOCA conditions simulated included exposure to 150 Mrad of accident radiation followed by exposure to steam (using the same LOCA profile as used in test sequence 1) and chemical spray.

Throughout the test, performance problems were observed for all the Group 4 specimens, including leakage currents and blown fuses. The specimens in Groups 1, 2, and 3 performed acceptably.

Following the LOCA steam exposure test, a post-LOCA inspection was performed in which in situ IR measurements were made on all specimens before and after opening the test chamber. The results showed generally lower IR values as compared to those taken prior to the LOCA steam exposure.

The Group 4 specimens were then removed from the test chamber and a post-LOCA inspection was performed. The nuclear grade Raychem splices were cut off on both ends of the specimens, after which acceptable IR measurements were obtained for four of the five cable specimens in Group 4. This indicated that the performance problems observed during the steam exposure were caused by problems in the splices and not the cables. Disassembly, inspection, and testing of the Raychem splices revealed water inside the splices. Cracks were also noted in the insulation inside the splice. It was concluded that moisture intrusion into the splices, together with the insulation faults within the splices, had contributed to the Group 4 performance anomalies. The installation of these splices on cables with cracked and embrittled jackets may not be a typical application of splices. Similar problems were observed in test sequence 1. Although custom engineered splice kits were used for this test sequence, and technicians were given additional training in the installation of 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 the 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.

One of the Group 4 specimens would not hold the full 500 volts used for IR testing even after its splices were removed. Further investigation showed that this specimen was damaged at one of the cable ties used to attach the test specimen to its test fixture. The cause of this failure was judged to be human error in handling the test specimen.

After post-LOCA inspections were completed, a voltage withstand test was conducted on each of the test specimens. In the final analysis, all cables performed acceptably except the damaged specimen.

An important conclusion from the results of this test sequence is that cable condition should be considered prior to the application of splices to cables in the field.

4.4 Test Sequence 4: Multiconductor Cables

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

The test specimens were #12 AWG, 3/C, 1,000V EPR-insulated cables with CSPE individual and outer jackets manufactured by Anaconda. The conductors were insulated with 30 mils of EPR covered with a 15-mil unbonded CSPE individual jacket and a 45-mil CSPE overall outer jacket. Also included in this test sequence were Samuel Moore cables #16 AWG, 2/C, 600V. 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 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. The pre-aging groups in this test sequence were:

- Group 1: Anaconda and Samuel Moore with no accelerated aging (control specimens)
- Group 2: Samuel Moore with accelerated aging to simulate 20 years of qualified life (84.85 hrs @ 250 °F + 25.99 Mrads)
- Group 3: Anaconda (169.20 hrs @ 302 °F + 53.60 Mrads) and Samuel Moore (169.05 hrs @ 250 °F + 51.57 Mrads) with accelerated aging to simulate 40 years of qualified life.

After accelerated aging, all cables were in good condition with no cracking evident. The LOCA conditions simulated included exposure to 150 Mrads of accident radiation followed by steam (346 °F and a pressure of 113 psig, peak conditions, as used in test sequences 1 and 3) and chemical spray. Note that in their original qualification test, Anaconda cables were qualified using a single-peak LOCA profile, while Samuel Moore cables were qualified using a double-peak LOCA profile.

Throughout the LOCA steam exposure, no abnormal observation was made for any of the test specimens.

The post-LOCA visual inspection of the Group 2 cables showed some degree of degradation to all the specimens. The multiconductor Samuel Moore specimens were still flexible and the outer jackets felt spongy to the touch. Large cracks were noted in the jackets, but the underlying insulation appeared to be in good physical condition. The CSPE individual jacket on the single conductor Samuel Moore specimens appeared torn, shriveled and dis-bonded from the insulation near the cable ends. Swelling of the insulation and jacket materials was noted for all specimens.

Visual inspection of the Group 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. The exposed portion of the individual conductor jackets appeared to be in good physical condition. The single conductor specimens appeared similar to those in Group 2, with the CSPE jacket shriveled and dis-bonded on sections that were not attached to the mandrel. The Group 3 Anaconda multiconductor specimens had multiple large cracks and ruptures in the outer jacket. Swelling was noted for all specimens.

During the post-LOCA voltage withstand test, all the Anaconda cables and the Samuel Moore specimens aged to simulate 20 years performed acceptably. However, 2 out of 3 Samuel Moore specimens aged to simulate 40 years could not hold the 2400 V test voltage on one conductor. Subsequent dissection and inspection of the two specimens revealed a single pin-hole in each of the failed conductors. These were judged to be caused by localized degradation of the insulation, which was punctured by the high test voltage applied in the voltage withstand test. The area around the pin-hole was burnt, indicative of an electric discharge. It was, therefore, concluded that the failure was due to localized degradation of the insulation, which caused the high potential test to puncture the insulation on the two failed conductors.

It should be noted that the submerged voltage withstand test is an extremely harsh, potentially destructive test that is performed during qualification testing as a means of providing additional assurance that the cables will perform acceptably during and after exposure to accident conditions, and that the cables are capable of withstanding unexpected overvoltages and electrical transients.

The data obtained related to differential swelling of jacket and insulation materials caused by moisture absorption (which could occur during a LOCA) provide evidence that 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 in this program, 3 experienced performance problems that would impact their ability to perform safety functions. Therefore, the significance of the differential swelling phenomenon depends on the materials of construction and the cable configuration.

4.5 Test Sequence 5: Bonded Jacket Cables

The objective of this test was to determine whether 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.

The following cable specimens were tested:

- Anaconda 3/C, #12 AWG, 1,000V cable: The conductors were insulated with 30 mils of EPR covered with a 15-mil unbonded CSPE individual jacket and a 45-mil CSPE overall outer jacket.

- Samuel Moore 2/C, #16 AWG, 600V cable (with shield and ground wire): The conductors were insulated with 20 mils of Dekoron (EPDM) covered with a bonded 10-mil Dekorad (CSPE) individual jacket and a 45-mil Dekorad (CSPE) overall outer jacket.

- Okonite 1/C #12 AWG, 600V cable: The conductor was insulated with 30 mils of Okonite (EPR) covered with a bonded 15 mil Okolon (CSPE) individual jacket.

There were no naturally aged cable specimens in this test sequence. The pre-aging groups included in this test sequence were:

Group 1: Specimens from Anaconda (A), Samuel Moore (S), and Okonite (O) with no pre-aging (control specimens)

Group 2: Specimens from A, S, and O with accelerated aging to simulate 20 years of qualified life (A: 84 hrs @ 302 °F + 25.69 Mrads; S: 84 hrs @ 250 °F + 25.99 Mrads; and O: 252 hrs @ 302 °F + 25.79 Mrads)

Group 3: Specimens from A, S, and O with accelerated aging to simulate 40 years of qualified life (A: 169 hrs @ 302 °F + 51.35 Mrads; S: 169 hrs @ 250 °F + 51.57 Mrads; and O: 504 hrs @ 302 °F + 51.49 Mrads)

After thermal and radiation aging, visual examination and elongation-at-break (EAB) measurements confirmed that all specimens in Group 2 were in acceptable condition. In Group 3, the Samuel Moore specimens were in good condition and moderately flexible. The Anaconda specimens appeared degraded and were somewhat stiff. The Okonite specimens were brittle (EAB value was less than 5%).

The LOCA conditions simulated included exposure to 150 Mrads of accident radiation, followed by steam (double-peak LOCA profile, as used in test sequences 1 and 3, with a test duration of 10 days) and chemical spray. This profile was chosen to envelop the original qualification test profiles used for all three cables (Anaconda cables were originally qualified using a single-peak profile).

After the LOCA irradiation, no cracking was evident in any of the Samuel Moore or Anaconda specimens. The Okonite specimens in Group 3 had several circumferential cracks in the CSPE individual jacket. Throughout the first portion of the LOCA steam exposure, which included the two transients to peak conditions, no anomalies were noted for any of the test specimens. However, immediately upon the initiation of the chemical spray (at 15 hours into the test), all Group 3 Okonite specimens showed leakage currents in the range of 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 monitoring circuit for the single-conductor Okonite specimens was incorrectly wired. This impaired the capability to monitor the leakage currents for these specimens, therefore, the exact time of failure could not be determined.

Post-LOCA examination of the specimens revealed that the Group 1 cables were in good condition. Group 2 cables showed some degree of degradation on all the specimens. The Samuel Moore cables were flexible, but small longitudinal cracks were noted in the jackets. The Anaconda specimens had multiple cracks in the outer jacket, which appeared to be due to swelling of the jacket. Also, one circumferential crack 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 along the length of the jacket. One of the specimens had split open, exposing the bare conductor underneath.

Visual inspection of Group 3 cables showed degradation on each of the specimens. The Samuel Moore specimens were still flexible, but both specimens had a large crack in the outer jacket exposing the individual conductor jackets underneath. The exposed individual jackets appeared to be in good condition. The Anaconda specimens had multiple longitudinal cracks in the outer jackets. A large circumferential crack was noted in the overall jacket of one cable, exposing the individual insulated conductor jackets underneath. All the Okonite specimens had longitudinal cracking of the composite jacket and underlying insulation that split open along the length of the cable, exposing the bare copper conductor.

After post-LOCA inspections, a voltage withstand test was conducted on each of the cable specimens. All the Samuel Moore and Anaconda cables performed acceptably. For the Okonite cables, 1 of the 2 specimens in Group 2 and all 3 specimens in Group 3 could not hold the 2400V test voltage. These cables were judged to have failed the test.

It was concluded that the failures observed in the Okonite specimens were caused by differential swelling of the bonded CSPE individual jacket and the underlying EPR insulation. Cracking was initiated in the CSPE individual jacket and propagated into the underlying EPR insulation because of the bonding. It should be noted that the Okonite pre-aging conditions used in the original qualification test were relatively severe.

It is also noted that the manufacturer qualified the 1/C bonded jacket cables on the basis of a qualification test performed on larger cables using a "similarity" rationale.

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

The following cables from four different manufacturers (Rockbestos, AIW, Samuel Moore, and Okonite) were tested in this sequence.

- Rockbestos cable insulated with 30 mils of XLPE insulation and a 45-mil Neoprene® outer jacket with the trade name "Firewall® III." This cable was of the same type as the 2/C cable used in test sequences 1 and 3.

- AIW cable insulated with 30 mils of EPR covered with a 15-mil unbonded CSPE individual jacket and a 45-mil CSPE overall outer jacket. This cable was of the same type as that used in test sequence 2.

- Samuel Moore cable insulated with 20 mils of Dekoron (EPDM) covered with a bonded 10-mil Dekorad (CSPE) individual jacket and a 45-mil Dekorad (CSPE) overall outer jacket. This cable was of the same type as that used in test sequences 4 and 5.

- Okonite cable insulated with 30 mils of Okonite (EPR) covered with a bonded 15-mil Okolon (CSPE) individual jacket. This cable was of the same type as that used in test sequence 5.

The pre-aging groups in this test sequence were:

Group 1: Rockbestos, Okonite, AIW, and Samuel Moore with no accelerated aging (control specimens).

Group 2: Rockbestos (1363 hours @ 302 °F + 77 Mrads), Okonite (756 hours @ 302 °F + 77 Mrads), AIW (252 hours @ 250 °F + 38 Mrads), and Samuel Moore (252 hours @ 250 °F + 77 Mrads) with accelerated aging to simulate 60 years of qualified life.

Subsequent to pre-aging, the visual inspections indicated that the Samuel Moore and AIW cables were in acceptable condition. The Neoprene® outer jackets on the Rockbestos specimens in Group 2 were brittle and appeared severely degraded with noticeable cracking and discoloration. The CSPE jacket on the Okonite specimens in Group 2 appeared to be in good physical condition, but circumferential hairline cracks were found in the jackets of all three preaged specimens.

The LOCA conditions simulated included exposure to either 75 (AIW only) or 150 Mrads of accident radiation followed by steam (double-peak LOCA profile, as used in test sequences 1 and 3, with peak conditions of 346 °F and a pressure of 113 psig and a duration of 10 days) and chemical spray.

During the steam exposure, performance problems were noted for all the pre-aged Okonite specimens. The fuse protecting the power supply for each of the Okonite specimens blew, indicating a short circuit in the instrumentation loop circuit. Minor leakage currents were noted for the Rockbestos specimens. No problems were noted for the AIW or the Samuel Moore specimens.

Post-LOCA visual inspection revealed that all the bonded jackets and insulation on all three pre-aged Okonite specimens were split open in major sections of the cables, completely exposing the copper conductor inside.

Visual inspection of the AIW control specimen found that the outer jacket was cracked and pulled away from the rest of the cable, caused by dimensional swelling of the jacket. Jacket degradation was also noted on the AIW specimens preaged to 60 years. The cracking noted was confined to the outer jacket; no evidence of insulation cracking could be found visually.

For Rockbestos specimens, numerous radial and longitudinal cracks were observed in the outer jacket over the entire length of the specimens. The cracking was confined to the outer jacket; no evidence of insulation cracking could be found visually. The Samuel Moore specimens appeared to be in good physical condition.

Following the post-LOCA investigation, the test specimens were subjected to a voltage withstand test. In general, all the specimens aged to 60 years exhibited a weakening of the insulation, which was manifested in the form of high leakage currents. Some specimens were unable to hold the 2400V test voltage.

These results indicate that degradation caused by 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.

4.7 Sandia Tests

4.7.1 <u>Tests on Cables</u>

In 1992, Sandia National Laboratories (SNL) conducted tests on cables manufactured by three different manufacturers, including Okonite. The tests were performed to determine the minimum insulation thickness necessary for installed cable to perform its intended function should the insulation be damaged during installation, maintenance, or other activities. Therefore, the thermal and radiation aging and LOCA testing for the cables were performed with reduced and full insulation thicknesses. The Okonite specimens tested were single-conductor, 600-volt, 12 AWG control cables insulated with EPR with a bonded Hypalon jacket (Okonite-Okolon). During LOCA testing, all 10 of the Okonite-Okolon cable samples failed. The other cables in this test program did not have bonded jackets and did not experience failures.

During this test program, the cables were first subjected to 130 megarads of radiation at the rate of 300 kilorads per hour for 433 hours and were then thermally aged at 158 °C (316 °F) for 336 hours. Based on the Arrhenius equation, accelerated thermal aging at this time and temperature is equivalent to a 40-year cable life at 69 °C (156 °F) for the jacket and 76 °C (169 °F) for the insulation. After thermal aging, through-wall cracks were noted on most of the Okonite-Okolon cables. However, the cracks did not prevent the cables from passing an insulation resistance (IR) test that was conducted in a dry environment.

After the aging and IR tests, the cables were subjected to a LOCA test. The test sequence was (1) 94 hours of testing to simulate the LOCA environment defined in Appendix A to IEEE Std. 323-1974, and (2) 146 hours at 121 °C (250 °F) for the remainder of the test. No chemical spray was used. The cables were energized by 110-volt dc power during the test with no load. One cable with full insulation thickness failed just after the test chamber conditions became saturated at 11-1/2 hours into the test. By the fifth day of the test, all the Okonite cables had failed, as indicated by blown 1-ampere fuses. The test chamber was opened on October 24, 1992, and the cables were visually inspected. The insulation and jacket on the Okonite cables had split down the length of the cable, and bare conductor was visible.

In another Sandia test, Okonite cables with bonded Hypalon jackets had failed similarly. For this test, the cables were thermally aged to the equivalent of a 40-year life at 56 °C (133 °F). One out of four Okonite-Okolon cables failed during LOCA testing. Another group of Okonite cables that had been aged to a 40-year life at 50 °C (122 °F) passed this testing.

Cables manufactured by Samuel Moore also failed during Sandia LOCA testing. These cables were Dekoron Dekorad Type 1952, two-conductor, twisted, shielded pair, 16 AWG instrument cables covered with ethylene-propylene diene monomer (a type of EPR) insulation with a bonded Hypalon jacket and an overall jacket of Hypalon. One cable in which one conductor failed had been thermally aged to a 20-year life at 55 °C (131 °F), while the other cable in which both conductors failed had been thermally aged to a 40-year life at 56 °C (133 °F). These failures were similar to the failure of the Okonite-Okolon cable in that the insulation and bonded jacket had split open. Other samples of Samuel Moore cable survived aging and accident testing under similar conditions.

These SNL test results raised questions in 1992 with respect to the environmental qualification of Okonite cables with bonded Hypalon jackets that have not been specifically qualified for service conditions exceeding 50 °C (122 °F) for 40 years. The staff reviewed the qualification data developed by the Okonite Company and noted that Okonite 2 kV cables with 0.76 mm [30 mil] bonded Hypalon jackets and 600-volt cables with unjacketed EPR insulation were previously tested. The 600-volt cables with 0.38 mm [15 mil] bonded Hypalon jackets were qualified based on the previous 2-kV and 600-volt test results. It was believed that if the unjacketed EPR insulation passed qualification testing, EPR insulation with a bonded jacket would also pass qualification testing. However, the Sandia test results indicated that Okonite cable with bonded Hypalon jackets may be susceptible to failure.

The qualification data reviewed by the staff for the Samuel Moore cables showed that cables with bonded Hypalon jackets had been previously tested by Isomedix, Inc. The tests documented qualification of the Dekoron Dekorad cable to a qualified life of 40 years at plant service conditions of 52 °C (126 °F) or less. The test results from SNL raised questions about the qualification of Samuel Moore Dekoron Dekorad Type 1952 cables when used at higher temperatures.

Other bonded-jacket cables, qualified for up to 90 °C (194 °F) applications as claimed by various vendors, may be susceptible to the same type of failures if not specifically tested in the bonded configuration. The difference in aging rates between the jacket and the insulation may be a factor in the failure of bonded-jacket cables. Therefore, qualification testing that does not use the jacketed configuration may not be representative of actual cable performance.

Depending on the application, failure of these cables could affect the performance of safety functions in nuclear power plants. The functional integrity of the cables could be affected if the cables are used inside containment, used in continuous power circuits, routed with power cables, or routed close to hot pipes.

In another test, Sandia National Laboratories also tested cables to determine the long-term aging degradation behavior of typical instrumentation and control cables used in nuclear power plants and to determine the potential for using condition monitoring for assessing residual life. The results of this testing are described in NUREG/CR-5772, "Aging, Condition Monitoring, and Loss-of-Coolant Accident (LOCA) Tests of Class 1E Electrical Cables," Volumes 1, 2, and 3. The tests were conducted on cross-linked polyolefin/poly-ethylene, ethylene propylene rubber, and miscellaneous Class 1E cable types. The test program generally followed the guidance of IEEE Std. 323-1974 and IEEE Std. 383-1974.

The test program consisted of two phases; both phases used the same test specimens. Phase 1 consisted of simultaneous thermal and radiation aging of the cables at approximately 100 °C (212 °F) and 0.10 kGy per hour (10 kilorads per hour), respectively. Three different sets of cable specimens were tested in this phase: one was aged to a nominal lifetime of 20 years, a second to 40 years, and a third to 60 years. Phase 2 was a sequential accident exposure consisting of 1100 kGy (110 megarads) of high-dose-rate irradiation at the rate of 6 kGy per hour (600 kilorads per hour) followed by a simulated exposure to LOCA steam. The test profile was similar to the one given in IEEE Std. 323-1974 for "generic" qualification. The cables were energized at 110 Vdc during the accident simulation. Insulation resistance was measured on line throughout the test. No chemical spray was used during the steam exposure, but a post-LOCA submergence test was performed on the cables that were aged to a nominal equivalent of 40 years.

Cable types that failed during the accident tests or that exhibited marginal insulation resistances were Rockbestos Firewall III, BIW Bostrad 7E, Okonite-Okolon, Samuel Moore Dekoron Dekorad Type 1952, Kerite 1977, Rockbestos RSS-6-104/LE Coaxial, and Champlain Kapton.

The Sandia National Laboratories test raised questions with respect to the environmental qualification (EQ) of certain cables that either failed or exhibited marginal insulation resistance values. The staff reviewed the test data and noted that cable types identified as Firewall III, Okonite, Dekorad, and Kapton failed during the simulated accident exposure, while BIW Bostrad, Rockbestos Coaxial, and Kerite exhibited marginal insulation resistances. It should be noted that the insulation resistance of the Rockbestos coaxial cables may be too low to meet specifications for use in General Atomics radiation monitor circuits, depending on the environment to which the cable will be exposed.

As part of the NRC-sponsored aging research program, SNL searched licensee event reports (LERs) to find LERs that might be related to cable aging. In NUREG/CR-5461, "Aging of Cables, Connections, and Electrical Penetrations Assemblies Used in Nuclear Power Plants," SNL concluded that although cables are highly reliable devices under normal plant operating conditions, with no evidence of significant increases in failure rate with aging, the performance experience with these components under actual accident conditions is small. The current LER data provide a very limited database for this purpose. The only significant data for cables subjected to design-basis events comes from EQ testing.

Depending on the application, failure of these cables during or following design-basis events could affect the performance of safety functions in nuclear power plants.

4.7.2 Conclusions on EQ Issues

Based on the results of the testing, the following conclusions can be drawn.

Accelerated Aging Techniques

> 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 during 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.

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. 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

> The data obtained related to differential swelling of jacket and insulation materials caused by moisture absorption, which could occur during a LOCA, provide evidence that 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 in this program, only 3 experienced performance problems that would impact their safety function. Therefore, the significance of the differential swelling phenomenon depends on the materials of construction and the cable configuration.

Bonded Jacket Cables

> The results of this test 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.

Extending Qualified Life

> The results indicate that degradation caused by 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.

4.8 Condition-Monitoring Tests

4.8.1 Condition-Monitoring Tests on Cables

As previously mentioned, two of the issues addressed by the research program relate to in situ condition monitoring (CM) of electric cables. Specifically, the issues being addressed were (1) identify CM techniques that can be used to effectively monitor the condition of cables in situ and (2) determine whether CM data can be used to predict accident survivability. The approach taken to address these issues was to first identify the criteria for an "ideal" CM technique. Eleven criteria were identified. With the anticipation that no single technique would meet all the criteria, promising CM techniques were reviewed and several were selected for further study. The following CM techniques were selected.

Visual Inspection

In comparison to the other CM methods, which produce quantitative results, visual inspections provide a qualitative assessment of cable condition. Cable attributes that are inspected visually include (1) color, including changes from the original color and variations along the length of cable, and the degree of sheen, (2) cracks, including crack length, direction, depth, location, and number per unit area, and (3) visible surface contamination, including any foreign material on the surface. Also, the rigidity of the cable is qualitatively determined by squeezing and gently flexing it.

Elongation-at-Break

Elongation-at-break (EAB) is a measure of a material's resistance to fracture under an applied tensile stress. It is defined as the percent increase in elongation at the time of fracture and is a well known and accepted method of measuring a polymer's condition. However, it is a destructive test that requires relatively large pieces of material. In this research program, the EAB test was used as the reference against which other CM techniques were compared.

Oxidation Induction Time

The time at which rapid oxidation of a material occurs when held at a constant, elevated test temperature in a flowing oxygen environment is termed the oxidation induction time (OITM). As a material ages, anti-oxidants added to the material during production are gradually lost, leaving the material susceptible to oxidation. By measuring the OITM and comparing it to values when the material was new, the condition of the material can be estimated.

Oxidation Induction Temperature

As with the OITM measurements, the oxidation induction temperature (OITP) is a measure of the amount of anti-oxidants remaining in a material. The test specimen is prepared in a way identical to those for OITM. However, the OITP is the temperature of the material at which rapid oxidation occurs as the test temperature is increased at a constant rate in oxygen.

Fourier Transform Infrared Spectroscopy

Fourier Transform Infrared (FTIR) Spectroscopy is a technique for analyzing the structure of molecules. The principle involves the measurement of absorbance or transmittance of infrared radiation by molecular structures, including those for polymers. As the radiation passes through a polymer, atoms absorb radiation and begin to vibrate. For a particular chemical bond, maximum vibration occurs for a specific wavelength of radiation. Therefore, by irradiating a specimen with a continuous spectrum of infrared radiation, and measuring the peaks (wavelengths) at which maximum absorbance or transmittance occurs, the chemical bonds that are vibrating may be identified from standard wavelengths that are available from the open literature. By identifying certain bonds that are known to form as the material degrades, the condition of the material can be characterized.

Compressive Modulus (Indenter)

Compressive modulus is a material property defined as the ratio of compressive stress to compressive strain below the proportional limit. As cable insulation and jacket materials age they tend to harden, which will cause the compressive modulus of the materials to increase. By monitoring this change in compressive modulus, an estimate of the degradation rate of the material can be made. To monitor changes in the compressive modulus, the Ogden Indenter Polymer Aging Monitor (Indenter) was used. This device presses a probe into the material being tested and measures the force required for the resulting displacement. These values are then used to calculate the compressive modulus of the material. The probe is controlled by a portable computer and appropriate software, which controls the travel of the probe to prevent damage to the cable.

Hardness

As a comparison to the indenter, simple hardness measurements were performed on the jacket and insulation specimens and evaluated as a potential CM technique. In theory, as the cable materials harden with age, a hardness test may be useful for correlating age degradation with changes in hardness readings. Hardness measurements are similar to the indenter measurement in that a probe is pressed against the cable and the cable surface deforms. The differences between the simple hardness measurement using a Shore Durometer and the indenter are the level of sophistication of the test and the sensitivity of the instrument in taking measurements.

Dielectric Loss

The phase angle between an applied test voltage and the total current in a circuit is known as the dielectric phase angle, and this can be measured with a signal analyzer. As the insulation on an electric cable deteriorates, it is expected that the leakage current will increase, while the capacitive current remains approximately constant. This would cause the dielectric phase angle to decrease. By monitoring the change in phase angle, the amount of deterioration can be estimated.

Insulation Resistance

Insulation resistance measurements are commonly performed to determine the current condition of cable insulation. By applying a voltage from the conductor to ground and measuring the resulting current flow, the resistance of the insulation separating them can be measured. As insulation degrades, it is expected that the insulation resistance will decrease.

Functional Performance Test

The main concern in monitoring cable condition is to determine whether degradation from service aging will affect the accident performance of the cable. Therefore, the performance of the cable during operation was evaluated as a CM technique to determine whether it provides information on the cable condition. To perform this evaluation, the test specimens were powered and loaded to simulate an actual circuit during accident testing. Changes in circuit current and leakage current were then monitored as the cable was exposed to simulated accident conditions.

Voltage Withstand

As part of the current qualification procedures, cables being qualified are subjected to a submerged voltage withstand test after accident testing. Each specimen is individually submerged in tap water at room temperature while being subjected to a test voltage of 80 Vac/mil of insulation thickness for a period of 5 minutes. As the test voltage is applied, the leakage current between the conductor and electrical ground is recorded. The resulting leakage current can be used as an indicator of insulation condition.

Each of the CM techniques was performed on the test specimens at preselected intervals during the pre-aging, accident testing, and post-LOCA testing, as appropriate. Note that the system functional tests and voltage withstand tests were associated only with the LOCA test sequence. The data were then evaluated to draw conclusions regarding the effectiveness of the technique.

4.8.2 Condition-Monitoring Test Results

One of the primary purposes of the research program for low-voltage I&C cables was to evaluate various CM methods for their effectiveness to detect degradation attributable to aging of polymers, as well as to obtain data useful for the assessment of accident survivability of installed cable systems.

In this regard, there are two ways to categorize the CM of electric cables.

(1) Assessment of the bulk properties of insulating materials, and

(2) Evaluation of the current condition of an entire installed cable system.

Research results indicate that meaningful information can be derived from testing samples of polymeric materials in controlled laboratory conditions. These methods include measurement of physical properties, chemical properties, and electrical properties. Some of these methods can be applied with some limitations for in situ assessment of installed cable systems. The biggest limitation being the “accessibility.” For example, it would not be possible to detect degradation of polymers at “hot-spots” and at localized anomalies where parts of cable systems are not readily accessible. Evaluation of localized samples of polymeric insulating materials, in situ or under controlled laboratory conditions, provides only a part of the information; it does not provide data to evaluate the condition of an entire cable system from end to end.

From a perspective of a system-level evaluation, some electrical measurement techniques are available to detect gross defects and failures and locate failure points. However, they are ineffective for detecting incipient defects prior to failures. Some of the known electrical measurement techniques and methods include insulation resistance, power factor and loss factor measurement, time domain reflectometry, and voltage withstand. Some of the emerging electrical technologies that have potential for a system-level evaluation of cable include dielectric spectroscopy, ionized gas method, and partial discharge measurement.

Based on the results of the testing, the following conclusions were drawn regarding the effectiveness of the techniques studied for monitoring cable condition.

Visual Inspection

> 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 whether further investigation of the cable condition is warranted. A significant limitation of this technique is that the cable must be visually accessible. It is suggested that visual inspection be considered for inclusion in any cable condition-monitoring program.

Elongation-at-Break

> EAB 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 was found to be a promising 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. While a small sample of cable material is needed to perform this test, the relatively small amount required should be obtainable without impacting cable performance. OITM can be used as an in situ technique.

Oxidation Induction Temperature

> 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 used as an in situ technique, but OITM is preferred at this time.

Fourier Transform Infrared Spectroscopy

> 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 age, the technical basis for the trend remains questionable.

Indenter

> The indenter was found to be a reliable device that provides 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 common cable jacket and insulation materials. Therefore, the indenter can be used as an in situ

technique for monitoring localized and accessible segments of 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 the cable insulating material is a potential concern with this technique.

Dielectric Loss (DL)

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 between an applied test voltage and the circuit current can be detected at various test frequencies that can be correlated to cable condition. This technique can be used as an in situ condition-monitoring technique. It is more effective when a ground plane is an integral element of a cable system.

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 polarization index enables the effects of temperature and humidity variations to be accounted for. This technique can be used as an in situ condition-monitoring 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 whether further condition monitoring is needed, this technique alone does not provide sufficient data to determine the condition of a cable. It is a "go - no go" type of test and may not be effective in detecting degraded conditions and impending failures. Further, functional performance testing is not considered an effective method for determining, in situ, the LOCA survivability for a particular cable.

Voltage Withstand

For a cable system to perform its intended function it must withstand the voltage in order to carry the necessary current and deliver power. Therefore, the capability of the insulating materials to withstand the circuit voltage is an indication of its dielectric performance. In order to detect defects in incipient status, applied voltages may be elevated considerably above the rated voltages of the systems; further, the equipment at either end of a cable system under test must be either disconnected or protected. Voltage withstand tests may result in unanticipated degradation of cables and could result in failures. Thus, the risks of causing either catastrophic or incipient damage to cable insulation make this an unsuitable method for assessing the LOCA survivability of low voltage electric cable in situ.

5. RISK ASSESSMENT

This section presents some previous studies related to cable environmental qualification, an estimate of the change in core damage frequency associated with I&C cable aging, and an estimate of the monetized benefit from the use of cable condition monitoring.

5.1 Review of Previous Studies

5.1.1 <u>SNL Study</u>

The SNL report NUREG/CR-5313, "Environmental Qualification (EQ)-Risk Scoping Study," includes rough estimates of the probability that a cable would fail during LOCA simulation conditions and develops certain risk perspectives. One of the important insights is that the EQ should focus on ensuring equipment operability for the first few days of accident exposure. The radioactive decay heat production rate decreases with time, resulting in operators having more time for recovery actions if failures occur after the first few days of an accident. By examining cable qualification reports (obtained without identifying the manufacturer), Sandia was able to obtain test results in which multiple samples were used and to obtain a rough estimate of 10% for a cable failure in a LOCA simulation. Sandia testing of safety-related cables also suggests this estimate for cable failures. However, the qualification test experience generally shows that the failures do not occur early in the LOCA accident simulation. Hence, they may not be risk significant. The report qualifies its conclusions by noting that, if jacket integrity is required, failure rates might be higher during the latter portions of the LOCA. Moreover, the 10% failure rate applied only to cable failures, not failures in splices or connectors.

5.1.2 <u>NRR/ANL Study</u>

The work of Tzanos and Hanan ("Identification, Characterization and Evaluation of Risk-Important Accident Scenarios related to EQ Issues," draft letter report, December 1993) at Argonne National Laboratory (ANL), performed under the auspices of NRR, was a scoping analysis of the potential risk impact of the failure of in-containment electrical components caused by a harsh environment. The study was a parametric study and did not attempt to estimate realistic failure rates in harsh environments. Because all the electrical components studied require cabling, the study can be used as a parametric study for the effects of cable failures in a harsh environment. The study, conducted for two PWRs (Surry and Sequoyah) and a BWR (Peach Bottom), was limited to core damage prevention and considered internal events only.

One of the conclusions was that the impact of harsh in-containment environment upon the core damage frequency (CDF) for PWRs is plant-dependent. For example, the effect of the harsh containment environment on sequences initiated by medium or large LOCAs and failure of hot leg recirculation are not important for Sequoyah or Surry, but may be important for plants for which hot leg recirculation is required and for which recirculation success requires opening motor-operated valves inside containment.

For Surry and Sequoyah, the important affected in-containment electrical components were the power-operated relief valves (PORVs) (and associated block valves) and the steam generator (SG) level control and detection components. If, because of the harsh environment, there was a 10% chance of failure of all the PORVs and the SG level controls, and if the human error probability for failing to control the auxiliary feedwater flow with conflicting information (or no information) on SG level is assumed to be equal to 0.1, then the increase in the CDF is 1.5E-4 per year. The frequency of very small LOCAs in the Surry and Sequoyah NUREG-1150 studies was 1.3E-2 per year. Then the frequency of very small LOCAs with failure of SG level detection and failure of the PORVs is (1.3E-2)*0.1=1.3E-3 per year. Because the PORVs are failed, the only way to remove decay heat is with the SGs; if the probability of the operator failing to control the SG level without valid SG level information is 0.1, then the contribution to the CDF is (1.3E-3)*(0.1)=1.3E-4 per year. This is the great bulk of the contribution from failure of all the PORVs and failure of SG level detection.

For Peach Bottom, only the solenoid-operated relief valves of the Automatic Depressurization System (ADS) were important. The CDF increases by about 4.0E-6 per year from a base case value of 4.5E-6 per year if there is a 10% chance of common-cause failure of the relief valves. Here, the most significant initiator is the medium break LOCA since, for smaller LOCAs, both the high pressure coolant injection (HPCI) and the reactor core isolation system (RCIC) are alternative decay heat removal paths to the use of the depressurization system. For the medium break LOCA, only the HPCI system is an alternative decay heat removal path.   Of the 4.0E-6 per year increase in CDF, the contribution of medium break LOCAs with common cause failure of the ADS valves was 2.6E-6 per year.

ANL was also tasked with gathering and evaluating existing reliability data bases, and they concluded that there was insufficient information to assess the failure rates of electrical components in a harsh environment. The Tzanos and Hanan study shows that the risk impact of a harsh in-containment environment is potentially significant.

5.1.3 BNL Study

Brookhaven National Laboratory (BNL) performed a scoping study on the effect of cable failures on plant risk (Samanta and Martinez-Guridi, Letter Report, January 2002). Because of the lack of realistic cable failure data, the results obtained were conditional on failure of the cables. Human error probabilities that could be affected by cable failures were treated parametrically, with values of the base case value and 0.1.   Surry (the individual plant examination (IPE) model) and Peach Bottom (the NUREG-1150 model) were considered.

In the Surry study, failure of containment pressure channels, if it led to operator failure to manually initiate the containment recirculation spray, had high importance. The containment pressure channel cables use two separate penetrations of the containment (there are four containment pressure channels and each containment penetration carries the cables from two containment pressure channels). The logic for actuation of the recirculation containment spray is such that three out of four of the containment pressure channels must trip in order to actuate the recirculation containment spray. If two out of four containment pressure channels fail, and if the operator error probability for failure to initiate recirculation spray is 0.1, then the CDF increases by about 2.3E-3 per year. Other sequences in the PWR were of much less importance. The Tzanos and Hanan study did not identify the sequence involving failure of the containment pressure channels because the Tzanos and Hanan study used the NUREG-1150 plant model, while the Samanta and Martinez-Guridi study used the Surry IPE model. The success assumptions are different in the two studies. The NUREG-1150 study did not need success of containment recirculation spray on small LOCAs, while the IPE study did. (In the NUREG-1150 study, heat removal through the steam generators was sufficient to prevent containment overpressure, and to prevent loss of net positive suction head for the low pressure injection system in recirculation mode, while recirculation containment spray was required to prevent these failures in the IPE.) The Samanta and Martinez-Guridi study did not identify the sequence involving failure of feed and bleed and failure of the steam generator heat removal, because the Samanta and Martinez-Guridi study considered one system at a time and did not consider simultaneous failure of two systems because of cable failures.

For the BWR, the BNL study, like the ANL study, identified common cause failure of the control cables for the relief valves in the depressurization system as important. Failure of these cables resulted in an increase in the CDF of 5.1E-5 per year. The BNL study shows that the risk associated with cable failures caused by a harsh in-containment environment can be significant.

5.2 Core Damage Frequency Estimates and Benefit Analysis

A rough estimate of the reduction in CDF and the monetized benefit of imposing a regulation requiring condition monitoring of cables and environmental monitoring of cables will be given here. In this rough estimate, the assumption will be made that such a regulation would reduce the risk from cable aging to zero, which of course maximizes the benefit. In addition, consideration of ongoing licensee voluntary activities will be considered, and a rough estimate of the benefit associated with these activities will be made. Two plants, Surry and Peach Bottom, will be considered for the benefit analysis. Limitations in the scope of the risk analysis are:

- External events are not included. Seismic events are not expected to be a large contributor. Seismically induced LOCAs have relatively small frequencies; seismically induced small-break LOCAs typically have a frequency of about 3E-6/yr, with smaller values for medium and large LOCAs. (See Buslik, Risk Considerations and Benefits Associated with GSI-191, August 8, 2001, Adams Accession No. ML0124300630). Fires could result in small-break LOCAs by, for example, a hot short that opened a pressurizer PORV or by failing reactor coolant pump seal cooling resulting in a reactor coolant pump seal LOCA in PWRs. These have not been evaluated, but are not expected to be large enough to significantly affect the results of the analysis.

- The estimates of the effect of cable aging on risk that are used in this analysis do not include the failures in connectors, terminal blocks, or electrical penetration assemblies. The estimates include only the failures of cable insulation. Connectors, terminal blocks, and electrical penetration assemblies are outside the scope of the generic issue.

- Splices are considered to be within scope but are not considered in the risk assessment. Our understanding is that if splices are properly made and care is taken not to make splices on cables degraded from aging, they will have acceptable failure probabilities. It is expected that if proper administrative procedures are followed, the potential for common mode failure of splices is small and, consequently, their contribution to the risk will be small.

- Only cable failures that lead to an increase in the CDF are considered to be a significant contributor to the risk from cable failures.

- The data used for estimating the probability of cable failures come from experiments on cables qualified to the new environmental qualification criteria (NUREG-0588, category I requirements) that require pre-aging before the LOCA simulations. It is assumed that cables qualified according to older environmental qualification criteria (DOR guidelines or NUREG-0588 Category II guidelines) are essentially equivalent to those qualified according to the newer environmental qualification criteria. There are approximately 84 plants qualified to older environmental qualification criteria.

- The cables are assumed to be in environments within the EQ envelope, even for plants in the license extension portion of operation with plant ages between 40 and 60 years.

- Okonite cables were excluded from the risk assessment.

The starting point of the analysis will be the BNL sensitivity study of Samanta and Martinez-Guridi, discussed above, but a sequence identified in the ANL study, the sequence involving failure of the steam generation level transmitters and failure of the cables to the pressurized PORV solenoid valves, will also be considered. In assessing the CDF associated with the failure of a particular set of instrumentation and control cables, one can divide the problem into three parts. In the first part, the Birnbaum importance associated with the failure of the components is calculated. In the second part, the probability of failure of the I&C cables are estimated. In the third part, the Birnbaum importance and the cable failure probabilities are combined to obtain an estimate of the contribution to the CDF from I&C cable failures, and the benefit calculations are performed.

5.2.1 Birnbaum Importance of Cable Failures

5.2.1.1 Surry

In the BNL sensitivity study (by Samanta and Martinez-Guridi) discussed earlier, the change in CDF associated with the failure of various sets of I&C cables was estimated, with human error probabilities being treated parametrically. The CDF, given a particular set of cables are failed, less the CDF given the particular set of cables are not failed, is called the Birnbaum importance of the set of cables. In calculating this Birnbaum importance, cables in redundant trains of a system are assumed failed simultaneously to obtain the conditional frequency of core damage, given the set of cables are failed. Therefore, common-mode failures of cables associated with the same system are included. The Birnbaum importance used was not a single-component Birnbaum importance; it was a Birnbaum importance for a set of components. If there were two redundant cables, A and B, then the frequency of core damage with failures of both A and B set to TRUE at the same time was calculated to obtain the conditional frequency of core damage. The contribution to the CDF of the cable failures is then the Birnbaum importance of the set of cables that are failed times the probability of common mode failure of the cables. It is assumed that if the cables in one train of a redundant system fail, the cables in the redundant trains fail with probability unity.

The above method is appropriate if one is considering only the cables in one system and considering all cable failures in the system to be common mode failures. It is therefore appropriate for the sequences identified in the BNL sensitivity study. However, the sequence (from the ANL study) involving failure of the steam generator level indicators and failure of the PORV solenoid valve cables cannot be included by the above method without generalization. The generalization of the method will be considered later, when the sequence identified in the ANL study is considered.

The analyses presented here will use the updated initiating event frequencies based, with modifications, on NUREG/CR-5750, "Rates of Initiating Events at U.S. Nuclear Power Plants:1987-1995," February 1999. The BNL sensitivity study used the initiating events from the Surry IPE, while the ANL study used the initiating event frequencies from the NUREG-1150 studies.

First, the sequence identified as most significant in the BNL study will be considered; this is the sequence involving failure of the containment pressure channels, discussed earlier. This is the only sequence from the BNL study that will be considered. The other cable failures considered in the BNL study had only a small effect. The only initiators of importance are LOCAs, including transient-induced LOCAs. As evaluated in the BNL study, these sequences consist of:

1. A LOCA (small, intermediate, or large) occurs
2. The cables associated with the containment pressure transducers fail.
3. This consequentially fails automatic initiation of recirculation containment spray.
4. The operator fails to manually initiate recirculation containment spray.
5. There is a loss of net positive suction head (NPSH) for the low and high head injection pumps in the recirculation mode, in which they take water from the containment sump and pump it into the reactor vessel.
6. Core damage follows.

For small-break LOCAs, this sequence is modified by the following considerations. The operator will, by his procedures, cool down and depressurize the reactor coolant system and use the low head injection pumps in recirculation mode. In most PWRs, the operator would place the RHR system into service. However, at Surry, the RHR system is inside containment, is not safety-grade, and is not environmentally qualified. The operator would prefer to use the safety-grade low pressure injection pumps rather than the RHR system, although there is a step in the procedures in which the operators are to consult with the shift technical advisor to see if the RHR should be placed into service. If the operator uses the low pressure injection system in recirculation mode (LPR), and the containment pressure and temperature go up, then the LPR pumps will cavitate. Low pressure pumps will not fail immediately. The operator may be alerted to cavitation of the low pressure pumps because of fluctuating motor pump current. At this point, even if confused as to the reason for the loss of NPSH, he will attempt to put the RHR system into service. That failing, he will enter emergency contingency action procedures ECA-1.1, which procedures for Surry have not been reviewed. He may switch the pumps back to the refueling water storage tank (RWST), and, when that empties, use the RWST of the other unit. He will have considerably longer to assess the need for recirculation containment spray.

The LOCA initiating event frequencies we will use are:

Small LOCAs from pipe breaks:	5E-4/yr
Stuck-open pressurizer safety valves:	1.8E-3/yr
RCP seal LOCAs in the small LOCA range:	1.0E-3/yr
Medium LOCAs:	4E-5/yr
Large LOCAs:	7E-6/yr

Of these frequencies, the frequencies for small pipe breaks and medium LOCAs came directly from NUREG/CR-5750. The frequency for stuck-open pressurizer safety valves is an update of the value given in NUREG/CR-5750. There has been only one stuck-open pressurizer safety valve in the small LOCA range in the years from 1987 through 2001. There are about 835 critical PWR reactor years in this time period. Using a Jeffreys prior (as did NUREG/CR-5750), one obtains a frequency of 1.5/T, or 1.8E-3/yr. Note that the frequency of stuck-open pressurizer safety valves includes the frequency of reactor trips in which the pressurizer safety valve sticks open after the reactor trip. In other words, it includes the frequency of what is sometimes called transient-induced stuck-open pressurizer safety valves. This is the way the data were collected for NUREG/CR-5750. If the frequency of reactor trips is reduced from the average trip frequency in the years 1987 to 2001, but the probability of a pressurizer safety valve sticking open per reactor trip is constant, then the estimated frequency of stuck-open pressurizer safety valves used (1.8E-3/yr) is overestimated from this effect.

The RCP seal LOCA frequency has been reduced from the value of 2.5E-3 per year given in NUREG/CR-5750. There have been no RCP seal LOCAs since 1980. Taking the time period from 1987 through 2001, and using a Jeffreys prior, one would estimate 0.5/835, or about 6E-4 per year for the RCP seal LOCA frequency, so 1E-3/yr is conservative with respect to this estimate. If, on the other hand, all PWR critical reactor years from 1969 to 2001 are considered, there are about 1381 reactor years, and two RCP seal LOCAs, yielding an estimate with a Jeffreys prior of 2.5/1381, or about 1.8E-3 per year. The estimate here falls somewhere in between, and takes some credit for improvement of RCP seal performance in the years since 1980. The large LOCA frequency is updated from the NUREG/CR-5750 value by the inclusion of the V.C. Summer event of 10/12/2000. LOCAs smaller than small-break LOCAs are treated as transients in the IPE. They have not been considered here. As far as the sequence involving failure of the containment pressure transmitters is concerned, the IPE success assumptions do not require recirculation containment spray for such very small LOCAs. Moreover, the environment is not expected to be sufficiently harsh for very small LOCAs for the failure of the instrumentation and control cables, at least in the early risk-significant time frame. Leakage currents in cables seem to be correlated to the pressure during simulated LOCA experiments, and decrease when the pressure (and steam density) are reduced. Hence these very small LOCAs are not considered here.

Only a rough estimate of the human error probability of the operator failing to actuate the containment recirculation sprays will be given. The LOCAs in the small-break range dominate the frequency of LOCAs. For small LOCAs, the BNL sensitivity study estimates that the operator has at least eight hours to initiate recirculation containment spray before loss of LPR pump NPSH. (This is an estimate; the IPE states that an hour is available for large LOCAs.) The operator has no procedural guidance to manually turn on the recirculation sprays in the absence of instrument read-outs telling him the pressure is 23 psia or greater. The containment pressure gages may read low because of leakage currents in the cables. A probability of 0.1 is assigned for the human error probability of failing to actuate the containment recirculation sprays before loss of LPR NPSH.

As for the probability of operator recovery actions by putting the RHR successfully into service (it may be unavailable because of maintenance, or it may fail because it is not environmentally qualified), or by other actions consistent with ECA-1.1, a 30% chance of failure for small-break LOCAs is estimated. For larger LOCAs, no credit is given for recovery if the operator has not turned on the containment recirculation sprays.

A Birnbaum importance of 1.0E-4 per year for failure of the containment pressure channels is obtained.

Now consider the contribution to the CDF from the sequences involving failure of the SG level transmitters, or failure of the PORV solenoid valve cables, or failure of both. The BNL sensitivity study cannot be used here because, as mentioned earlier, the BNL study considered only one system at a time. In addition, the fact that the operator may fail to control the auxiliary feedwater system given failure of the steam generator level transmitters seems not to have been considered in the BNL study, because there was no operator error for this event in the IPE, and only operator errors appearing in the IPE were considered in the BNL study. In addition to the use of the updated initiating event frequencies given earlier, we will also modify the success criteria for feed and bleed, over those used in the IPE (as submitted to the NRC). In the IPE model, success for feed and bleed required the operation of both pressurizer PORVs. However, the current IPE model used by the plant assumes that only one out of two PORVs is needed for success. This was the same criterion used in the NUREG-1150 study for Surry.

The human error probability has to be estimated for failure of the operator to control the auxiliary feedwater system (AFWS) when the reading of the SG level is higher than the true level. Thus, automatic control of the AFWS would result in inadequate cooling of the reactor core. The emergency response guidelines (ERGs) for Westinghouse plants, in ERG E-0, state that the operator should look at the core average temperature and, if it is above the no-load core average temperature and increasing, the operator should increase SG dump and maintain the water level in the SG within the narrow range, until the no-load temperature is reached, for the core average temperature. However, if the SG level is maintained within the narrow range, perhaps the operator will not get the desired response for the core average temperature. It is highly unlikely that all redundant SG level instrumentation will fail so that they all read consistent values. So the operator will suspect an error in the readings of the SG level instrumentation. The operator has sufficient information from the reactor core resistance temperature detectors to maintain core cooling, and not overcool the reactor. In addition, if there is indication of inadequate core cooling, such as high core exit temperatures, the operators will go to the appropriate emergency procedures (Functional Restoration guideline FR.C.1). The SNL EQ risk scoping study, NUREG/CR-5313, estimates a probability of 0.1 for the human error probability of the operator controlling the AFWS, and this value will be adopted. It may be conservative because of improved procedures.

For these sequences, an expression is needed for the increase in CDF in terms of the relevant Birnbaum importance. Define

X = the event of failure of all of the SG level transmitter cables
Y = the event of failure of the cables to both PORV solenoid valves
C = the event of core damage

Denote by fr{A|B} the frequency of event A given B.

Then the frequency of core damage may be written as:

$$fr\{C\} = fr\{C|\bar{X}\bar{Y}\}pr\{\bar{X}\bar{Y}\} + fr\{C|X\bar{Y}\}pr\{X\bar{Y}\} + fr\{C|\bar{X}Y\}pr\{\bar{X}Y\} + fr\{C|XY\}pr\{XY\} \qquad \textbf{(1)}$$

when the cable failures are considered. In the base case, where the cables do not fail, the frequency of core damage is given by

$$fr\{C|\bar{X}\bar{Y}\} \qquad \textbf{(2)}$$

since the cables do not fail in the base case so that:

$$pr\{\bar{X}\bar{Y}\} = 1 \qquad \textbf{(3)}$$

Now,

$$pr\{\overline{X}\overline{Y}\} = 1 - pr\{X\overline{Y}\} - pr\{\overline{X}Y\} - pr\{XY\} \quad \textbf{(4)}$$

Substituting Eq(4) into Eq(1), and subtracting Eq(2) from Eq(1), one finds that the increase in the CDF from the cable failures is given by

$$B(X|\overline{Y})pr\{X\overline{Y}\} + B(Y|\overline{X})pr\{\overline{X}Y\} + B(XY)pr\{XY\} \quad \textbf{(5)}$$

where the Birnbaum importances are defined by

$$B(X|\overline{Y}) = fr\{C|X\overline{Y}\} - fr\{C|\overline{X}\overline{Y}\} \quad \textbf{(6)}$$

$$B(XY) = fr\{C|XY\} - fr\{C|\overline{X}\overline{Y}\} \quad \textbf{(7)}$$

$$B(Y|\overline{X}) = fr\{C|Y\overline{X}\} - fr\{C|\overline{Y}\overline{X}\} \quad \textbf{(8)}$$

The differences in CDFs given by the Birnbaum importances arise solely from small-break LOCAs, since AFWS or feed and bleed are not required for medium or large LOCAs, and since transients do not produce a harsh environment inside containment, so the cables are presumed not to fail, especially in a common-mode fashion. Moreover, only one sequence on the small LOCA event tree is relevant, the one in which AFWS and feed and bleed fail. (In the SAPHIRE IPE model, this is sequence 10 on the small LOCA event tree.) The Birnbaum importance of Eq(6) represents the increase in the CDF from failure of the SG level cables, when the PORV cables are given not to fail. Then feed and bleed has its normal probability of failure, about 0.004 when a one out of two success criterion is used for the PORVs. This Birnbaum importance is equal to the frequency of a small-break LOCA (about 3E-3 per year) times the probability of failure of the operator to control the AFWS given loss of steam generator level indication (estimated at 0.1), times the probability of failure of feed and bleed (estimated at 0.004), when the PORV cables are given not to fail, and is about 1E-6 per year. The Birnbaum importance of Eq(8) is the increase in the CDF from failure of the PORV cables, when the SG level indicator cables are given not to fail. The AFWS then has its normal failure probability, about 7E-5 per year, and the Birnbaum importance is equal to the frequency of small break LOCAs times the normal probability of failure of the AFWS, or about 2E-7 per year. The Birnbaum importance of Eq (7) represents the increase in the CDF from simultaneous failure of the SG level indicators and the PORV solenoid cables. It is equal to the product of the small LOCA frequency and the probability of failure of the operator to control the AFWS when the SG level indication is failed (or reading incorrectly). Estimating the operator error as 0.1, this Birnbaum importance is about 3E-4 per year.

5.2.1.2 Peach Bottom

No data changes in either initiating events or component data were made from the BNL Samanta and Martinez-Guridi report in obtaining the Birnbaum importances. The BWR plant used in this report was Peach Bottom Unit 2.

The failure of control cables of the ADS and non-ADS Relief valves have a Birnbaum importance of 5.1E-5 per year, at Peach Bottom, from the BNL report by Samanta and Martinez-Guridi. (Human errors are not involved.) The failures of these cables are the only cable failures that contribute significantly to the core damage frequency.

5.2.2 Probability of Failure of Instrument and Control Cables

For estimates of the failure probability of cables, the starting point is the results of NUREG/CR-5772, as summarized in Information Notice 93-33.

The first question is whether to assume that there is a trend of increasing failure rate with cable age. Jacobus, in NUREG/CR-5772, Vol. 2, argues that, for the EPR cables tested, the difference in failure rates between cables aged to simulated lifetimes of 40 years or less and those aged to a simulated lifetime of 60 years is not statistically significant.

Combining the cables subjected to accelerated aging for 3 months (20 years equivalent service time) and the cables subjected to accelerated aging for 6 months (40 years equivalent service time), Jacobus notes that there was one failure out of 40. The point estimate (maximum likelihood estimate) of the failure probability is 1/40, or .025, as given in the Jacobus report. However, the upper confidence limit of 0.025+0.049 = 0.074 appears incorrect. From the exact binomial distribution, the upper limit should be 0.113 at a 95% upper confidence limit; the Poisson approximation gives 0.119. What Jacobus apparently did was say the upper limit was given by: $p_{point}+1.96s$, where the standard deviation s is given by $\sqrt{(np_{point})}$, and p_{point} is the maximum likelihood estimate of the failure probability, f/n, where f is the number of failures and n is the number of trials. If the normal distribution approximation were valid, this would give the 97.5% upper bound, but it is not valid here. For cables subjected to accelerated aging for 9 months (60 years equivalent service time), there were 3 failures out of 23 and the point estimate of the failure probability is 13%, with a 95% upper confidence limit of 0.304, from the exact binomial distribution (0.337 from the Poisson approximation). (The Jacobus report gave an upper (97.5%) confidence limit of 26.7%, but this was based on a normal distribution approximation, not valid here.) The Jacobus report states that the difference in failure rates between those aged to 40 years equivalent service time or less and those aged to 60 years equivalent service time is not statistically significant. Although there are erroneous approximations made in the Jacobus report, this conclusion is valid. By use of Fisher's exact test on the 2 x 2 contingency table (one row is the number of failures, the other row is the number of successes; one column refers to cables aged to 40 years or less, and the other column to cables aged to 60 years), one finds that one cannot reject the null hypothesis at the 95% confidence level, relative to the alternative hypothesis that cables aged to 60 years have a greater failure rate than the cables aged to 40 years or less. However, the null hypothesis could be rejected at the 86% confidence level. On a physical basis one expects a trend of greater failure probability at greater cable age. Cables aged longer have greater embrittlement, at least after a certain minimum aging. The fact that the null hypothesis cannot be rejected with the data at hand does not mean that with the collection of a greater amount of data the null hypothesis could not be rejected.

These estimates of failure rates will therefore be based on the 40-year equivalent service time, or less, estimates. The 60-year service time estimates are not appropriate, even for license renewal, because as part of the license renewal application the licensee must demonstrate that the cables remain within their qualification envelope.

The cable aging experiments given in NUREG/CR-5772 assumed a plant ambient temperature of 55 °C, and an activation energy of 1.15 eV. Jacobus obtained a failure (sufficient to blow a fuse) in Samuel Moore Dekorad cable at a simulated age of 20 years. However, this simulated age depends on the validity of the activation energy and plant ambient temperature assumed. From Information Notice 92-81, the Samuel Moore cables had been qualified for 40 years at plant service conditions of 52 °C. From NUREG/CR-6704, vol. 1, p. 2-11, the service pre-aging for the Samuel Moore cables consisted of 168 hours at 121 °C. This implies an activation energy of 1.22eV. Using this value of activation energy, the accelerated aging for 3 months in the SNL tests, intended to correspond to a service lifetime of 20 years, actually corresponded to a service lifetime of 39 years. It is assumed that the failure occurred after a plant age of 20 years, but at less than 40 years.

The following assumptions are made in our analysis:

1. We considered only failures to a simulated age of 40 years. In other words, the cables are assumed to be always operated within their EQ envelope. If operated to 60 years, it is assumed that the cable is operated with an insulation temperature sufficiently low so that the cable remains in its qualification envelope.

2. We did not consider Okonite. Our risk assessment is not applicable to Okonite cables. There have been failures of bonded-jacket Okonite cables when BNL tested them according to their EQ conditions. It is observed that the EQ tests were harsh, and intended to qualify the cables for a service temperature of 90 °C. However, any information available that could be used to assess the reliability of Okonite bonded-jacket cables at more realistic service temperatures was not reviewed because of lack of resources. Accordingly, the estimate of cable failure probability given should not be considered to apply to Okonite cables.

3. We did not use data on Kapton. Kapton makes up less than 1% of the cables in nuclear power plants. (See SAND96-0344, "Aging Management Guideline for Commercial Nuclear Power Plants-Electrical Cables and Terminations," Table 3-4.) Note also that some Kapton cables were damaged so that the failures were not considered valid failures.

4. We excluded coaxial cables. The instrumentation and control cables we are considering (not cables in radiation monitoring circuits) are not coaxial, and do not require the high IR values that coaxial cables do.

5. We used the criteria for low IR given in Information Notice 93-33.

6. In accordance with above remarks on the Dekoran activation energy and EQ temperature, the Dekoran failure was considered to occur at about 40 years, not 20 years. This is the only complete failure (blown fuse), given the exclusion of the cables above.

7. We observed that the BIW IR values (about 2.5E3 ohm-100m) and the Kerite low IR value (about 1E3 ohm-100m) correspond to low IR failures for instrumentation cables

but not for control cables. Hence the only relevant failure for control cables was the total failure of the Dekoran cable.

Further, note that the BIW Bostrad tests obtained IR values about an order of magnitude higher than in the Sandia tests. However, the study was insufficient to establish the reason for this. It could have been that the activation energy and EQ temperature for these cables were such that the simulated lifetime of 20 years in the SNL experiments corresponded in actuality to a much longer lifetime than 20 years. The estimate of 55 °C for the EQ temperature and 1.15eV for the activation energy used in the SNL experiments were only average values used for all cable materials.

From the data in Information Notice 93-33, with the above adjustments, a failure probability (sufficient to blow a fuse) for the cables of about 0.016 is obtained. However, the single failure that occurred, on which this estimate is based, occurred at about 222 hours after the start of the LOCA simulation. Hence, it may not be very risk significant. For risk-significant early failures, the estimate is reduced from 0.016 to 0.01. One could argue that, out of the 64 cables considered, none failed early. An estimate of one-half of a failure out of 64 trials would then give a value a bit less than 0.01.

For control cables, the only valid failure would be the complete failure discussed above, since the IR values measured would not fail control cables, according to criteria given in Information Notice 93-33 (failure corresponds to IR<2500 ohm-1000 feet for instrument cable, IR<500 ohm-1000 feet for control cables. Accordingly, 0.01 is used for the probability of failure of a control cable.

The low IR values given in Information Notice 93-33 do indeed correspond to failures for instrument cables. There were 9 low-IR failures out of 64 conductors, for an estimate of 0.14 for low-IR failures. Adding the complete failure (blown fuse) probability, one obtains an estimate of 0.15 for the failure probability of instrument cables. This value may be high. In NUREG/CR-6704, BNL reported the results of cable tests. If one confines oneself to the BNL EQ tests intended to simulate service lifetimes less than or equal to 40 years, there were no failures or leakage currents during the LOCA simulations, except for those attributable to splices or those occurring in Okonite bonded-jacket cables. The BNL tests used the accelerated aging conditions corresponding to the original qualification tests of the manufacturer. In addition, a low IR failure, according to Information Notice 93-33 criterion, may not cause enough of an instrument reading error to appreciably affect actuation set points or human error probabilities. However, in this study the concern is with failure of containment pressure indications, and pressure transmitters are sensitive to leakage currents. Also, SG level transmitters are pressure transmitters and therefore are also sensitive to leakage currents. A leakage current across a pressure transmitter will invariably lead to a pressure reading that is high compared to the true pressure. For containment pressure, this instrument error would be such as to actuate the sprays earlier than they should be actuated and, likely, would have only a negligible contribution to risk. Leakage to ground is more difficult to evaluate, and the understanding is that it could go in either direction or have a negligible effect on the instrument reading. The low IR failures will not be partitioned into "safe" failures and "unsafe failures," but this obviously introduces a conservative bias in the results.

These failure probabilities are treated as if there were complete dependence between redundant trains. That is, the conditional probability of a cable failing, given the failure of the similar cable in a redundant train, is taken as unity. This is conservative. Information Notice 92-81 notes, for example, that although some samples of Samuel Moore cable failed in the SNL testing, others survived. Thus there is not complete dependence between the failures. This also introduces a conservative bias in our results.

The probability of joint failure of a control circuit and an instrumentation circuit is needed. We are particularly interested in the probability of joint failure of the control circuit to the solenoid operators of the pressurizer PORVs and the steam generator level instrumentation, under conditions of a small-break LOCA. Results will not be too sensitive to the conditional probability of failure of the steam generator level instrumentation, given failure of the control circuits for the pressurizer PORVs, and consequently a conservative value of unity will be taken for this probability. The probability of joint failure of the pressurizer PORV control circuits and the steam generator level transmitter circuits is then 0.01.

5.2.3 Uncertainties in the Cable Failure Probability

There are a variety of uncertainties in the estimate:

- The probabilities of cable failure were obtained by a simple average over various types of cables considered by Jacobus in NUREG/CR-5772, without any regard to whether the cables could be considered as a sample from a homogeneous population. All that was done was to exclude Kapton, Okonite, and coaxial cables, as noted above. It might have been better to weight the cable failures by the prevalence of the cables in the plants, but this may not help much when considering a specific plant.

- The failure probabilities assumed the cables were just within their qualification envelope. If the cable temperature is only a few degrees less than the EQ temperature it may experience considerably less aging, and the cable failure probability will be less.

- The failure probability of a cable in one redundant train, given failure of the redundant cable in the other train, was taken as unity, which is, of course, conservative.

- The LOCA simulations used appear to be conservative in many respects. The accident radiation dose received is not appropriate for conditions before core damage. Moreover, the accident LOCA conditions simulated are conservative for small-break LOCAs, which are, because of their frequency, dominant contributors to the calculated core damage frequencies. On the other hand, the experiments reported by Jacobus in NUREG/CR-5772 did not include the effects of containment spray. (The BNL experiments did.)

As a whole, it is believed that there is a conservative bias in the results, especially for the PWR in which failures of instrument cables played an important role.

5.2.4 Benefits from Averting Accidents Associated with I&C Cable Aging (Per-Plant Basis)

This section will consider the monetized benefits associated with averting accidents associated with I&C cable aging. These benefits will be considered here on a per-plant basis, discounted to the present (year 2002). The benefits to be considered are:

  - Expected averted population dose to 50 miles, monetized at $2000/personrem (year 2002 dollars)

  - Expected averted offsite financial costs

- Expected averted onsite financial costs (cleanup and decontamination; replacement power)

- Expected averted onsite occupational dose.

The plant being considered is assumed to currently be 24 years old, with 16 years of remaining life in its current license period, and 36 years remaining if the plant license is renewed for an additional 20 years. The risk from cable aging is assumed to be zero until the plant reaches 30 years of age, and then is assumed to remain constant for the remainder of its lifetime, until age 40 or 60 years, depending on whether or not the plant license is renewed. It is true that there is some probability for failure of the cables at, say, 20 years. Sandia measured low insulation resistances in the Bostrad cables at 20 years. However, it is believed that there is a monotonic increase in the failure probability as the cables age, at least until a certain age is reached, and treating the cable failure probability as a constant between 30 and 60 years of service lifetime is an approximation. In addition, the fact that Bostrad measured an order of magnitude higher insulation resistance may mean that the activation energy of 1.15eV assumed by Sandia is sufficiently in error so that the Bostrad cables would not experience failure until a later in-plant age.

The assumption is made that the regulatory actions taken to reduce the cable aging risk, expected to include cable condition monitoring and environmental monitoring, would essentially reduce the risk associated with cable aging to zero. This is of course conservative.

Two cases are considered; in the first case, credit for voluntary industry actions is not given, while in the second case credit is given. Current industry voluntary actions are assumed to be limited to ensuring the cable environment is within the cable's EQ envelope with respect to temperature and dose, and to inspecting cables visually near their connections to a component when maintenance on that component is performed. The benefit calculations already assumed, without credit for industry actions, that the licensee would ensure the cable environment is consistent with the cable's EQ envelope. (In fact, this appears to be more a required licensee action than a voluntary action.) As for licensee voluntary actions with respect to visual inspection, this appears to have somewhat limited benefit, since (1) cable inspection would occur only near its termination at a component undergoing maintenance, (2) the inspection would be only visual, and (3) the frequency of inspection would be uncertain. The industry voluntary actions are assumed to decrease the benefits from imposition of a formal condition monitoring program by only 30%.

5.2.4.1 Surry Plant

For the population dose, the data given for Zion in Table 5.3 of NUREG/BR-0184 (Regulatory Analysis Technical Evaluation Handbook, January 1997) were used. The data for Zion in this table do not use the actual population density around the Zion site, but rather that for a site that had an 80th percentile population density. The particular values taken from Table 5.3 of NUREG/BR-0184 for Zion were for a LOCA. The calculations done for Table 5.3 of NUREG/BR-0184 were based on NUREG-1150 models. The dominant LOCA in the NUREG-1150 calculation for Zion was that which arose from a loss of component cooling water with consequential reactor coolant pump seal LOCA and loss of high pressure injection. In such a sequence, the reactor cavity is not filled at the time of vessel breach, and the radioactive source term may be larger (because of less scrubbing of the radioactive releases by the reactor cavity water) than if the failure occurred during recirculation, with more water in the reactor cavity. This is a conservative approximation, for this case. It is assumed that the probability of early containment failure was 0.02. This value was obtained by estimating the probability of early containment failure as 0.05 for a sequence in which vessel breach occurs with the reactor vessel internal pressure high (> 200 psi), and as 0.01 for a sequence in which the reactor vessel pressure at vessel breach was low (< 200 psi). A 20% chance of vessel breach at high pressure was assumed. This corresponds to the NUREG-1150 estimate for a small-break LOCA. Since small-break LOCAs are the major contributor here, this is a reasonable best estimate.

The discount rate used to convert costs in the future to present value was 7%. For averted offsite financial consequences, the Sequoyah NUREG-1150 study was used, with modifications to correct errors in the calculation of offsite financial consequences that were found by Mubayi (see NUREG/CR-4695). The CRIC-ET code (see: Letter report for FIN L1672, "NUREG-1150 Data Base Assessment Program: A Description of the Computational Risk Integration and Conditional Evaluation Tool (CRIC-ET) Software and the NUREG-1150 Data Base, prepared by T.D. Brown, J.D. Johnson, S.L. Humphreys, and J.J. Gregory, Sandia National Laboratories, March 1995) was used, with the offsite financial consequences data modified to correct for the errors in the NUREG-1150 calculation. One reason Sequoyah was used was that it was less time consuming to make the changes to the consequence data for Sequoyah than it would have been for Zion. Also, the Zion site may be atypical, if only one calculation is being performed. Again a 2% chance of early containment failure was assumed, which is conservative because of the contribution of large and medium LOCAs where the probability of early containment failure is less. The sequences chosen were LOCA sequences with failure of containment sprays, which matches this case.

For onsite financial costs, cleanup and decontamination is given on page 5.42 of NUREG/BR-0184 as $1.5E9 per accident, in 1993 dollars. At http://www.jsc.nasa.gov/bu2/inflateGDP.html the conversion factor to year 2002 dollars is 1.17. The costs were assumed to be spread over 10 years after the accident and were discounted accordingly, using a 7% discount rate. For replacement power costs, formulas for a generic reactor are given on page 5.44 of NUREG/BR-0184. These formulas are empirical, and the error in their use has not been determined. The generic reactor is a 910 MWe reactor.

The averted onsite occupational dose was calculated following the guidelines in NUREG/BR-0184. The best estimate immediate dose (per accident) is 3,300 person-rem, and the best estimate long-term dose (per accident) is 20,000 person-rem. The long-term dose is spread over a 10-year period after the accident.

A Birnbaum importance of 1.0E-4 per year was obtained for the cables associated with the containment pressure channels at Surry. This was by far the most important set of cables at Surry, using the Samanta and Martinez-Guridi report, if the operator error of failing to turn on the recirculation sprays is 0.1. Using the probability of cable failure of 0.15, one obtains a CDF of 1.5E-5 per year (without taking voluntary industry actions into account). (Note that this way of doing the calculation assumes the probability of cable failure is the same for all size LOCAs; otherwise, one would have to treat each LOCA size individually.)

Another sequence, not considered in the Samanta and Martinez-Guridi report, must be considered. In this sequence there are failures of the control cables to the solenoids of the pressurized PORVs and failures of the steam generator level transmitters. With the data being used, of the three terms in eq(5) giving the increase in CDF from failures of the steam generator level cables and the cables to the PORV solenoids, the dominant term is the one involving B(XY), which represents the increase in the CDF when both the steam generator cables and PORV cables fail, times the probability of their joint failure. Earlier B(XY) was estimated as about 3E-4 per year, and the joint probability of failure of the cables in question as 0.01. The increase in the CDF is about 3E-6 per year. The sum of the other two terms in eq(5) increase the CDF by about 2E-7 per year, and will be neglected.

Therefore, the total CDF from cable failures is about 2E-5 per year, 1.5E-5 per year from failure of the cables associated with the containment pressure transmitters, and 3E-6 per year from failure of the PORV and steam generator level transmitter cables.

The results are given in Table 1. The value of t is the number of years of reactor operation with the plant at risk for I&C cable failures from aging. The value of t = 10 years corresponds to the case of a plant without license renewal, and t = 30 years corresponds to the license renewal case. The change in CDF is 1.9E-5 per year without taking into account voluntary industry actions and is 1.3E-5 per year taking voluntary industry actions into account.

The total monetized benefit, for the case of no license renewal (t = 10 years), is $190,000 per plant, with no credit for voluntary industry actions, and it is $133,000 per plant with credit for voluntary industry actions. Of this, the contribution of averted onsite costs is $140,000 per plant for the case of no credit for voluntary industry actions, and it is $96,000 per plant for the case of credit for voluntary industry actions.

For the case of license renewal, the total monetized benefit is $500,000 per plant with no credit for voluntary industry actions and $350,000 per plant with credit for voluntary industry actions. Of this, the contribution of averted onsite costs is $410,000 per plant for the case of no credit for voluntary industry actions and $290,000 per plant if credit is given.

5.2.4.2 Peach Bottom

Here, an estimate of the contribution to the CDF from cable aging will be given for Peach Bottom, and estimates of the monetized benefits of regulatory action to reduce the cable aging risk will be given. Again, the regulatory actions are assumed to reduce the risk from cable aging to zero.

The only sequence of importance is the sequence consisting of the failure of the control cables of the ADS and non-ADS relief valves. As noted above, the Birnbaum importance of these control cables is 5.1E-5 per year. Using the estimated value of the probability of control cable failure of 0.01, one obtains a contribution to the CDF of 5E-7 per year; this is the dominant contribution. Thus, the estimate of the contribution to the CDF from failures of aged cables at Peach Bottom is about 5E-7 per year.

An estimate of the monetized benefits obtainable by reducing to zero the risk associated with cable aging will now be given for Peach Bottom. For this estimate, the population doses of an averted accident (per accident) will be taken from Table 5.4 of the regulatory analysis handbook, NUREG/BR-0184. These population doses are average doses obtained by weighting the doses for each type of accident (e.g., station blackout or anticipated transient without scram) by their base case frequencies and dividing by the total CDF. Also, the offsite property damage costs, per accident, are taken from Table 5.6 of the regulatory analysis handbook. They are again frequency-weighted property damage costs, weighted by the frequency of the accidents in the base case. Ideally, one would like to use population doses and offsite financial costs specific to the accidents averted by fixing the cable aging problem, but the resources were not available to do this. The other aspects of the analysis are similar to what was done for Surry. Again, voluntary industry actions were assumed to reduce the benefits of regulatory action by 30%. The results are given in Table 2. The change in CDF is

5E-7 per year not taking into account voluntary industry actions, and 4E-7 per year taking them into account.

The total monetized benefit, for the case of no license renewal (t = 10 years), is $22,000 per plant with no credit for voluntary industry actions and $15,000 per plant with credit for voluntary industry actions. Of this, the contribution of averted onsite costs is $3,700 per plant for the case of no credit for voluntary industry actions and $2,600 per plant for the case of credit for voluntary industry actions.

For license renewal, the total monetized benefit is $43,000 per plant with no credit for voluntary industry actions and $30,000 per plant with credit for voluntary industry actions. Of this, the contribution of averted onsite costs is $11,000 per plant for the case of no credit for voluntary industry actions and $7,700 per plant if credit is given.

5.3 Discussion of Uncertainties

The uncertainties in the probability of failure of the cables were qualitatively discussed earlier. In addition, there are uncertainties in the initiating event frequencies and in the human error probabilities. For initiating event frequencies, small-break LOCAs, including reactor coolant pump seal LOCAs and stuck open pressurizer safety/relief valves, are important in PWRs, and small-break LOCAs are also important in BWRs. An error factor of three is estimated for the initiating event frequency. The human error in the most important sequence at Surry, namely failure to actuate the recirculation containment spray, was assessed to have a mean value of 0.1. The error factor is estimated here to be 3. The point estimate of the failure of the channels of the containment pressure indications, because of cable failures, was taken as 0.15, which likely is biased high. Ignoring the uncertainty in the cable failure probability and considering only the dominant sequence from cable failures at Surry, then the three error factors of 3 combine to an error factor of 6.7, assuming the individual probabilities are lognormally distributed. Including the error in the cable failure probability, one would get perhaps an error factor of 9 if the likely bias high of our point estimate of the cable failure probability is ignored. For a mean value of 2E-5 per year for the CDF and an error factor of 9, a median value of 8E-6 per year is obtained, with a 95% upper confidence limit of 7E-5 per year for the contribution of cable failures to the CDF at Surry. All distributions are assumed to be lognormal. (The CDF is assumed constant for plant ages between 30 and 60 years.)

No estimate of uncertainty was made for Peach Bottom. The estimates of benefits obtained were rather small, and there could be a conservative bias because NUREG/CR-5750 initiating event frequencies were not used.

There are uncertainties arising from plant-specific differences. For PWRs, it is likely that the sequence consisting of failure of the containment pressure transmitter cables on a LOCA, followed by failure of the operator to manually start the recirculation containment spray pumps, has a frequency that is more or less representative, or conservative with respect to other PWRs. This particular sequence would apply to only a few plants. However, a sequence in which a LOCA occurs, some instrumentation circuitry fails, and the operator fails to recover could be more or less representative for many plants. Therefore, for PWRs, the CDF obtained may be more or less representative, or perhaps high, compared to other PWRs. The representativeness of Peach Bottom as a surrogate for other BWRs was not investigated.

5.4 Summary of the Risk Assessment and Benefits Section

If the CDF associated with cable failures were reduced to zero, then, for the PWR studied (Surry), the CDF would be reduced by about 2E-5 per year; and for the BWR studied (Peach Bottom), the CDF would be reduced by about 5E-7 per year. These changes in CDF would be reduced by 30% if credit for voluntary industry initiatives were given. The monetized benefits are given in Tables 1 and 2. The monetized benefits from requiring measures (such as condition monitoring) to reduce the contribution to the CDF of cable failures appear to be relatively modest. It is to be remembered that the analysis assumed that the cables were always operated within their EQ envelope, and that cables qualified to the old EQ requirements (DOR guidelines or NUREG-0588 Category II guidelines) behaved the same as cables qualified to the new EQ guidelines (NUREG-0588, Category I requirements). For example, even if the old EQ requirements did not require pre-aging before LOCA simulation, it was assumed that pre-aging was done in practice.

Table 1. BENEFITS FROM AVERTING ACCIDENTS FROM FAILURE OF AGED I&C CABLES--Surry Plant (Benefits on per-plant basis)

A. WITHOUT CREDIT FOR VOLUNTARY INDUSTRY ACTIONS

Core Damage Frequency = 1.9E-5 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
10	4.38E+04	6.43E+03	1.37E+05	3.18E+03	1.90E+05
20	6.56E+04	9.62E+03	2.86E+05	4.77E+03	3.66E+05
30	7.64E+04	1.12E+04	4.11E+05	5.55E+03	5.04E+05

B. WITH CREDIT FOR VOLUNTARY INDUSTRY ACTIONS

Core Damage Frequency = 1.3E-5 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
10	3.07E+04	4.50E+03	9.59E+04	2.23E+03	1.33E+05
20	4.59E+04	6.73E+03	2.00E+05	3.34E+03	2.56E+05
30	5.35E+04	7.84E+03	2.88E+05	3.88E+03	3.53E+05

Key:

t = Number of years of reactor operation for benefit calculation
OffHealth = Expected averted monetized offsite health costs
OffProp = Expected averted offsite property costs
OnProp = Expected averted onsite property costs (cleanup and decontamination, replacement power)
OnDose = Expected averted onsite occupational dose costs

TotalCost = Expected total averted costs
(All costs are in 2002 dollars and are discounted to year 2002.)

Table 2. BENEFITS FROM AVERTING ACCIDENTS FROM FAILURE OF AGED I&C CABLES-- Peach Bottom (Benefits on per-plant basis)

A. WITHOUT CREDIT FOR VOLUNTARY INDUSTRY ACTIONS

Core Damage Frequency = 5.1E-7 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
10	9.64E+03	8.36E+03	3.66E+03	8.52E+01	2.17E+04
20	1.44E+04	1.25E+04	7.65E+03	1.28E+02	3.47E+04
30	1.68E+04	1.46E+04	1.10E+04	1.49E+02	4.25E+04

B. WITH CREDIT FOR VOLUNTARY INDUSTRY ACTIONS

Core Damage Frequency = 3.6E-7 per year

t	OffHealth	OffProp	OnProp	OnDose	TotalCost
10	6.75E+03	5.85E+03	2.56E+03	5.96E+01	1.52E+04
20	1.01E+04	8.75E+03	5.36E+03	8.96E+01	2.43E+04
30	1.18E+04	1.02E+04	7.70E+03	1.04E+02	2.97E+04

Key:

t = Number of years of reactor operation for benefit calculation
OffHealth = Expected Averted Monetized Offsite Health Costs
OffProp = Expected Averted Offsite Property Costs
OnProp = Expected Averted Onsite Property Costs (cleanup and decontamination, replacement power)
OnDose = Expected Averted Onsite Occupational Dose Costs
TotalCost = Expected Total Averted Costs
(All costs are in 2002 dollars, and are discounted to year 2002.)

6. TECHNICAL ASSESSMENT OF GSI-168

One of the initial steps in the research program was to review information already available to avoid duplications and unnecessary research. In April 1996, the NRC issued a two-volume technical report, NUREG/CR-6384, "Literature Review of Environmental Qualification of Safety-Related Cables," which documented past and on-going EQ research on safety-related cables. The report identified seven major technical issues related to EQ. These seven major issues were broken down into 43 sub-issues. Of the 43 sub-issues, 19 were considered unresolved (see Section 1). Public meetings were held to discuss the results of the literature review. A consensus was reached among the staff and the EQ experts that only six technical issues needed further review (see Section 3). Discussion of these issues is covered in Section 6.1 below.

The research approach consisted of (a) identification of the most popular in-containment cables currently used in U.S. nuclear power plants (Approximately 89% of the currently operating plants had cables with XLPE insulation in containment, and approximately 73% had cables with EPR insulation; these two cable types constituted 77% of cables used in a nuclear power plant), (b) acquisition of naturally aged cables; (c) pre-aging and LOCA testing, and (d) evaluation of condition-monitoring techniques. In all, six LOCA tests were performed and different condition-monitoring techniques were evaluated (Section 4).

The overall technical assessment of GSI-168 on EQ of low-voltage I&C cables is based on the results of LOCA tests and the evaluation of condition-monitoring techniques. The overall technical assessment is primarily based on a deterministic approach. Risk assessment is discussed in Section 5.

6.1 Technical Assessment

Six issues were considered and their research results are presented here.

6.1.1 Issue 1: *How do the properties of cables subjected to the accelerated aging techniques used in the original qualification compare with the properties of naturally aged cables of equivalent age?*

A comparison was made between naturally aged cables and artificially aged cables to determine the acceptability of currently accepted aging models, namely the use of Arrhenius methodology for thermal aging. The research results showed that the naturally aged cables, when subjected to equivalent years of service life conditions in terms of thermal and radiation environment, performed better than the artificially aged cables. The research results conclude that the artificial aging parameters used in past qualification tests conservatively simulate the assumed service conditions to which the cables were qualified. The data obtained suggest that the accelerated aging predictions using the Arrhenius model (in spite of its limitations) for thermal aging and the equal-dose/equal-damage model for radiation aging provide adequate estimates of the degradation experienced during actual service aging.

In a separate study on "The Acceptability of the Arrhenius Methodology for Environmental Qualification (EQ) for LOCA and Post-LOCA Environments" (ADAMS Accession Number ML003701987), the staff made the following conclusions that are relevant to the technical assessment of this issue.

1. The Arrhenius methodology has been shown to be a valid means of modeling temperature effects and for evaluating thermal degradation of polymers, with some limitations. These limitations include: (i) Arrhenius methodology is acceptable when the thermal degradation of the polymer involved is dominated by a single reaction within the temperature range of interest, and (ii) Arrhenius methodology can be used to evaluate the effects of varying temperature conditions provided it is based on the principle of cumulative damage to the polymers involved.

2. In the opinion of the EQ experts, adequate technical basis exists to justify the application of Arrhenius methodology for integrated time-temperature equivalent analysis.

In view of the above observations and conclusions, the staff considers the issue of uncertainties associated with accelerated aging methodology from an EQ perspective for low-voltage I&C cables is appropriately addressed in the current regulation, regulatory guides, and national consensus standards. Therefore, the issue is considered resolved.

6.1.2 Issue 2: *What are the limitations in using an estimated value of the activation energy to predict the chemical degradation during thermal aging?*

A key input to the Arrhenius model for thermal aging is the activation energy of the material involved. There are uncertainties in the activation energies for various materials, and it has been shown that the predicted qualified life of a cable changes significantly with a small variation in activation energy. An issue addressed by the research program was to determine whether activation energies used in past qualification tests to predict qualified life were reasonable.

The research test results showed that, for both XLPE and EPR types of 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 materials, 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 insulating 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 EPR insulated cables. Thus, testing done in the research program confirmed that the activation energies for the XLPE and EPR materials used in the original qualification tests are representative of the materials evaluated in the tests.

In view of the above observations and conclusions, the staff considers the issue of uncertainty associated with activation energies from an EQ perspective for low-voltage I&C cables that utilize XLPE and EPR types of insulation is appropriately addressed. Other types of insulation were not studied in this program. As stated earlier, cables with XLPE and EPR types of insulation are widely used in nuclear power plants. Therefore, it can be concluded that the manufacturers have used reasonable activation energies in past qualification tests.

Therefore, the issue is considered resolved.

6.1.3 Issue 3: ***Do multiconductor cables have different failure mechanisms than single-conductor cables? If so, are these failure mechanisms accounted for in the qualification process?***

An issue addressed in the research programs is whether multi-conductor cables have any unique failure mechanism compared to single conductor cables. Each cable was tested in both the multiconductor and single conductor configuration. After accelerated aging, all cables were observed to be in good condition. Throughout the LOCA steam exposure, no abnormal observations were made. However, two out of three cables failed during the post-LOCA Simulation Test. These were Samuel Moore multi-conductor cables, pre-aged to the equivalent of 40 years of service life.

During the post-LOCA Simulation test, the specimens failed a voltage withstand test at a voltage lower than 2400 V AC. Subsequent postmortem examination revealed the following:

> (i) There was no general degradation of the insulation (normally attributable to thermal and radiation aging) along the length of the cable specimens.
>
> (ii) No unique failure mechanism was observed between the single-conductor and multi-conductor cables.

In view of the above-mentioned test results and conclusions, the staff considers that the issue of a unique failure mechanism for multi-conductor vs. single conductor low-voltage I&C cables is resolved in the context of GSI-168.

However, failure of Samuel Moore cables warrants further discussions (See Section 6.2). This is not the first time that the Samuel Moore cables failed during a LOCA test. As discussed earlier, these cables also failed to meet the pre-established acceptance criteria in Sandia tests (see Section 4.7).

6.1.4 Issue 4: ***Do cables with bonded jackets have different failure mechanisms than cables with unbonded jackets? If so, are these failure mechanisms accounted for in the qualification process?***

An issue that was addressed in LOCA test 5 was whether bonded jacket cables have any different failure mechanisms than unbonded jacket cables. If so, are these unique mechanisms properly accounted for in the qualification process?

As discussed in Section 4, the Samuel Moore and Anaconda specimens performed acceptably during pre-aging and during the LOCA test 5. However, the Okonite specimens experienced significant degradation during the pre-aging process and catastrophic failures during the LOCA test.

Based on the review and analysis of original qualification test reports, significant variations were noted in the thermal aging parameters between types of cables manufactured by different vendors.

> (i) Okonite cables are rated at 194 °F (90 °C) for 40 years of operation. They were pre-aged at 302 °F (150 °C) for 504 hours. Activation energy--1.44 eV.

(ii) Anaconda cables are rated at 156 °F (69 °C) for 40 years of operation. They were pre-aged at 302 °F (150 °C) for 169 hours. Activation energy--1.18 eV.

(iii) Samuel Moore cables are rated at 136 °F (58 °C) for 40 years of operation. They were pre-aged at 250 °F (121 °C) for 169 hours. Activation energy--1.36 eV.

From the comparison of the above-mentioned aging parameters, it is noted that Okonite specimens received significantly more severe thermal aging than the other specimens. The differences were primarily due to the activation energies used and the specified rated temperatures for 40 years of service life. These cables were retested by Okonite and the test results are discussed below.

The generic implication of failures of single conductor bonded Okonite Cables is discussed later in this section.

In tests, the Okonite cables were tested in accordance with Okonite report NQRN-1A. It should be noted that the Okonite Company did not test single conductor bonded cables and that the cables were declared qualified based on a similarity rationale (similar materials but different configuration).

The test results caused the qualification basis for Okonite bonded-jacket cables to be reviewed.

In December 2001, the Okonite Company performed LOCA tests to reevaluate the rated temperature for their single conductor bonded-jacket cables. A test report, NEQ 46120-1 (ADAMS Accession Number ML020320170), was submitted to the staff in January 2002. In these new tests, an activation energy of 1.24 eV was used (as opposed to 1.44 eV used in the original qualification). It should be noted that the test report NQRN-1A does not explicitly state this number. However, this activation energy value was calculated by the staff based on the information contained in the report. Okonite provided technical justification for using an activation energy of 1.24 eV (Okonite letter to Satish Aggarwal dated January 25, 2002 (ADAMS Accession NumberML020320170). In the Okonite tests, test specimens with less severe thermal aging (up to 225 hours at 150 °C and 200 Mrad, and 300 hours at 150 °C and 100 Mrad) completed the test program (all failed except one most severally thermally aged specimen). These conditions translate to 75 °C and 77 °C, respectively, for 40 years of service life. If these cables are used in plants in which the service conditions for 40 years of operation exceed 77 °C, these cables must be replaced prior to 40 years of service life.

A request was also made to NEI to address, as an industry initiative, the failures of Okonite cables. NEI conducted a survey of plants on the use of Okonite-Okolon single conductor cables in the context of applications in environment exceeding 60 °C. NEI survey results revealed that, except for four plants, the service conditions for these cables do not exceed 60 °C.

Based on the above, the staff concluded that the failure of Okonite cables does not warrant any further regulatory action. The Okonite Company is expected to reissue their test report, NQRN-1A (with the new test report NEQ 46120-1), to all appropriate licensees.

6.1.5 Issue 5: *Are there any effective condition-monitoring techniques for determining cable condition in situ?*

6.1.6 Issue 6. *Can condition-monitoring techniques be used to predict LOCA survivability?*

These two technical issues 5 and 6 are closely related; therefore, they are discussed together.

Based on the overall evaluation and analysis of various condition monitoring methods, it is concluded that:

> (i) Several condition-monitoring methods are effective for evaluating properties of bulk insulating materials. These evaluations are possible with certain limitations for in situ measurements. Examples are EAB, OITM, Indenter.
>
> (ii) Several electrical measurement techniques that are useful to detect and locate gross defects and failures in installed cable systems are: Time Domain Reflectometry (TDR) and dielectric loss/power factor (DL/PF) measurements.

No single condition-monitoring technique is non-intrusive and effective to detect degradation in incipient states prior to failures of installed cable systems. A combination of condition-monitoring techniques could be used for assuring that the cables will perform their intended functions during normal operation and LOCA conditions.

With regard to the effectiveness of the various condition-monitoring methods evaluated in the research program to predict LOCA survivability, with regard to various condition indicator parameters (CIP) over time will have to be used for predicting LOCA survivability of installed cable systems. Data on CIPs related to physical properties and electrical properties of various segments of the installed cable systems will be needed in conjunction with suitable predictive models. Then, based on the research results, it is possible to determine residual life of the insulating materials involved and predict their LOCA survivability.

Assuming that the operational environments are known and that one is able to time-trend the CIPs such as dielectric loss/power factor, elongation-at-break, or oxidation induction time/temperature, in conjunction with the data gathered in the research program for 20, 40, and 60 years of service life, condition-monitoring methods could be used to predict LOCA survivability of XLPE and EPR types of low-voltage I&C cables. As stated earlier, the research program was limited to widely used representative samples of cables.

In view of the above, the staff concludes that, while condition-monitoring methods may be viable at their current level of development, application-specific demonstrations are needed to ensure that the techniques can predict LOCA survivability.

As stated earlier, although a single reliable condition-monitoring technique does not exist, walkdowns to look for any visible signs of anomalies attributable to cable aging, coupled with the monitoring of operating environments, have proven to be effective and useful.

6.2 Review Questions and Interaction with Nuclear Industry

During 2000-2001, the staff met several times with the nuclear industry to discuss the NRC test results. During these meetings, four specific questions were raised by the staff, based on their review of the LOCA tests. Subsequent to these meetings, the staff raised three additional questions. IEEE and NEI both provided their written responses. A summary of these responses, including staff responses, to these seven questions follows.

Question 1. Need for Monitoring Plant Environments and Condition Monitoring

Question: (a) For maintaining qualification throughout the qualified life of safety-related I&C cables, should the licensees provide information on how the environments are monitored to detect localized hot-spots and to ensure that the original test conditions are not exceeded in operating nuclear power plants?

(b) Is it prudent to perform some kind of condition monitoring of I&C cables that may include walkdowns to look for any visible signs of anomalies attributable to cable aging?

(c) What are the industry initiatives?

<u>Basis for Question 1</u>: The overall EQ process provides reasonable assurance that, when qualified in accordance with the NRC regulations, cables will perform their intended safety function during their qualified life. Specifically, 10 CFR 50.49(e)(5) contains provisions for aging that require, in part, consideration of all significant types of aging degradation that can affect the component's functional capability. Compliance with 10 CFR 50.49 provides reasonable assurance that the cables will perform their intended function during accident conditions after exposure to the effects of service aging.

Licensees are expected to provide assurance that safety-related equipment will perform its intended function throughout its installed life and operating environmental conditions will not exceed those assumed during the original qualification. It was expected that licensees would monitor environments (temperature and radiation) in operating plants, at least in certain areas, so that they know where the "hot-spots" are. Licensees were encouraged to consider surveillance, testing, and maintenance (see Revision 1 of Regulatory Guide 1.89, "Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants"). The qualification of safety-related equipment must be maintained throughout the service life.

Inspection, surveillance, condition monitoring, and trending of selected parameters for any installed safety-related cable system can potentially increase knowledge regarding aging effects and confidence in cable-system reliability and performance.

IEEE Response: Plant operators determine their environmental conditions in a number of ways. The starting point is conservative design (temperature and radiation). Information is also obtained from existing plant instrumentation or use of additional monitoring devices.

Implementation is (1) system walkdowns, (2) evaluation of cable conditions during maintenance and calibrations, and (3) one-time or ongoing inspections to address cable aging.

I&C cables have not experienced any significant aging. These cables are subjected to environments well within their qualification. In limited cases where the installed cables see harsh environments (hot-spots, if they exist, are at the process end device), based on economics, several options are exercised (early replacements, modification of environments, or some form of condition monitoring).

The nuclear industry continues to advance the state of the art in cable condition monitoring from the simplest techniques through the most sophisticated.

Industry Response: Compliance with NRC regulations and ongoing licensee practices for the establishment and maintenance of equipment qualification programs provide reasonable assurance of performance of safety-related cables under postulated accident conditions. NRC inspections and NRC review of license renewal applications adequately support this finding.

Aging evaluations are ongoing throughout the plant life. When unexpected adverse conditions are identified, the affected electric equipment, including cables, is evaluated and appropriate corrective actions are taken.

Monitoring or inspection of environmental conditions or component parameters may be used to ensure that the component is within the bounds of its qualification basis.

Fundamentally, the combination of licensee-specific activities and industry-supported activities supports a conclusion that there is a high level of confidence that installed safety-related cables remain qualified to perform their design functions in the event of an accident.

Licensees do not make splices if the jackets of the cables are found cracked.

Staff Response: In most cases, I&C cables are subjected to environments well within their qualification parameters. Where the installed cables experience harsh environments and become known to the inspection and maintenance personnel, licensees exercise several options (early replacements, modification of environments, or some form of condition monitoring). The staff notes that the industry recognizes the need for monitoring or inspection of environments. However, the staff does not have knowledge of current practices at each nuclear power plant.

The qualification criterion is “zero” failures, based on testing of a single prototype. Because of the failures of some I&C cables in the NRC tests, the original qualification bases have been challenged. In light of these failures, knowledge of plant environments becomes critical to ensure that the cables are within the bounds of their qualification basis.

Although a single reliable condition-monitoring technique does not exist, walkdowns to look for any visible signs of anomalies attributable to cable aging, coupled with monitoring operating environments, have proven to be effective and useful.

Question 2: Testing of a Single Prototype

Question: Should the IEEE standards be revised to require testing of multiple specimens?

Basis for Question 2: Based on IEEE standards, single prototype testing has been used for many applications and will almost certainly be used in future applications. However, based on recent research results, the use of a single cable specimen for environmental qualification warranted further discussion with the nuclear industry.

The analysis of test failures into random and common-mode categories is significantly enhanced by testing multiple specimens. If one of these specimens fails but the others perform throughout the program, the justification that the failure was random becomes significantly more sound.

IEEE Response: The cost of testing multiple specimens is prohibitive. IEEE has chosen the alternative route of overtesting a single prototype during the accident exposure through use of qualification margins.

Overtesting assures that if one specimen passes an environmental qualification test, then all like specimens will function through an actual accident.

For cables, a small segment of cable can represent any or all of the cable of the same type in a qualification program. An IEEE standard requires a minimum of 10 feet of cable in a specimen.

Revision of IEEE standards is not warranted at this time.

Industry Response: IEEE methodology relies on conservatism and was not intended to develop statistical confidence levels. Pragmatically, there is little or no difference in the level of confidence achieved by testing a single 30-foot specimen or cutting a cable into three 10-foot specimens and testing all three specimens. Consequently, it is reasonable to conclude that little additional confidence would be achieved by testing multiple specimens from the same source cable.

The IEEE methodology achieves adequate assurance that safety-related cables will function during realistic design basis accidents by relying on margins and conservatism in test conditions and performance requirements.

Staff Response: The staff reaffirms that the requirement of testing a single prototype in a qualification program is adequate. No change related to the number of our specimens required is recommended for IEEE standards.

Question 3. Post-LOCA Simulation Test

Question: What are the technical bases for this post-LOCA Simulation test? Should this requirement be changed in IEEE Std. 383?

<u>Basis for Question 3:</u> IEEE Std. 383 requires a submerged voltage-withstand test (80V/mil ac or 240V/mil dc) for 5 minutes. This is a post-LOCA test. For a 30-mil thickness, the test voltage is 2400V. According to IEEE Std. 383-1974, the post-LOCA simulation test demonstrates an adequate margin of safety. Several test specimens that were pre-aged to 40 and 60 years of equivalent service life in NRC tests failed the submerged voltage-withstand test (some cables failed voltage-withstand tests at a significantly lower voltage than 2400 V). What is the significance of failures of Samuel Moore cables in Sandia and NRC post-LOCA submerged voltage-withstand tests?

IEEE Response: The post-LOCA test, as stated in IEEE Std. 383-1974, demonstrates a margin of safety. The test has been designed to ensure that cables will remain functional during post-accident conditions.

The current IEEE requirement is appropriate.

Industry Response: Failures during the post-LOCA portion should not bring into question the adequacy of the cables. This test is a margin requirement. The post-LOCA test provision of IEEE Std. 383 is not required to achieve compliance with NRC regulations.

These failures (1) are not safety significant, (2) do not bring into question the qualification of the Samuel Moore cables, (3) do not have generic implications, and (4) are not a basis for changes in industry qualification practices.

The NRC test program was more severe and may account for the failures. Both programs (used originally by the manufacturer and the NRC) used too high a post-LOCA test voltage. Both programs also subjected the cable samples to two transients during the LOCA simulation (one transient would have been sufficient).

Staff Response: The staff agrees that the post-LOCA test demonstrates a margin of safety and a successful test provides reasonable assurance that the safety-related cables will be functional during the post-accident conditions.

The staff believes that the NRC test was a representative test since it was based on (i) testing of a single prototype and (ii) the original qualification parameters used by the manufacturers.

In IEEE Std. 383, IEEE chose to prove that the cables had resilience following the LOCA test. That is, the insulation wall was still flexible and did not have cracks or punctures. To do this, IEEE implemented a mandrel bend test to indicate flexibility remained and a go/no-go voltage withstand test to prove that the insulation wall was sound over the complete length. Because low-voltage cable has a large thickness of insulation for mechanical purposes, if the wall is continuous and has flexibility, function is assured for a significant duration through this test. The electrical test did not evaluate the dielectric characteristics of the insulation. Rather, it proved that a certain minimum wall thickness was still in place. The test does not evaluate insulation resistance or impedance at operating voltages and provides no information about the capability of the insulation to support normal function beyond proving that there is an adequate wall of insulation in place. It proves that the insulation is in place and has no cracks that could cause shorting should conducting materials enter and cause a bridge to surrounding conductors or metals. The successful test proves that the cables are “robust” in design, in spite of all uncertainties in the qualification process, such as testing of single prototype, manufacturing variations, etc.

IEEE has reaffirmed that this test is needed and there are no plans to change this requirement. The original qualification criteria is “zero” failure based on testing of a single prototype. Since the cables failed in post-LOCA simulation test, the original qualification bases have been challenged. Therefore, knowledge of the degradation of cables becomes critical during the service life. Knowledge of the environments is essential to establish that the operating environments do not exceed the qualification parameters assumed during the qualification. As stated earlier, walkdowns to look for any visible signs of anomalies attributable to cable aging coupled with the monitoring of operating environments have proven to be effective and useful.

In a general response, the industry stated that the aging evaluations are ongoing throughout the plant life. When unexpected adverse conditions are identified, the condition of the affected cables is evaluated and appropriate corrective actions are taken. However, the staff does not have knowledge of current practices at each nuclear power plant.

Question 4. Testing of I&C cables for 60 years of service life

Question: (a) Should cable aging be addressed as part of an aging management program for detecting aging degradation of safety-related I&C cables for 60 years of service life?

(b) How do we ensure that the service environmental conditions will not exceed the environmental conditions assumed in the analysis for demonstrating requalification to 60 years of service life?

<u>Basis for Question 4:</u>

If one uses the Arrhenius equation to calculate thermal aging conditions, the ratio of accelerated aging time to simulated service time remains constant as long as there is no change in activation energy, aging temperature, and service temperature. Therefore, one can clearly obtain the 60-year aging time by multiplying the 40-year aging time by 1.5. This was the technical basis for choosing 60-year accelerated aging time in the NRC tests. Of the 12 cables pre-aged to 60 years and tested, eight experienced failures during the post-LOCA submerged voltage withstand test. The results indicate that some low-voltage I&C cables may not have sufficient margins beyond the 40 years of their qualified life. If the service environmental conditions are assumed to be those used in the original qualification, then these cables may not perform their intended functions at the end of the 60 year service life, and subjected to LOCA conditions. Many I&C cables, at their existing ratings, may not have sufficient margins for 60 years of their service life.

If the service environmental conditions in operating nuclear power plants are lower than those assumed in the original qualification, then it is expected that the I&C cables would perform their intended safety functions. One of the options under the current license renewal rule permits extending qualified life based on the facts that the service environments are lower than those assumed in the original qualification of the I&C cables.

IEEE Response: The EQ program is an aging management program for I&C cables in containment.

Use of cables with high temperature/radiation capabilities or having cables within cool normal plant conditions may postpone (or even eliminate) the need for a cable management program.

Industry Response: The 60-year simulated aging conditions in NRC tests were overly severe. The fact that some of these 150%-aged cables failed a post-LOCA voltage withstand test is neither surprising nor unexpected.

The failures occurred at the voltage levels from 500 V ac to 1500V ac. These voltages substantially exceed typical I&C circuit operating voltages.

The failures in the NRC tests have no safety significance.

Licensees will maintain the current licensing basis during the renewal period. During the review of license renewal applications, the staff has concluded that licensee activities are supportive of establishing and maintaining I&C cable qualification during the renewal period. The activities described by these licensees are representative of practices throughout the industry.

I&C cables are not continually operated at or near the limiting service conditions used to establish their qualified life during 40 years. The qualified life of virtually all I&C cables can be extended into the renewal period by simply reanalyzing existing qualification information.

For the I&C cables, the ambient temperatures at most cable locations, including hot spots, are substantially below the 60-year limiting operating temperature. Adequate margin will continue to exist during the renewal period.

Staff Response: Licensees are required to continue to maintain qualification during the license renewal term, as during the 40-year term.

If the NRC test was successful, no further action would be necessary for license renewal. Since the test failed, it can be concluded that these cables cannot be operated at qualification temperatures for 60 years. If the operating conditions are lower than the qualification temperatures, the margin could be used to extend the life of the cable. Knowledge of the environments continues to be critical to ensure the operating environments do not exceed the qualification parameters for license renewal.

As stated earlier, walkdowns to look for any visible signs of anomalies attributable to cable aging coupled with the monitoring of operating environments have proven to be effective and useful.

Question 5: Failures of Samuel Moore Cables

See Question 3 above.

Question 6: Failures of Cables in Sixty Year-Aged Test

See Question 4 above.

Question 7: Bonded Jacket Cables: Generic Implication

Question: Are there any generic implications of failures of Okonite single-conductor bonded cables?

Industry Response: The root cause of the qualification problem with Okonite single-conductor bonded cables is the lack of qualification testing for a representative bonded jacket cable construction.

The other manufacturers of similar EPR-Hypalon bonded jacket cable styles tested the cables in appropriate configurations.

If licensees utilize other bonded jacket styles, they should either establish qualification based on testing that uses a representative bonded jacketed configuration or establish aging limits, that would preclude a similar bonded jacket failure mechanism.

Staff Response: The staff notes that the qualification temperature of 90 °C of Okonite single conductor bonded cables is not supported by recent tests performed by Okonite for 40 years of service life.

The staff agrees that if licensees utilize other bonded jacket styles (whether they are single conductor or multi-conductors), they should either establish qualification based on testing that uses a representative bonded jacketed configuration or establish aging limits, which would preclude a similar bonded jacket failure mechanism as observed for Okonite cables.

6.3 Overall Technical Assessment

One of the principle findings of the research conducted in support for the resolution of GSI-168 is that the current EQ process is adequate for the EQ of low-voltage I&C cables for the current license term of 40 years. Therefore, the overall EQ process provides reasonable assurance that, when qualified in accordance with the NRC regulations, the cables will perform their intended function during their qualified life. In 10 CFR 50.49, the effects of significant aging mechanisms are required to be addressed as part of EQ of electric equipment important to safety in harsh environment. Specifically, 10 CFR 50.49(e)(5) contains provisions for aging that require, in part, consideration of all significant types of aging degradation that can affect the component's functional capability. Compliance with 10 CFR 50.49 ensures that the component (cable) will perform its intended function during accident conditions after exposure to the effects of service aging.

During the EQ rulemaking, the staff concluded that the “qualification” for meeting 10 CFR 50.49 is verification of design. In addition, the licensees were expected to provide assurance that safety-related equipment will perform its intended function throughout its installed life and operating environmental conditions will not exceed those assumed during pre-aging. It is expected that the licensees will monitor environments (temperature and radiation) in operating plants, at least in certain critical areas, so that they know where the hot-spots are. The licensees were encouraged to consider surveillance, testing, and maintenance.

The objective of our regulations and IEEE standards is to provide reasonable assurance of cable performance during accident conditions. The methodology in IEEE standards relies on conservatism in test conditions. These conservatisms include:

1. Many qualification tests have been designed to appropriately accelerate the effects of continuous exposure of the insulation to 90 °C.

2. Margins are added to required accident temperature, pressure, radiation, operating time, and electrical parameters to account for cable production variations and test measurement variations and uncertainties.

3. The cable test profile was intended to establish combined qualification for both PWR and BWR inside containment conditions by enveloping various hypothetical LOCA and MSLB events from different plant designs. A typical test profile including two transients is conservative.

4. Cable qualification test accident simulations are typically run for 10 days or longer.

5. The accident radiation dose assumptions for LOCA-qualified inside-containment cables are based on the guidance of TID 14844. This results in containment source terms that represent a severely damaged core and non-mechanistic instantaneous release assumptions. Both these considerations substantially increase the calculated accident integrated radiation dose values that are required for cable qualification.

6. Subjecting test cables to 100% of accident radiation dose prior to steam exposure is a significant test conservatism.

7. The accident radiation level typically used during qualification is a very conservative simulation for both insulation and jacket materials.

8. The post-LOCA mandrel bend test provides an important performance margin. A successful test provides further confidence that the cables will adequately perform under actual accident conditions.

In summary, typical cable qualification test programs include numerous conservative practices which collectively provide a high level of confidence that installed plant cables will adequately perform during accident events. These conservative practices support the adequacy of using a single prototype (or a small number of test specimens) during the qualification test program.

The bottom line is that a successful test provides a high level of confidence. However, when a cable fails the test (such as in NRC and Sandia's tests), the qualification margins are reduced. These failures indicate that the original qualification bases have been challenged. Therefore, knowledge of the operating environment and the condition of cables becomes critical during the service life. As stated earlier, walkdowns to look for any visible signs of anomalies attributable to cable aging coupled with the knowledge of operating environments have proven to be effective and useful. The industry stated that the aging evaluations are ongoing throughout the plant life. When unexpected adverse conditions are identified, the condition of the affected cables is evaluated and appropriate corrective actions are taken. In this technical assessment, it is assumed that the licensees are implementing these good practices, although we do not have any specific evidence that this is being done uniformly by all licensees. Since we inspected nuclear power plants for compliance with 10 CFR 50.49 more than 15 years ago, it seems logical to reevaluate our position to conclude if any further action is warranted.

Further, as discussed in Sections 6.1 and 6.2, with respect to specific technical issues related to (1) use of the accelerated aging techniques, (2) use of the estimated value of the activation energy, (3) unique and different failure mechanisms of multiconductor cables vs. single conductor cables (with the exception of the failures of Samuel Moore cables), (4) use of a single prototype for testing, and (5) the technical basis for post-LOCA simulation test, the current practices have been found to be adequate.

However, the significant research findings need to be communicated to the nuclear industry. Therefore, the staff should consider issuance of a Generic Communication consistent with the generic communication process. Specifically, the Generic Communication may address the following areas: (1) results of tests conducted on cables for service life of 40 years and 60 years; (including a description of the testing program: research approach, condition monitoring (e.g., effectiveness of visual inspection), test results - failures, failure mode, etc, splice failures, failures of bonded jacket, failures of cables in LOCA test for 60 years service life); (2) a summary of Okonite test results and subsequent NRC actions and industry initiatives; (3) a summary of research findings on condition monitoring techniques; (4) a summary of the industry good practices for condition monitoring; and (5) the importance of knowledge of operating environments during the license renewal period.

Thus, this Generic Communication will accomplish several objectives: (1) it will alert the licensees of the research results, particularly observed failures in several tests and their implications; (2) provide information on available conditioning monitoring techniques; (3) provide information on industry practices which will help each licensee to evaluate and develop its own practice during 40 years of service life and beyond; and (4) emphasize the importance of knowledge of plant environments and highlight the role of condition monitoring.

The state of the art for incorporating cable failures in a probabilistic risk assessment is still evolving, and currently assumptions need to be made on the failure rate and common cause effects based on sparse data. One of the key assumptions of the risk assessment, discussed in Section 5, is that operating environments are lower than those assumed during qualification. This assumes knowledge of environmental conditions at the operating power plants. The risk assessment suggests that, at our current level of understanding, a cost-beneficial improvement is not supported.

6.4 Conclusions

1. The technical assessment of Generic Safety Issue GSI-168 is complete. The staff recommends dissemination of research results and other information, as discussed in Section 6.3, consistent with the generic communication process. The monitoring of plant environments is essential to ensure that the operating conditions do not exceed those assumed during the qualification. Walkdowns to look for any visible signs of anomalies attributable to cable aging coupled with the monitoring of operating environments have proven to be effective and useful.

2. Knowledge of operating environments continues to be a critical factor for license renewal. If the environmental service conditions are less severe than those used in the original qualification and cables are not degraded, then the licensees can use the margin between the operating environment and the qualification environment to analytically extend the life of the cables.