INTERIM REPORT

INVESTIGATION OF RAYCHEM CABLE INSTALLED IN THE BRUNSWICK PLANT

PHASE 1—PRELIMINARY EVALUATION AND TEST PLAN

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1. INTRODUCTION

This report summarizes Franklin Research Center's (FRC) Phase 1 efforts in conducting a technical evaluation of the adequacy of certain Raychem electrical cables for Class 1E service at Carolina Power and Light Company's (CP&L) Brunswick plant. The objectives of this phase of work include reviewing background files provided by the U.S. Nuclear Regulatory Commission (NRC), organizing and summarizing pertinent technical facts, and providing the basis of a program for evaluating the adequacy of the installed cable.

Section 2 presents background information on the alleged inadequacy of some cables installed at the Brunswick plant. Section 3 summarizes the test and surveillance programs undertaken by Raychem Corp., CP&L, and United Engineers & Constructors, Inc. (UE&C) in response to this allegation. A variety of tests was performed on jacketed cables and individual conductors to verify the dielectric and moisture resistance properties of these cables. Summaries of the test or surveillance program methodology, test conditions, and observed results are provided. Sections 4 and 5 present the basis of a program for evaluating the adequacy of the cable. This program, based on the evidence reviewed in Section 3, recommends cable testing as the preferred method for resolving basic questions concerning the ability of the cable to function adequately for normal and design basis event (DBE) service conditions.

2. BACKGROUND

In a March 1976 letter to the NRC [1], Mr. F. A. Slautterback, a former Quality Assurance Manager at Raychem Corporation, alleged that cable returned from the Brunswick site for remarking was tested as unsatisfactory due to potential water absorption and loss of dielectric strength problems. Information was provided that, in February 1975, cables failed to meet some of the moisture-related production test criteria described in IPCEA S-66-524, "Cross-linked-thermosetting-polyethylene-insulated Wire and Cable for the Transmission and Distribution of Electrical Energy" [2]. Those criteria included wet dielectric breakdown, insulation resistance, and accelerated water absorption tests; no information was provided on wet dielectric strength or long-term water immersion tests in Reference 1. The specific cable cited was multiconductor 1000-V Flamtrol cable with 0.045-in conductor and 0.08-in jacket cross-linked polyethylene insulations.*

Reference 1 further alleged that the inability of the cable to meet moisture-related test criteria was because irradiation energies used during the insulation cross-linking process could not penetrate certain multiconductor Flamtrol cables. In the manufacturing of Flamtrol cable, cross-linking of the polyethylene jacket insulation is performed by electron irradiation of an assembled cable; part of this cross-linking process includes the addition of a cross-linking aid (called a prorad) to the polyethylene insulation before irradiation. The use of an insufficient electron beam energy could result in an inadequate electron penetration of the insulation and, as a direct consequence, the buildup of a space charge layer. This space charge buildup could cause:

1. inhibition of the cross-linking process in the polyethylene jacket resulting in reduced dielectric properties of the jacket with increases in temperature and/or age.

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*It is common practice to refer to this cable by its aggregate jacket and conductor insulation thickness as 0.125-in insulated cable.

2. incomplete consumption of the prorad in the jacket. Prorad is water soluble and, in time, could be replaced by moisture; water treeing could result in the presence of voltage stress.
3. a change in the propertier of the conductor insulation. Insulation with adequate characteristics before assembly into the cable jacket could have reduced dielectric properties due to the space charge buildup from the electron irradiation of the entire cable assembly.

It should be apparent that several mechanisms exist by which the dielectric properties of the cable can be jeopardized.

3. TEST AND SURVEILLANCE PROGRAMS

Six tests and one ongoing cable surveillance program described in the following sections were performed to investigate potential insulation-related problems of Flamtrol cable. Five of the programs were limited exclusively to cable at the Brunswick plant; test programs performed specifically for other plants (e.g., Diablo Canyon) involved cables of different insulation thicknesses and, therefore, are not relevant to this review.

Environmental qualification tests performed [3] in accordance with IEEE Std 383-1974, "IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations" [4], are discussed in Sections 4 and 5.

FRC notes that the information reviewed consisted primarily of memos, letter correspondence, and summary test result data supplied from NRC files. FRC, therefore, must assume that the reported facts are accurate and that the tests were performed as stated.

3.1 RAYCHEM CORP. "PHASE I" TESTS, SPRING 1975 [5]

Raychem Corp. implemented an internal review of their failure to meet cable testing requirements. The testing portion of this program was limited to immersion testing of samples from each of the four cable reels that failed the above tests. Samples taken from each of the four cable reels were subjected to the following tests:

1. Long-Term Cable Jacket Immersion Test - Samples were immersed in water for 140 days with the cable jacket ends out of water.
2. Long-Term Cable Immersion Test - Four samples were tested as in (1) above except that the cable jacket ends were below the water surface. This procedure allowed water to get under the cable jacket and surround the cable component wires, according to Reference 5.

No failures occurred in the first test; however, there were failures in the second test with the jacket ends submerged. According to Raychem [5], "In the second lot, there were a few failures, all of which occurred in that portion of the component wires which were unprotected by the cable jacket and all of which were associated with mechanical damage in the process of removing the cable jacket."

3.2 RAYCHEM CORP. "PHASE II" TESTS, APRIL 1976 [5]

Samples of 4-year-old cable were removed from the Brunswick cable yard and subjected to production testing. These tests included ac and dc dielectric withstand and insulation resistance tests. All cables were successfully tested.

Raychem does not provide details on the type of cable tested, insulation thicknesses, or specific tests performed in Reference 5. Therefore, it is inappropriate to draw any conclusion as to the suitability of the subject Flamtrol cable from this information.

3.3 FIRL TESTS, APRIL 1976 [5,6,7]

Eight samples of jacketed multiconductor Flamtrol cable from the Brunswick site were tested in accordance with the electrical requirements of the "Completed Cable Test" of IPCEA S-66-524, Part 3.6.2. Total conductor and jacket insulation thicknesses were 0.105 and 0.125 in, respectively. Details of the specific tests performed are as follows:

1. Voltage Test (IPCEA S-66-524, Part 3.6.2.1) - Following a 24-hour immersion in tap water, 5.5 kV ac was applied sequentially to each cable conductor; all other conductors were at ground potential. The test voltage was applied for 5 min to each conductor and ground.

2. Insulation Resistance (IR) Measurement (IPCEA S-66-524, Part 3.6.2.2.) - After completion of the ac voltage test, the IR of each conductor was measured with 500 V dc applied for 1 min between each conductor and all other conductors at ground potential.

3. Direct-Current Voltage Test (IPCEA S-66-524, Part 3.6.2.3) - At completion of the IR measurements, a 16.5 kV dc potential was applied sequentially to each conductor with all other conductors at ground potential. The test voltage was maintained on each conductor for 5 min.

All cable samples successfully withstood the 5.5 kV ac voltage and 16.5 kV dc voltage tests. Measured IR values satisfied the IPCEA acceptance criteria as well as the more conservative Raychem criterion of 20,000 megohms per 1000 ft.

It should be noted that water was not allowed to enter the ends of the cable where the jacket had been stripped back.

3.4 CP&L/UE&C BRUNSWICK SITE TESTS, APRIL-MAY 1976 [5,6]

Tests were performed at the Brunswick site to determine Flamtrol cable functional capability. Thirty-four spare multiconductor cables installed in various cable trays, damp tunnels, concrete trenches, and buried duct runs were selected; cable insulation thicknesses were 0.105 and 0.125 in. The in-plant cables tested were shipped to the site in 1972 and 1973 and were originally from the same eight cable reels as the FIRL test specimens [7]. The following tests were performed on each cable:

1. Insulation Resistance Measurements - IR readings were made using a 500 V dc megger from each conductor to ground, and then from one conductor to all other conductors and ground. No information was provided on the duration of the applied test voltage, e.g., 1 min.

2. Alternating or Direct-Current Voltage Tests - An ac or dc potential was applied sequentially to each conductor with all other conductors at ground potential. For cables in ac service, test voltages were 1, 2, and 4.5 kV ac; dc service cables had test voltages of 1.5, 3, and 13.5 kV dc applied. The maximum values (4.5 kV ac and 13.5 kV dc) were based on 80% of the voltage withstand requirements for new completed cable.

Thirty-two of the 34 cables tested passed all tests. Of the two cables with problems (both with 0.105-in insulation), one passed the IR and 1.5 and 3 kV dc withstand tests; however, excessive leakage current was experienced during the 13.5 kV dc tests. Water was discovered inside the jacket at one end of the cable; after removal of 30 ft at that end, the cable passed the 13.5 kV dc test. The second cable with testing problems exhibited low IR readings. The cable was divided into eight sections. Those sections that were dry had high IR values and passed ac voltage withstand tests. Two sections, both with low IR readings, were observed to contain water inside the jacket ends.

3.5 RAYCHEM CORP. "PHASE III" TESTS, APRIL 1976 [5]

Raychem tested conductors from each of 487 cables in stock manufactured over a 4-year period. These tests consisted of the following:

1. Insulation Resistance Measurement (IPCEA S-66-524, Part 6.15) - Insulated conductors were removed from each cable assembly and placed in a water bath at ambient temperatures for a period of 4 hours. IR measurements of the conductor (to the grounded water) were made at 500 V dc. The test voltage was applied for 1 min.

2. Dielectric Breakdown Test - Following the above IR test, each conductor's insulation was tested to its ultimate dielectric breakdown strength. The type of test voltage, i.e., ac or dc, was not specified.

A review of the test results by Raychem [5] indicated that:

> "Overall reduction in dielectric breakdown strength was limited to unshielded cable in which the sum of the component wire insulation and cable jacket wall thickness was approximately 0.120 inch or greater. Virtually all such examples were confined to constructions in which component wires had insulation walls of 0.045 inch and jacket walls were 0.08 inch. Age or other variables made absolutely no difference."

Raychem further stated, "Checks were made to insure readings other than normal were true measures of the component insulation and not damage associated with removing component wires from the cable," i.e., low IR or dielectric measurements due to conductor mechanical damage were excluded.

The "Phase III" cable test presumably resulted in the performance of the experimental studies described briefly in Section 3.6.

3.6 RAYCHEM CORP. JACKET IRRADIATION STUDY, MAY 1976 [8]

Raychem performed experimental studies on four 7/C, #12 Flamtrol cables. In each case the conductor wire insulation wall and jacket thicknesses were 0.045 and 0.08 in, respectively. Shielded and unshielded cables were irradiated with 2 MeV electrons to cause cross-linking of the jacket polyethylene insulation; one unshielded cable was irradiated with 3 MeV electrons.* The electrical properties of the cables and conductors were tested as follows:

1. Cable Insulation Resistance Measurement - Cables were immersed for 15 hours in water with the jacket ends under water. IR was measured at 500 V dc between each conductor and all other conductors and water at ground potential.

2. Cable Alternating-Current Voltage Withstand Test - On completion of the IR measurments, 5.5 kV ac was applied between each conductor and all other conductors and water at ground potential. Voltage was applied for 1 min.

3. Component Conductor Insulation Resistance Measurement - Conductors were removed from irradiated cable and immersed in water for 15 hours. IR was measured at 500 V dc between each conductor and water at ground potential.

4. Component Conductor Alternating-Current Voltage Withstand Test - On completion of the IR measurements, 5.5 kV ac was applied between the conductor and water at ground potential. Voltage duration was 1 min.

5. Component Conductor Alternating-Current Breakdown Voltage Test - On completion of the withstand test in (4) above, the voltage was increased until insulation breakdown occurred.

No 5.5 kV ac withstand failures occurred for the cables; however, the unshielded cable irradiated at 2 MeV exhibited low IR between certain conductors and ground.

All conductors from disassembled cables, with the exception of the unshielded cable irradiated at 2 MeV, exhibited acceptable IR, 5.5 kV ac withstand, and ac breakdown voltage characteristics. The majority of the conductors in the unshielded 2 MeV cable had low IR measurements and experienced some dielectric breakdowns during the 5.5 kV ac withstand test.

Based on the tests performed during the jacket irradiation study, Raychem concluded the following [8]:

1. With unshielded, jacketed multiconductor cables, space charge effects can occur during cable jacket irradiation at 2 MeV when the combined jacket and component insulation wall thickness is approximately .125 in (.080-in jacket and .045-in component insulation).

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*A total of 8 specimens were used; i.e., 4 each for the cable and conductor tests.

2. When such space charge effects occur, they can cause decreases in IR and dielectric strength of some cable components.

3. Space charge effects do not occur when the combined jacket and component insulation wall thickness is approximately .125 in if the cable jacket is irradiated at 3 MeV. The higher energy electrons completely penetrate the component wire insulation and, thereby, provide an ionized path to a grounded conductor so that a space charge cannot form.

4. Similarly, the presence of a shield prevents the formation of a space charge by providing a conducting path to ground.

3.7 CP&L SURVEILLANCE PROGRAM, 1978-1981 [9]

On the recommendation of UE&C [6], CP&L established a continuing surveillance program on multiconductor Flamtrol cable. This program, first performed in 1978, consists of making and recording annual IR measurements with a 1000 V dc megger on cable spares located throughout the plant. Each conductor is tested to all other conductors and ground. Investigative action is taken for any IR measurement less than 500 megohms.

In 1978, 1979, and 1980 there were, respectively, five, four, and three cables with measured IR values less than 500 megohms. It was observed in each case that the ends of these cables were wet or showed signs of moisture. In 1981 all cables had IR values of 1000 megohms or greater.

Of the 81 cables included in this surveillance program, 8 cables were identified as tested in the 1976 onsite test program of spare installed cables (see Section 3.4, CP&L/UE&C Brunswick Site Tests).

4. QUALIFICATION TESTING OF FLAMTROL CABLE

The review in Section 3 of the tests performed on Raychem Flamtrol cable at the Brunswick plant suggests that there is uncertainty whether Flamtrol cables with combined conductor and jacket wall insulation thickness greater than 0.12 in can function adequately in a moist or wet environment.

Reference 3, cited by CP&L as evidence of qualification of Flamtrol cable at the Brunswick plant, documents tests performed in accordance with IEEE Std 383-1974. In the nuclear industry, cable qualified to IEEE Std 383-1974 is considered capable of functioning under normal operating and DBE conditions. This standard provides guidance for qualifying cable for Class 1E applications, through the performance of type tests; it requires evaluation of significant environmental conditions, such as temperature, moisture, radiation, and chemical or mechanical effects, which could affect the performance of the cable under normal operating and DBE conditions. Futhermore, the standard allows that, "Qualification of one cable may permit extrapolation of results to qualify other cables of the same type, with consideration being given to cable dimensions and probable modes of failure." The Raychem qualification programs tested unjacketed single-insulated conductors for moisture resistance and 0.09-in insulated 1000-V control cable under LOCA conditions. Raychem then used these results as a basis for extrapolating qualification to all other Flamtrol cables. However, from the review of the information presented in Section 3, it appears that the characteristics of cables with combined (conductor and jacket) insulation thickness of 0.12 in or greater at the Brunswick plant differ from those of the cable tested in Reference 3. FRC believes these differences to be significant and concludes that results from the cited tests on Raychem cable cannot be extrapolated to infer qualification of Flamtrol cable with 0.12-in insulation. Two primary areas where the test results from the qualification program may not be representative of the performance of the installed cable are discussed in Sections 4.1 and 4.2.

4.1 MOISTURE RESISTANCE UNDER NORMAL OPERATION

Section 2 of IEEE Std 383-1974 provides guidance for demonstrating cable qualification for temperature and moisture resistance for normal operation. Qualification can be demonstrated by providing evidence that cross-linked polyethylene cable has been manufactured to and acceptably meets the moisture-related production testing criteria of IPCEA S-66-524. Table 1 of IEEE Std 383-1974 considers a single #12 or #14 conductor acceptable for these tests.

Flamtrol cables were qualified for moisture resistance by conducting a production run test on an unjacketed conductor with 0.045-in insulation [3] for accelerated water absorption and for dielectric strength. Although not stated, the tests appear to be in accordance with IPCEA S-66-524, Part 3.6.2.

Information in Sections 3.1, 3.5, and 3.6 of this report indicates that test results would be questionable if a single conductor with 0.045-in insulation removed from a 0.12-in Flamtrol cable could pass these tests, because of changes in insulation characteristics caused by space charge buildup during the jacket cross-linking process. There was no evidence of moisture resistance under normal operation because the actual test cited was for a conductor with apparently different insulation properties.

4.2 PERFORMANCE UNDER DBE CONDITIONS

The multiconductor Flamtrol cable tested by Raychem [3] was a 7-conductor, 1000-V cable with 0.03-in conductor and 0.06-in jacket wall insulation thicknesses. From the information reviewed in Section 3 of this report, it can be expected that the insulation characteristics of the tested cable in the presence of moisture would be different from those of the 0.12-in insulated cable. There is, therefore, some concern regarding the ability of the 0.12-in insulated Flamtrol cable to pass a DBE test, especially if the jacket were severely degraded as a result of the LOCA simulation or during installation, or if moisture got into the ends of the cables during the LOCA simulation.

4.3 RECOMMENDATION FOR TEST PROGRAMS

Because analytical prediction of cable performance under long-term normal or DBE conditions is difficult, type testing is customarily used in qualification of cable in the nuclear industry. The test results in Section 3 provide a legitimate basis for concern about the ability of this cable to perform satisfactorily for its intended service conditions. FRC recommends that the investigative program for determining the functional ability of the Brunswick Flamtrol cable include laboratory testing. This approach appears to be the most direct method for resolving this complex technical problem.

5. FLAMTROL WORK PLAN - DIRECTION AND TECHNICAL APPROACH

The goal of this task is to determine whether certain Raychem Flamtrol cables installed at the Brunswick plant can adequately perform their intended function under anticipated service conditions. Because sufficient information is not available on the actual cable installed in the plant and its functional requirements, service conditions, and physical and electrical characteristics, a definitive evaluation of the adequacy of the cable is not possible at this time; likewise, it is not feasible to define an evaluation program completely. Based on the limited information currently available, FRC has determined that two fundamental concerns must be resolved. These concerns, posed in the form of questions below, define the initial direction and scope of efforts necessary to achieve the objective of this task:

1. Can Flamtrol cables, as installed at Brunswick, with intact or damaged jackets function adequately in a moist or submerged environment under otherwise normal operating conditions?*
2. Can Flamtrol cables, as installed at Brunswick, with intact or damaged jackets function adequately in a DBE service environment?

A work plan has been devised which attempts to resolve questions concerning the functional adequacy of the Flamtrol cable as directly as possible through testing. Test program development will be influenced by available information and intermediate program results; thus, the scope of the current work plan is based on anticipated results. Since all relevant information is not available at this time, the program will necessarily have decision and branch points which will affect subsequent portions of the program. FRC has attempted to limit the number of branch points by making anticipatory judgments about the results of the program data search. Furthermore, instead of developing new theoretical criteria, FRC has attempted to use existing or standard industry practice wherever possible. These criteria are presumably conservative and based on collective experience and wisdom.

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*"As installed at Brunswick" implies that terminations and splices should be considered in the overall evaluation of the functional capability of Flamtrol cable; testing of these items is not considered necessary at this time.

The basic work plan consists of the following:

- cable identification
- onsite inspection
- sample selection
- test program - wet environment under normal operating conditions
- test program - DBE service conditions
- evaluation.

The first three items above will provide input for the test program development; conceivably, the findings of tests and evaluations early in the program could result in the restructuring of the planned test program before the question of the functional capability of Flamtrol cable is resolved.

Sections 5.1 through 5.5.1.5 discuss the anticipated direction of effort.

5.1 CABLE IDENTIFICATION

Information must be provided on the Raychem Flamtrol cable installed at the Brunswick plant, its application and intended function, and expected environmental service conditions. The following information is required for developing a test program and for the final evaluation of the test results:

1. Installed Flamtrol cable
    a. identification of the unshielded multiconductor cable with combined insulation/jacket thickness equal to or greater than 0.12 in
    b. number of conductors and construction
    c. reel number and markings
    d. 1000 V rating
    e. actual service voltages and currents
    f. load description
2. Application and functional requirements
    a. normal service function
    b. DBE function(s)
    c. circuit requirements (e.g., voltage, IR, capacitance)

CP&L's references to date have not supplied all the information identified in items in (1) and (2); however, the needed information should be readily available from CP&L.

3. Normal service environment
   a. temperature range
   b. humidity and moisture
   c. submergence
   d. chemical exposure and composition

The normal service environmental parameters should be obtained from CP&L and checked against the cable specification. Anticipated environmental extremes (e.g., occasional submergence or high temperatures) should be cataloged.

4. DBE service environment
   a. temperature profile as a function of time
   b. pressure profile as a function of time
   c. humidity
   d. radiation
   e. submergence
   f. spray
   g. operating time requirement

CP&L has provided DBE environmental parameters for general plant locations in response to IE Bulletin 79-01B, "Environmental Qualification of Class 1E Equipment" [10]. Clarification of some items will be required.

Documentation of the above information on a cable-by-cable basis is a time-consuming task which is not warranted. Selection of the most severe functional and environmental service requirements for each type of multiconductor cable would allow evaluation to proceed on an initial, conservative basis. Cable-by-cable review should be considered only for those cases in which conservative evaluation results in unreasonable or unacceptable requirements.

5.2 ONSITE INSPECTION

The purpose of the site visit is to obtain and document inplant information that is unobtainable from more readily available sources. The site visit should include the following:

1. Verification of accuracy of cable information. This task is essentially an audit of the cable-specific information identified in Section 5.1. FRC will suggest candidate audit items after review of the information identified in Section 5.1.
2. Installed cable inspection. Installed cable should be inspected for evidence of jacket damage or abrasion. FRC notes that inspection of complete cable lengths may be impossible due to enclosed (fire-proofed) cable trays and conduit runs. Maximum cable pulling tension should be reviewed if records exist. Cable runs should be reviewed for evidence of moisture and water accumulation. Plant areas susceptible to the effects of high and low energy line breaks should be reviewed to determine if cables are routed through these areas. Cable junctions, splices, and terminations should be inspected to verify that qualified equipment and methods are used.
3. Sample selection. Inplant cable spares will be selected for later removal and shipment to the designated test laboratory. The actual number of samples selected will be determined in the developed test program.
4. Spare cable surveillance test. An onsite review of surveillance test procedures, records, and equipment should be performed. A specific inspection should be made of those cables previously exhibiting low IR values in the annual surveillance programs [9].

5.3 SAMPLE SELECTION

There is no evidence to suggest that in-use cable would have properties significantly different from those of spare cable; therefore, the impact on plant operations can be minimized by using samples taken from installed cable spares or reel samples. If possible, the sample selection should include removed spare cable that has been exposed to moist environments. Cable damage during installation should be considered in test sample selection because spare cable used in long pull sections through conduit or ducts may have abraided jackets.

Reference 11 indicates that Flamtrol cables with total insulation thicknesses of 0.09, 0.105, 0.120, 0.125, 0.135, and 0.140 in have been installed at the Brunswick plant. Although a detailed review has not been performed, it appears that few spare cables are available with insulation thicknesses of 0.120, 0.135, and 0.140 in. Based on the space charge degradation mechanism discussion in Section 3, failure of 0.125-in cable to pass tests would consititute a basis for concluding that failure of the 0.120-, 0.135-, and 0.140-in cable is likely. It is anticipated that the majority of the specimens tested will be cables with 0.125-in insulation; however, at least one specimen from each of the categories with other insulation thicknesses should be tested to confirm that the pertinent characteristics are independent of insulation thickness.

5.4 TEST PROGRAM - WET ENVIRONMENT UNDER NORMAL OPERATING CONDITIONS

The recommendation for type testing Flamtrol cable for operation in a moist or submerged normal environment is based on the review of testing and surveillance programs found in Section 3. Specific observations are as follows:

1. Unshielded Flamtrol cable with 2 MeV electron cross-linking has failed IPCEA component production tests or similar tests (see Sections 3.1, 3.5, and 3.6).
2. Similar cables, presumably without space charge effects, have passed tests similar to the IPCEA component insulated conductor tests (see Section 3.6).
3. Unshielded Flamtrol cable with 2 MeV electron cross-linking has exhibited low IR when completed cables have been tested with jacket ends immersed in water (see Section 3.6).
4. An intact cable jacket with jacket ends above water has provided an "adequate" moisture protective function (see Sections 3.1 and 3.3).
5. Exposed or open cable jacket ends can allow infiltration of moisture into Flamtrol cable with substantial loss of IR (see Sections 3.4 and 3.7).
6. Flamtrol cable is stiff and inflexible compared to other control cables. There may be a greater likelihood of damaging insulated

conductors when removing jacketing or installing cable (see Sections 3.1 and 3.6).

A test program to evaluate the functional capability of Flamtrol cable under normal service conditions should consist of the following:

1. Moisture resistance tests on individual insulated conductors
    a. IR measurement
    b. voltage withstand test
    c. accelerated water absorption test
2. Jacketed cable tests in a wet environment under normal operating conditions with damaged and intact jackets
    a. age conditioning
    b. IR measurement test
    c. voltage withstand test

Details on the above test program items are provided in Sections 5.4.1 through 5.4.2.5.

5.4.1 Moisture Resistance Tests on Individual Insulated Conductors

The first step in the evaluation of the functional capability of Flamtrol cable in a moist environment should be moisture resistance tests identical to those performed by Raychem in Reference 3. These tests should be basically production tests of single-insulated conductors similar to tests described in IPCEA S-66-524; however, the specimens should be removed from samples of completed Flamtrol cable which are suspected of having the space charge phenomenon defect.

The primary objective of these tests is to determine whether the moisture resistance properties of 0.12-in insulated Flamtrol cable are different from those of cable used in the qualification test program in Reference 3. A secondary objective is to establish a documented set of data on the results of the IPCEA moisture resistance tests on Flamtrol cable.

5.4.1.1 IR Measurements

IR measurements should be performed on insulated conductors immersed in water. The method described in IPCEA S-66-524, Part 6.15 should be used in the test program.

5.4.1.2 Voltage Withstand Test

A dielectric strength test should be included at a potential of 100 V/mil. The insulated conductors should be immersed in water for 24 hours (i.e, the same conductor is used in the IR measurement test and the accelerated water absorption test). IPCEA S-66-524, Part 3.6.2.1 requires 5.5 kV ac test voltage; however, a 4.5 kV ac voltage (as used in the Raychem tests) should be used.

5.4.1.3 Accelerated Water Absorption Test (AWAT)

An AWAT should be performed on the insulated conductors after completion of the above tests using electrical method EM-60 as described in IPCEA S-66-524, Part 5.6.

5.4.2 Jacketed Cable Tests in a Wet Environment Under Normal Operating Conditions

Based on the review in Section 3, some conductors are expected to fail during the moisture resistance tests. In order to better assess the ability of the completed cable to function, an additional set of tests is proposed which addresses the functional capability of jacketed safety-related cables in a specific environment. The environmental conditions of interest are the normal service conditions with the addition of moisture and water.

Section 3 indicates that the exposure of insulated conductors to moisture in completed cable has resulted in unacceptable IR and dielectric withstand test performance. Undetected jacket damage incurred during installation, or cracking as a result of age or temperature, can result in cable failure in a wet environment. Current operating history does not provide evidence of functional performance because cables with damaged jackets or age-degraded jackets may never actually have operated in a wet environment; in fact, some cables may be expected to operate in this type of environment only as the result of some rare plant upset condition. Testing is, therefore, required to verify functional capability.

5.4.2.1 Cables with Damaged Jackets

The ability of a damaged cable jacket to keep water from the insulated conductors must be tested by simulating jacket damage. For example, a conservative (e.g., 1-in) sized slit could be made in the cable jacket and the entire cable tested. If IR and voltage withstand test results are acceptable, it can be concluded that the cable jacket integrity is sufficient to prevent treeing failure due to direct wetting of the conductor insulation or wetting through capillary action and, therefore, undetected cable damage is not a significant problem. If, on the other hand, IR and voltage withstand test results are not acceptable, it must be concluded that jacket integrity must be maintained at all times.

The approaches used to simulate cable damage and the means for potentially introducing moisture into a damaged cable will require engineering judgment. However, conservative, yet reasonable, criteria can be determined only after onsite cable inspection. For example, it may be possible from the onsite inspection of installed cable and construction QA records (or by using probabilistic sampling methods) to postulate the largest undetected cable jacket tears or jacket penetration depths due to abrasion during installation.

Possible methods for simulating jacket damage include slitting completely through the insulation or to the insulation half-thickness, abraiding the jacket surface, or age conditioning tightly coiled samples to simulate age-related cracking in high mechanical stress areas. Jacket-damaged cables should then be placed in a shallow trough filled with water. The depth of water should be based on an estimate of the maximum hydrostatic head developed in cable troughs or in conduit or duct runs. The cable should be operated at rated voltage and current for a period of time defined by post-accident safety system operating requirements (e.g., 30 or 180 days); periodic IR and dielectric withstand measurements should be made during this time. If, as a result of the onsite visit, it is determined that cable jacket ends may be exposed to moisture, the cable jacket ends should be submerged in the trough; otherwise, the jacket ends should be elevated above water and exposed only to humidity effects.

5.4.2.2 Cables with Intact Jackets

Information in Section 3 suggests that Flamtrol cable performance is adequate in a wet environment only as long as jacket integrity is maintained. A test should be performed consisting of operating intact cables under conditions similar to those discussed in Section 5.4.2.1 for the damaged cable, i.e., at rated voltage and current for a period of time defined by post-accident considerations.

As part of the overall evaluation, Brunswick operating experience should be reviewed to determine if some Flamtrol cable has routinely operated in a wet environment. If it is determined that sufficient operating experience in a wet environment does exist, IR measurements should be made and the results compared with those for cables in the annual surveillance program. In this way, additional information on cable functional capability in a wet environment under normal operating conditions could be made available for the overall evaluation.

5.4.2.3 Age Conditioning

Raychem's thermal and radiation age conditioning procedure and rationale should be reviewed during development of the test program. If the approach is considered acceptable, then age conditioning should be performed in accordance with the Raychem procedure to produce specimens aged to the equivalent of 40 years. Since the installed cable spares are approximately 8 to 10 years old, the actual accelerated thermal aging time (for aging temperatures identical to Raychem's) will be less than that in Reference 3. Similarly, prior in-service radiation exposure must be taken into account in determining the required aging irradiation dose. In the event that Raychem's aging procedure is considered nonconservative, the pre-test aging times or radiation exposure should not exceed the values used in Reference 3. This approach will result in age conditioning of the cable specimens to a simulated age of less than 40 years; however, by limiting accelerated aging conditions to Raychem's aging bases, the introduction of additional test program considerations due to different aging bases is avoided.

Exposure to elevated temperatures and irradiation during accelerated aging actually improves the physical and dielectric properties of some cable insulations and, hence, could improve their ability to withstand environmental testing-induced stresses. This improvement in cable characteristics can take place if the age conditioning causes a curing-like process instead of a degradation process in the cable; curing may dominate for a period and degradation may dominate subsequently. Whether age conditioning results in net degradation or improvement of the moisture resistance of Flamtrol cable is unknown. Therefore, testing should be performed on the naturally aged (8- to 10-year-old) specimens as well as on the age-conditioned specimens.

5.4.2.4 IR Measurements

Periodic IR measurements should be performed using the method described in IPCEA S-66-524, Part 6.15. Part 7.8, Control Cables, of IPCEA S-66-524 permits IR tests to be made without immersion of the completed cable. However, IR measurements should be performed on immersed cables in this test program in order to evaluate the susceptibility of Flamtrol cable to moisture-induced failures.

5.4.2.5 Voltage Withstand Test

Periodic dielectric strength tests should be performed on immersed cables using the method outlined in IPCEA S-66-524, Part 6.14. Test voltages of 4.5 kV ac and 13.5 kV dc should be used as specified in Part 7.8 for completed control cables.

The number of withstand tests to be performed must be determined as part of the test plan development because repeated withstand tests could degrade the cable seriously enough to cause failure. However, data from periodic withstand tests during the wet environment testing provide an indication (through leakage/charging current measurements) of the condition of the cable over time and, therefore, enable an assessment to be made of the functional capability of the cable relative to the functional duration requirements at the Brunswick plant. It is recommended that a limited number (e.g., 3 to 5) of voltage withstand tests be performed on the specimens to provide adequate information on the cable dielectric properties while still minimizing the risk associated with degradation caused by the testing method.

5.5 TEST PROGRAM - DBE SERVICE CONDITIONS

The recommendation for testing of Flamtrol cable under DBE conditions is based, in part, on observations in Section 5.4 for wet environmental conditions. Based on available information in Reference 10, the Brunswick inside-containment LOCA environment would represent the severest set of DBE conditions at the plant for the Flamtrol cable. Concerns specific to DBE conditions include the following:

1. Previous qualification testing under simulated LOCA conditions was performed on 0.09-in (and smaller) insulated cable. Based on the evidence in Section 3, it appears that conductor insulation of such cable would not be degraded by space charge effects caused by the jacketed cable fabrication process.
2. Cable experiences several (e.g., 2 to 6) orders of magnitude decrease in IR during simulated LOCA exposure. The 0.12-in Flamtrol cable appears to require an intact jacket to maintain acceptable IR in the presence of moisture. Thus, it is possible that the effects of aging, radiation, and steam/spray could degrade jacket insulation to the point where adequate insulation properties cannot be maintained throughout the LOCA exposure.
3. The cable tested in Reference 3 exhibited minor surface cracking and crazing after the LOCA exposure, but overall cable performance was unaffected. The extent to which thicker jackets could crack, and the resultant impact on cable functional performance, cannot be assessed from previous qualification tests [3].

A program for evaluating the functional capability of Flamtrol cable under DBE service conditions should consist of the following tests on cable with damaged and intact jackets:

1. age conditioning
2. radiation exposure
3. LOCA simulation
4. post-LOCA simulation
5. electrical tests.

5.5.1 Testing of Cables with Damaged and Intact Jackets

The combined effects of cracking, minor jacket damage, steam, spray, and radiation during a LOCA could lead to the transport of sufficient moisture to the conductor region of the cable and possible insulation failure. To FRC's knowledge, there is no reliable way of extrapolating the results from previous Raychem tests on other cables to determine whether the 0.12-in insulated cable jacket can maintain adequate integrity during and after LOCA conditions. Furthermore, it is FRC's experience that identical cables tested under different LOCA conditions (e.g, temperature, pressure, dose rate) often exhibit dramatic and unpredictable drops in IR. The ability of the cable to maintain adequate jacket integrity can be reasonably determined only by test.

Cables with intact jackets should be LOCA tested. If there is sufficient evidence from the inplant inspection to indicate that jacket damage may have resulted during installation, cables with simulated jacket damage should also be LOCA tested. The method for jacket damage simulation should be similar to that described in Section 5.4.2.1. Damaged cable would not be LOCA tested if it is determined that such cable cannot pass the submergence test described in Section 5.4.2.1 (i.e., failure for DBE steam/spray conditions will be assumed if the cable fails the submergence test for a wet environment under normal operating conditions).

5.5.2 Cable Testing Program

Flamtrol cable should be tested for operation during a DBE in a manner that closely follows the guidance of IEEE Std 383-1974; Raychem tests generally followed the recommendations of this standard. For the tests to be performed here, the following guidelines are proposed:

1. In cases where the Raychem tests are at variance with the specific guidance in IEEE Std 383-1974, the testing will be performed as recommended in IEEE Std 383-1974.
2. In those cases where IEEE Std 383-1974 provides limited guidance and user interpretation is required to develop test procedures, the methods used in the Raychem test will be employed (e.g., voltage and current loading scheme for multiconductor cables).

The Raychem Flamtrol qualification test had simultaneous radiation exposure and LOCA simulation; however, IEEE Std 383-1974 does permit sequential testing consisting of radiation exposure followed by LOCA steam and spray. Whether simultaneous exposure is necessary for the proposed test program cannot be determined at this time. However, it has been FRC's experience that sequential testing does not yield results that are significantly different from results of simultaneous testing when cable is tested under DBE conditions. Furthermore, sequential testing is the currently accepted industry practice for cable qualification tests. From a practical standpoint, sequential testing is preferred because long-term large hot cell availability is not required; test chamber setup inside a hot cell is not required, allowing greater testing flexibility; and overall test costs are reduced. Therefore, unless a definite technical preference for simultaneous testing is determined, a sequential testing program can be developed.

The general DBE testing program is described in Sections 5.5.2.1 through 5.5.2.5.

5.5.2.1 Age Conditioning

The requirement and basis for testing aged and unaged cable specimens under DBE conditions are similar to those discussed in Section 5.4.2.3 for cables operating in a normal environment. There is, however, an additional reason for testing unaged cables (i.e., cables not conditioned beyond their natural age) under DBE conditions. Accelerated thermal aging combined with LOCA testing could result in degradation of the jacket to the extent that jacket integrity cannot be adequately maintained, thus resulting in cable insulation failure due to the presence of moisture near the conductors. In the event that the predominant failures occur in the age-conditioned specimens, it may be possible to estimate the time frame in which aging degradation becomes critical with respect to the ability of the jacket, and hence the cable, to function adequately.

5.5.2.2 Radiation Exposure

Prior to LOCA testing, all specimens should receive a gamma irradiation dose of 200 Mrd, which is identical to the cable exposure in the Raychem qualification tests [3]. Approximately 50 Mrd is considered as the radiation aging dose, and the remaining 150 Mrd as the accident dose. The dose rate used in the Raychem tests was approximately 0.2 Mrd/h; however, if sequential testing is performed, a higher dose rate (e.g., 0.5 Mrd/h) could be used to reduce overall test time without jeopardizing cable performance.

5.5.2.3 LOCA Simulation

The Brunswick plant-specific containment design temperature/pressure profile plus margin should be used to establish the LOCA test environment conditions. This test environment will be less severe than the temperature/pressure environment used by Raychem in its qualification testing. Such an approach is justifiable because the objective of the test program is to determine whether the DBE functional performance of the Flamtrol cable installed in the Brunswick plant is adequate and considered acceptable by IEEE Std 383-1974, Part 2.4.3.* The plant-specific LOCA temperature/pressure profile, including duration, must be obtained from CP&L, although preliminary information is available in Reference 10. It should be noted that demineralized water spray should be used in the tests, as permitted in IEEE Std 323-1974, instead of the boric acid spray used in Reference 3, because the Brunswick plant has a demineralized water spray system.

Throughout the LOCA simulation, cables are loaded at rated current and voltage, except when periodic IR measurements are made. Cable jackets will

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*IEEE Std 383-1974 references IEEE Std 323-1974, "IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations," which provides guidance on establishing simulated service condition test profiles.

extend outside of the test chamber because jacket integrity is the primary concern during the LOCA tests.

5.5.2.4 Post-LOCA Simulation

After the LOCA exposure, the cables should be removed from the test chamber and given a post-LOCA simulation test as described in IEEE Std 383-1974, Part 2.4. Specimens should be straightened, recoiled around a mandrel, soaked in tap water, and subjected to IR and voltage withstand tests.

5.5.2.5 Electrical Tests

The cables should be electrically loaded at rated current and voltage throughout the LOCA test, except when periodic IR measurements are made.

After the first 30 days of the LOCA simulation, the test chamber should be filled with water, and IR measurements and 1-minute voltage withstand tests performed. (This procedure was used in the Raychem tests and would allow an interim comparison of test results with those in Reference 7.)

The LOCA simulation should then be continued to the end of the LOCA period, at which time the mandrel wrap test, final IR measurements, and 5-minute voltage withstand tests should be performed. An ac potential of 80 V/mil is used, with the insulation thickness taken as twice the conductor wall thickness.

5.6 EVALUATION

Development of the test program would constitute the second phase of the Raychem Flamtrol evaluation. The third phase would include the actual testing and evaluation of the results to determine the functional capability of the Flamtrol cable for normal and DBE service conditions at the Brunswick plant. If the testing is carried out as proposed in Section 5 and satisfactory test results are obtained, it should be possible to conclude that the cable is satisfactory. However, it is possible that specimen failure may occur for reasons not related to functional adequacy (e.g., overstressing caused by specimen handling or failure of test equipment). In such a case, failure analysis and supplementary testing may be required to resolve the question of the functional capability of the Brunswick Flamtrol cable. Depending on the specific results of the tests, it may be possible to recommend (1) surveillance programs to minimize undetected cable degradation, (2) infield modifications, such as additional moisture sealing requirements for connections and junctions, or (3) replacement of selected cables based on functional requirements to reduce overall risk.

6. REFERENCES

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