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The Effect of LOCA Simulation Procedures on Cross-Linked Polyolefin Cable's Performance

L. D. Bustard

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Sandia National Laboratories
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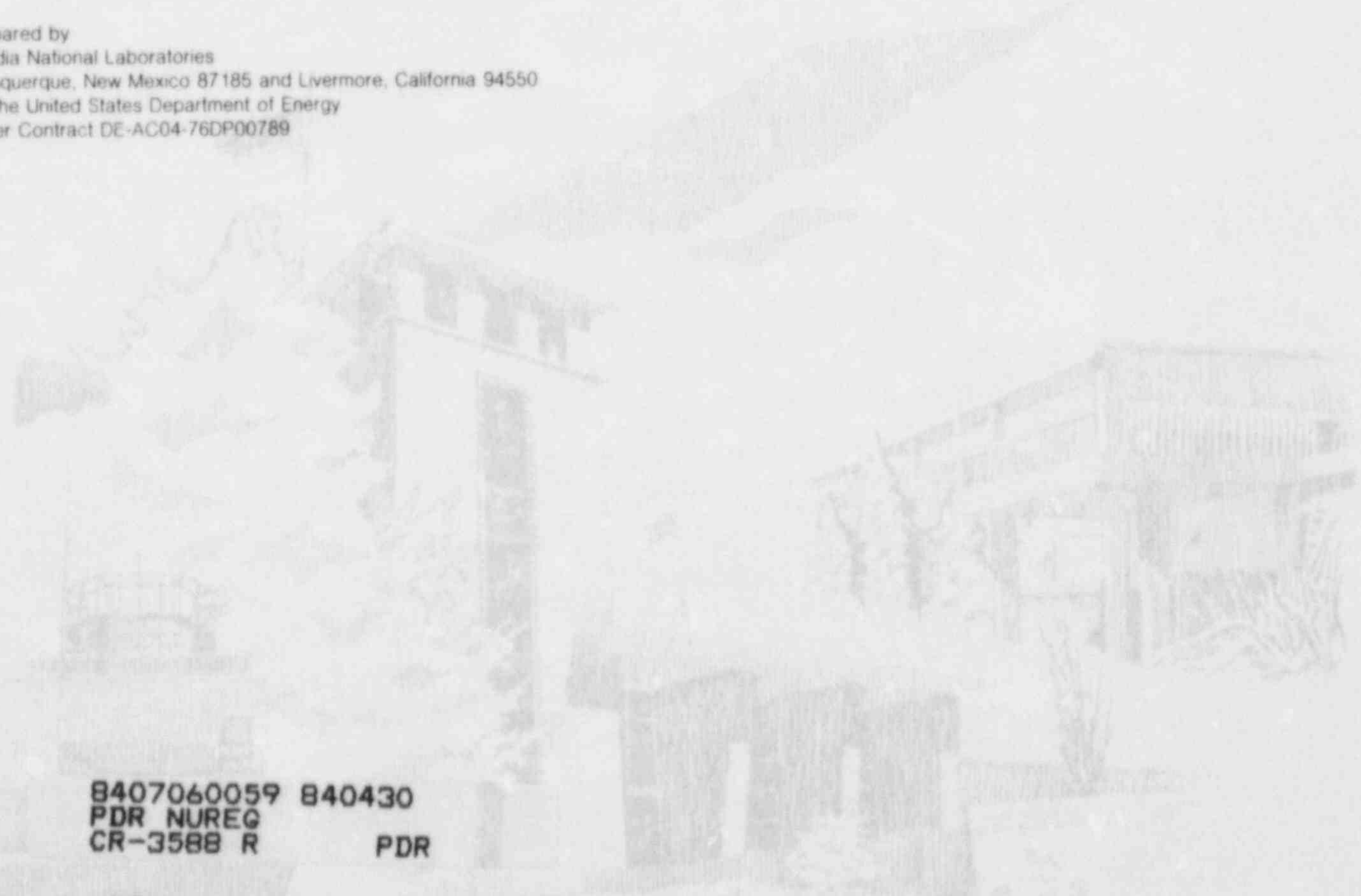

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THE EFFECT OF LOCA SIMULATION PROCEDURES ON CROSS-LINKED POLYOLEFIN CABLE'S PERFORMANCE

L. D. Bustard

Sandia National Laboratories
Albuquerque, New Mexico 87185
Operated by
Sandia Corporation
for the
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2. L. D. Bustard, The Effect of LOCA Simulation Procedures on Ethylene Propylene Rubber's Mechanical and Electrical Properties. SAND83-1258, NUREG/CR-3538, October 1983.

ABSTRACT

Electrical and mechanical properties of three commercial cross-linked polyolefin (XLPO) materials, typically used as electrical cable insulation, have been monitored during three simulations of nuclear power plant aging and accident stresses. For one XLPO cable we first performed accelerated thermal aging, then irradiated the samples to the combined aging and LOCA total dose. Finally, we applied a steam exposure. For a second and third set of XLPO cables we used simultaneous applications of elevated temperature and radiation stresses to preaccident age our specimens. We followed these aging exposures by simultaneous radiation and steam exposures to simulate a LOCA environment.

Our measurement parameters during these tests included: dc insulation resistance, ac leakage current, ultimate tensile strength, ultimate tensile elongation, percentage dimensional changes, and percentage moisture absorption. We present test results for three XLPO materials.

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KEYWORDS

CSPE - Chlorosulfonated polyethylene; a jacket material employed in several of the multiconductor constructions

Desorbed - To lose moisture content

e - Ultimate tensile elongation

EPR - Ethylene-propylene rubber. Includes ethylene-propylene copolymer, EPM, and ethylene-propylene-diene terpolymer, EPDM, as subsets.

HIACA - High Intensity Adjustable Cobalt Array. A Sandia National Laboratories' irradiation facility capable of producing a simultaneous radiation, steam, and chemical spray exposure or a simultaneous radiation and elevated temperature exposure.

HYPALON - Trade name of DuPont for chlorosulfonated polyethylene, CSPE.

IEEE - The Institute of Electrical and Electronics Engineers.

Insulation Specimens - Insulation samples used to monitor dimensional and weight changes as well as to measure the ultimate tensile elongation and the ultimate tensile strength.

I.R. - Insulation resistance. During our measurements the bulk resistivity is monitored; surface currents are shunted past the ammeter using a guarding circuit. Measurements were performed after a 1-minute electrification at 500 Vdc.

LOCA - Loss of Coolant Accident; a hypothesized design basis event for nuclear power plants.

Neoprene - Trade name of DuPont for polychloroprene rubber.

Sequential Test - A sequential exposure to elevated temperature followed by irradiation followed by a steam exposure. Our sequential test did not include chemical spray during the steam exposure. Oxygen was swept from the chamber at the start of the steam exposure.

Simultaneous Test #1 - A simultaneous exposure to radiation and elevated temperature followed by a simultaneous exposure to radiation and steam. Our test did not include chemical spray. Oxygen was swept from the chamber at the start of the steam exposure.

Simultaneous Test #2 - An exposure similar to simultaneous test #1.

T - Ultimate tensile strength.

Tap Water - Water used for immersing cables during some insulation resistance and all voltage withstand tests. Water obtained from Sandia Area V potable water supply. For simultaneous test #2, posttest measurements, the water conductivity was 360 mmhos/cm.

TEFZEL - Trade name of DuPont for a copolymer of ethylene and tetrafluoroethylene.

Tensile Specimens - Insulation samples used to monitor dimensional and weight changes as well as to measure the ultimate tensile elongation and the ultimate tensile strength.

Voltage Withstand Test - Part of the acceptance criteria specified by IEEE Std. 383-1974, Sections 2.3.3.4 and 2.4.4.

Ultimate Tensile Elongation - The strain at which a tensile specimen fails.

Ultimate Tensile Strength - The stress at which a tensile specimen fails.

XLPE - Cross-linked polyethylene, a subset of XLPO.

XLPO - Cross-linked polyolefin.

EXECUTIVE SUMMARY

Electrical and mechanical properties of three commercial cross-linked polyolefin (XLPO) materials (XLPO A, B, and C) typically used as electrical cable insulation, have been monitored during simulations of nuclear power plant aging and accident stresses. For one XLPO B cable, we first performed accelerated thermal aging, then irradiated the samples to the combined aging and LOCA total dose. Finally, we applied a steam exposure. For a second (XLPO B) and third (XLPO A, B, and C) set of XLPO cables we used simultaneous applications of elevated temperature and radiation stresses to preaccident age our specimens. We followed these aging exposures by simultaneous radiation and steam exposures to simulate a LOCA environment. In addition to electrical cables, separate tensile specimens (XLPO A, B, and C) were exposed during the second simultaneous test.

We had three major goals for our XLPO experimental program.

1. We wanted to experimentally determine whether qualification testing of XLPO single conductors is more severe than XLPO multiconductor testing. Historically, it has been suggested that a multiconductor jacket provides additional protection not available to a single conductor.

2. We wanted to investigate if cable electrical performances and insulation mechanical properties are sensitive to whether simultaneous or sequential stress exposures are employed during simulations of aging and accident environments.

3. We wanted to monitor insulation moisture absorption and tensile properties to gain insight concerning mechanical property changes that may cause cable electrical degradation.

Our experimental results indicate:

1. The electrical properties for XLPO A and B cable products did not depend on whether single conductor or multiconductor testing was performed. XLPO C single conductors were not included in our test program because of experimental limitations. (The test setup limited the number of cables that could be included in the experimental program.)

2. For XLPO B, electrical performance during our simultaneous tests was similar to that achieved during the sequential test. For XLPO A and C cables, electrical performance during our simultaneous tests was similar to that achieved during the manufacturer's sequential tests.

3. In a previous report[1] we noted severe degradation of an ethylene-propylene rubber (EPR) multiconductor during simultaneous testing. We hypothesized that dimensional swelling of the insulation (associated with moisture absorption) caused multiconductor jacket splitting with resultant damage to the insulated conductors. Ultimate tensile elongation measurements for this EPR-product indicated that the insulation elongation was substantially reduced and therefore susceptible to mechanical damage. In contrast to the results for this EPR material, dimensional swelling for each of the three XLPO insulations was much less severe. Likewise, the XLPO ultimate tensile elongation values were higher. Thus, the lack of XLPO mechanical damage during our tests is not surprising.

4. The XLPO multiconductor cable constructions included chlorosulfonated polyethylene (CSPE) and Neoprene outer jackets. We observed substantial visual degradation of these jacket materials during our simultaneous testing exposures.

1.0 Introduction

In a previous report we discussed "The Effects of LOCA Simulation Procedures on Ethylene Propylene Rubber's Mechanical and Electrical Properties."[1] As we performed experiments on the ethylene-propylene rubber (EPR) cables and insulation specimens, we received from several manufacturers cross-linked polyolefin (XLPO) and cross-linked polyethylene (XLPE) cables. Wherever feasible, we included these cables in our EPR experimental program.

Cross-linked polyolefin and cross-linked polyethylene are popular insulations used for electrical cabling in nuclear power plants. The term polyethylene refers to a subset of the more generic material class polyolefin. Hence, in this report we use polyolefin to describe both polyethylene and polyolefin cable insulations.

We obtained three XLPO cables from three different manufacturers. One cable (XLPO B) was received prior to the start of the sequential and simultaneous #1 tests described in Reference 1. This XLPO cable was included in each of these two tests. All three XLPO cables, as well as XLPO insulation specimens, were tested during a second simultaneous test. Table 1.1 summarizes the experimental exposures employed for the various XLPO cables and tensile specimens. In this report we document our experimental procedures and results for the XLPO cables. Since the XLPO cables were tested with the EPR cables, our discussion of experimental procedures will be very similar to that provided in Reference 1. However, there are some important differences. Most notably, the XLPO B cables exposed during the sequential and simultaneous #1 tests experienced different radiation total doses than did most of the EPR cables. Dose rate gradients within the test chambers were responsible for the differences in total dose.

We had three major goals for our XLPO experimental program.

1. We wanted to experimentally determine whether qualification testing of XLPO single conductors is more severe than XLPO multiconductor testing. Historically, it has been suggested that a multiconductor jacket provides additional protection not available to a single conductor. IEEE Std 383-1974[2] Table 1 supports this perspective by allowing single conductor test results to be used as a qualification basis for multiconductor control cables.

2. We wanted to investigate if cable electrical performance and insulation mechanical properties are sensitive to whether simultaneous or sequential stress exposures are employed during simulations of

Table 1.1

Experimental Exposures Employed for the Various XLPO Cables and Tensile Specimens

	Sequential Test	Simultaneous Test #1	Simultaneous Test #2
XLPO A:			
Single conductors			X
Multiconductors			X
Tensile Specimens			X
XLPO B:			
Single Conductors			X
Multiconductors	X	X	X
Tensile Specimens			X
XLPO C:			
Single Conductors			
Multiconductors			X
Tensile Specimens			X

aging and accident environments. NRC regulation 10CFR50.49, Section e(7) states that "Synergistic effects must be considered when these effects are believed to have a significant effect on equipment performance."[3]

3. We wanted to monitor insulation moisture absorption and tensile properties to gain insight concerning mechanical property changes that may cause cable electrical degradation.

To achieve the first goal we included both XLPO A and B single conductor and multiconductor cables in simultaneous test #2. The single conductor cables were obtained by carefully disassembling multiconductor cables. This insured that identical processing techniques were employed for both the multiconductor and the single conductor test specimens. Because of a limited number of electrical penetrations in our test chamber, XLPO C was not exposed as a single conductor. All three XLPO products were exposed as multiconductors.

To achieve the second goal, the performance of XLPO B multiconductors were monitored during both sequential and simultaneous accelerated aging and LOCA simulations. For XLPO A and C we monitored cable performance during simultaneous testing and compared our results to the manufacturer's results for sequential testing.

To achieve the third goal, XLPO A, B, and C insulation tensile specimens were exposed to simultaneous test #2. Weight and dimensional changes as well as ultimate tensile properties were monitored periodically during the test exposures. Both unaged and aged specimens were exposed to the second simultaneous test accident simulation. This allowed us to assess the influence of aging on insulation moisture absorption and tensile properties.

During our experiments, three commercial XLPO products were exposed to aging and accident simulations. This practice ensures that test conclusions for one XLPO cable product are not indiscriminately applied to all XLPO products. By testing several products we hoped to differentiate between generic XLPO conclusions and specific product conclusions.

For each of the XLPO products we tested, electrical performance during our simultaneous tests was similar to that reported by the manufacturer during its sequential qualification tests. XLPO electrical properties also did not depend on whether single conductor or multiconductor testing was performed. The XLPO multiconductor cable constructions included chlorosulfonated polyethylene (CSPE) and Neoprene outer jackets. We observed substantial visual degradation of these jacket materials during our simultaneous testing exposures.

2.0 Experimental

2.1 Materials*

We tested three commercial XLPO products obtained from three different manufacturers.

XLPO A: A three-conductor control cable with XLPO insulation covering 12 ga seven stranded tinned copper conductors. This multiconductor cable included an aluminum-mylar overall shield with a 12 ga drain wire. The overall jacket material was chlorosulfonated polyethylene. The certificate of compliance accompanying the cable listed IEEE Std 383[2] as an applicable specification.

XLPO B: A three-conductor 600V control cable with XLPO insulation covering 12 ga seven stranded tinned copper conductors. This multiconductor cable was jacketed with a neoprene outer jacket. The certificate of compliance accompanying the cable certified that the cable meets or exceeds the requirements of specifications IEEE 383-1974,[2] and IEEE 323-1974.[4]

XLPO C: A three-conductor 600V control cable with XLPO insulation covering 12 ga seven stranded copper conductors. The overall jacket material was chlorosulfonated polyethylene. This product is marketed for nuclear applications but we were unable to obtain from the manufacturer a certificate of compliance certifying that our cable conforms to IEEE standards.

Our research program performed LOCA research tests on:

1. Cables as received from the factory.
2. Single conductors (XLPO A and B). These conductors were obtained by carefully removing the multiconductor outer jacket and sheaths and then separating the individual conductors from each other.

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*Additional TEFZEL and EPR cables were also tested. Results for EPR were published in Reference 1. Results for TEFZEL will be published in a separate report.

3. Insulation tensile specimens. Prior to aging we removed jackets and sheaths from XLPO-insulated conductors and then carefully stripped the insulation from stranded copper conductors.

2.2 Facilities

The High Intensity Adjustable Cobalt Array (HIACA) facility at Sandia National Laboratories was used to expose XLPO cables and insulation specimens to aging and accident simulations. For sequential testing techniques a stainless steel chamber containing the cables was first used as a recirculating air oven chamber. It was then placed in the radiation environment and finally it was used as a steam chamber. For the simultaneous testing exposures, a second stainless steel chamber was used as a recirculating air oven with simultaneous radiation exposure. For the accident simulation this chamber was used as a steam vessel with simultaneous radiation exposure. Figure 2.1 schematically illustrates this capability. For the simultaneous aging and accident environmental exposures, the stainless steel chamber was positioned inside the gamma irradiation facility. After either steam or heated air was introduced into the chamber, cobalt pencils were raised to a position around the chamber to provide the desired simultaneous radiation and steam or elevated temperature environments. The radiation dose rate was adjusted by varying the number of cobalt pencils that are positioned about the chamber. The radiation capabilities of the HIACA facility are further documented in Reference 5.

Thermal aging was performed using the stainless steel steam chambers as ovens. A Chromalox Series 4231 SCR Power and Temperature Controller was used to regulate a 20 kW heater. Air circulation between the heater and chamber was maintained by four Dayton 100W Model 4C005 fans for the sequential and simultaneous #1 tests. For the second simultaneous aging exposure, the Dayton fans were replaced by a single 1.5 kW (2 HP) Paxton model RM87 blower. Valves in the recirculation line provided fresh air input to ensure oxygen supply throughout the thermal aging exposure. A Kurz Air Velocity Meter, Model 441, was used to monitor recirculating and fresh air flow rates to the chamber. This allowed us to calculate the amount of fresh air supplied to the chamber.

The steam system utilizes a 4.5 kW (6 HP) electric boiler which is too small to achieve the rise time requirements of LOCA testing. We store energy from the boiler in two 0.6 m^3 accumulators from which the steam is valved either to the steam chamber inside the gamma irradiation cell or to a chamber outside the irradiation cell. Alternatively, the steam can be valved to both chambers at the same time.

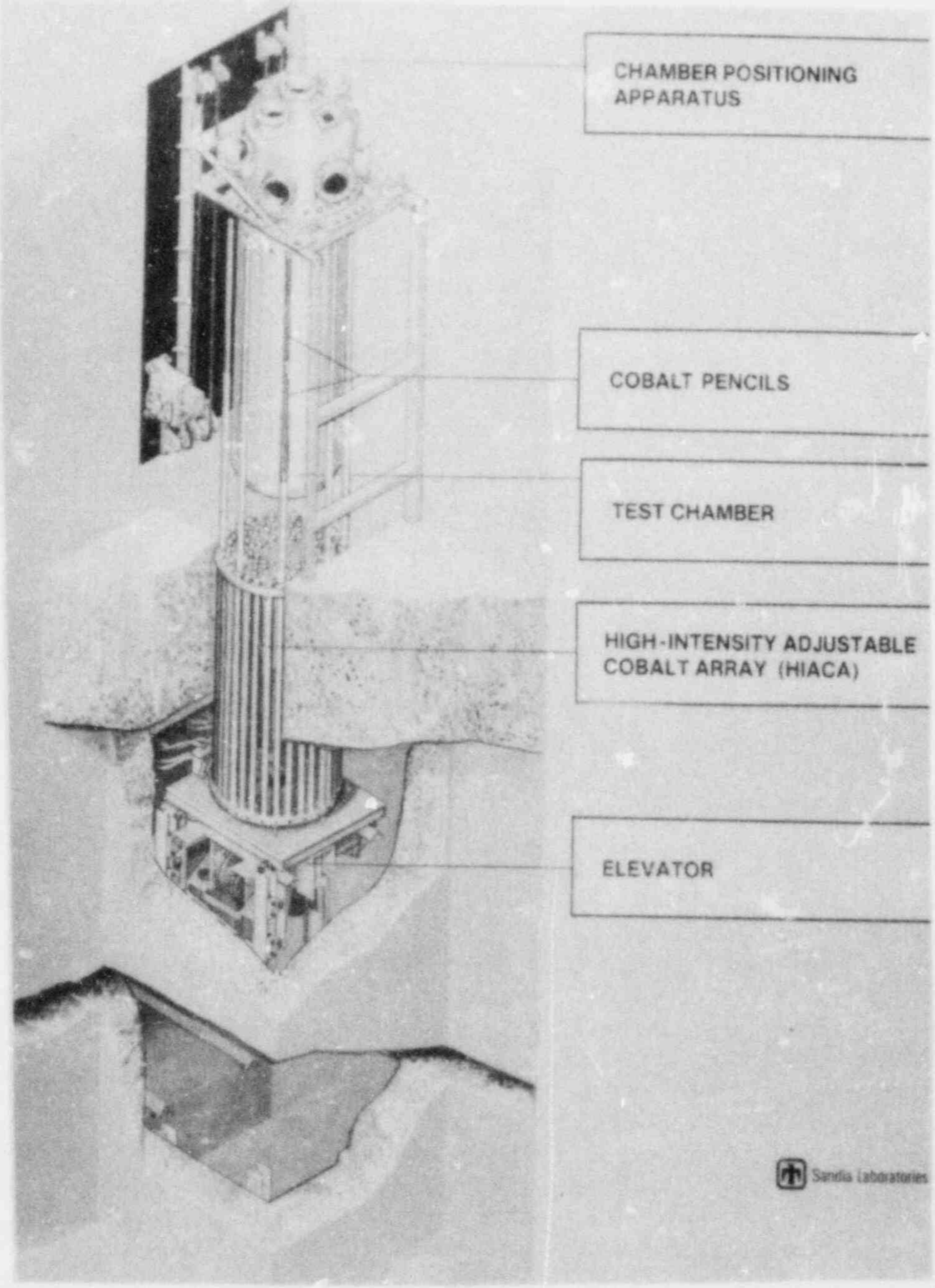

Figure 2.1. HIACA Test Facility

An Instrom^{tm} testing machine with pneumatic jaws was used to measure sample ultimate tensile strength and ultimate tensile elongation. Initial jaw separation was 50.8 mm (2 in); the samples were strained at 127 mm/min (5 in/min). An Instrom^{tm} electrical tape extensometer clamped to the sample monitored the strain.

A Hipotronics HM3A Megohmmeter was used for insulation resistance measurements. A Hipotronics HD100 Hipot Tester and a Hipotronics 715-10 Type CS14-1630 AC Dielectric Test Set were used to monitor leakage current versus applied AC voltage. The first tester was used whenever leakage currents were between 0 and 5 mA; the latter tester was used to determine leakage currents between 10 and 750 mA.

To load the cables during the steam exposures, each conductor was connected in series to a commerical 480 Vac, 3-phase, 60-cycle ungrounded distribution system. A series resistor limited the current to 0.6 amp. For the sequential test and simultaneous test #1, a Model 4612 Magtrol Power Analyzer was employed to monitor the current and voltage. During simultaneous test #2, the Magtrol Power Analyzer was removed from the circuit during the first steam transient after excessive water leakage from Tefzel cables located above it caused it to malfunction. Backup Triplett a.c. panel voltmeter and ammeter were employed. The steam chamber and cable mandrels were grounded throughout the test.

2.3 Sequential Test

2.3.1 Test Setup

One XLPO B cable length and 14 EPR cable lengths were exposed during the sequential test. The EPR test results have been previously reported.[1]

The sequential test was performed using a stainless steel steam chamber with ~0.4 m^3 of internal volume: the height is 200 cm and the diameter 52 cm. The top portion of the chamber (43 cm in length) contained all the penetration flanges through which cables, thermocouples, and other instrumentation entered and exited the chamber. The mandrels on which the cables were wrapped were suspended from the top portion of the chamber but were physically located inside the bottom portion of the chamber. This latter section of the chamber is 157 cm long. During radiation exposures the chamber was supported as shown in Figure 2.1. During thermal aging and the accident steam exposures, the chamber rested upright on the floor outside the Sandia Gamma Irradiation Facility.

The XLPO B cable was wrapped on a 30 cm diameter mandrel. After wrapping the cable twice around the mandrel, the cable leads were spiraled up the inside of the mandrel to the exit port. A rubber stopper was fed from each end of the cable and inserted into a modified Swagelok^{tm} fitting. The modified Swagelok^{tm} fitting, when tightened, compressed the rubber stopper and provided a steam seal. Figure 2.2 illustrates the sequential test setup.

The XLPO B cable was located on the top mandrel of the three mandrels shown in Figure 2.2. Its position below the top surface of the mandrel was 4.5 cm to 7.6 cm. The top of the mandrel was located 31 cm below the flange which connects the top and bottom portion of the steam chamber. The XLPO B cable length inside the chamber was 5.0 m. Each XLPO B cable lead outside the steam chamber was ~7.6 m long. This length was chosen to match the lengths used in the simultaneous accident environment tests. These long segments were necessary to pass each cable from the steam chamber to the outside of the gamma irradiation cell during the simultaneous tests. Insulation resistance and leakage current measurements were performed at this outside location.

2.3.2 Thermal Aging

During thermal aging, hot air was circulated from a heater to a port in the top of the stainless steel chamber. A rectangular aluminum duct along the inside wall of the chamber extended from the hot air entrance port to the bottom of the chamber. Air flow exited the duct along its entire length and was directed parallel to the walls of the chamber (see Figure 2.3). An auxiliary duct and blower were used to remove cooler air from the top of the chamber and recirculate it to the bottom of the chamber to ensure mixing. A valve on this latter recirculation line was adjusted during the first 22 hours of the 168-hour thermal exposure until the best temperature uniformity was obtained.

During recirculation of air from the chamber to the heater and back to the chamber, fresh air was added. We used air velocity measurements along the heater recirculation line to estimate the total air flow to the chamber as approximately 2 m^3/min. Of this, approximately 0.2 m^3/min. was fresh air. This insured that oxygen was not depleted during thermal aging.

Twenty-four thermocouples were positioned in the chamber to monitor temperature uniformity during thermal aging. Four of the thermocouples were spaced 90° apart circumferentially around the mandrel at the XLPO B position. (The thermocouples were positioned 5.8 cm below the top of the mandrel; the XLPO B cable position below the top of the mandrel was 4.5 cm to 7.6 cm.) The remaining 20 thermocouples were used to monitor the temperature distribution near the EPR cables and insulation specimens. One of these

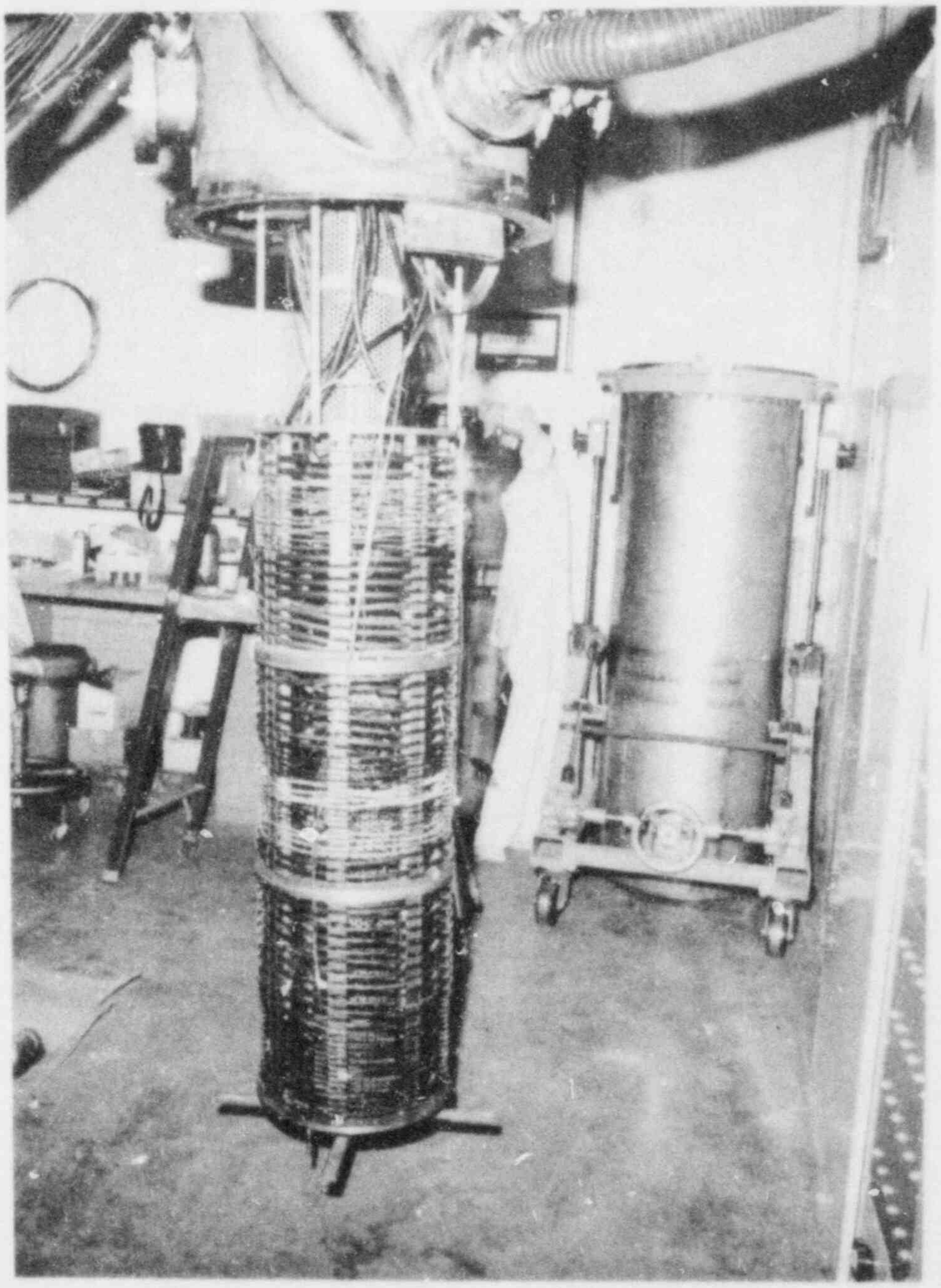

Figure 2.2. Sequential Test Setup Prior to the Start of Thermal Aging

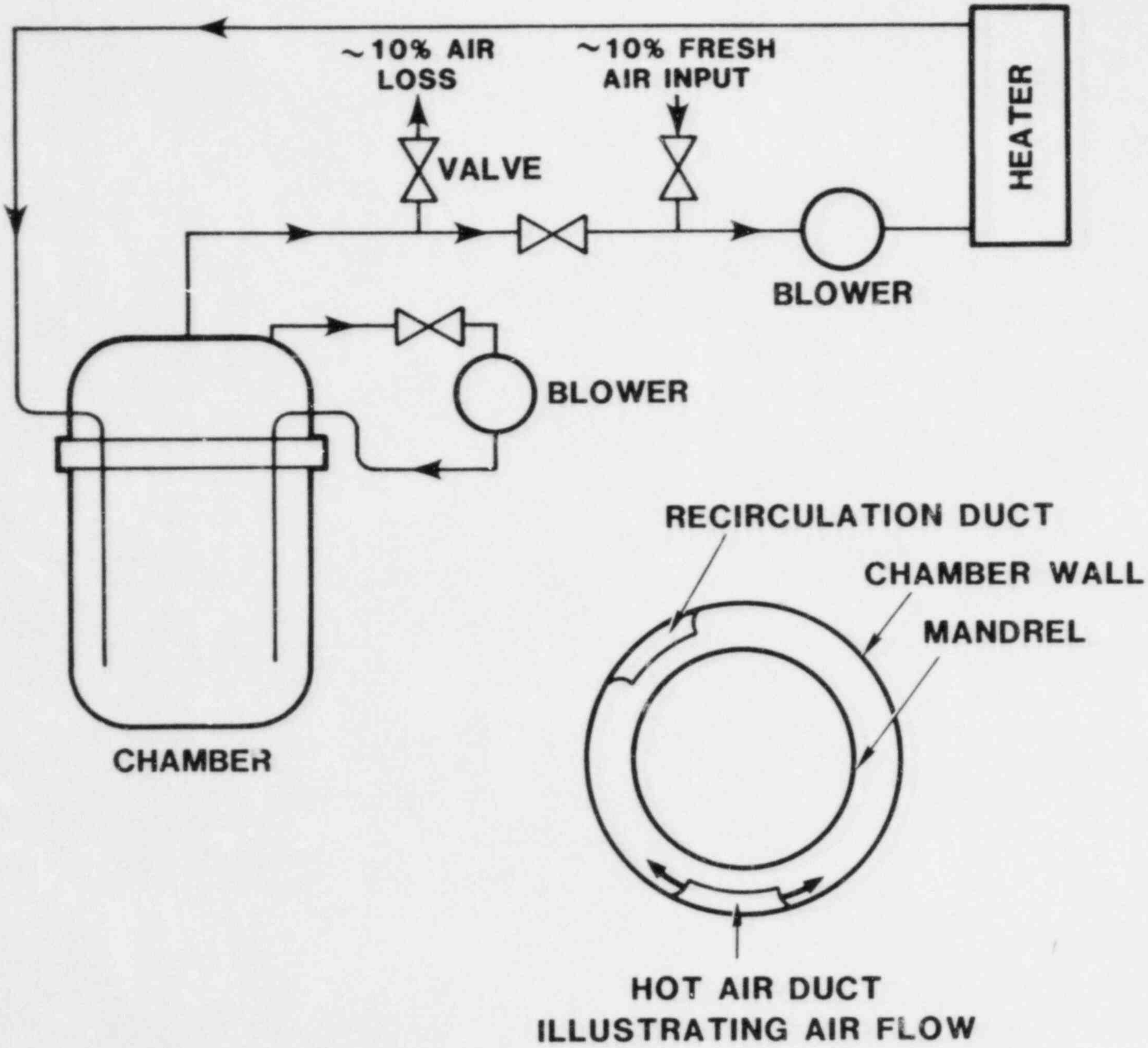

Figure 2.3. Thermal Aging Air Flow System During Sequential Aging

thermocouples was also used for heater control purposes; another was employed to provide a strip chart record of the thermal exposure. Table 2.1 presents the test chamber temperature distribution midway through the 168-hour thermal exposure. Table 2.2 summarizes the temperature readings versus time for several of the thermocouple positions.

Table 2.2 demonstrates the excellent temperature stability achieved once valve adjustments were completed at 22 hours. Table 2.1 illustrates that the temperature distribution was large within the chamber and also at the XLPO B location. This produced a large variation in accelerated age. The desired thermal exposure was seven days at 139°C. This elevated temperature exposure was based on Arrhenius techniques. Our thermal aging calculations were based on a postulated nuclear plant containment environment of approximately 55°C, a life of approximately 40 years and an activation energy of 1.04 eV. We chose the activation energy value as representative of single stress thermal degradation data found in the literature for EPR[6] (the predominat type of cable exposed during the sequential test).

Reference 7 lists two activation energy citations for cross-linked polyethylene, namely 1.13 eV and 1.23 eV. Though these citations are for different XLPO products than XLPO B, they suggest that our choice of E_A = 1.04 eV is conservative. For our choice of aging parameters, a ± 3°C temperature gradient yields a ± 25 percent variability in the accelerated age. A ± 5°C gradient produces a ± 40 percent variability in the accelerated age.

Our seven-day, 139°C thermal aging exposure was less severe than that used by XLPO B's cable manufacturer during qualification tests. A qualification report for this material indicated that the single conductors (insulation only) were aged at 150°C for well in excess of seven days.

The XLPO B multiconductor has a NEOPRENE jacket, but the manufacturer did not include it in the qualification test. Reference 7 provides aging data for a Neoprene material (a different manufacturer). Ultimate tensile elongation data yielded an activation energy of .94 eV. Therefore, accelerated aging for the NEOPRENE jacket may not be "equivalent" to a 40-year life.

2.3.3 Radiation Exposures

At completion of thermal aging, we removed the heater ducts from the stainless steel chamber. Accomplishment of this task was performed without disturbing the cables since the ducts were on the outside. We then performed insulation resistance measurements after filling the chamber with tap

Table 2.1

Thermocouple Readings 84 Hours After Start of 168-Hour Sequential Thermal Exposure

(a) Distance Below top of Mandrel (cm)	Temperature (°C) 0°	90°	180°	270°
5.8	140	129(7)	137	136
20.0	142(6)	--	141	139
54.9	--	143	142(4)	144(5)
92.4	138	145(3)	138	133
109.5	135(1)	141(2)	132	131

(b) Distance Below Top of Mandrel (cm)	Temperature (°C)
16.2	136
53.3	138
65.7	142
96.0	139

(a) Thermocouples were positioned around the circumference of the mandrel, spaced 90° apart and within 2.5 cm of the cables. The hot air duct was located at the 0° position; the recirculation duct was between the 90° and 180° position.

(b) Thermocouples were positioned along the outer rim of the perforated cylinder used to support tensile specimen baskets.

(c) (1)-(7) in the table indicate thermocouple positions monitored by Table 2.2.

Table 2.2

Temperature Versus Time Profile During Sequential Thermal Exposure. Thermocouple Positions (1)-(7) Are Identified in Table 2.1

	Temperature (°C) at Thermocouple Position						
Elapsed Time	1	2	3	4	5	6	7
0 hrs	23	23	24	23	23	23	23
0 hrs, 10 min	51	70	78	70	84	64	65
0 hrs, 20 min	75	101	115	96	116	98	91
0 hrs, 30 min	97	123	139	116	139	123	113
0 hrs, 45 min	118	143	158	135	158	150	133
1 hr	122	142	150	138	149	151	133
1 hr, 30 min	125	141	145	140	147	149	134
2 hrs	127	141	143	139	145	148	134
3 hrs	131	136	140	137	135	137	128
5 hrs	133	137	140	137	135	136	128
7 hrs	129	142	143	139	145	146	134
10 hrs	137	141	145	142	138	141	134
15 hrs	138	142	146	142	139	141	134
20 hrs	138	142	146	143	139	141	135
25 hrs	136	141	145	142	144	142	131
30 hrs	135	141	145	142	144	142	130
35 hrs	135	141	145	142	144	142	129
40 hrs	136	142	146	143	145	143	132
45 hrs	135	140	145	141	144	142	129
50 hrs	135	140	145	142	143	142	129
55 hrs	135	141	145	142	144	142	130
60 hrs	135	141	145	142	144	142	130
65 hrs	135	141	145	142	144	143	131
70 hrs	135	140	145	141	144	142	131
75 hrs	135	140	145	142	144	142	130
80 hrs	136	140	145	142	144	142	130
85 hrs	135	141	145	142	145	142	130
90 hrs	135	141	145	142	145	142	130
95 hrs	135	141	145	142	144	142	130
100 hrs	135	140	145	142	143	142	129
105 hrs	135	141	146	142	144	142	131
110 hrs	135	141	146	142	145	142	130
115 hrs	135	140	145	142	144	142	130
120 hrs	135	141	145	142	145	142	130
125 hrs	135	141	145	142	144	142	130
130 hrs	135	140	144	142	144	142	130
135 hrs	135	140	145	142	145	142	130
140 hrs	135	140	145	141	144	142	130
145 hrs	135	140	145	142	144	142	130
150 hrs	135	141	145	142	145	142	131
155 hrs	135	140	145	142	144	142	130

Table 2.2 (cont.)

	Temperature (°C) at Thermocouple Position						
Elapsed Time	1	2	3	4	5	6	7
160 hrs	135	141	145	142	145	142	130
165 hrs	135	140	145	142	144	142	130
168 hrs	135	141	145	142	145	142	130
169 hrs	92	89	90	91	91	91	95
171 hrs	57	58	56	58	58	56	59
173 hrs	41	42	40	41	41	41	42
175 hrs	33	33	32	33	33	32	33

water. After draining the water and allowing the cables to dry, we performed the aging radiation exposure.

We performed this exposure using three irradiation time intervals to give a total irradiation time of 60 hrs, 15 mins:

- a five minute exposure to allow for radiation mapping of the chamber
- a 21-hour, 52-minute exposure
- a 38-hour, 18-minute exposure

A 6-hour, 34-minute interruption separated the second and third exposures to allow for modification of the gamma irradiation facility ventilation. This was necessitated by an increased ozone concentration. Appendix A further discusses this unanticipated event. Ambient temperature during the latter two irradiations varied between 39°C and 45°C. We did not supply fresh air makeup to the chamber during the irradiations, but we did open ports of the stainless steel chamber to allow for natural air exchange between the cables and the gamma irradiation cell. The gamma irradiation cell was ventilated during the irradiation. We used a Victoreen Radicon Model 550 Integrating/Rate Electrometer with a Model 550 air ionization probe to measure the dose rate at one position along the centerline of the chamber. 106 Harshaw TLD-400's (calcium fluoride manganese activated thermoluminescent detectors) were placed at 53 positions to map the relative dose rates with respect to the single Victoreen measurement. The dose rate along the chamber centerline (40 cm below the top of the mandrel) was .65 ± .03 Mrd/h (air equivalent). The dose rate at the cable windings was 11% higher. Table 2.3 summarizes the dose rate profile with respect to distance below the top of the mandrel. From Table 2.3 we estimate the dose rate at the XLPO B cable to be .65 ± .05 Mrd/h (air equiv.). Thus the total aging dose was 39 ± 3 Mrd.

At completion of radiation aging we did both a visual inspection and insulation resistance measurements. We then performed the accident irradiation exposure for 171 hours at the same dose rate (.65 ± .05 Mrd/h). The total accident dose was 111 ± 9 Mrd (air equiv.). During the accident irradiation we monitored the air temperature at the cables. It varied between 40 and 44°C.

After the accident irradiation, we once again did a visual examination and performed insulation resistance measurements. The entire chamber with cables was then stored at ambient conditions until the start of the LOCA steam simulation (51 days after the completion of the accident irradiation).

Table 2.3

Radiation Dose Rates During Sequential Radiation Exposures

Distance below top of mandrel (cm)	Radiation dose rate (air equiv.) at cable windings
0	.59 ± .05 Mrd/h
15	.76 ± .06 Mrd/h
41	.72 ± .06 Mrd/h
69	.72 ± .06 Mrd/h
95	.76 ± .06 Mrd/h
114	.63 ± .05 Mrd/h

2.3.4 Steam Exposure

Figure 2.4 summarizes our intended steam temperature test profile while Table 2.4 summarizes the achieved test conditions. Our exposure profile is similar to the IEEE 323-1974, Appendix B profile,[4] but also different in several respects, most notably:

1. After four days of steam exposure we interrupted the steam exposure for approximately an hour to remove baskets containing EPR tensile specimens. The chamber temperature dropped to ~75° during the interruption (Table 2.4). XLPO tensile specimens were not included in the sequential test.

2. We used a 104°C saturated steam exposure after four days until the end of the test.

3. We did not apply chemical spray during the exposure.

4. We did not start our transient ramps at 60°C.

As allowed by IEEE 323-1974, Appendix A, we followed the temperature profile and allowed the pressure to correspond to saturated conditions for Albuquerque, New Mexico (171°C corresponds to 106 psig).

Two nonconformances kept us from achieving the intended steam profile.

1. During the initial ramp a penetration fitting for one of the EPR cables leaked excessively. It was immediately retorqued and the steam ramp restarted. The elapsed time to achieve the first ramp was thirteen minutes. We added 15 minutes to the duration of the first 171°C peak of the profile. The XLPO B cable did not exit the chamber at the affected penetration.

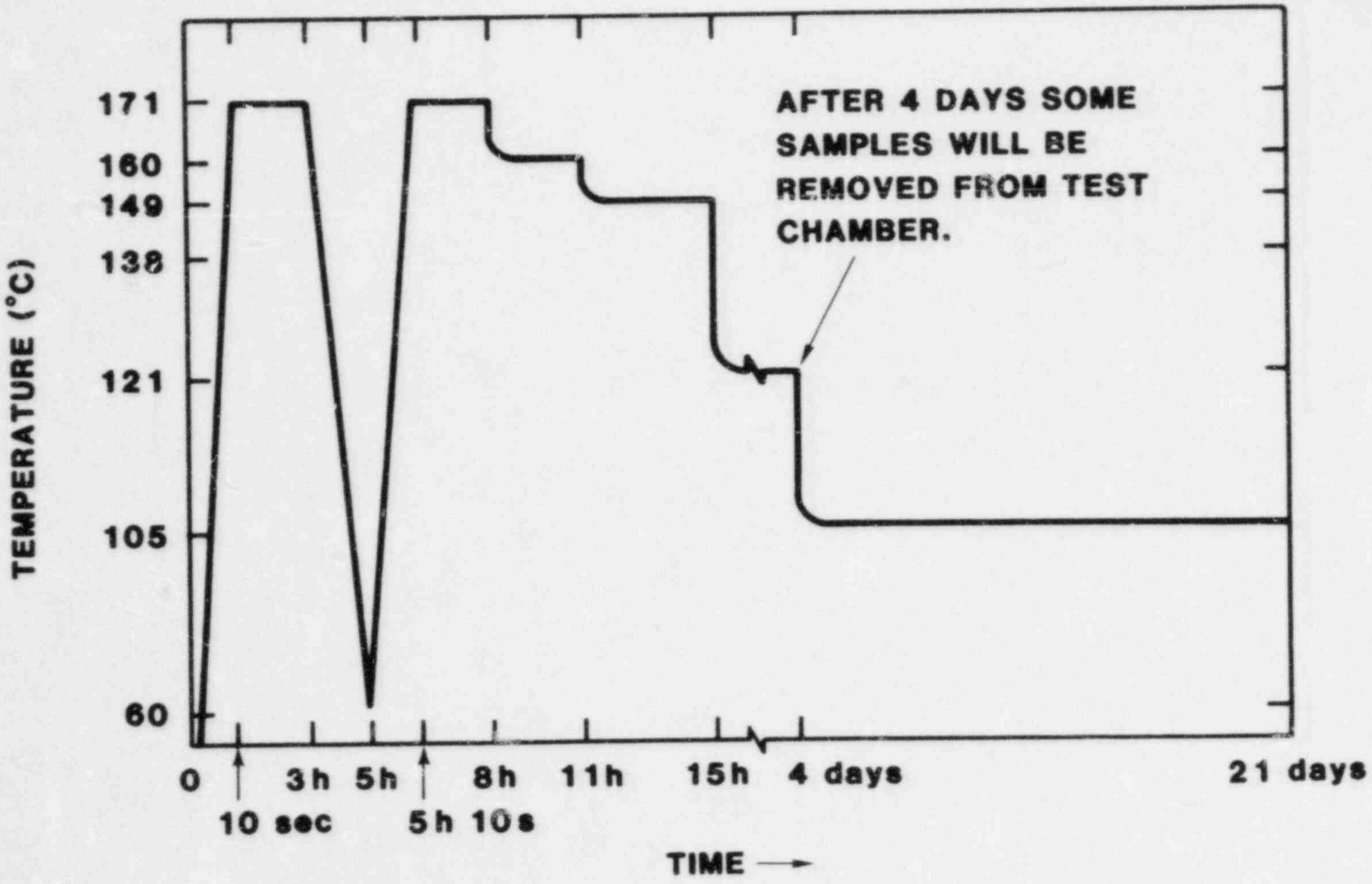

Figure 2.4. Sequential Steam Accident Exposure Profile (as proposed by test plan). Pressures correspond to saturated steam conditions in Albuquerque, New Mexico (171°C corresponds to 106 psig).

2. On day nine of the steam exposure our steam supply system failed and the steam chamber cooled down to ambient temperatures and pressures. On day 11 we opened the chamber and performed ambient insulation resistance measurements. We resumed the steam exposure on day 12 and continued the steam exposure until day 24. Our total steam exposure lasted 21 days.

Table 2.4 summarizes our test conditions during the steam exposure. The steam conditions for simultaneous test #1 are also summarized to illustrate the similarities between the sequential and simultaneous #1 test. Note: both steam chambers were connected in parallel to the steam supply system. Simultaneous test #1 also included a XLPO B cable.

Throughout the steam exposure the cables were loaded at 480 Vac and 0.6 A. This exposure was interrupted to allow for insulation resistance measurements.

At the completion of the steam exposure and after the chamber had cooled, we performed a visual examination and then filled the chamber with tap water. Insulation resistance and leakage current measurements were then performed. These measurements were made without disturbing the cables that were wrapped on the mandrels. We did <u>not</u> follow the procedures of IEEE Std 383-1974[2], Section 2.4.4 which states that the cables "should be straightened and recoiled around a mandrel with a diameter of approximately 40 times the overall cable diameter" prior to performing the voltage withstand tests.

2.4 Simultaneous Test #1

2.4.1 Test Setup

One XLPO B cable length and fourteen EPR cable lengths were exposed during simultaneous test #1. The EPR test results have been previously reported.[1]

The simultaneous test #1 was performed using a stainless steel steam chamber with ~.3 m^3 of internal volume. The height is 125 cm and the diameter 52 cm. The top portion of the chamber (43 cm in length) contained all the penetration flanges through which cables, thermocouples, and other instrumentation entered and exited the chamber. The mandrels on which the cables were wrapped were suspended from the top portion of the chamber but were physically located inside the bottom portion of the chamber. This latter section of the chamber is 81 cm long. During both the aging and the accident exposures the chamber was supported as shown in Figure 2.1. This allowed for a simultaneous radiation exposure with the thermal aging and the accident steam exposures.

Table 2.4

Steam Profiles Achieved During the Sequential and Simultaneous #1 Steam Exposures. Except during transient ramps and where noted,*, the temperatures correspond to saturated steam conditions in Albuquerque, New Mexico. An * indicates the chamber was opened to remove samples or the steam system had failed and saturated steam conditions were not maintained

Elapsed Time	Sequential Chamber Temperature (°C)	Simultaneous #1 Chamber Temperature (°C)
0.0	Introduced steam to both chambers	
2 s	129	134
27 s	94	174
52 s	82	167
1 m, 42 s	74	150
3 m, 47 s	70	151
6 m, 42 s	68	150
10 m, 02 s	67	151
11 m, 42 s	66	150
12 m, 07 s	173	150
12 m, 57 s	173	175
15 m	171	173
30 m	171	173
1 h, 0 m	172	173
2 h, 0 m	171	173
3 h, 0 m	171	172
3 h, 15 m	171	173
3 h, 30 m	165	167
3 h, 45 m	159	161
4 h, 0 m	152	153
4 h, 30 m	133	134
	Pressure Transducer Connected to Simultaneous Chamber Changed	
5 h, 0 m	105*	108*
5 h, 15 m	93*	112*
5 h, 15 m, 22 s	171	163
5 h, 15 m, 47 s	172	174
5 h, 18 m	171	172
6 h	171	172
7 h	172	172
8 h, 12 m	171	172
8 h, 18 m	170	171
8 h, 23 m	168	169
8 h, 38 m	163	164
8 h, 48 m	160	161

Table 2.4 (cont.)

Elapsed Time	Sequential Chamber Temperature (°C)	Simultaneous #1 Chamber Temperature (°C)
9 h	160	162
10 h	160	161
11 h	160	161
11 h, 20 m	160	161
11 h, 30 m	154	155
11 h, 40 m	149	150
12 h	150	151
13 h	150	151
14 h	150	151
15 h	150	151
15 h, 10 m	150	151
15 h, 20 m	147	147
15 h, 30 m	140	140
15 h, 40 m	133	134
15 h, 50 m	123	123
16 h	122	122
17 h	122	122
19 h	121	122
21 h	122	122
1 d, 1 h	122	122
1 d, 11 h	122	123
1 d, 21 h	122	123
2 d, 2 h	122	123
2 d, 12 h	122	123
2 d, 22 h	122	123
3 d, 8 h	121	123
3 d, 18 h	121	123
3 d, 23 h	121	122
4 d, 0 h, 42 m	121	123
4 d, 1 h, 11 m	111	115
4 d, 1 h, 20 m		Opened chamber
4 d, 1 h	105	87*
4 d, 1 h, 51 m	Opened chamber	
4 d, 2 h, 12 m	78*	75*
4 d, 2 h, 30 m		Reintroduced steam
4 d, 2 h 42 m	75*	106
4 d, 3 h	Reintroduced steam	
4 d, 3 h, 11 m	105	105
4 d, 8 h	104	105
4 d, 13 h	105	105
4 d, 22 h	105	105
5 d, 8 h	104	105
5 d, 18 h	105	105
6 d, 4 h	104	105
6 d, 14 h	104	105

Table 2.4 (cont.)

Elapsed Time	Sequential Chamber Temperature (°C)	Simultaneous #1 Chamber Temperature (°C)
7 d, 0 h	105	105
7 d, 10 h	105	105
7 d, 20 h	105	106
8 d, 6 h	105	106
8 d, 16 h	105	106
9 d, 2 h	105	106
9 d, 2 h, 42 m	103	104
	Steam supply failure	Steam supply failure
9 d, 3 h, 11 m	95*	96*
9 d, 4 h, 11 m	64*	75*
9 d, 5 h, 11 m	48*	56*
9 d, 6 h, 11 m	37*	45*
9 d, 8 h, 11 m	27*	33*
9 d, 10 h, 11 m	23*	28*
12 d, 4 h, 25 m	20*	20*
12 d, 4 h, 27 m	22*	21*
		Reintroduced steam
12 d, 4 h, 29 m	22*	102
12 d, 4 h, 30 m	22*	103
	Reintroduced steam	
12 d, 4 h, 31 m	105	106
12 d, 4 h, 32 m	105	106
12 d, 4 h, 45 m	104	105
12 d, 5 h	105	105
12 d, 10 h	104	105
12 d, 18 h	104	105
13 d	104	105
13 d, 10 h	104	105
13 d, 20 h	105	105
14 d, 6 h	104	105
14 d, 16 h	105	105
15 d, 2 h	104	105
15 d, 12 h	104	105
15 d, 22 h	105	105
16 d, 8 h	104	105

Table 2.4 (cont.)

Elapsed Time	Sequential Chamber Temperature (°C)	Simultaneous #1 Chamber Temperature (°C)
16 d, 18 h	105	105
17 d, 4 h	105	105
17 d, 14 h	104	105
18 d	104	105
18 d, 10 h	104	105
18 d, 20 h	104	105
19 d, 6 h	104	105
19 d, 16 h	104	105
20 d, 1 h	104	104
20 d, 11 h	105	105
20 d, 22 h	105	105
21 d, 7 h	105	106
21 d, 17 h	105	105
22 d, 3 h	105	105
22 d, 13 h	104	105
22 d, 23 h	105	106
23 d, 9 h	105	106
23 d, 19 h	105	106
24 d, 5 h	105	105
24 d, 15 h	105	106
25 d, 1 h	105	106
25 d, 1 h, 55 m		Steam shut off Chamber opened
25 d, 2 h, 15 m	105	86*
25 d, 2 h, 40 m	Steam shut off	
25 d, 2 h, 45 m	94*	70*
25 d, 3 h, 15 m	72*	61*

A XLPO B cable was wrapped on the top of two mandrels that were bolted together end to end. The top surface of the two mandrels was located 13 cm below the flange which connects the top and bottom portion of the steam chamber. Because of nonuniformities in the radiation field for most of the top mandrel, a portion of this mandrel was not used to wrap cables. The XLPO B cable was wrapped twice around the 30 cm outer diameter of the top mandrel at a distance of 19 cm to 24 cm below the top surface of the mandrel. The XLPO B cable length inside the chamber was 4.7 m. After wrapping the cable on the mandrel, the cable leads were spiraled up the inside of the mandrels to the exit ports. A rubber stopper was fed from each end of the cable and inserted into a modified Swagelok^{tm} fitting. The modified Swagelok^{tm} fitting, when tightened, compressed the rubber stopper and provided a steam seal. Figure 2.7 illustrates the simultaneous test #1 setup.

We positioned the XLPO B cable on the mandrel and prepared the cable flange penetrations prior to all aging and accident environmental exposures. Except for additional tightening of the modified Swagelok fittings, the cable lengths inside the chamber were not disturbed throughout the test. We used the stainless steel chamber as a recirculating air oven, placed it in our radiation field, and used it as a steam pressure vessel. Insulation resistance and leakage current measurements were performed by filling the chamber bottom with tap water. We did visual examinations by using a crane to raise the top part of the chamber from the bottom part. Since the cables and mandrels were completely supported by the chamber top, no damage to the cables occurred during this operation.

Each XLPO B cable lead outside the steam chamber was ~7.6 m (25 ft) long. These long segments were necessary to pass each cable from the steam chamber to the outside of the gamma irradiation cell. Insulation resistance and leakage current measurements were performed at this outside location.

2.4.2 Simultaneous Thermal and Radiation Aging

We positioned the stainless steel chamber in the gamma irradiation facility and connected it to the heater via a port in the top of the chamber. A rectangular aluminum duct along the inside wall of the chamber extended from the hot air entrance port to the bottom of the chamber. Air flow exited the duct along its entire length and was directed parallel to the walls of the chamber (see Figure 2.5). Unlike the sequential test, an auxiliary duct and blower were <u>not</u> used to remove cooler air from the top of the chamber to ensure proper mixing and better temperature

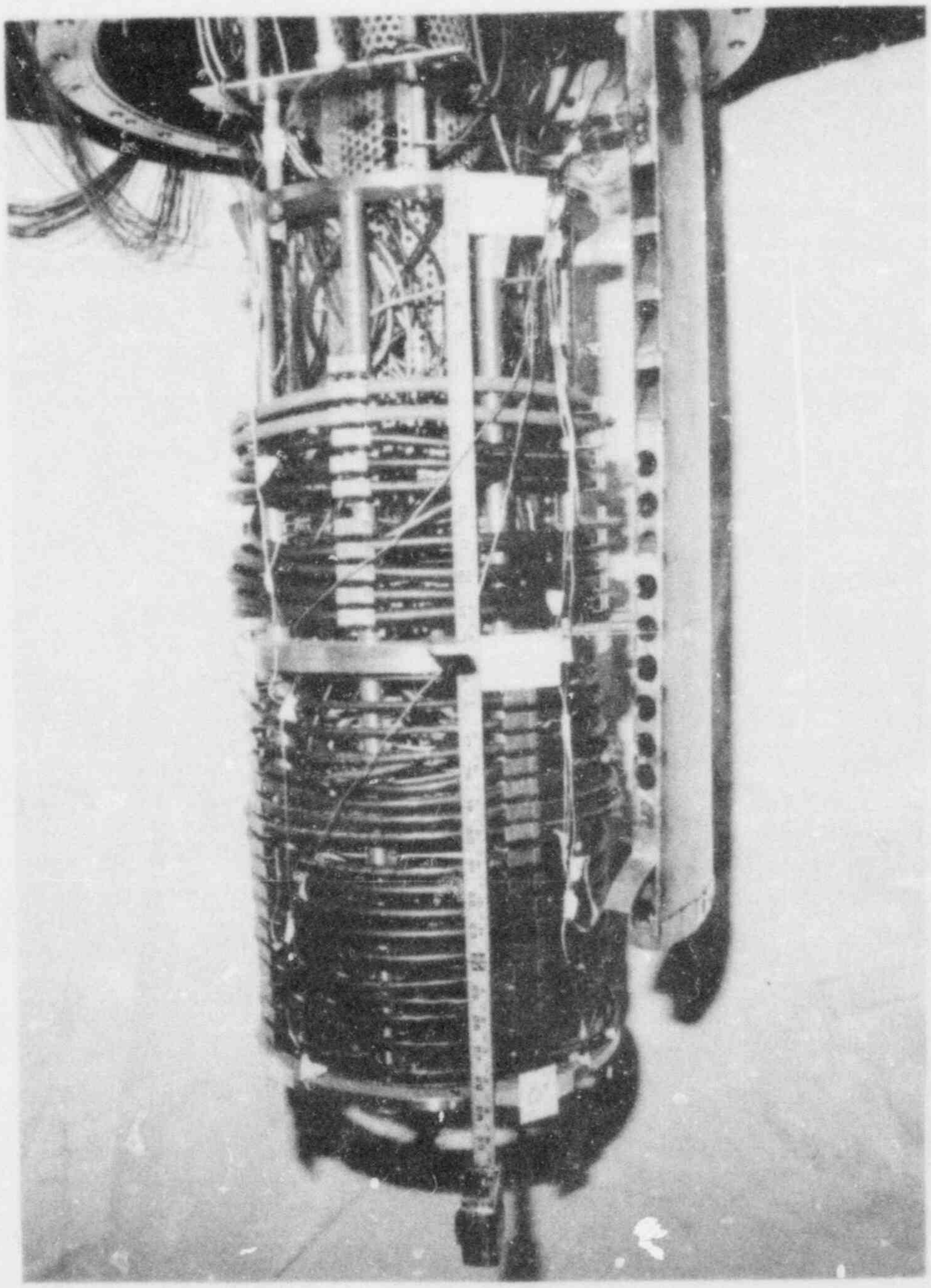

Figure 2.5. Simultaneous Test #1 Setup Prior to the Start of Thermal Aging

uniformities. Rather, during the first four and a half hours of thermal aging the heater was turned off three times and the test chamber opened to allow for adjustment of the air flow distribution from the hot air duct. (Previous measurements using a dummy load illustrated that the air flow pattern was sensitive to the cable wrapping configuration; therefore adjustments were necessary for each cable setup.) After restarting the heater the third time, the chamber overheated for approximately an hour. (Maximum temperature during the transient was 175°C.)

We thermally aged the cables for 171.5 hours and then allowed the chamber to naturally cool to ambient conditions. Since the heater was off three times for the first four and a half hours, the actual aging time was ~169 hours, similar to the 168-hour exposure used during the sequential test.

During recirculation of air from the chamber to the heater and back to the chamber, fresh air was added. We used air velocity measurements along the heater recirculation line to estimate the total air flow to the chamber as approximately 2 m^3 min. Of this, approximately 0.2 m^3 min was fresh air. This ensured that oxygen was not depleted from the chamber during aging.

Twenty thermocouples were positioned in the chamber to monitor temperature uniformity during thermal aging. Eight of these thermocouples were positioned near the XLPO B cable. One set of four thermocouples was positioned 14 cm below the top of the mandrel; another set of four thermocouples was positioned 27 cm below the top of the mandrel. The XLPO B cable was located 19 to 24 cm below the top of the mandrel. For each set of thermocouples, the thermocouples were positioned around the circumference of the mandrel, spaced 90° apart. Of the twenty thermocouples, one was used for control purposes; another was used to provide a strip chart record of the thermal exposure. The remaining 18 thermocouples were connected to a datalogger. Periodic temperature measurements were recorded throughout the thermal exposure. Table 2.5 presents the temperature distribution inside the chamber midway through the thermal exposure. Table 2.6 summarizes the temperature readings versus time for several of the thermocouple positions. As for the sequential test, the desired thermal aging exposure was seven days at 139°C (see Section 2.3.2).

For 122.5 hours of the 171.5 hour thermal exposure we simultaneously irradiated the cables and tensile specimens. We performed this radiation exposure using three irradiation time intervals:

Table 2.5

Thermocouple Readings 85 Hours After the Start of the 171-1/2 Hour Thermal Aging Exposure (Part of Simultaneous #1 Radiation and Thermal Exposure)

(a) Distance below top of mandrel (cm)	Temperature (°C) 0°	90°	180°	270°
14	137	136	137	137(7)
27	139(5)	138	139(6)	139
52	143	140(3)	---	140(4)
67	136(1)	139(2)	142	139

(b) Distance below top of mandrel (cm)	Temperature (°C)
13	135
38	142
61	139

(a) Thermocouples were positioned around the circumference of the mandrel, spaced 90° apart and within 2.5 cm of the cables. The hot air duct is close to the 0° position.

(b) Thermocouples were positioned along the outer rim of the perforated cylinder used to support tensile specimen baskets.

(c) (1)-(7) in the table indicate thermocouple positions monitored by Table 2.6.

Table 2.6

Temperature Versus Time Profile During Simultaneous #1 Thermal and Radiation Aging Exposure. Thermocouple positions (1)-(7) are identified in Table 2.5

	Temperature (°C) at Thermocouple Position						
Elapsed Time	1	2	3	4	5	6	7
0	19	19	19	19	19	18	19
20 min	128	153	165	154	102	143	116
1 hr	141	143	142	145	139	137	137
1 hr, 20 min	140	141	141	143	139	135	136
Heater off at 1 hr, 20 min							
2 hrs, 10 min	57	54	53	58	57	55	58
Heater on at 2 hr, 10 min							
2 hrs, 20 min	131	150	140	123	128	150	124
3 hrs	140	144	143	137	142	146	141
Heater off at 3 hrs							
3 hrs, 25 min	84	81	81	84	85	80	84
Heater on at 3 hrs, 25 min							
3 hrs, 40 min	138	148	143	135	137	150	140
4 hrs	141	146	145	140	143	148	144
Heater off at 4 hrs							
4 hrs, 30 min	77	75	72	74	75	77	79
Heater on at 4 hrs, 30 min							
4 hrs, 45 min	132	147	161	151	149	143	127
5 hrs	134	140	143	142	139	139	134
5 hrs, 15 min	140	145	152	150	147	144	137
5 hrs, 30 min	158	166	175	172	168	164	154
5 hrs, 45 min	155	160	163	163	160	160	155

Table 2.6 (cont.)

Elapsed Time	Temperature (°C) at Thermocouple Position 1	2	3	4	5	6	7
6 hrs	151	154	158	157	155	154	150
6 hrs, 15 min	139	141	141	141	141	143	142
6 hrs, 30 min	135	137	138	138	137	138	137
7 hrs	135	137	139	139	137	138	135
10 hrs	134	137	138	139	137	138	135
15 hrs	135	137	138	138	137	137	135
20 hrs	134	137	139	138	137	138	135
25 hrs	136	138	140	140	138	138	136
30 hrs	136	138	140	140	139	139	137
35 hrs	136	138	141	140	139	139	137
40 hrs	136	138	140	140	139	139	137
45 hrs	136	138	140	140	139	139	137
50 hrs	136	138	140	140	138	139	137
55 hrs	136	138	140	140	138	139	137
60 hrs	136	138	140	140	139	139	136
65 hrs	136	139	141	140	139	139	137
70 hrs	136	138	140	140	139	139	137
75 hrs	136	138	141	140	139	139	137
80 hrs	136	138	141	140	139	139	137
85 hrs	136	139	140	140	139	139	137
90 hrs	136	138	140	140	139	139	137
95 hrs	136	139	140	140	139	139	137
100 hrs	136	138	140	140	139	139	137
105 hrs	136	138	140	140	139	139	137
110 hrs	136	138	141	140	139	139	137
115 hrs	136	138	140	140	138	139	137
120 hrs	136	138	140	140	138	138	137
125 hrs	134	137	139	140	137	137	134
130 hrs	134	137	140	139	137	137	134
135 hrs	134	137	139	139	138	137	134
140 hrs	134	137	140	139	138	137	134
145 hrs	134	137	139	139	138	137	134
150 hrs	136	138	140	139	138	138	136
155 hrs	136	138	140	140	138	138	137
160 hrs	134	137	140	139	138	137	135
165 hrs	135	137	139	139	138	137	135
170 hrs	134	137	140	139	137	137	134
171-1/2 hrs	135	137	140	139	138	137	135
172 hrs	93	90	91	92	91	89	--
173 hrs	36	27	25	27	39	25	28

- 114-hour exposure starting 6 hours, 40 minutes after the start of the thermal aging exposure

- 1 hour, 10-minute exposure starting 146 hours after the start of the thermal aging exposure

- 6 hours, 20-minute exposure starting 148 hours after the start of the thermal aging exposure

The irradiation was interrupted because of an increased ozone presence. This unanticipated occurrence is further discussed in Appendix A.

After completion of the simultaneous radiation and thermal exposures, we performed room temperature dosimetry to establish the aging dose rate. A Victoreen Radicon Model 550 Integrating/Rate Electrometer with a Model 550 air ionization probe was used to measure the dose rate at one position along the centerline of the chamber. Fifty-two Harshaw TLD-400's (calcium fluoride manganese activated thermoluminescent detectors) were placed at 25 positions to map the relative dose rates with respect to the Victoreen measurement. Table 2.7 summarizes the irradiation profile data for simultaneous test #1. The XLPO B cable (located 19 cm to 24 cm below the top surface of the mandrel) received a dose rate of .30 ± .03 Mrd/h (air-equiv.). Thus, the total aging radiation dose was 37 ± 4 Mrd (air-equiv.).

In addition to mapping the aging dose rate profile, we also mapped the dose rate profiles for each of the three Co-60 source arrangements that were used during the simultaneous radiation and steam exposures. This data is presented in Table 2.7. For the XLPO B cable which was located 19 to 24 cm below the top of the mandrel, the three accident dose rates were .62 ± .05 Mrd/h; .14 ± .01 Mrd/h, and .07 + .05/-.04 Mrd/h.

At completion of the simultaneous aging program we did both a visual inspection and insulation resistance measurements. The entire chamber with cables was then stored at ambient conditions until the start of the LOCA steam and radiation simulation (8 days after completion of the aging exposure).

2.4.3 Simultaneous Steam and Radiation Exposure

Figure 2.6 summarizes our intended steam and radiation profile while Table 2.4 summarizes the achieved test conditions. Our exposure profile is similar to the IEEE 323-1974, Appendix B profile,[4] but also different in several respects, most notably:

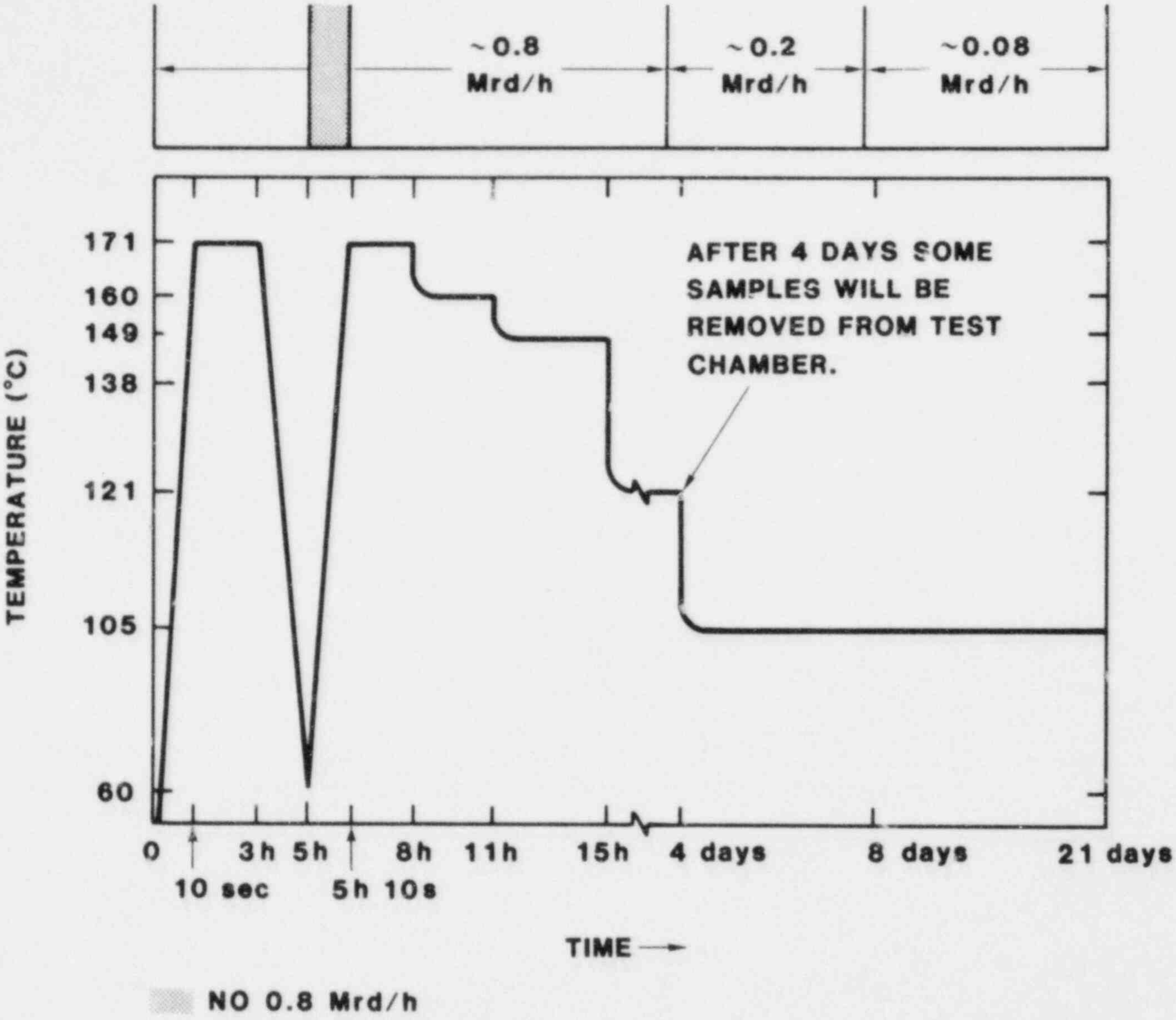

Figure 2.6. Simultaneous Test #1 Accident Exposure Profile (as proposed by test plan). Pressures correspond to saturated steam conditions in Albuquerque, New Mexico (171°C corresponds to 106 psig).

Table 2.7

Radiation Dose Rates (air-equiv) Used During Simultaneous Test #1. Measurements were Performed at Ambient Air Conditions upon Completion of the Aging Exposure

Measurement location below top of mandrel	Aging Dose Rate (Mrd/h)	Accident Dose Rates* (Mrd/h)		
		1	2	3
50 cm (along centerline)	.32 ± .01	.62 ± .03	.16 ± .01	.062 ± .002
Within 2.5 cm of the cables		Average of several measurement locations around circumference of the mandrel.		
14 cm	.28 ± .03	.59 ± .05	.13 ± .01	$.06^{+.04}_{-.03}$**
37 cm	.34 ± .03	.67 ± .05	.17 ± .02	$.08^{+.06}_{-.05}$**
55 cm		.77 ± .06		
72 cm	.32 ± .03	.68 ± .05	.17 ± .02	.07 ± .01

*The three different dose rates columns refer to the three Co-60 configurations used during simultaneous test #1.

**Large uncertainties reflect gradients in radiation field.

1. After four days of steam exposure we interrupted the steam exposure to remove baskets containing EPR tensile specimens. The chamber temperature dropped to ~75°C during the interruption (Table 2.4). XLPO B tensile specimens were not included in simultaneous test #1.

2. We used a 104°C saturated steam exposure after four days until the end of the test.

3. We did not apply chemical spray during the exposure.

4. We did not start our transient ramps at 60°C.

As allowed by IEEE 323-1974, Appendix A, we followed the temperature profile and allowed the pressure to correspond to saturated conditions for Albuquerque, New Mexico (171°C corresponds to 106 psig).

Two nonconformances kept us from achieving the intended steam and radiation profile.

1. The initial ramp was achieved in less than 30 seconds (see Table 2.4). However, a steam leak in the sequential chamber resulted in the simultaneous chamber cooling to 150°C during the first 13 minutes of the profile. We added 15 minutes to the duration of the first peak of the profile.

2. On day 9 of the steam exposure our steam supply system failed and the steam chamber cooled to ambient temperatures and pressures. Twenty-one hours later we stopped the irradiation of the samples. On day 11 we opened the chamber and performed ambient insulation resistance measurements as well as a visual inspection. We resumed the steam and radiation exposures on day 12 and continued these exposures until day 25. Our total steam exposure lasted 21 days.

Table 2.4 summarizes our steam temperatures during the simultaneous test #1. The steam conditions for the sequential test are also provided to illustrate the similarities between the sequential and simultaneous #1 test. Note: both steam chambers were connected in parallel to the steam supply system.

Table 2.8 presents the accident irradiation history for the XLPO B cable in simultaneous test #1. The total accident dose was 99 ± 23 Mrd (air-equiv.). This gives a total accident and aging dose of 136 ± 27 Mrd (air-equiv.) For comparison, the sequential test total dose was 150 ± 12 Mrd (air-equiv.).

Table 2.8

Simultaneous Test #1 Accident Irradiation History for XPLO B. Reported dose rates are air equivalent values

Time	Total Accident Dose (air equiv)	Event
0 hrs	0	Start 1st steam ramp
0 hrs, 30 min	0	Start irradiation at .62 Mrd/h
5 hrs	2.8 ± .2	Stop irradiation and prepare for 2nd steam ramp
5 hrs, 15 min	2.8 ± .2	Start 2nd steam ramp
5 hrs, 23 min	2.8 ± .2	Start irradiation at .62 Mrd/h
4 d, 1 hr, 5 min	60 ± 5	Stop irradiation and prepare to remove EPR tensile specimens
4 d, 1 hr, 20 min	60 ± 5	Open steam chamber to remove EPR tensile specimens
4 d, 2 hr, 30 min	60 ± 5	Restart steam exposure
4 d, 3 hr, 15 min	60 ± 5	Restart irradiation at .14 Mrd/h
8 d, 2 hr	74 ± 6	Reduce irradiation to .07 Mrd/h
9 d, 3 hr	76 ± 7	Unanticipated cooldown of steam chamber begins
9 d, 23 hr	77 ± 8	Stopped irradiation
11 d, 4 hr, 30 min	77 ± 8	Restarted steam exposure
11 d, 4 hr, 45 min	77 ± 8	Restarted irradiation (.07 Mrd/h)
24 d, 1 hr, 50 min	99 ± 23	Stopped radiation and steam exposures, opened chamber to removed tensile specimens

Throughout the steam exposure the XLPO B cable was loaded at 480 Vac and 0.6 A. This exposure was interrupted to allow for insulation resistance measurements and during the unanticipated cooldown.

At the completion of the steam exposure and after the chamber had cooled, we performed a visual examination and then filled the chamber with tap water. Insulation resistance and leakage current measurements were then performed. These measurements were made without disturbing the cables that were wrapped on the mandrels. We did not follow the procedures of IEEE Std 383-1974,[2] Section 2.4.4 which states that the cables "should be straightened and recoiled around a mandrel with a diameter of approximately 40 times the overall cable diameter" prior to performing the voltage withstand tests.

2.5 Simultaneous Test #2

2.5.1 Test Setup

Ten XLPO, eight EPR, and two TEFZEL cable lengths were exposed during simultaneous test #2. XLPO, EPR, and TEFZEL insulation tensile specimens were also exposed during the test. The EPR test results have been previously reported.[1]

The simultaneous test #2 was performed using a stainless steel steam chamber with ~0.4 m^3 of internal volume. The height is 200 cm and the diameter 52 cm. The top portion of the chamber (43 cm in length) contained all the penetration flanges through which cables, thermocouples, and other instrumentation entered and exited the chamber. The mandrels on which the cables were wrapped were suspended from the top portion of the chamber but were physically located inside the bottom portion of the chamber. This latter section of the chamber is 81 cm long. During both the aging and the accident exposures the chamber was supported as shown in Figure 2.1. This allowed for a simultaneous radiation exposure with the thermal aging and the accident steam exposures.

Cables were wrapped on three mandrels that were bolted together end to end. The top of the mandrels was located 13 cm below the flange which connects the top and bottom portion of the steam chamber. Because of nonuniformities in the radiation field for most of the top mandrel, all of the cables were wrapped on the bottom two mandrels. We wrapped the single conductors on the inside of the mandrels using a 25 cm diameter. The multiconductors were wrapped on the outside of the mandrel on a 30 cm diameter. After wrapping the cables on the mandrels, the cable leads were spiraled up the inside of the mandrels to the exit ports.

A rubber stopper was fed from each end of the cable and inserted into a modified Swagelok^{tm} fitting. The modified Swagelok^{tm} fitting, when tightened, compressed the rubber stopper and provided a steam seal. Figure 2.7 illustrates the simultaneous test #2 setup.

We positioned the cables on the mandrels and prepared the cable flange penetrations prior to all aging and accident environmental exposures. Except for additional tightening of the modified Swagelok fittings, the cable lengths inside the chamber were not disturbed throughout the test. We used the stainless steel chamber as a recirculating air oven, placed it in our radiation field, and used it as a steam pressure vessel. Insulation resistance and leakage current measurements were performed by filling the chamber bottom with water. We did visual examinations by using a crane to raise the top part of the chamber from the bottom part. Since the cables and mandrels were completely supported by the chamber top, no damage to the cables occurred during this operation.

Each cable lead outside the steam chamber was ~7.6 m (25 ft) long. These long segments were necessary to pass each cable from the steam chamber to the outside of the gamma irradiation cell. Insulation resistance and leakage current measurements were performed at this outside location.

Table 2.9 lists each XLPO cable placed in the chamber for simultaneous #2 testing. (Note: Several EPR and TEFZEL cables were also tested and are not listed.) The total length of each cable inside the steam chamber is given as well as each cable's location on the mandrel.

A perforated stainless steel cylinder was positioned along the centerline of the mandrels. Two 23 cm (9 in) long perforated stainless steel baskets containing XLPO, EPR, and TEFZEL insulation specimens were placed inside this cylinder during the aging and accident exposures.

2.5.2 Simultaneous Thermal and Radiation Aging

We positioned the stainless steel chamber in the gamma irradiation cell and connected it to a heater and blower. Airflow from the heater passed through a manifold containing twenty valves. Each valve was connected to a copper tube which entered a port to the interior of the chamber. The copper tubes were bundled into groups of 5 tubes and positioned vertically 90° apart around the circumference of the mandrel. Holes in the tubes directed airflow away from the cables towards the wall of the chamber. (Figure 2.7 illustrates the thermal aging setup.) Airflow to different positions in the chamber was controllable by valve adjustments external to the chamber. Hence we were able to adjust the temperature uniformity inside the chamber after the start of

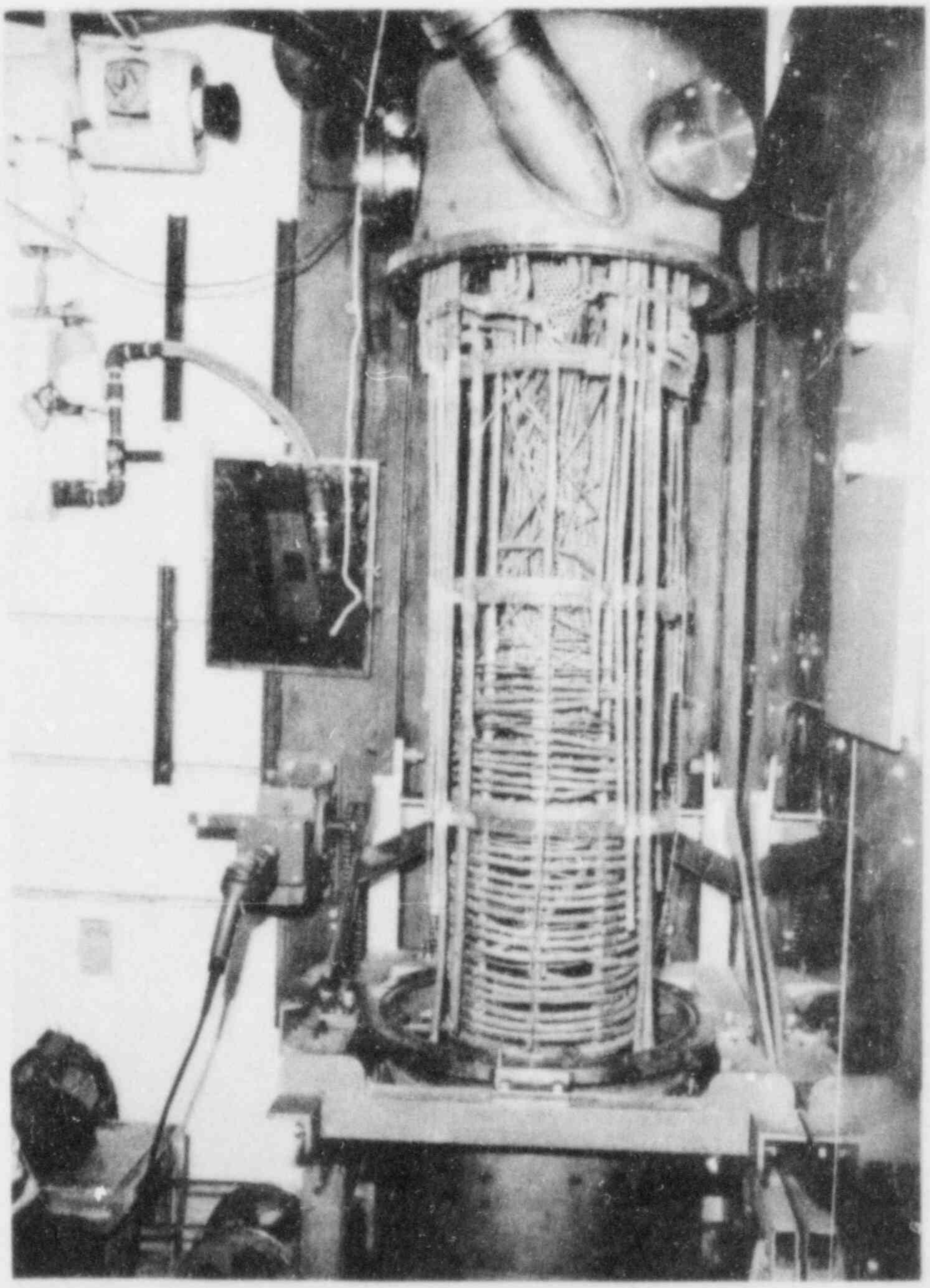

Figure 2.7. Simultaneous Test #2 Setup at the Completion of Aging

Table 2.9

Cable Positions on Mandrel During Simultaneous Test #2

Cable Description*		Cable Length Inside Chamber (m)	Distance Below Top of Mandrel (cm)
25 cm diameter wrappings			
XLPO B:	insulated single conductor #1	5.4	44-46
XLPO A:	insulated single conductor #2	5.2	58-61
XLPO B:	insulated single conductor #2	5.2	63-66
XLPO A:	insulated single conductor #1	5.7	87-91
30 cm diameter wrappings			
XLPO C:	multiconductor #2	6.2	53-58
XLPO C:	multiconductor #1	6.0	62-65
XLPO A:	multiconductor #2	6.4	66-70
XLPO B:	multiconductor #2	6.9	79-84
XLPO A:	multiconductor #1	7.1	92-97
XLPO B:	multiconductor #1	7.0	98-105

*TEFZEL and EPR cables were also wrapped on the mandrel during this test.

thermal aging without opening the chamber (as was done for simultaneous test #1).

We thermally aged the cables for 169 hours and then allowed the chamber to cool to ambient conditions. During thermal aging, airflow from the heater to the chamber included fresh air. We used air velocity measurements along the heater recirculation line to estimate the total airflow to the chamber as approximately 1.4 m^3/min. Of this, approximately 0.2 m^3/min was fresh air. This ensured that oxygen was not depleted from the chamber during aging.

Twenty-four thermocouples were positioned in the chamber to monitor temperature uniformity during thermal aging. We positioned five of the thermocouples at three positions along the outer rim of the stainless steel perforated cylinder used to support tensile specimen baskets. Seventeen thermocouples were positioned at 16 different locations within 2.5 cm of the cables wrapped on the mandrels. Two thermocouples were positioned near the top of the chamber at the exit ports. Twenty-two of these thermocouples were connected to a datalogger, one was connected to a strip chart recorder, another was used for control purposes. Table 2.10 presents the temperature distribution midway through the thermal exposure. Table 2.11 summarizes the temperature values versus time for several of the thermocouple positions. As for the sequential test, the desired thermal aging exposure was seven days at 139°C (see Section 2.3.2). In addition to the XLPO and Neoprene materials previously discussed, simultaneous test #2 included CSPE multiconductor jacketing for XLPO A and XLPO C. The activation energy for CSPE (a different manufacturer) is 1.07 eV,[8] slightly conservative compared to the 1.04 eV assumed in Section 2.3.2.

For 143 hours of the 169 hour thermal exposure we simultaneously irradiated the cables and tensile specimens. This radiation exposure was continuous. We used our simultaneous test #1 dosimetry corrected for Co-60 decay to estimate the gamma dose rates during aging (see Table 2.12). The average dose rate was .30 ± .03 Mrd/h (air-equiv). Thus the aging radiation dose was 43 ± 4 Mrd.

At completion of the simultaneous aging program we performed a visual inspection, insulation resistance and AC leakage current measurements. The entire chamber with cables was then stored at ambient conditions until the start of the LOCA steam and radiation simulation (eight days after completion of the aging exposure.)

2.5.3 Simultaneous Steam and Radiation Exposure

Figure 2.8 summarizes our intended steam and radiation profile while Table 2.13 summarizes the achieved test

Table 2.10

Thermocouple Readings 85 Hours After the Start of a 169 Hour Thermal Aging Exposure (Part of simultaneous #2 Radiation and Thermal Exposure)

(a) Distance below top of mandrel (cm)	Temperature (°C) 0°	 90°	 180°	 270°
44 cm	140	139	140	142(7)
67 cm	142	140(5)	140	141(6)
91 cm	140(3)	139	141(4)	140
111 cm	133	132	140(1)	130(2)

(b) Distance below top of mandrel (cm)	Temperature (°C)
40	138
58	137
99	133

(a) Thermocouples were positioned around the circumference of the mandrel, spaced 90° apart and within 2.5 cm of the cables. The copper heating tubes were also positioned around the circumference of the mandrel, spaced 90° apart, and displaced 45° from the thermocouples.

(b) Thermocouples were positioned along the outer rim of the perforated cylinder used to support tensile specimen baskets.

(c) (1)-(7) in the table indicate thermocouple positions monitored by Table 2.11.

Table 2.11

Temperature Versus Time Profile During Simultaneous Test #2 Thermal and Radiation Aging Exposure. Thermocouple Positions (1)-(7) are Identified in Table 2.10

	Temperature (°C) at Thermocouple Position						
Elapsed Time	1	2	3	4	5	6	7
0 hrs	34	35	34	35	35	35	35
0 hrs, 18 min	81	78	74	83	79	85	77
0 hrs, 28 min	103	97	96	106	102	107	102
0 hrs, 48 min	133	124	128	136	134	139	137
0 hrs, 58 min	144	135	138	147	145	150	149
1 hr, 8 min	147	136	142	147	148	150	151
1 hr, 18 min	139	129	136	138	140	141	143
1 hr, 28 min	133	125	130	133	133	137	139
2 hrs	133	131	136	138	140	141	142
3 hrs	136	129	140	137	138	141	142
4 hrs	140	133	139	140	137	140	141
5 hrs	142	132	141	143	138	141	142
10 hrs	140	131	140	141	137	139	140
15 hrs	141	132	140	141	138	140	141
20 hrs	140	131	140	141	138	138	141
25 hrs	140	130	139	141	139	140	141
30 hrs	139	129	139	140	138	140	141
35 hrs	139	129	139	140	138	139	141
40 hrs	140	130	140	141	140	140	142
45 hrs	140	130	140	142	140	141	142
50 hrs	140	130	140	141	139	140	142
55 hrs	140	130	140	141	140	140	142
60 hrs	140	130	140	141	139	140	142
65 hrs	paper feed failure						
70 hrs	140	130	140	141	140	141	142
75 hrs	140	129	140	141	139	141	142
80 hrs	140	130	140	142	140	141	142
85 hrs	140	130	140	141	140	141	142
90 hrs	140	130	140	142	140	141	143
95 hrs	139	129	140	141	140	140	142
100 hrs	140	129	140	142	140	141	142
105 hrs	139	129	140	142	140	141	142
110 hrs	140	130	141	142	140	142	143
115 hrs	139	128	140	142	140	141	142
120 hrs	139	129	140	142	140	141	142
125 hrs	139	129	140	142	140	141	142
130 hrs	139	128	140	142	140	141	142
135 hrs	139	128	140	142	140	141	143

Table 2.11 (cont.)

	Temperature (°C) at Thermocouple Position						
Elapsed Time	1	2	3	4	5	6	7
140 hrs	138	128	139	141	139	140	142
145 hrs	139	128	140	142	140	141	143
150 hrs	138	128	140	142	140	141	143
155 hrs	138	128	148	141	140	141	142
160 hrs	138	128	140	142	140	141	143
165 hrs	139	130	141	142	139	141	142
169 hrs	139	131	141	142	139	140	141
170.5 hrs	64	68	64	64	65	65	69
172.5 hrs	41	41	41	41	40	41	41

Table 2.12

Radiation Dose Rates (air-equiv.) Used During Simultaneous Test #2. Dose Rates were Calculated from Table 2.7 Data Allowing for Eight Months Co-60 Decay Between Exposures

Measurement location below top of mandrel	Aging Dose Rate (Mrd/h)	Accident Dose Rates* Mrd/h 1	2	3
50 cm (along centerline)	.29 ± .01	.57 ± .03	.15 ± .01	.057 ± .002
Within 2.5 cm of the cables				
14 cm	.26 ± .03	.54 ± .05	.12 ± .01	.06 ± .04** .03
37 cm	.31 ± .03	.61 ± .05	.16 ± .02	.07 ± .05
55 cm		.71 ± .06		
72 cm	.29 ± .03	.62 ± .05	.16 ± .02	.06 ± .01

*The three different dose rate columns refer to the three Co-60 configurations used during simultaneous test #2.

**Large uncertainties reflect gradients in radiation field.

Note: Co-60 pencils extend from 10 cm to 130 cm below the top of the mandrel. Hence the 72 cm dosimetry data is applicable to those cables and tensile specimens positioned between 72 and 111 cm below the mandrel.

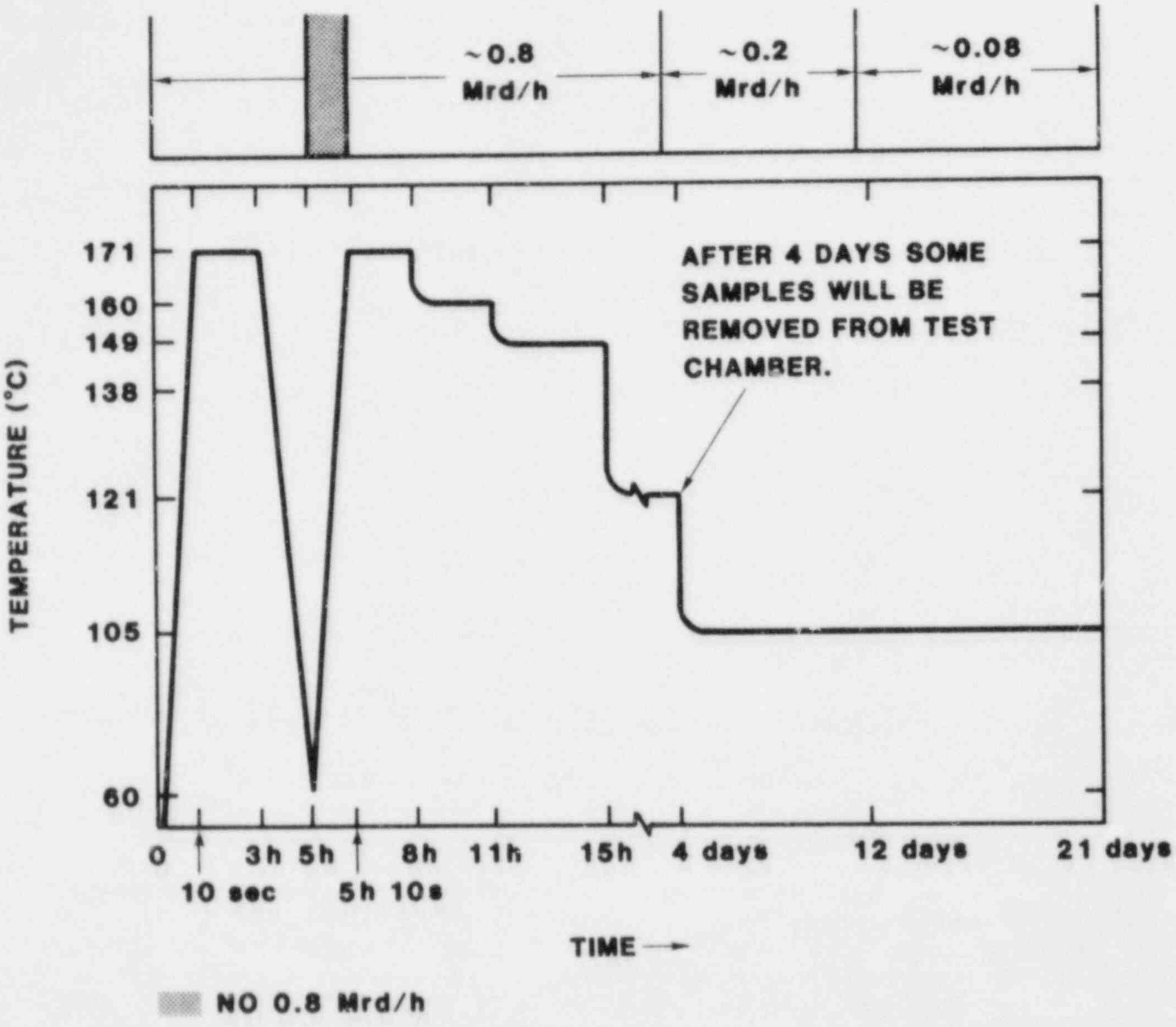

Figure 2.8. Simultaneous Test #2 Accident Profile (as proposed by test plan). Pressures correspond to saturated steam conditions in Albuquerque, New Mexico (171°C corresponds to 106 psig).

conditions. Our steam profile is similar to the IEEE 323-1974, Appendix B profile,[3] but also different in several respects, most notably:

1. After four days of steam exposure we interrupted the steam exposure to remove baskets containing tensile specimens. The chamber temperature dropped to ~88°C during the interruption (Table 2.13).

2. We used a 104°C saturated steam exposure after four days until the end of the test.

3. We did not apply chemical spray during the exposure.

4. We did not start our transient ramps at 60°C.

As allowed by IEEE 323-1974, Appendix A, we followed the temperature profile and allowed the pressure to correspond to saturated steam conditions for Albuquerque, New Mexico (171°C corresponds to 106 psig).

Three nonconformances kept us from achieving the steam and radiation profile.

1. Prior to the first ramp we momentarily passed steam through the chamber (which was open to ambient conditions).

2. During the first 171°C saturated steam peak, water accumulated in the bottom of the steam chamber and submerged some cables. We estimate the maximum water level as between 67 and 91 cm below the top of the mandrel. (See Table 2.9 for cable positions.) We drained the water from the chamber 1-1/2 hours after the start of the first steam peak. This problem did not recur.

3. On day 16 of the steam exposure our steam supply system failed and the steam chamber cooled to ambient temperatures and pressures. Eight hours later we stopped the irradiation of the samples. On day 18 we opened the chamber and performed ambient insulation resistance and leakage resistance measurements. We also performed a visual inspection. We removed all the tensile specimens. On day 21 we resumed the steam and radiation exposures for the cables. We ended these exposures on day 25 for a total steam exposure of 21 days.

Table 2.13 summarizes our steam temperatures during simultaneous test #2. Table 2.14 presents the accident irradiation history. The total accident dose was 106 ± 20 Mrd (air-equiv). This gives a total accident and aging dose of 149 ± 24 Mrd (air-equiv).

Table 2.13

Steam Profile Achieved During Simultaneous Test #2. Except during transient ramps and where noted,*, the temperatures correspond to saturated steam conditions in Albuquerque, New Mexico. An * indicates the chamber was opened to remove samples or that saturated steam conditions were not maintained

Elapsed	Chamber temperature (°C) at distance below top of mandrel			
	111 cm	91 cm	67 cm	44 cm
0 hrs	26*	22*	30*	27*
momentarily passed steam through the chamber				
10 sec	75*	88*	85*	86*
20 sec	65*	79*	78*	79*
30 sec	60*	72*	71*	74*
40 sec	56*	65*	66*	70*
1 min	52*	57*	60*	67*
2 min	49*	51*	55*	61*
2 min, 30 sec	49*	50*	54*	60*
First ramp started; water accumulation				
2 min, 40 sec	142*	162*	157*	165*
2 min, 50 sec	143*	165*	169*	171*
3 min	---	169*	170*	171*
4 min	135*	167*	171*	171*
5 min	137*	165*	171*	171*
17 min	141*	160*	169*	171*
27 min	141*	159*	169*	171*
1 hr	140*	157*	168*	171*
1 hr, 17 min	144*	159*	166*	168*
1 hr, 27 min	146*	159*	166*	168*
Start drawing water from chamber				
1 hr, 37 min	168*	169*	170*	170*
1 hr, 47 min	171	172	172	171
2 hrs	171	172	172	172
3 hrs	171	172	171	171
3 hrs, 17 min	171	172	172	172
3 hrs, 37 min	165	165	165	165
4 hrs	156	156	156	156
4 hrs, 27 min	138	138	138	138
5 hrs	116	117	116	116
5 hrs, 20 min	100	104	103	105
5 hrs, 20 min, 10 sec	130	136	127	143
5 hrs, 20 min, 20 sec	162	162	162	164
5 hrs, 20 min, 30 sec	171	171	171	171
6 hrs	171	171	171	171
7 hrs	171	171	171	171
8 hrs	171	171	171	171

Table 2.13 (cont.)

	Chamber temperature (°C) at distance below top of mandrel			
Elapsed	111 cm	91 cm	67 cm	44 cm
8 hrs, 20 min	171	172	171	171
8 hrs, 30 min	169	170	170	170
9 hrs	160	161	161	161
10 hrs	160	161	160	160
11 hrs	161	161	161	161
11 hrs, 40 min	160	160	160	161
11 hrs, 50 min	158	158	158	158
12 hrs	152	153	152	153
12 hrs, 10 min	149	149	149	149
13 hrs	149	150	149	149
15 hrs	149	149	149	149
15 hrs, 20 min	140	140	140	140
15 hrs, 30 min	133	133	133	133
15 hrs, 40 min	123	123	124	123
15 hrs, 50 min	121	122	121	121
16 hrs	121	121	121	122
20 hrs	121	122	121	122
1 d, 6 hrs	122	122	122	122
1 d, 16 hrs	122	122	122	122
2 d, 2 hrs	122	122	122	122
2 d, 12 hrs	122	122	122	122
2 d, 22 hrs	122	122	122	122
3 d, 8 hrs	122	122	122	122
3 d, 18 hrs	122	122	122	122
4 d, 20 min	121	121	121	121
Opened chamber				
4 d, 50 min	90*	90*	90*	89*
4 d, 1 hr, 20 min	88*	88*	88*	88*
Reintroduced steam				
4 d, 1 hr, 50 min	105	106	106	106
4 d, 4 hrs	105	105	105	105
4 d, 14 hrs	105	106	106	106
5 d	105	106	106	106
5 d, 10 hrs	105	105	105	105
5 d, 20 hrs	106	106	106	106
6 d, 6 hrs	105	105	105	105
6 d, 16 hrs	105	106	106	106
7 d, 2 hrs	105	105	105	105
7 d, 12 hrs	106	106	106	106
7 d, 22 hrs	106	106	106	106
8 d, 8 hrs	106	106	106	106
8 d, 18 hrs	106	107	107	106
9 d, 4 hrs	106	106	106	106
9 d, 14 hrs	106	106	106	106
10 d	106	106	106	106
10 d, 10 hrs	106	106	106	106

Table 2.13 (cont.)

Elapsed	Chamber temperature (°C) at distance below top of mandrel 111 cm	91 cm	67 cm	44 cm
10 d, 20 hrs	105	106	106	106
11 d, 6 hrs	105	105	105	105
11 d, 16 hrs	106	106	106	106
12 d, 2 hrs	106	106	106	106
12 d, 12 hrs	106	106	106	106
12 d, 22 hrs	106	106	106	106
13 d, 8 hrs	106	106	106	106
13 d, 18 hrs	105	106	106	105
14 d, 4 hrs	105	106	106	106
14 d, 14 hrs	106	106	106	106
15 d	107	107	107	107
15 d, 10 hrs	106	106	106	106
15 d, 20 hrs	106	106	106	106
16 d, 6 hrs	106	106	106	106
16 d, 14 hrs	105	105	105	105
Steam supply failure				
16 d, 15 hrs	92*	93*	92*	93*
16 d, 17 hrs	60*	61*	62*	61*
16 d, 19 hrs	47*	47*	47*	48*
16 d, 21 hrs	40*	40*	40*	40*
16 d, 23 hrs	36*	36*	36*	36*
17 d	35*	35*	35*	35*
17 d, 5 hrs	32*	32*	32*	32*
17 d, 10 hrs	31*	31*	31*	31*
17 d, 20 hrs	30*	29*	30*	30*
21 d, 1 hr, 42 min	27*	28*	28*	29*
21 d, 1 hr, 43 min	27*	28*	29*	32*
21 d, 1 hr, 44 min	28*	30*	102*	102*
Reintroduced steam				
21 d, 1 hr, 45 min	103	103	103	103
21 d, 1 hr, 46 min	105	105	105	105
21 d, 2 hrs	105	105	105	105
21 d, 5 hrs	106	105	106	106
21 d, 10 hrs	105	106	105	106
21 d, 20 hrs	105	105	106	106
22 d, 6 hrs	105	105	105	105
22 d, 16 hrs	105	106	106	106
23 d, 2 hrs	105	105	106	105
23 d, 12 hrs	105	106	106	106
23 d, 22 hrs	106	107	107	106
24 d, 8 hrs	105	105	105	105
24 d, 18 hrs	105	105	105	105
25 d, 4 hrs	105	106	106	106
Steam turned off				

Table 2.14

Simultaneous Test #2 Accident Irradiation History. Reported Dose Rates are Air Equivalent Values Obtained from Table 2.12 (Average Values for the 37, 55, and 72 cm Measurement Locations)

Time	Total Accident Dose (air equiv)	Event
0 hrs	0	Start steam exposure
0 hrs, 14 min	0	Start irradiation at .65 Mrd/h
5 hrs, 8 min	3.3 ± .3 Mrd	Stop irradiation and prepare for 2nd steam ramp
5 hrs, 20 min	3.3 ± .3 Mrd	Start 2nd steam ramp
5 hrs, 34 min	3.3 ± .3 Mrd	Start irradiation at .65 Mrd/h
4 d, 20 min	63 ± 5 Mrd	Stop irradiation and prepare to remove tensile specimens
4 d, 1 hr, 25 min	63 ± 5 Mrd	Restart steam exposure
4 d, 1 hr, 43 min	63 ± 5 Mrd	Start irradiation at .16 Mrd/h
5 d, 2 hr	67 ± 5 Mrd	Interrupt irradiation for 12 minutes
11 d, 23 hr, 20 min	93 ± 9 Mrd	Reduce irradiation to .06 Mrd/hr
12 d, 22 hr	94 ± 10 Mrd	Interrupted irradiation for 14 minutes
12 d, 21 hr, 50 min	97 ± 13 Mrd	Switched Co-60 configuration, dose rate = .06 Mrd/h
16 d, 14 hr	99 ± 14 Mrd	Start of unanticipated cooldown
16 d, 23 hr, 35 min	100 ± 15 Mrd	Stop irradiation
21 d, 1 hr, 45 min	100 ± 15 Mrd	Restart steam exposure
21 d, 4 hrs, 14 min	100 ± 15 Mrd	Restart irradiation at .06 Mrd/h
25 d, 4 hrs	106 ± 20 Mrd	End steam and radiation exposure

Throughout most of the steam exposure the cables were loaded at 480 Vac and 0.6 A. Exceptions were during the first transient peak (severe water leakage from the Tefzel cables also in the chamber required us to disconnect the loading circuit temporarily; see Appendix A), during insulation resistance measurements, and during the unanticipated cooldown period.

During the unanticipated cooldown we removed the tensile insulation specimens and then weighed them and measured their dimensions. These samples were not reinserted into the chamber prior to restarting the steam exposure.

At the completion of the steam and radiation exposures we performed a visual examination and then filled the chamber with water. Insulation resistance and leakage current measurements were then performed. These measurements were made without disturbing the cables that were wrapped on the mandrels. We did not follow the procedures of IEEE 383-1974, Section 2.4.4, which states that the cables "should be straightened and recoiled around a mandrel with a diameter of approximately 40 times the overall cable diameter" prior to performing the voltage withstand tests.

3.0 Results

3.1 Electrical Results

Two XLPO A multiconductor cables, two XLPO A single conductor cables, two XLPO B multiconductor cables, two XLPO B single conductor cables, and two XLPO C multiconductor cables were exposed during simultaneous test #2. A single XLPO B multiconductor cable was exposed during the sequential test. A second XLPO B multiconductor cable was exposed during simultaneous test #1.

Insulation resistance (I.R.) measurements were performed periodically throughout the aging and accident exposures. I.R. values were measured after a one minute 500 Vdc electrification. For a few measurements, the I.R. values were less than the range of our megohmeter at 500 Vdc. We reduced the applied voltage to 100 Vdc and repeated the measurement. (These I.R. values are marked on the figures as 100 V values.)

Figures 3.1 and 3.2 illustrate the I.R. behavior for the XLPO A single conductors and multiconductors, respectively. Figures 3.3 and 3.4 provide I.R. values for the XLPO B single conductors and multiconductors, respectively, while Figure 3.5 demonstrates the I.R. performance of the XLPO C multiconductors. For the single conductors, we measured the I.R. between the conductor and the grounded steam chamber (which contained either steam or water). For the XLPO A multiconductors, we measured I.R. between the conductor and

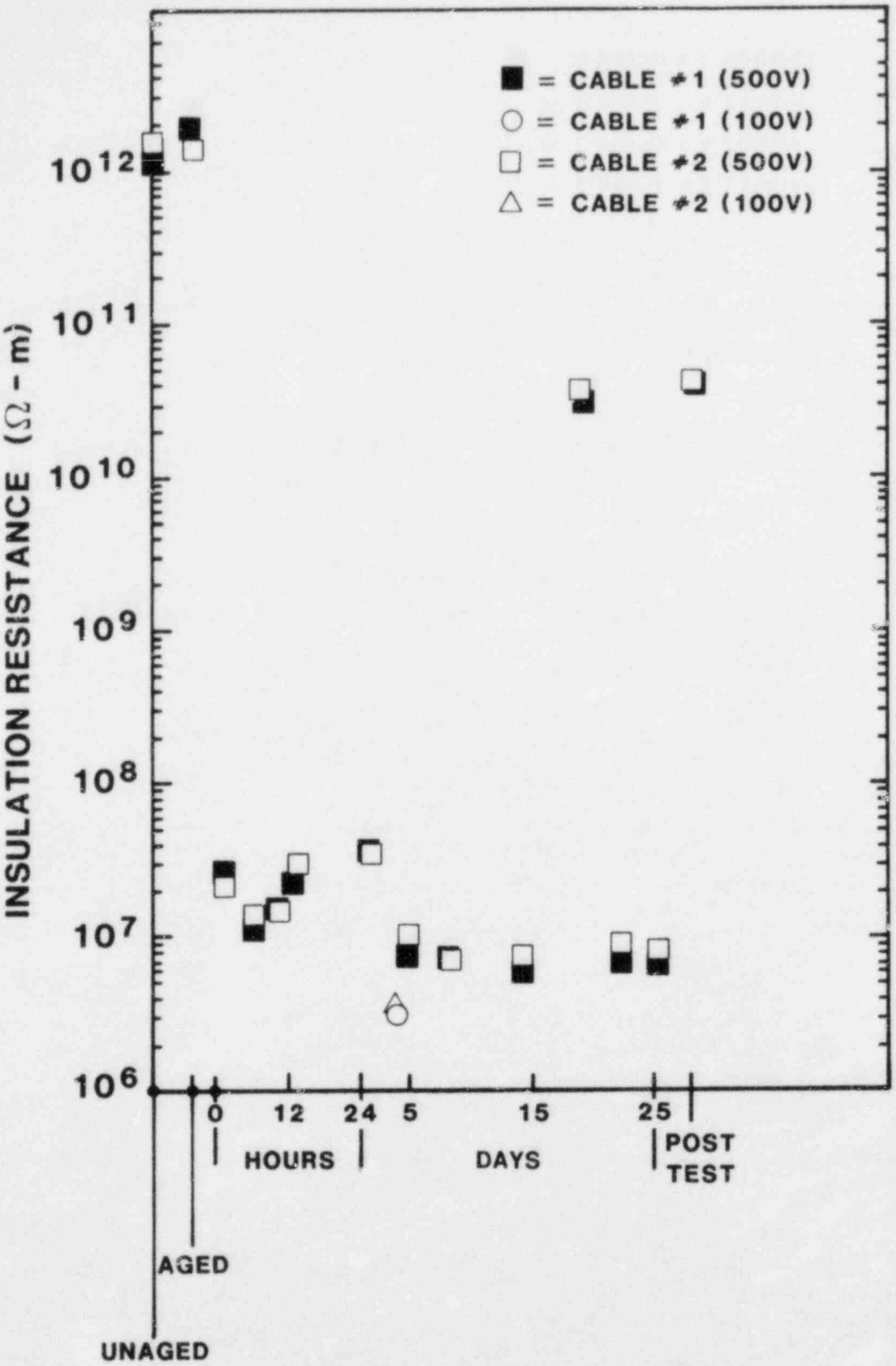

Figure 3.1. Insulation Resistance for XLPO A Single Conductors During Simultaneous Test #2

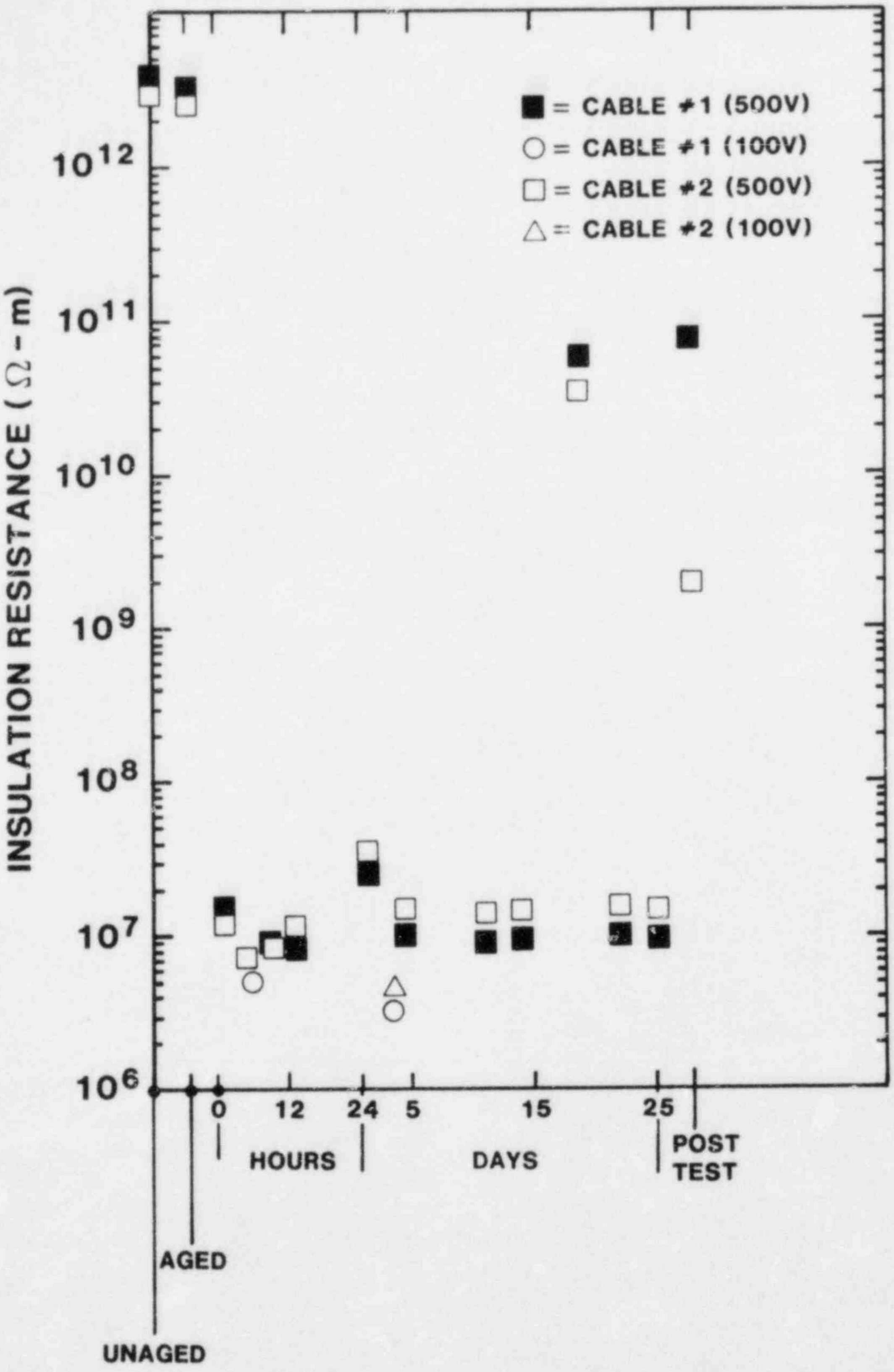

Figure 3.2. Insulation Resistance for XLPO A Multiconductors During Simultaneous Test #2

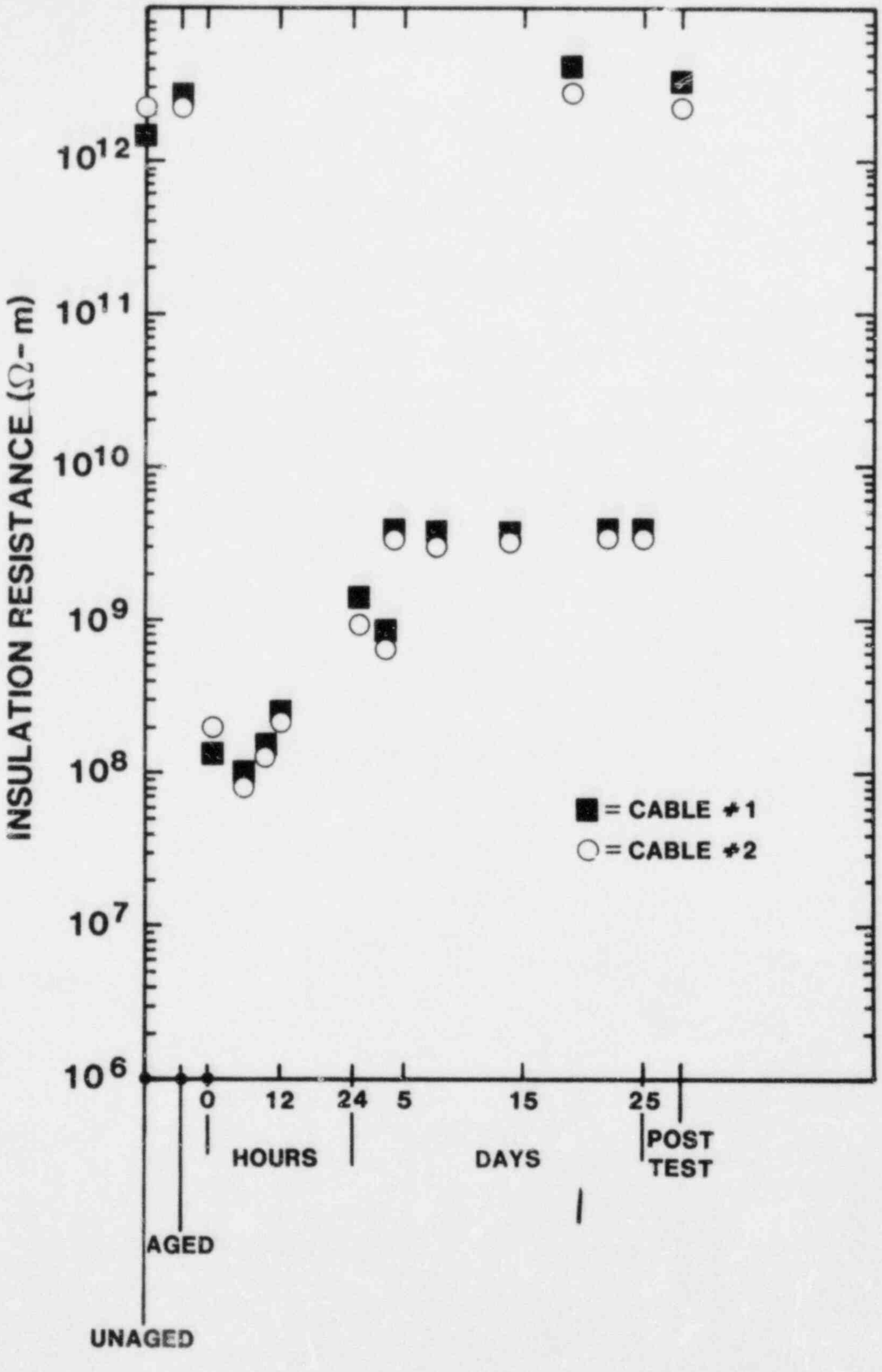

Figure 3.3. Insulation Resistance for XLPO B Single Conductors During Simultaneous Test #2

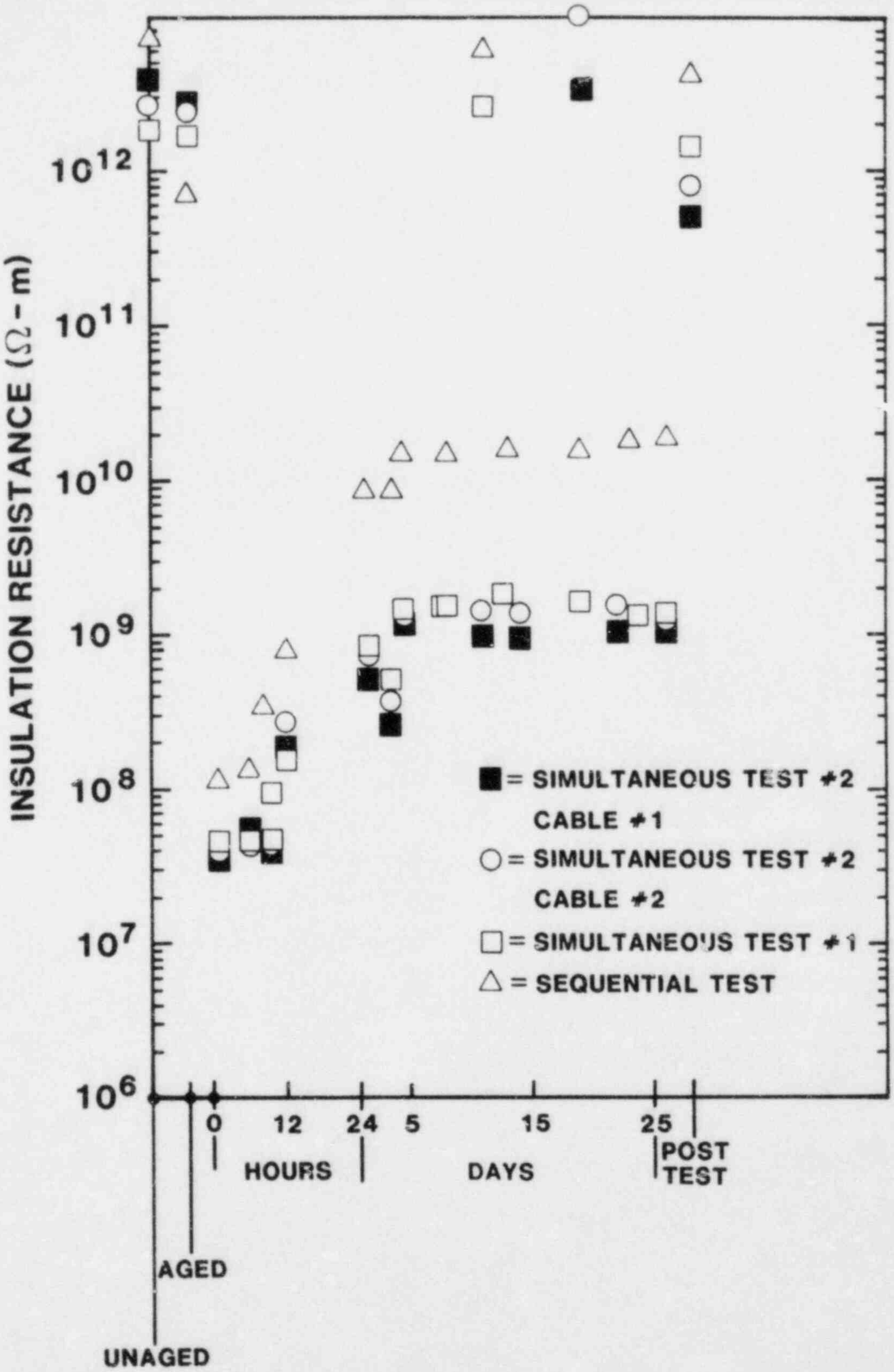

Figure 3.4. Insulations Resistance for XLPO B Multiconductors

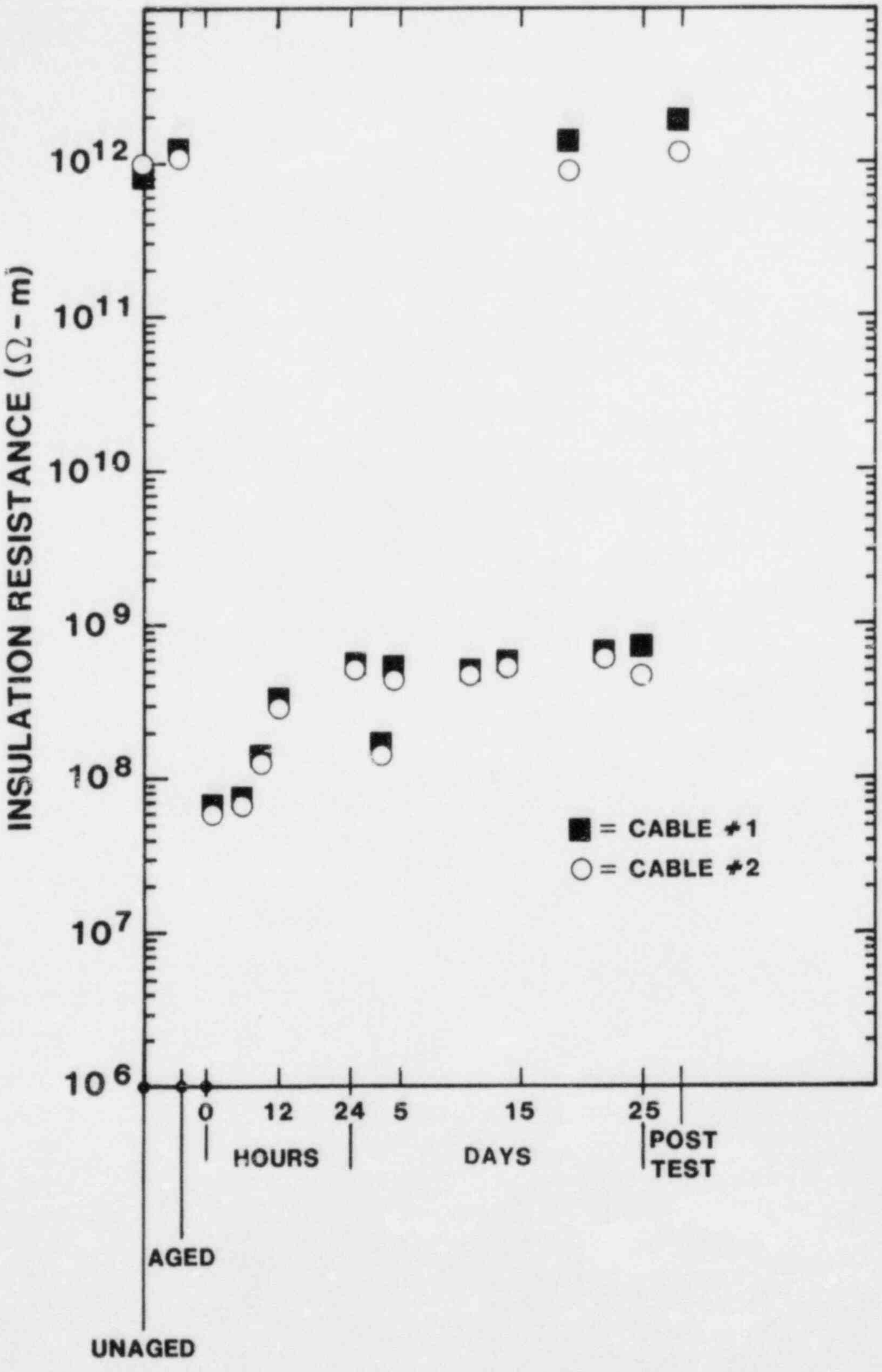

Figure 3.5. Insulation Resistance for XLPO C Multiconductors During Simultaneous Test #2

the ground wire and shield of the multiconductor construction. The other conductors of the multiconductor were guarded. The XLPO B and XLPO C multiconductor constructions did not include ground wires and shields. We measured the insulation resistance between the conductor and the grounded steam chamber (which contained either steam or water). The other conductors of the multiconductor were guarded. Insulation resistance measurements recorded for day 11 (the sequential and simultaneous #1 tests) and for day 19 (simultaneous #2 test) were during unanticipated room temperature cooldowns and are several orders of magnitude larger than those recorded during the steam exposure.

Tables 3.1 through 3.3 summarize our leakage current data for XLPO A, B, and C. During these tests, one conductor of the multiconductor was connected to the high voltage terminal of the testing unit. The other conductors were grounded. The cable was also immersed into a grounded tap water bath. For XLPO A multiconductors, the ground wire and shield were also grounded. The single conductor measurements were between the conductor and a grounded tap water bath.

3.2 Insulation Specimens

We used XLPO A, B, and C insulation specimens to monitor weight changes, dimensional changes, and tensile properties. Both unaged and aged (simultaneous test #2 aging) specimens were exposed to our simultaneous test #2 accident simulation. We removed specimens after the first four days and on the 18th day of our LOCA simulation. (Note: Day 18 was during the unanticipated cooldown; the samples had experienced 16 days of LOCA simulation.) Tables 3.4-3.6 summarize the percentage increase in specimen weight, length, width, and thickness during simultaneous test #2 for XLPO A, XLPO B, and XLPO C, respectively. Ultimate tensile elongation and ultimate tensile strength were measured prior to aging, after aging, and after four and sixteen days of LOCA exposure. Tensile measurements were made several months after removing the specimens from the environmental chamber. This was done to allow for completion of moisture desorption from the samples. Tensile measurement results are given in Tables 3.7-3.9.

3.3 Jacket Behavior

XLPO A and XLPO C multiconductor cables included a chlorosulfonated polyethylene (CSPE) outer jacket. XLPO B was constructed with a Neoprene outer jacket.

At completion of simultaneous test #2, XLPO A's CSPE jacket was intact with no visual evidence of cracking. In contrast, XLPO C's CSPE jacket was substantially visually degraded. Figure 3.6 illustrates these observations.

Table 3.1

Leakage Currents for XLPO A Cables During Simultaneous Test #2

Measurements were made at the Completion of a one-minute electrification for the 600, 1200, and 1800 Vac exposures and at the completion of a five-minute electrification at 2400 Vac. Measurements were between the copper conductor and a grounded water bath.

Applied Voltage	Leakage Current (mA)	
	Cable #1	Cable #2
<u>Single Conductors</u>:		
Unaged		
600 Vac	0.5	0.5
Aged		
600 Vac	0.6	0.5
Posttest		
600 Vac	0.7	0.7
1200 Vac	1.4	1.3
1800 Vac	2.1	1.9
2400 Vac	2.8	2.5
<u>Multiconductors</u>:		
Unaged		
600 Vac	1.1	1.0
Aged		
600 Vac	1.0	1.0
Posttest		
600 Vac	1.5	1.5
1200 Vac	3.0	2.9
1800 Vac	4.5	4.4
2400 Vac	<10	<10

Table 3.2

Leakage Currents for XLPO B Cables During Testing

Measurements were made at the completion of a one minute electrification for the 600, 1200, and 1800 Vac exposures and at the completion of a five minute electrification at 2400 Vac.

Applied Voltage	Leakage Current (mA)			
	Sequential test	Simultaneous Test #1	Simultaneous Test #2	
			Cable #1	Cable #2
Single Conductors:				
Unaged				
600 Vac			0.4	0.4
Aged				
600 Vac			0.4	0.5
Posttest				
600 Vac			0.6	0.7
1200 Vac			1.3	1.3
1800 Vac			1.8	2.0
2400 Vac			2.4	2.7
Multiconductors:				
Unaged				
600 Vac			0.6	0.6
Aged				
600 Vac			0.4	0.4
Posttest				
600 Vac	0.7	0.9	0.8	0.7
1200 Vac	1.5	1.8	1.5	1.4
1800 Vac	2.2	2.6	2.2	2.2
2400 Vac	2.9	3.4	2.9	2.8

Table 3.3

Leakage Currents for XLPO C Multiconductors During Simultaneous Test #2

Measurements were made at the completion of a one-minute electrification of the 600, 1200, and 1800 Vac exposures and at the completion of a five-minute electrification at 2400 Vac. Measurements were between the copper conductor and a grounded water bath.

	Applied Voltage	Leakage Current (mA)	
		Multiconductor #1	Multiconductor #2
Unaged	600 Vac	0.6	0.6
Aged	600 Vac	0.5	0.5
Posttest			
	600 Vac	0.7	0.6
	1200 Vac	1.4	1.3
	1800 Vac	2.1	1.8
	2400 Vac	3.2, >750*	2.4

*Note: Multiconductor #1 had a leakage current of 3.2 mA at 2400 Vac for two of its three conductors. The third conductor had a leakage current greater than 750 mA.

Table 3.4

Percentage Increase for XLPO A Insulation Specimen Properties During Simultaneous Test #2

	Samples Aged before LOCA	Samples Unaged before LOCA
Weight Increase		
4 d LOCA	9	4
Unanticipated Cooldown	15	10
Length Increase		
4 d LOCA	0	0
Unanticipated Cooldown	2	0
Outer Diameter Increase		
4 d LOCA	5	3
Unanticipated Cooldown	6	4

Table 3.5

Percentage Increase for XLPO B Insulation Specimen Properties During Simultaneous Test #2

	Samples Aged before LOCA	Samples Unaged before LOCA
Weight Increase		
4 d LOCA	33	15
Unanticipated Cooldown	58	32
Length Increase		
4 d LOCA	5	0
Unanticipated Cooldown	12	5
Outer Diameter Increase		
4 d LOCA	14	8
Unanticipated Cooldown	22	14

Table 3.6

Percentage Increase for XLPO C Insulation Specimen Properties During Simultaneous Test #2

	Samples Aged before LOCA	Samples Unaged before LOCA
Weight Increase		
4 d LOCA	14	26
Unanticipated Cooldown	25	37
Length Increase		
4 d LOCA	0	2
Unanticipated Cooldown	2	5
Outer Diameter Increase		
4 d LOCA	10	10
Unanticipated Cooldown	12	15

Table 3.7

Ultimate Tensile Properties for XLPO A

The LOCA tensile measurements were performed after the sample weight had stabilized.

	Unaged at Start of LOCA		Aged at Start of LOCA	
Condition	e/eo	T/TO*	e/eo	T/TO*
Unaged	1.00 ± .03 (380 ± 10)	1.00 ± .03 (19.0 ± 0.5 MPa)	1.00 ± .03 (380 ± 10)	1.00 ± .03 (19.0 ± .05 MPa)
Aged	–	–	.58 ± .03	.82 ± .03
4 d LOCA	.30 ± .02	.79 ± .04	.25 ± .02	.86 ± .04
16 d LOCA	.23 ± .02	.75 ± .04	.16 ± .05	.72 ± .04

*We normalized T/TO using the unaged cross-sectional areas.

Table 3.8

Ultimate Tensile Properties for XLPO B

The LOCA tensile measurements were performed after the sample weight had stabilized.

Condition	Unaged at Start of LOCA		Aged at Start of LOCA	
	e/eo	T/TO*	e/eo	T/TO*
Unaged	1.00 ± .06 (320 ± 20)	1.00 ± .08 (17.2 ± 1.3 MPa)	1.00 ± .06 (320 ± 20)	1.00 ± .08 (17.2 ± 1.3 MPa)
Aged	-	-	.79 ± .10	.92 ± .10
4 d LOCA	.50 ± .06	.88 ± .08	.42 ± .03	.81 ± .05
16 d LOCA	.41 ± .05	.87 ± .07	.30 ± .12	.73 ± .07

*We normalized T/TO using the unaged cross-sectional areas.

Table 3.9

Ultimate Tensile Properties for XLPO C

The LOCA tensile measurements were performed after the sample weight had stabilized.

Condition	Unaged at Start of LOCA e/eo	T/TO*	Aged at Start of LOCA e/eo	T/TO*
Unaged	1.00 ± .10 (330 ± 30%)	1.00 ± .07 (14.7 ± 1.0 MPa)	1.00 ± .10 (330 ± 30%)	1.00 ± .07 (14.7 ± 1.0 MPa)
Aged	–	–	.64 ± .07	1.12 ± .16
4 d LOCA	.47 ± .08	.96 ± .14	.29 ± .04	.96 ± .08
16 d LOCA	.30 ± .04	.85 ± .09	.17 ± .06	.75 ± .14

*We normalized T/TO using the unaged cross-sectional areas.

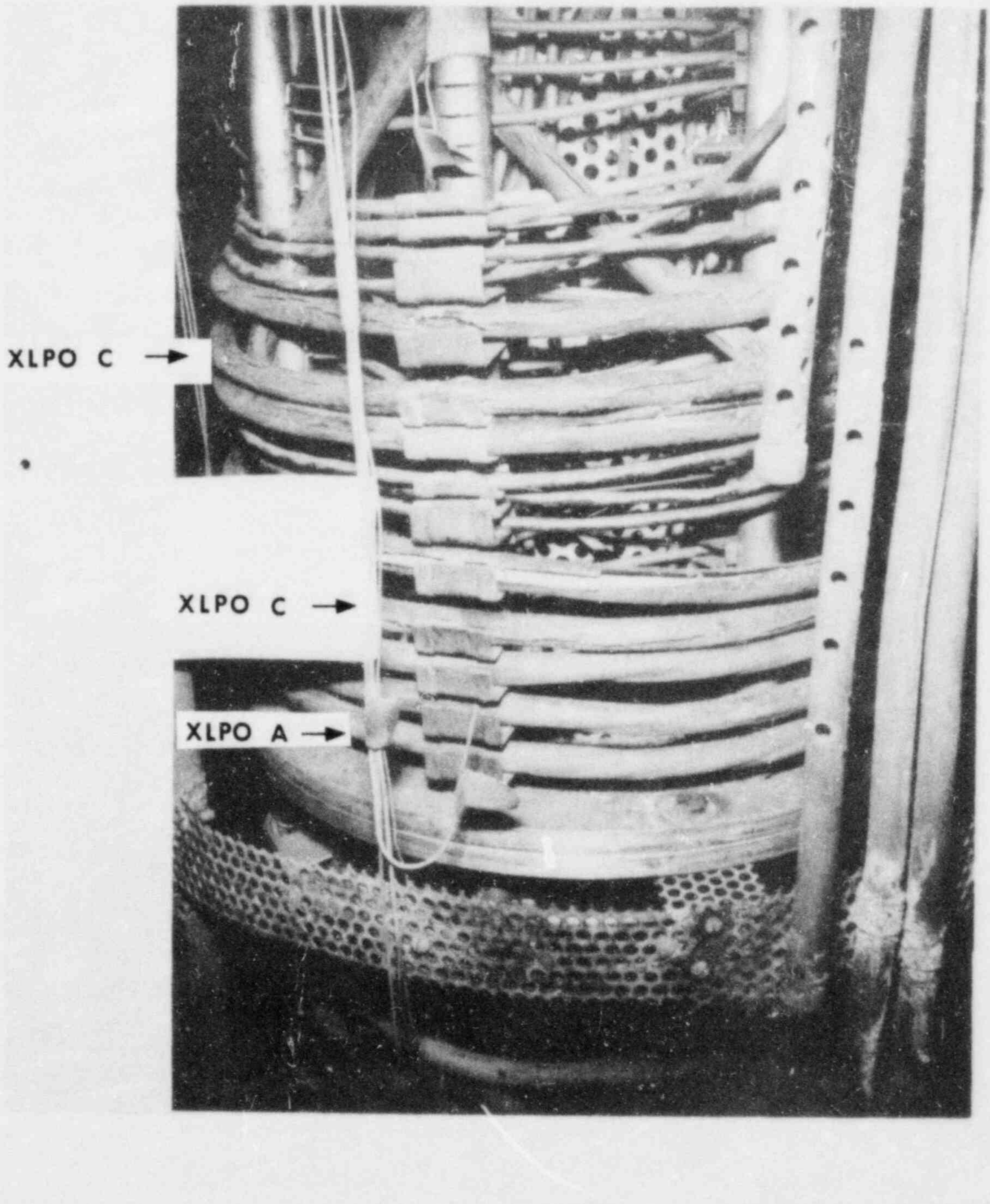

Figure 3.6. CSPE Jacket Condition (XLPO A and XLPO C cables) at Completion of Simultaneous Test #2

XLPO B with a Neoprene jacket was exposed during the sequential and simultaneous test. At completion of all the tests, the Neoprene jacket exhibited longitudinal cracking. The degradation was more severe for the simultaneous testing techniques. Figures 3.7 and 3.8 illustrate XLPO B's jacket condition at completion of the sequential test. XLPO B's Neoprene jacket condition at the completion of simultaneous test #1 is shown in Figure 3.9 while its condition during the unanticipated cooldown of simultaneous test #2 is shown in Figure 3.10.

4.0 Discussion

XLPO A and XLPO B cables were exposed during simultaneous test #2 both as single conductors and multiconductors. Figures 3.1 and 3.2 illustrate that the I.R. behavior for XLPO A cables was similar for the two types of cable constructions. Figures 3.3 and 3.4 illustrate the same conclusion for the XLPO B cables. Tables 3.1 and 3.2 provide leakage current data for XLPO A and XLPO B cables respectively. For XLPO B, there is no significant difference between the single conductor and multiconductor results. For XLPO A, leakage currents for the multiconductors were approximately twice that measured for the single conductors. However, the XLPO A single conductor "leakage" cable lengths were less than half that of the XLPO A multiconductor "leakage" cable lengths. XLPO A multiconductors included a ground wire and shield. Hence the multiconductor leakage measurement is for both the ~6m length immersed in grounded tap water and the ~15m length external to the grounded tap water. For the single conductors, leakage was measured only for the ~5 m length immersed in grounded tap water. (See Section 2.3.3.1 for description of test setup.) We conclude that the electrical properties for XLPO A and XLPO B cables did not depend on whether single conductor or multiconductor testing was performed.

XLPO B multiconductor cables were exposed to the sequential and both simultaneous tests. The thermal aging, radiation, and steam environments were similar for all three tests. For example, Table 4.1 summarizes the radiation exposure data for XLPO B multiconductors during each of the tests and illustrates that the total radiation dose for each of the tests differed by less than 10 percent. Figure 3.4 illustrates that there is no more than an order of magnitude difference in XLPO B I.R. values for simultaneous and sequential testing. Table 3.2 demonstrates that testing technique does not impact the leakage current for XLPO B during posttest measurements.

XLPO A and XLPO C cables were only exposed to simultaneous test #2. Tables 3.1-3.3 illustrate that these cables had comparable posttest leakage currents as XLPO B which was tested sequentially. Table 4.2 compares XLPO A and

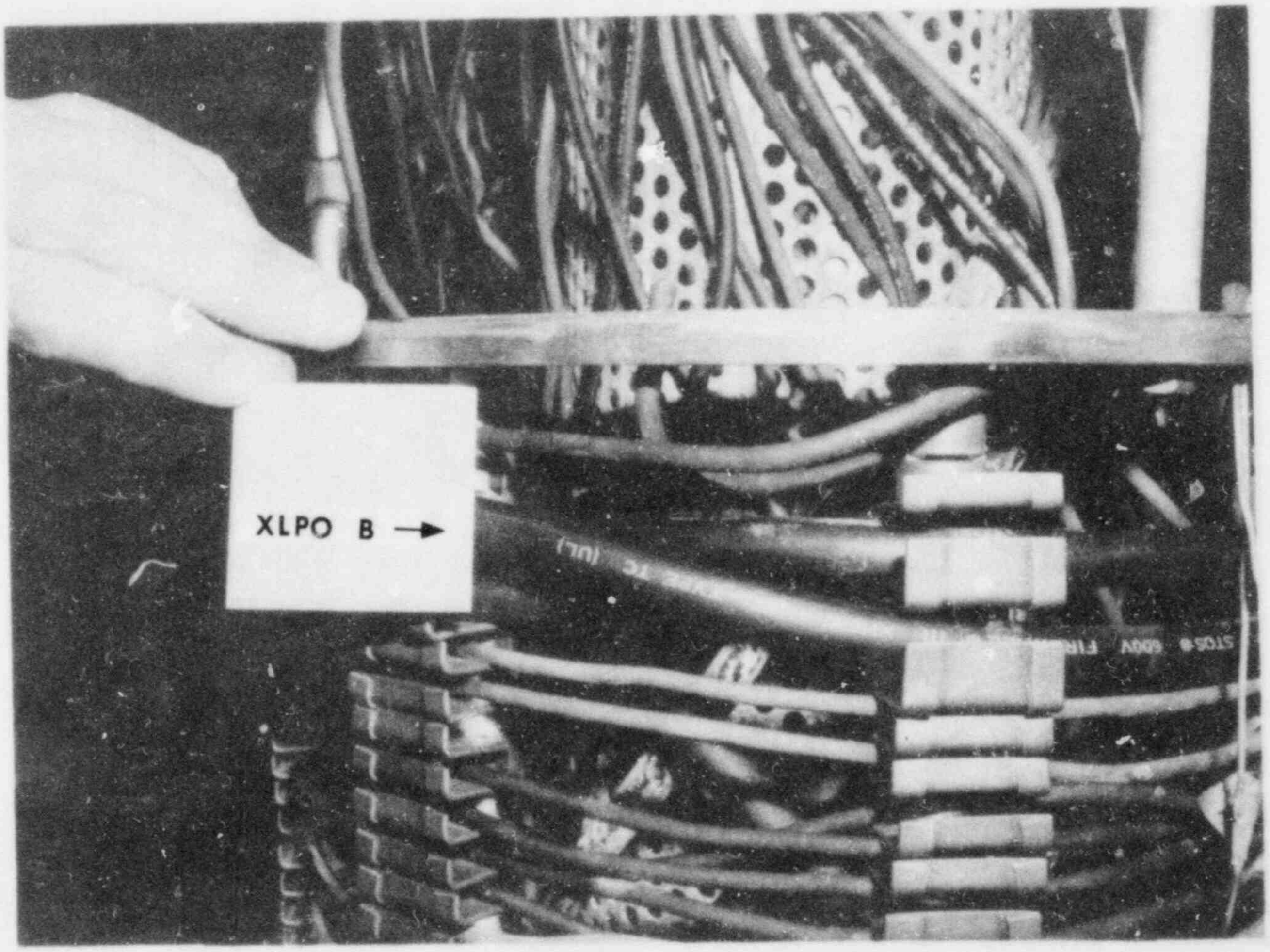

Figure 3.7. Neoprene Jacket (XLPO B cable) at Completion of the Sequential Test

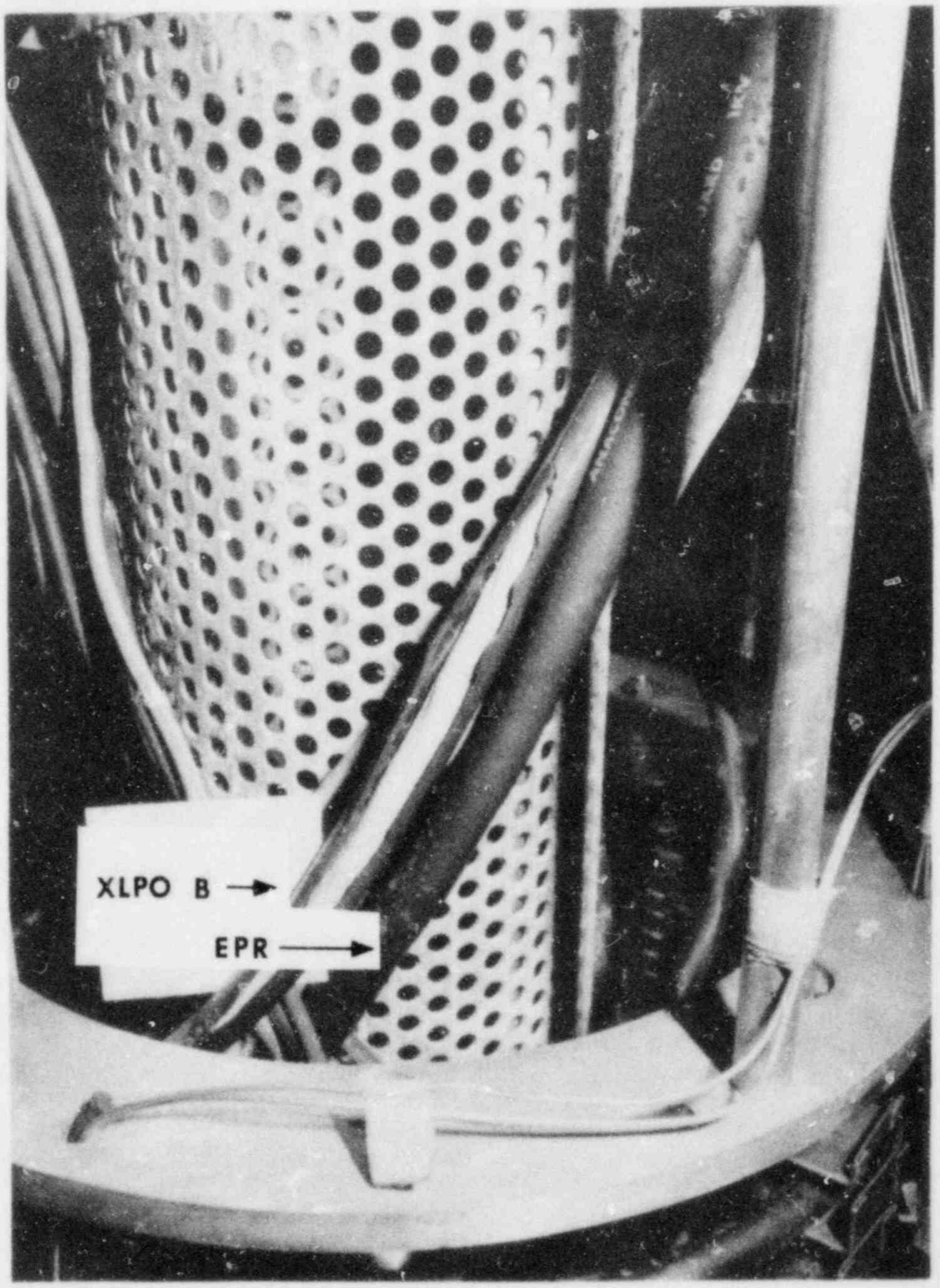

Figure 3.8. Neoprene Jacket (XLPO B cable) at Completion of the Sequential Test

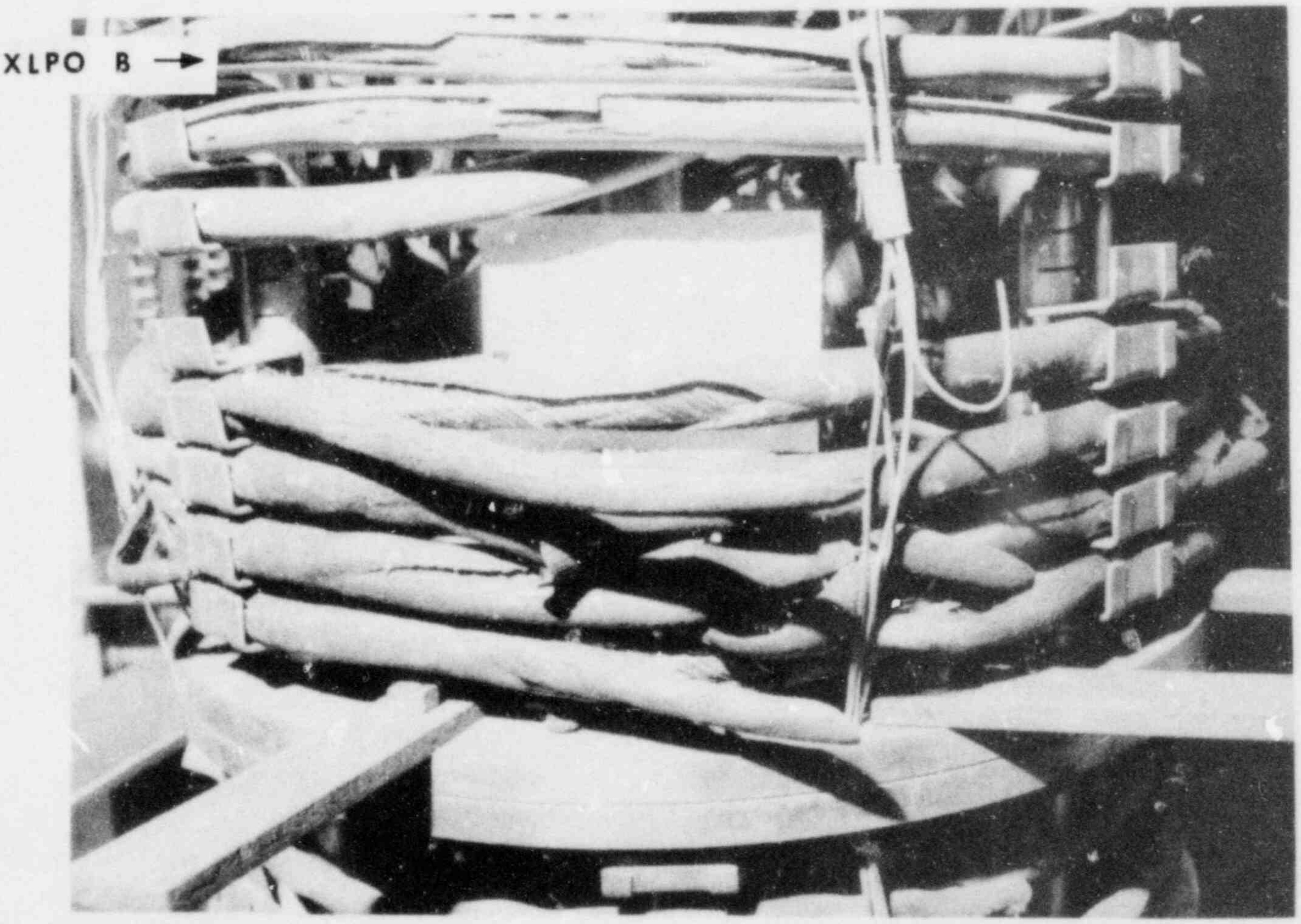

Figure 3.9. Neoprene Jacket (XLPO B cable) at Completion of Simultaneous Test #1

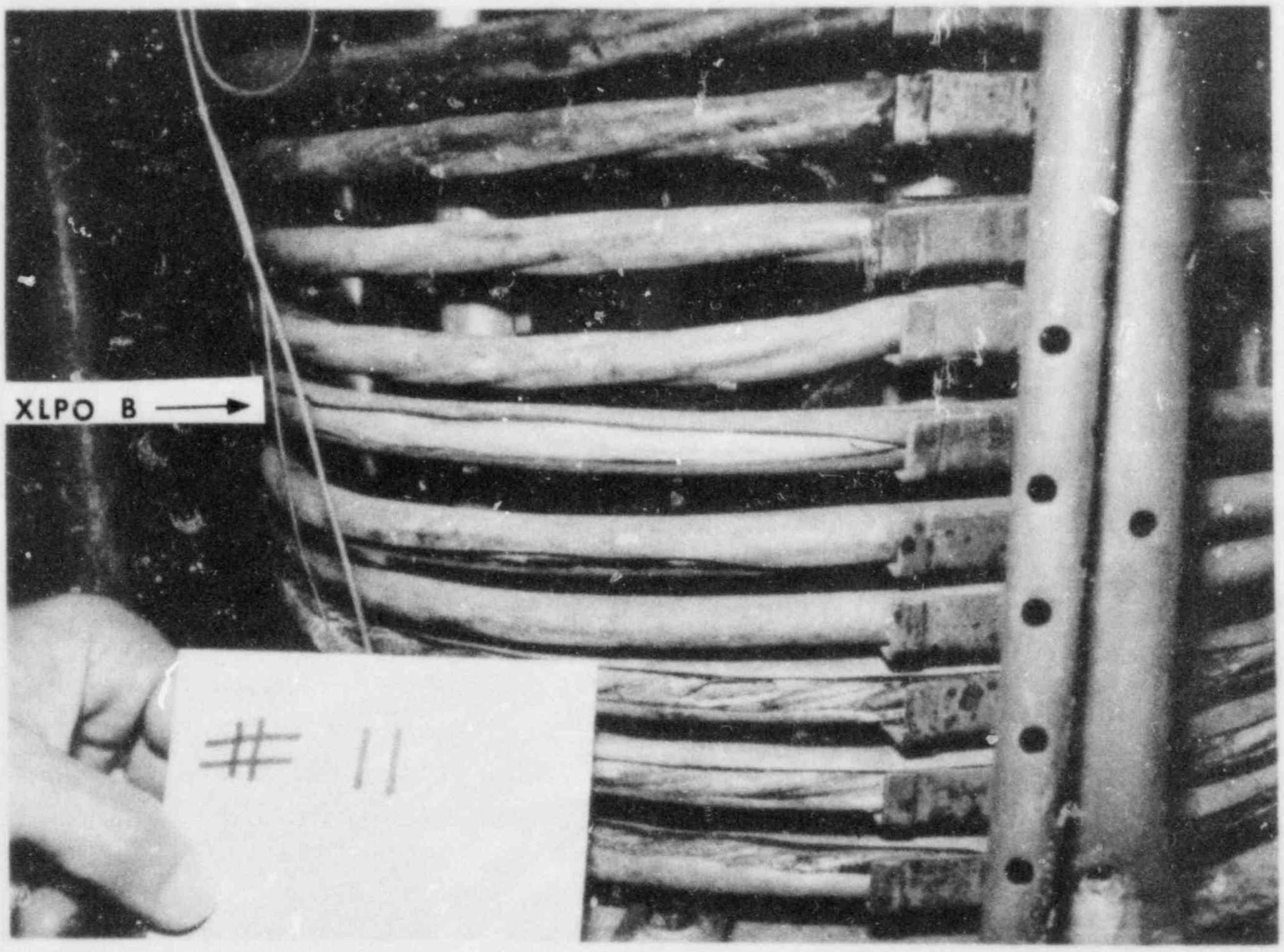

Figure 3.10. Neoprene Jacket (XLPO B cable) During Unanticipated Cooldown of Simultaneous Test #2

Table 4.1

Radiation Doses Applied to XLPO B Multiconductor Cables During Testing

Radiation Dose (Mrd - air equiv.)

Test	Aging	Accident	Total
Sequential	39 ± 3	111 ± 9	150 ± 12
Simultaneous #1	37 ± 4	99 ± 23	136 ± 27
Simultaneous #2	43 ± 4	106 ± 20	149 ± 24

Table 4.2

Comparison Between Sandia Simultaneous Test and Manufacturer's Sequential Tests for XLPO A and XLPO C

	Sandia	Manufacturer's Tests	
	Simultaneous Test #2	XLPO A	XLPO C
Thermal Aging	7 d at 139°C	7 d at 150°C	7 d at 136°C
Total Radiation Dose	149 Mrd	200 Mrd	200 Mrd
Steam Profile	21 d modified IEEE Std 323, Appendix A (Saturated steam)	30 d IEEE Std 323, Appendix A (Saturated steam)	30 d, higher temperatures than IEEE Std 323, Appendix A. Saturated steam except for 12 minutes at 385°F (196°C), 455 kPa (66 psi).
Cable Length in Steam Chamber	~6m	~11m	Unknown
<u>Electrical Performance</u>:			
1. Leakage current, 2400 Vac, 5 minutes	XLPO A ≤10 mA XLPO C ~3 mA	<50 mA	<10 mA
2. Minimum recorded I.R. valve during test	XLPO A = .5 MΩ XLPO C = 9 MΩ	.3 MΩ @ 100 VdC	<.05 MΩ @ 10V (Report suggests failure at penetration)

XLPO C electrical performance during our simultaneous test to electrical performance during the sequential tests performed by the manufacturers. Test similarities and differences are also summarized in Table 4.2. We conclude that electrical performance during our simultaneous test was comparable to or better than the electrical behavior observed during the manufacturer's sequential tests.

XLPO C's CSPE jacket was substantially visually degraded by our simultaneous #2 test (see Figure 3.6). This is consistent with previous descriptions of CSPE behavior during simultaneous testing.[1] Surprisingly, XLPO A's CSPE jacket showed no evidence of degradation at completion of simultaneous test #2 (see Figure 3.6). Thus we conclude that CSPE jacket degradation depends strongly on the specific manufacturer and cable product.

We did not test XLPO A and XLPO C's CSPE jackets sequentially. XLPO C's qualification report indicates that sequential testing caused severe degradation of its CSPE jacket. Longitudinal and circumferential cracks were reported as well as complete loss of the jacket from parts of the cable. The manufacturer's test was to higher steam temperatures (196°C) than our tests (171°C). The effect of LOCA peak temperature on CSPE jacket degradation has not been reported.

XLPO B's Neoprene jacket was also substantially degraded by our simultaneous testing exposures (see Figures 3.9 and 3.10). Neoprene jacket degradation during sequential testing is illustrated by Figures 3.7 and 3.8. It is less severe than that observed during our simultaneous testing. Our results are consistent with ultimate tensile property behavior of Neoprene reported by Kusama, et al.[9] They observed more tensile degradation for simultaneous exposures than for sequential test exposures.

In Reference 1 we noted severe degradation of an EPR multiconductor during simultaneous testing. We hypothesized that dimensional swelling of the insulation (associated with moisture absorption) caused multiconductor jacket splitting with resultant mechanical damage to the insulated conductors. Ultimate tensile elongation measurements for this EPR product (EPR D in Reference 1) indicated that the insulation elongation was substantially reduced and therefore, susceptible to mechanical damage. During our testing of the three XLPO cable products, we monitored insulation ultimate tensile properties as well as weight and dimensional changes. Table 4.3 compares the XLPO properties to that noted previously for EPR D. The weight and dimensional changes for XLPO A, B, and C are substantially less than that observed for EPR D. Ultimate tensile elongation values are larger than EPR D's. Thus the lack of XLPO electrical degradation (caused by mechanical degradation) is not surprising.

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In Reference 1 we also noted more moisture absorption (i.e., weight gain) and dimensional changes for aged samples compared to unaged samples. XLPO A and B also exhibited this effect of aging. Unaged XLPO C, in contrast, absorbed more moisture than did aged XLPO C. For XLPO C, the ultimate tensile strength was enhanced by aging; suggesting additional cross-linking of the polymer matrix; with a resultant reduction in moisture absorption.

Our test facility employed saturated steam conditions for the accident simulations. Hence, oxygen was swept from the experimental chamber at the start of the accident exposures. The importance of oxygen presence during steam exposures has been recently investigated. Gillen, et al.,[10] report for XLPO and XLPE safety-related cable products that oxygen presence during steam exposures has no effect on either the XLPO and XLPE material weight changes (moisture absorption) or the ultimate tensile properties. In contrast, Kusama, et al.,[9] report that oxygen is a degradation factor for a commercial XLPE insulation. However, they describe this material as "formulated for cable in general use" while other materials they investigated are described as "formulated for fire-retardent safety-related cable used in nuclear reactors." For neither of these studies were simultaneous thermal-irradiation aging techniques used prior to the LOCA simulations. We are currently investigating whether the importance of oxygen during LOCA simulations depends on the preconditioning (aging) technique. XLPO A and XLPO C materials are being studied.[11] Upon completion of these experimental tests, we will be better able to predict whether the addition of oxygen during our steam exposures would have more severely degraded our mechanical and electrical results.

Table 4.3

Insulation Specimen Properties at Completion of Simultaneous Testing

Product	% Weight Gain	% Outer Diameter Increase	e/eo*	e* (%)
XLPO A	15	6	.16 ± .05	60 ± 20
XLPO B	58	22	.30 ± .12	96 ± 38
XLPO C	25	12	.17 ± .06	56 ± 20
EPR D (Ref. 1)	173	53	.13 ± .02	31 ± 5

*Measurements performed after moisture desorption had stabilized.

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Appendix A: Summary of Unanticipated Events During Testing

Our sequential and simultaneous tests did include several unanticipated occurrences. In this appendix we summarize these events.

1. Event: During the first four and a half hours of thermal aging for simultaneous test #1, the heater was turned off three times and the chamber opened to allow for adjustment of the heater ducts. Hence the cables and insulation samples were thermally cycled.

   Discussion: We redesigned the heater ducting before performing simultaneous test #2. This latter test did not thermally cycle the cables and insulation samples.

2. Event: During thermal aging for simultaneous test #1, the chamber overheated for approximately an hour. The maximum temperature during this transient was 175°C.

   Discussion: During thermal aging for simultaneous test #2 the chamber temperature did not exceed 150°C (see Table 2.11). Moreover, during thermal aging for the sequential test we also momentarily achieved temperatures near 150°C at the start of the thermal exposure.

3. Event: The sequential radiation aging exposure was interrupted when an "ozone" odor was detected outside the gamma irradiation facility.

   Discussion: The air ventilation pumps for the gamma irradiation facility failed approximately five minutes before irradiation was stopped. Ozone, generated during the gamma irradiation, was therefore not vented to the atmosphere but rather accumulated in the facility and seeped to worker locations where its odor was detected. The ventilation system was repaired and the aging irradiation was continued after a 6 hour, 34 minute interruption.

4. Event: The simultaneous test #1 radiation aging exposure was interrupted when an "ozone" odor was detected outside the gamma irradiation facility.

   Discussion: Ozone detection equipment was retrieved and setup to monitor the ozone concentration inside the gamma irradiation facility. (Note: the test chamber containing the cables was located inside the facility. During irradiation, the inside of the chamber was ~139°C. Air circulation between the chamber and the inside of the gamma facility resulted in one "air exchange" every minute and a half. The ozone detection equipment monitored ozone concentrations in the facility, but not directly in the heated experimental chamber.) The irradiation was restarted after a 25 hour, 20 minute interruption and ozone levels of ~.1 PPM were monitored. After a 1 hour, 10 minute exposure, irradiation was stopped to allow for replacement of facility ventilation filters. An additional 6 hour, 20 minute aging irradiation was then performed. Ozone levels varied between .05 and .15 PPM during this irradiation. Background ozone levels when irradiation was not being performed were ~.05 PPM.

During the simultaneous test #2 aging irradiation, ozone presence outside the irradiation facility at worker locations was not noted and the irradiation was not interrupted.

5. Event: During the first ramp of the sequential test, a penetration leaked excessively and had to be retorqued. The ramp was continued after retorquing the penetration. Since the simultaneous chamber was initially connected in parallel to the sequential chamber, the leak in the sequential chamber affected the steam profile for simultaneous test #1. Upon discovery of the leak, the simultaneous chamber was isolated from the sequential chamber and its ramp continued separatley. Table 2.4 summarizes the time-temperature history for these steam exposures.

   Discussion: The penetration that leaked excessively contained only feedthroughs for EPR multiconductor cables. This unanticipated event did not occur for simultaneous test #2.

6. Event: Prior to the first ramp of simultaneous test #2 we momentarily passed steam through the chamber (which was open to ambient conditions).

   Discussion: Both the entrance and exit ports for the steam flow were located in the top section of the chamber. The nonconformance did not occur during simultaneous test #1.

7. Event: During the first peak of simultaneous test #2 a Tefzel cable excessively leaked water onto our current and voltage loading circuit causing it to

fail. We reconfigured and repaired the loading circit and resumed current and voltage loading of cables.

Discussion: Insulation resistance was measured periodically during the remainder of the steam exposure. Anomalous I.R. behavior was not observed immediately after this unexpected occurrence.

8. Event: During the first peak of simultaneous test #2 water accumulated in the bottom of the steam chamber and submerged some cables. We estimate the maximum water level as between 67 and 91 cm below the top of the mandrel. We drained the water from the chamber 1-1/2 hours after the start of the first steam peak.

   Discussion: Examination of Table 2.13 indicates that water submergence lowered the exposure temperature for those cables submerged.

9. Events: On day 9 of the simultaneous test #1 steam exposure the steam supply system failed and the steam chamber cooled to ambient temperatures and pressures. Twenty-one hours later the irradiation was stopped. On day 12, the steam and radiation exposures were resumed. On day 16 of the simultaneous test #2 steam exposure the steam supply system failed and the steam chamber cooled to ambient temperatures and pressures. Eight hours later the irradiation was stopped. On day 21 we resumed the steam and radiation exposures.

   Discussion: Insulation resistance values for the XLPO cables made after the unanticipated events were comparable to those measured immediately preceding the steam failures (see Table 3.1).

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Electrical and mechanical properties of three commercial cross-linked polyolefin (XLPO) materials, typically used as electrical cable insulation, have been monitored during three simulations of nuclear power plant aging and accident stresses. For one XLPO cable we first performed accelerated thermal aging, then irradiated the samples to the combined aging and LOCA total dose. Finally, we applied a steam exposure. For a second and third set of XLPO cables we used simultaneous applications of elevated temperature and radiation stresses to preaccident age our specimens. We followed these aging exposures by simultaneous radiation and steam exposures to simulate a LOCA environment.

Our measurement parameters during these tests included: dc insulation resistance, ac leakage current, ultimate tensile strength, ultimate tensile elongation, percentage dimensional changes, and percentage moisture absorption. We present test results for three XLPO materials.

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