October 25, 1996

Mr. G. K. Henry, Chairman
IEEE/NPEC
ComEd Quad Cities Station
Design Engineering
22710 206th Avenue North
Cordva, IL 61242

Dear Mr. Henry:

Enclosed for your review and comment is a copy of the draft NUREG/CR6412, "Aging and Loss-of-Coolant Accident (LOCA) Testing of Electrical Connections," dated July 31, 1996.

Comments will be most helpful if received by November 22, 1996. We plan to publish the final report in December 1996.

Sincerely,

Original signed by
Satish K. Aggarwal

Satish K. Aggarwal, Senior Program Manager
Office of Nuclear Regulatory Research

Enclosure: As stated

cc:
A. Marion, NEI
J. Hutchinson, EPRI
W. Horin, NUGEQ

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WASHINGTON, D.C. 20555-0001

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NUREG/CR-6412
SAND96-????

Aging and Loss-of-Coolant Accident (LOCA) Testing of Electrical Connections

Manuscript Completed: July 1996
Manuscript Published: ??

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Abstract

Experiments were performed to assess the aging and loss-of-coolant accident (LOCA) behavior of electrical connections to determine their suitability for life extension. In all, 12 different types of connections commonly used in nuclear power plants were tested. These included 2 types of terminal blocks, 3 types of conduit seals, 2 types of connectors for installation into a device, and 5 in-line splices and connectors. The connections were aged for 6 months under simultaneous thermal (99°C) and radiation (46 Gy/hr) conditions to simulate 60 years in a nuclear power plant environment. A simulated LOCA consisting of sequential high dose rate irradiation (5 kGy/hr) and high temperature steam exposures followed the aging. Connection functionality was monitored using insulation resistance measurements during the aging and LOCA exposures. Because only 5 of the 10 non-terminal block connection types passed a post-LOCA, submerged dielectric withstand test, further detailed investigation of electrical connections related to life extension is warranted.

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1 Introduction and Objectives

This report presents an experimental program regarding the aging and loss-of-coolant accident (LOCA) behavior of electrical connections. While numerous similar studies have been performed in the past on electrical cables, a similar body of work does not exist for the connections that are used to terminate the cables. This report investigates a wide range of connections that are commonly used in nuclear power plants, including terminal blocks, conduit seals, connectors, and splices.

1.1 Objectives

The objective of this report is to provide initial information on the long-term aging degradation and LOCA behavior of nuclear-qualified electrical connections subjected to environmental exposures similar to those used for previous research testing of nuclear-qualified electrical cables. The specific program objectives were as follows:

- To assess the accident performance of electrical connections aged more slowly (*i.e.*, at lower temperatures and radiation dose rates) than in typical industry tests and under simultaneous conditions.
- To investigate the performance of connections aged to a 60-year life to determine their suitability for life extension beyond the current nominal 40-year qualified life.

As this effort is an initial program to investigate electrical connections, it was decided to include as broad a range of connections as possible. In all, 12 different types of connections; consisting of 2 types of terminal blocks, 3 types of conduit seals, 2 types of connectors for installation in a device, and 5 in-line splices and connectors; were tested. Because of the large number of tested connection types, it was not possible to perform detailed testing on each connection type, to test enough of each type to get a good statistical sample, or to investigate and develop condition monitoring techniques applicable to connections. Rather, this test program provides an initial scoping of whether or not more detailed testing of connections is warranted.

1.2 Approach

To accomplish these objectives, an experimental program consisting of two phases was undertaken, both using the same specimens:

- A 6-month long, simultaneous thermal (99°C = 210°F) and radiation aging (45.6 Gy/hr = 4.56 krad/hr) exposure to simulate 60 years in a nuclear power plant at an ambient temperature of 55°C (131°F) and a total radiation dose of 200 kGy (20 Mrad).
- A simulated LOCA exposure consisting of a 1000 kGy (100 Mrad), high dose rate (5 kGy/hr = 500 krad/hr) radiation exposure sequentially followed by a steam exposure.

In each phase, the connections were monitored electrically to assess their functionality and to appraise if the electrical monitoring could detect connection degradation. No detailed condition monitoring was performed and there was no attempt to develop or evaluate techniques that could monitor the aging degradation of the electrical connections. The test program generally followed the guidance of IEEE 323-1974 [15], IEEE 383-1974 [43], and IEEE 572-1985 [44].

These test conditions are very similar to those in the NUREG/CR-5772 series of reports [16, 17, 18] in which a broad range of electric cables were investigated. The only major difference is that the NUREG/CR-5772 reports assumed a 40-year aging radiation dose of 400 kGy (40 Mrad) and an accident radiation dose of 1100 kGy (110 Mrad), while the current report assumes a 60-year aging radiation dose of 200 kGy (20 Mrad) and an accident radiation dose of 1000 kGy (100 Mrad). The lower doses were chosen for the current report to be more representative of actual nuclear power plant conditions.

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2 Experimental Apparatus and Technique

This section describes the tested electrical connections, the experimental apparatus and techniques used to perform measurements, and the test conditions used for the test program.

2.1 Test Facilities

All environmental exposures were performed using the Low Intensity Cobalt Array (LICA) facility and the Steam Exposure Facility, both located in the north end of Building 867 in Technical Area 1 at Sandia National Laboratories in Albuquerque, NM.

The LICA facility consists of radioactive sources and various fixtures located at the bottom of a water pool as shown in Figure 2.1—only a large chamber cobalt fixture was used for the current test. The pool water provides radiation shielding. The LICA facility is used to perform both accident irradiation and simultaneous radiation and thermal aging of test specimens.

Radiation is produced by cobalt-60 sources supplied by Neutron Products Inc. (Dickerson, MD). There are 32 cobalt-60 sources that can be used in the large chamber fixtures. Each source is 673.1 mm (26.5 in) long by 15.9 mm (0.625 in) outside diameter—cobalt is contained only in the middle 609.6 mm (24 in) of each source. The total activity of the 32 sources was approximately 51 kCi as of Jan. 1992.

To irradiate test samples, the cobalt-60 sources were placed in one of the two large chamber fixtures sitting at the bottom of the pool. A side view of a large chamber fixture (and a test chamber) is shown in Figure 2.2, and a top view of one of the fixtures is shown in Figure 2.3 giving the configuration of the tubes in which the cobalt-60 sources are placed. The two fixtures are identical except that one has only 16 source locations around the test chamber opening instead of the 32 locations shown in Fig. 2.3. The large chamber fixtures are made of aluminum and are water tight (*i.e.*, they are filled with air) to minimize the amount of shielding between the cobalt sources and the test chamber.

Detailed drawings of the type of test chamber used for this test program (also see Fig. 2.2) and the test fixturing are shown in Figure 2.4. One stainless steel test chamber was used for all parts of the test program. The test chamber has approximately 0.45 m^3 of internal volume, with an inside diameter of 521 mm (20.5 in) and a total height of approximately 2115 mm (83 in). The test chamber head (approximately 508 mm (20 in) in height) contains all the penetration flanges through which the cables attached to the connections, thermocouples, heater power lines, air, and steam enter and exit the chamber. The bottom section of the chamber has a height of approximately 1607 mm (63 in). A ground wire was attached to the test chamber so that the chamber serves as a ground for electrical measurements.

The connections were mounted on a mandrel suspended from the test chamber head; there is no attachment by either the mandrel or the test specimens to the test chamber bottom. This allows the test chamber bottom to be removed to gain access to the test specimens without disturbing them. The specimens remained attached to the mandrel for all phases of the environmental exposure—the test chamber also serves as a pressure vessel when connected to the steam system. This minimizes the possibility of damage to the specimens when the test chamber is moved from the LICA facility to the steam system because the test specimens do not have to be removed from one test chamber and then reinstalled into another.

The mandrel consists of a pair of stainless steel rings attached to one another with eight stainless steel rods. The cables attached to the connections go into and then back out of the test chamber—they enter the test chamber through a penetration in the test chamber head, are attached vertically to the mandrel (parallel to the mandrel rods), and then loop back up through the center of the mandrel and finally exit the test chamber through another penetration in the test chamber head. Figure 2.5 shows a top view of the arrangement of connections in the test chamber. Two Hoffman A-806CHNF enclosures, each containing one Marathon and one States terminal block, were mounted inside the mandrel. A 0.25 inch diameter weep hole was located at the bottom of each enclosure. The cables entered and exited each enclosure through an elbow and a short section of conduit located inside the test chamber.

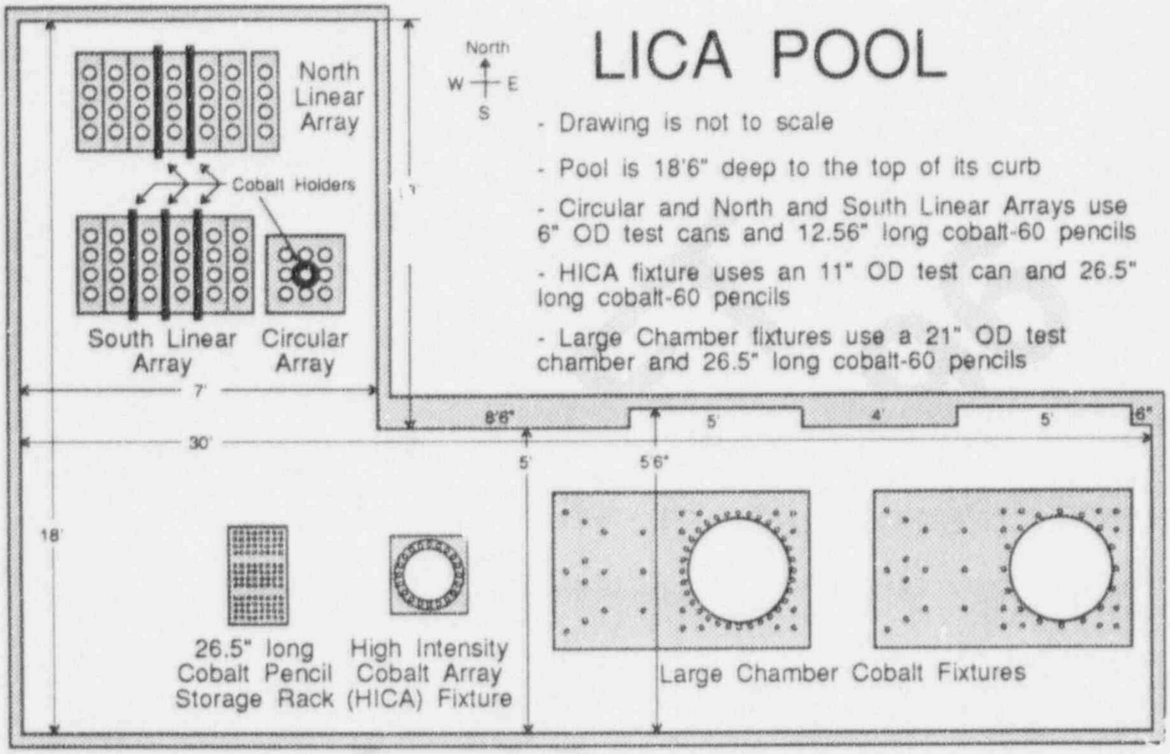

Figure 2.1: Plan view of the LICA pool and fixtures—not to scale.

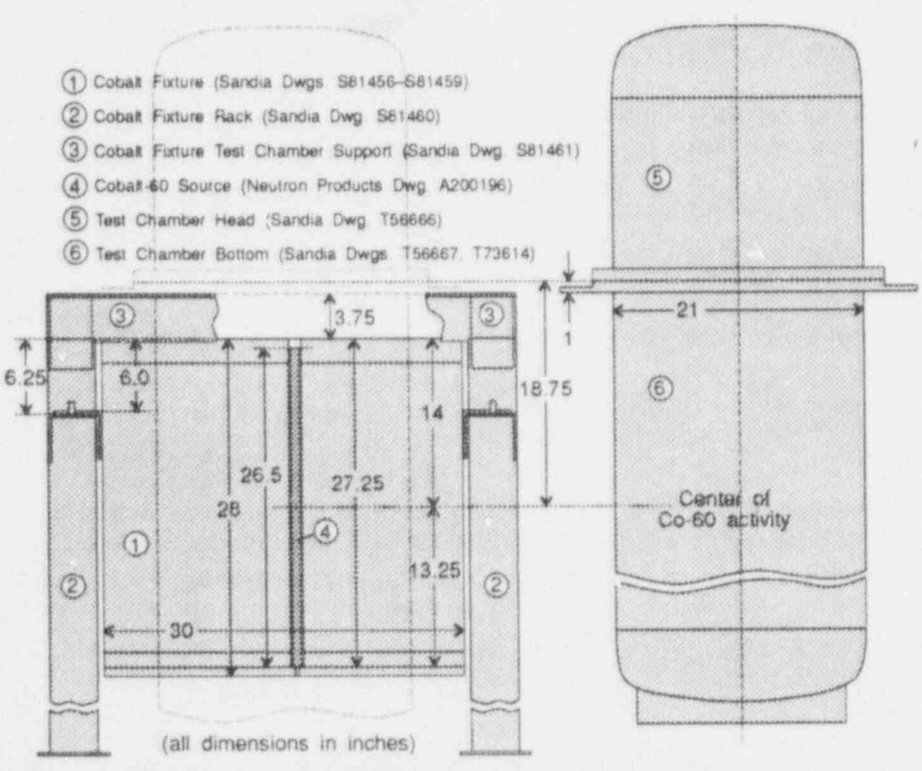

Figure 2.2: Sketch of a test chamber and large chamber cobalt fixture.

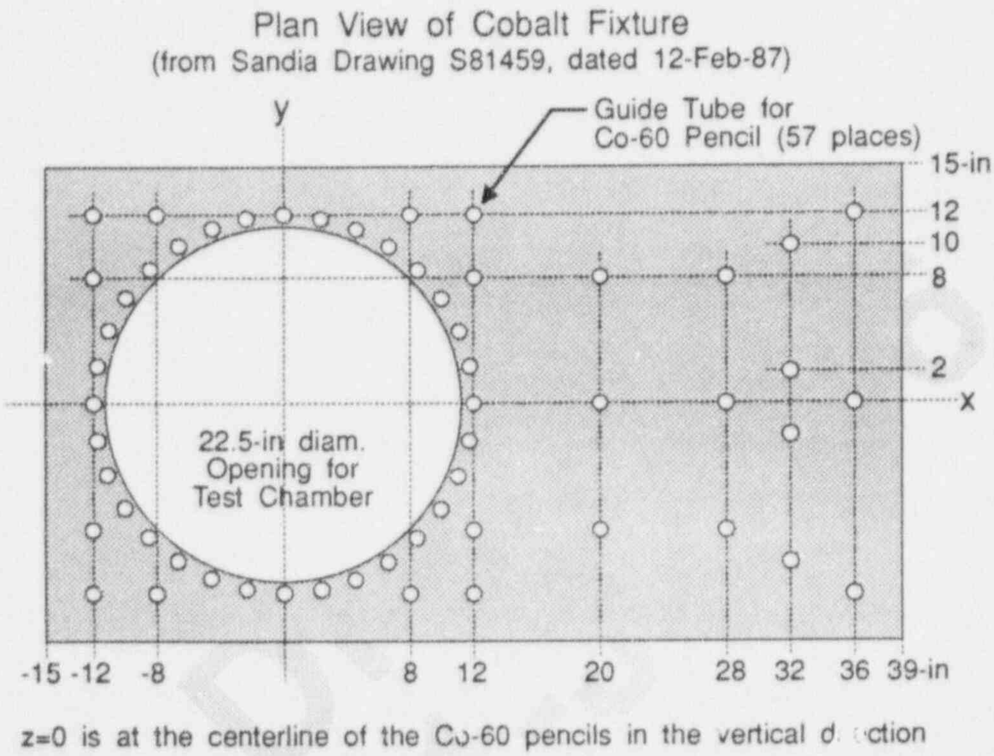

Figure 2.3: Plan view of large chamber cobalt fixture showing the fixture coordinate system and possible cobalt source locations.

The Steam Exposure Facility was used to perform the steam exposure for loss-of-coolant accident (LOCA) simulations. This system incorporates superheaters and a large accumulator to produce the initial temperature/pressure transients required during an accident steam exposure simulation.

2.2 Tested Electrical Connections

Connection test specimens; consisting of terminal blocks, conduit seals, connectors, and splices; were chosen on the basis of their usage in commercial nuclear power plants. Information gained from the NRC Equipment Qualification Inspection Program was a major input for assessing plant usage of connections.

Table 2.1 lists the specimens that were tested. In all, 12 different types of connections; consisting of 2 types of terminal blocks, 3 types of conduit seals, 2 types of connectors for installation in a device, and 5 in-line splices and connectors; were tested. In addition, 2 types of cable runs with no connections were tested. Two specimens of each connection and cable type were tested, except for the 3 specimens of the EGS Grayboot connector[1]; thus, a total of 25 connections and 4 cable runs without connections were tested.

The terminal blocks were added to the test program to address issues related to a previous study of terminal blocks by Craft [5, 6]. Because these issues differed from the test program objectives, all additional discussion of terminal blocks and the terminal block results is contained in Appendix A

As indicated in Table 2.2, a total of 23 cables (65 conductors) entered the test chamber for the non-terminal block connections. An additional 13 cables (39 conductors) exited the test chamber; these were the return legs of the cables that entered the chamber for the in-line splices and connectors, and the cable runs with no connections.

All the connections, except for the coaxial connectors

[1] One EGS Grayboot connector is needed for each conductor, thus three Grayboot connectors were used for one 3-conductor cable.

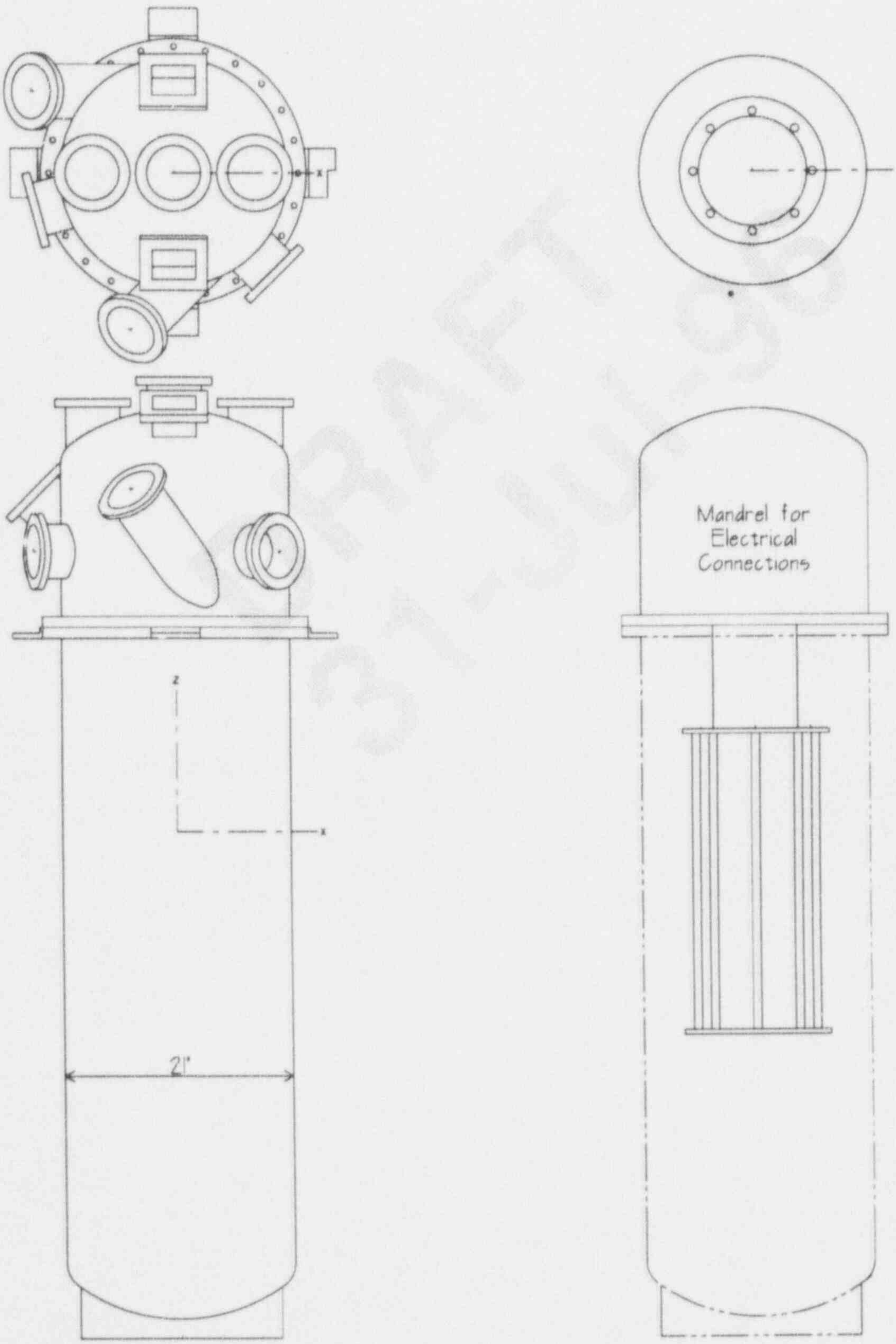

Figure 2.4: Detail of the test chamber and a sketch of the mandrel on which the electrical connections were mounted—drawn to scale.

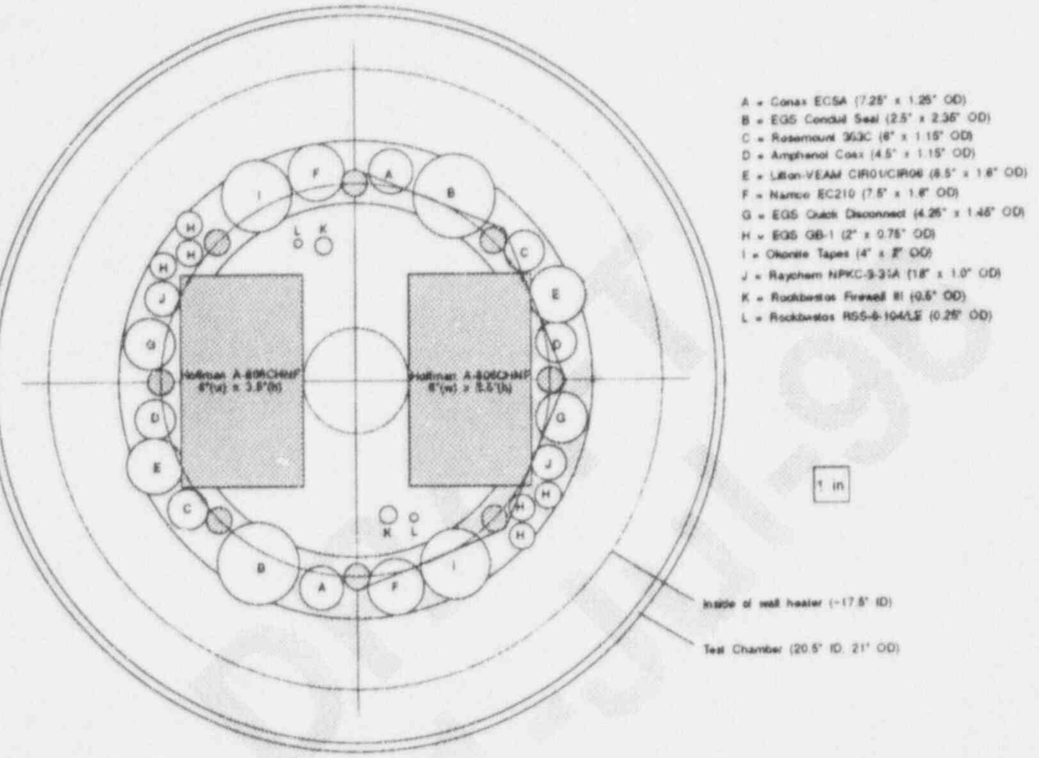

Figure 2.5: Top view of the test chamber and mandrel showing how the connections were arranged.

mentioned below, are Class 1E qualified and were supplied with a Certificate of Compliance or Conformance that indicates the standards to which they have been qualified, the relevant qualification documents, and the manufacturing lot and date. The unqualified Amphenol 82-816/16100/34500 coaxial connectors were included in this test for the following reasons:

- The Amphenol 82-816-1000 type HN straight plug coaxial connector (the -1000 suffix indicates that the insert material is polystyrene) is not qualified, but is used in Class 1E qualified radiation monitors such as the RD-23 detector assembly of the General Atomics High Range Radiation Monitor.
- The Amphenol 34500-1000 type N straight plug coaxial connector (the -1000 suffix indicates that the insert material is polyethylene, not polystyrene as for the 82-816-1000) has been previously tested in Westinghouse Report No. PEN-TR-79-53, July 23, 1979. This connector is used in the Class 1E qualified Victoreen Model 877 Radiation Monitor.
- The Amphenol 16100 adapter (HN jack to N jack) was solely used to mate the two Amphenol coaxial connectors together for testing purposes.

Rockbestos Firewall III XLPE multiconductor cable (12 AWG, 3 conductor) and Rockbestos RSS-6-104/LE coaxial cable were used to install connections that were not delivered already installed on a length of cable by the manufacturer. Both these cables are nuclear qualified and have been previously tested to the equivalent of 60 years [16, 18]. Using these cables to make the connections helped to ensure that the testing isolated the effects of aging on the connections, rather than simply failing the cable. However, to provide a baseline for the effect of the test exposures on the cables, two of each of the Rockbestos cables without any connections were also included in the test chamber for the entire duration of the test.

All connections were installed according to the manufacturer's instructions as listed in Table 2.3. The conduit seals and connectors that would normally be installed into a device such as a limit switch or pressure transmitter had their device side terminated into small, sealed chambers, called a "device enclosure", that simulate such devices. Each such connection had its own device enclosure, which was fabricated from stainless steel tube and Swagelok tube

Table 2.1: Tested Electrical Connections.

Electrical Connection	Number of Devices	Number of Conductors	Number of Penetrations[a]
Terminal Blocks			
Marathon 1604 NUC	2	9[b]	3 × 0.5 in
States ZWM-25004	2	9[b]	3 × 0.5 in
Conduit Seals			
Conax Electric Conductor Seal Assembly	2	4[c]	2 × 0.22 in
Patel/EGS Conduit Seal	2	6[b]	2 × 0.5 in
Rosemount 353C Conduit Seal	2	4[d]	2 × 0.15 in
Connectors (for installation into a device)			
Namco EC210 1/2-inch Series	2	8[e]	2 × 0.5 in
Patel/EGS 1/2-inch Quick Disconnect	2	6[f]	2 × 0.5 in
In-Line Splices and Connectors			
Amphenol 82-816-1000/16100/34500-1000	2	2[g]	4 × 0.25 in
EGS GB-1 Grayboot Connector	3	3[b]	2 × 0.5 in
Litton-VEAM CIR01/CIR06	2	6[b]	4 × 0.5 in
Okonite T-95/No. 35 Tape Splice	—	6[b]	4 × 0.5 in
Raychem NPKC-3-31A Splice Kit	2	6[b]	4 × 0.5 in
Other (cable runs with no connections)			
Rockbestos Firewall III cable (12AWG)	2	6	4 × 0.5 in
Rockbestos RSS-6-104/LE cable	2	2	4 × 0.25 in

[a] The number of cables that enter and exit the test chamber. Penetration diameters are rough estimates.
[b] Connection was installed using Rockbestos Firewall III cable (3 conductor, 12AWG).
[c] Supplied with 6 ft of cable (2 conductor, 14AWG) which was spliced to Rockbestos Firewall III (3 conductor, 12AWG) outside the test chamber.
[d] Supplied with 6 ft of cable (2 conductor, 22AWG) which was spliced to Rockbestos Firewall III (3 conductor, 12AWG) outside the test chamber.
[e] Supplied with Okonite FMR cable (4 conductor, 14AWG).
[f] Supplied with Rockbestos Firewall III cable (3 conductor, 12AWG).
[g] Connection was installed using Rockbestos RSS-6-104/LE coaxial cable.

fittings (Swagelok Co., Solon, OH) as shown in Figure 2.6. After using an Alcatel ASM 51 Helium Leak Tester to verify that all the device enclosures were "leak tight" (helium leak rate of less than 10^{-7} cc/sec), the conductors that pass through the connection were inserted into the device enclosure, using phenolic inserts to hold the ends of the conductors in known relation to one another, and the connection and device enclosure were threaded together. There was no attempt to physically check if the connections were leaking during the test. Leaking connections could be identified during the test only if the data measurements begin to show anomalies, or at the conclusion of the test if the device enclosure had moisture inside when it was opened.

The Amphenol 82-816/16100/34500 coaxial connectors were affixed to coaxial cable as specified in Ref. [1, pp.12,16] (the 82-816 uses a type HN typical clamp termination and the 34500 uses a type N standard clamp termination). To ensure an environmental seal, the coaxial connectors were covered with Raychem WCSF-N heat-shrinkable tubing (with the necessary shims); sizing and installation was according to Raychem instructions [32, 33, 29].

2.3 Test Conditions

The environmental exposure consisted of two phases:

- Simultaneous thermal/radiation aging to simulate 60 years in a nuclear power plant at an

Table 2.2: Conductor Numbers for the Connections (not including terminal block conductors).

EGS Conduit Seal	red conductor	white conductor	black conductor	
cable 7	01	02	**03**[a]	
cable 8	04	05	**06**	
Namco EC210	red conductor	white conductor	black conductor	green conductor
cable 9	07	08	**09**	10
cable 10	11	12	**13**	14
EGS Quick Disconnect	red conductor	white conductor	black conductor	
cable 11	15	16	**17**	
cable 12	18	19	**20**	
Conax ECSA	conductor 1	conductor 2		
cable 13	21	**22**		
cable 14	23	**24**		
Rosemount 353C	striped conductor	unstriped conductor	shield	
cable 15	25	26	**27**	
cable 16	28	29	**30**	
Raychem splice	red conductor	white conductor	black conductor	
cable 17a/17b	31a/31b[b]	32a/32b	**33a/33b**	
cable 18a/18b	34a/34b	35a/35b	**36a/36b**	
Okonite tape	red conductor	white conductor	black conductor	
cable 19a/19b	37a/37b	38a/38b	**39a/39b**	
cable 20a/20b	40a/40b	41a/41b	**42a/42b**	
Litton-VEAM	red conductor	white conductor	black conductor	
cable 21a/21b	43a/43b	44a/44b	**45a/45b**	
cable 22a/22b	46a/46b	47a/47b	**48a/48b**	
Amphenol coaxial	conductor	shield		
cable 23a/23b	49a/49b	**50a/50b**		
cable 24a/24b	51a/51b	**52a/52b**		
EGS Grayboots[c]	red conductor	white conductor	black conductor	
cable 25a/25b	53a/53b	54a/54b	**55a/55b**	
Firewall cable	red conductor	white conductor	black conductor	
cable 26a/26b	56a/56b	57a/57b	**58a/58b**	
cable 27a/27b	59a/59b	60a/60b	**61a/61b**	
coaxial cable	conductor	shield		
cable 28a/28b	62a/62b	**63a/63b**		
cable 29a/29b	64a/64b	**65a/65b**		

[a]Conductor numbers listed in bold were electrically grounded during aging, accident irradiation, and the accident steam exposure.

[b]Conductors numbered with a "b" suffix were left as an open circuit; they are the return legs of the "a" suffix conductors for the in-line splices and connectors, and the cable runs with no connections.

[c]The EGS Grayboot connector is for a single conductor, thus three Grayboot connectors were used for one 3-conductor cable.

Table 2.3: Installation Instructions for the Test Specimens.

Connection	Installation Instructions
Terminal Blocks	
Marathon 1604 NUC	—
States ZWM-25004	—
Conduit Seals	
Conax Electric Conductor Seal Assembly	[3]
Patel/EGS Conduit Seal	[8]
Rosemount 353C Conduit Seal	[37]
Connectors (for installation into a device)	
Namco EC210 1/2-inch Series	[21, 22]
Patel/EGS 1/2-inch Quick Disconnect	[9]
In-Line Splices and Connectors	
Amphenol 82-816-1000/16100/34500-1000	[1, pp.12,16][38]
EGS GB-1 Grayboot Connector	[11]
Litton-VEAM CIR01/CIR06	[20]
Okonite T-95/No. 35 Tape Splice	[24, pp.2–3,10][25]
Raychem NPKC-3-31A Splice Kit	[30]
Other (cable runs with no connections)	
Rockbestos Firewall III cable	—
Rockbestos RSS-6-104/LE cable	—

ambient temperature of 55°C (131°F) and a total radiation dose of 200 kGy (20 Mrad).

- A LOCA simulation consisting of an accident radiation dose of 1000 kGy (100 Mrad) sequentially followed by an accident steam exposure.

2.3.1 Simultaneous Radiation and Thermal Aging

The aging simulates 60 years in a nuclear power plant at an ambient temperature of 55°C (131°F) and a total integrated aging radiation dose of 200 kGy (20 Mrad). To accomplish this, an accelerated simultaneous aging exposure was performed for 6 months (182.625 days) at 98.8°C (209.8°F) and a dose rate of 45.6 Gy/hr (4.56 krad/hr).

The test temperature required for the thermal aging was calculated using the Arrhenius relation [12, Eqn. (4-16) and sections 4.1, 4.4 and 8.3.2],

$$\frac{t_2}{t_1} = \exp\left[\frac{E_a}{k_b}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right], \qquad (2.1)$$

which can be rewritten as,

$$T_2 = \frac{T_1}{1 + \frac{T_1 k_b}{E_a}\ln(\frac{t_2}{t_1})}, \qquad (2.2)$$

where

- t_i = aging time.
- T_i = aging temperature (absolute temperature).
- E_a = activation energy of the material.
- k_b = Boltzmann's constant ($= 1.3807 \times 10^{-23}$ J/K $= 8.6174 \times 10^{-5}$ eV/K [19, Appendix A]).

Table 2.4 gives the activation energies of the tested connections, and a plot of the required aging temperature as a function of activation energy is shown in Figure 2.7. Using the data in Table 2.4, an activation energy of $E_a = 1.15$ eV was chosen to give conservative data for most of the connections. For the 1.15 eV activation energy, the Arrhenius relation gives a required aging temperature of 98.8°C (209.8°F).

Radiation dosimetry was performed to quantify the radiation field to which the test samples were exposed. The dose mapping was performed using thermoluminescent dosimeters (TLDs) on the actual test configuration (*i.e.*, the TLDs were placed in the

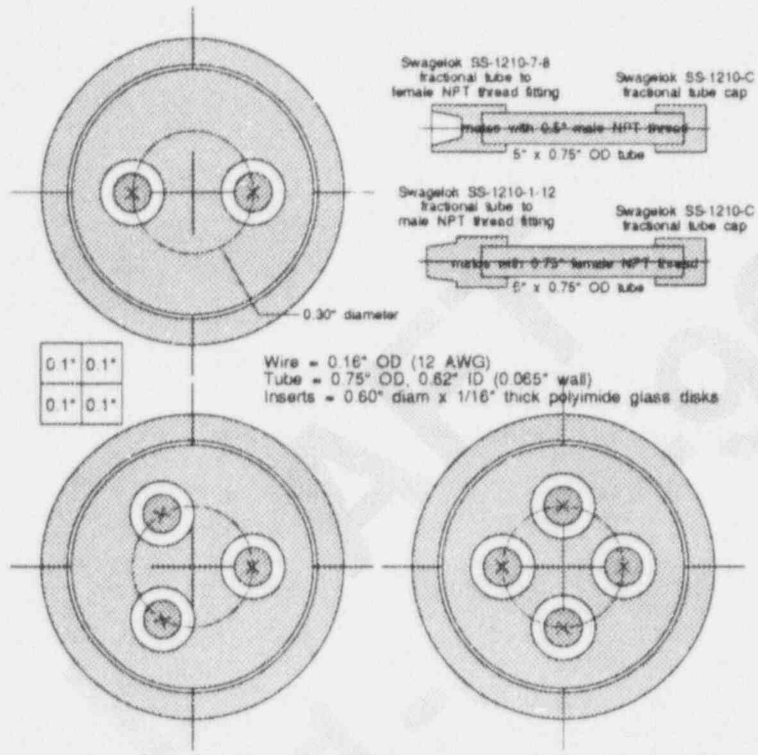

Figure 2.6: Sketch of the device enclosures used for installation of conduit seals and connectors that would normally be installed in a device.

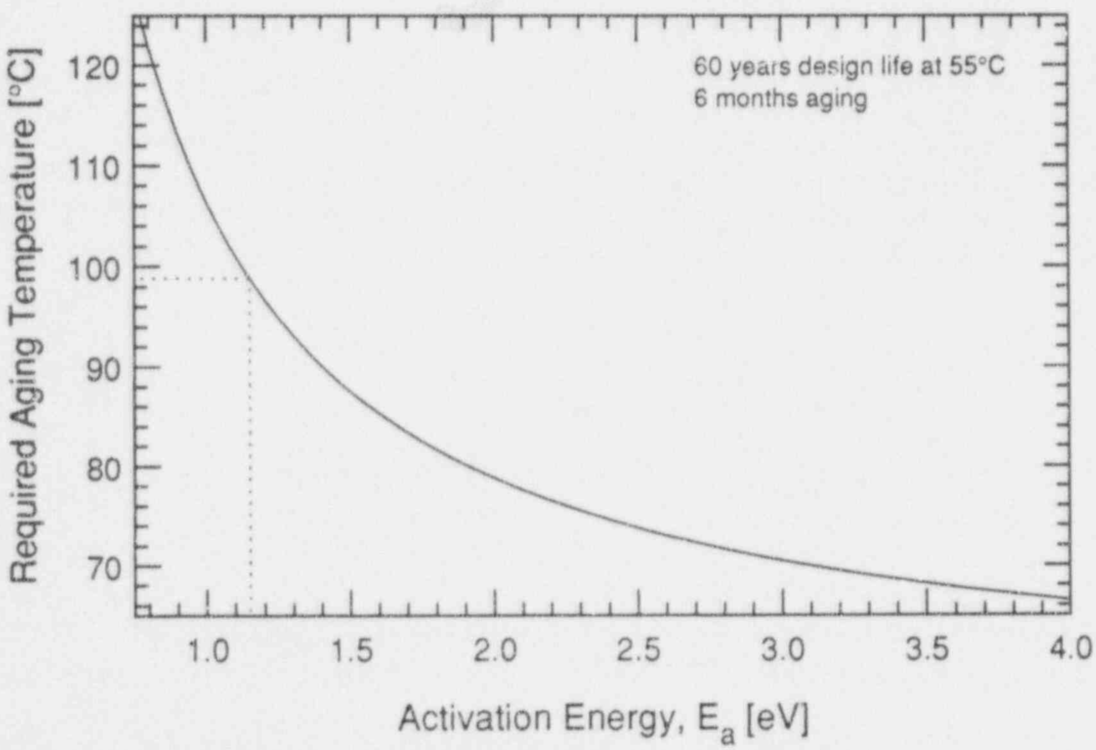

Figure 2.7: Required aging temperature as a function of activation energy, E_a.

Table 2.4: Activation energies of the specimens to be tested.

Connection	Activation Energy	Reference
Terminal Blocks		
Marathon 1604 NUC	1.21 eV	[39, p.XII-34]
States ZWM-25004	1.27 eV	[40]
Conduit Seals		
Conax Electric Conductor Seal Assembly	3.916 eV	[4, p.7]
Patel/EGS Conduit Seal	2.29 eV	[26, A.1, p.10]
Rosemount 353C Conduit Seal	1.29 eV	[36, p.A-3]
Connectors (for installation into a device)		
Namco EC210 1/2-inch Series	0.8 eV	[41]
Patel/EGS 1/2-inch Quick Disconnect	1.05 eV	[27, A.1, p.11]
In-Line Splices and Connectors		
Amphenol 82-816-1000/16100/34500-1000	not Class 1E	—
EGS GB-1 Grayboot Connector	0.92 eV	[10, A.1, p.9]
Litton-VEAM CIR01/CIR06	1.15 eV	[42]
Okonite T-95/No. 35 Tape Splice	1.23/0.65 eV ?	?
Raychem NPKC-3-31A Splice Kit	1.34 eV[a]	[31, p.6]
Other (cable runs with no connections)		
Rockbestos Firewall III cable	1.3412 eV (insul.)	[34, p.49]
Rockbestos RSS-6-104/LE cable	2.7479 eV (insul.)	[35, p.44]

[a]Reference gives activation energy of 31 kcal/mol which was converted to eV/molecule using the conversion factors: 1 cal = 4.184 J, 1 eV = 1.602×10^{-19} J, and 1 mole = 6.022×10^{23} molecules (also see [12, p. 8-30]).

test chamber after the connections and necessary test hardware were already installed).

The Litton-VEAM CIR01/CIR06, Namco EC210, Patel/EGS 1/2-inch Quick Disconnect, and the EGS GB-1 Grayboot connectors were subjected to periodic disconnect/connect cycling during the aging to simulate usage. As two samples of each connection were tested—one remained connected for the entire duration of the test and the other underwent the periodic disconnect/connect cycling during the aging to simulate usage. The cycling (10 disconnect/reconnect cycles) occurred before the start of the aging and after aging exposures of 66.7 and 133.3 kGy (2 and 4 months of aging). It was necessary to remove the test chamber from the radiation environment to perform the cycling.

Test chamber temperature was maintained using electric wall and inlet air heaters. The wall heater is a sheet stainless steel cylinder with a wrapping of Cerra blanket insulation on the outside, then a layer of uninsulated Nichrome wire, and a final layer of Cerra insulation on the outside. The chamber temperature was set using temperature controllers and type K thermocouples (Style AC mineral insulated thermocouples with Inconel sheathing, Gordon Co., Richmond, IL) as sensors. Temperature uniformity was improved by insulating the test chamber and providing air circulation. A flow of 3.3 l/sec (7 ft^3/min) or greater of outside air (approximately 30 air changes per hour) was supplied to the test chamber to maintain circulation and ambient oxygen concentration. Twenty thermocouples were used to monitor the temperature inside the test chamber. Aging conditions (temperature, airflow, and cable excitation) were monitored using the system shown schematically in Figure 2.8, the resulting data are shown in Figure 2.9.

During the aging, all the conductors in each connection except for one ground conductor were energized with 110 Vdc (and no current) as indicated in Table 2.2. The test chamber was rotated three times during aging to help ensure a uniform radiation dose for all the tested connections.

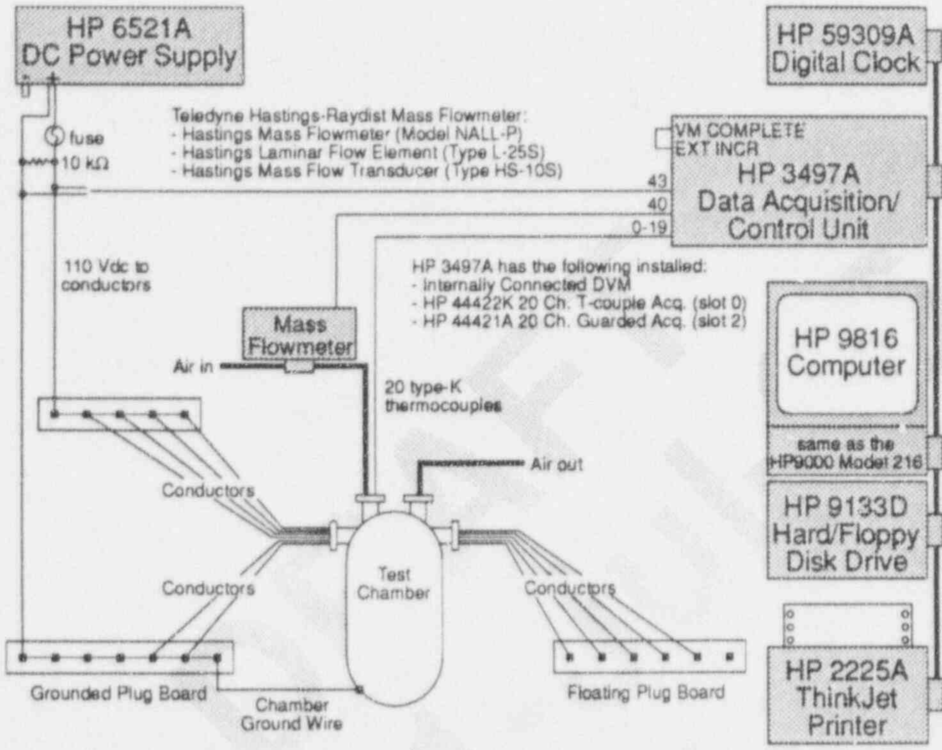

Figure 2.8: Schematic of the system used to monitor test chamber conditions during aging and accident irradiation.

2.3.2 Loss-of-Coolant Accident Simulation

A loss-of-coolant accident (LOCA) simulation was performed after completion of the aging. The LOCA simulation consisted of an accident radiation exposure followed by an accident steam exposure. The accident exposures used the same test chamber as the aging exposure to limit the amount of handling of the connection specimens.

Accident Radiation Exposure

An accident radiation exposure was performed after completion of the aging.

The accident irradiation was performed for 200 hours at a dose rate of 5 kGy/hr (500 krad/hr) for an accident radiation dose of 1000 kGy (100 Mrad). Radiation dosimetry was performed to quantify the accident radiation field to which the test samples were exposed. The dose mapping was performed using thermoluminescent dosimeters (TLDs) on the actual test configuration (*i.e.*, the TLDs were placed in the test chamber after the connections and necessary test hardware were already installed). Previous testing by Buckalew [2] has shown that accident radiation exposures are conservatively simulated by isotropic gamma ray sources such as the cobalt-60 used for this test. During the accident radiation exposure, the temperature was not controlled and thus was near the ambient temperature of the LICA pool water. Air circulation into the test chamber continued as during the aging exposure. The conductors were energized at the same 110 Vdc and no current as during the aging.

Accident irradiation conditions (temperature, airflow, and cable excitation) were monitored using the system shown schematically in Figure 2.8, the resulting data are shown in Figure 2.10. Because of the near symmetry of the radioactive cobalt sources around the test chamber, the test chamber was not rotated during the accident irradiation.

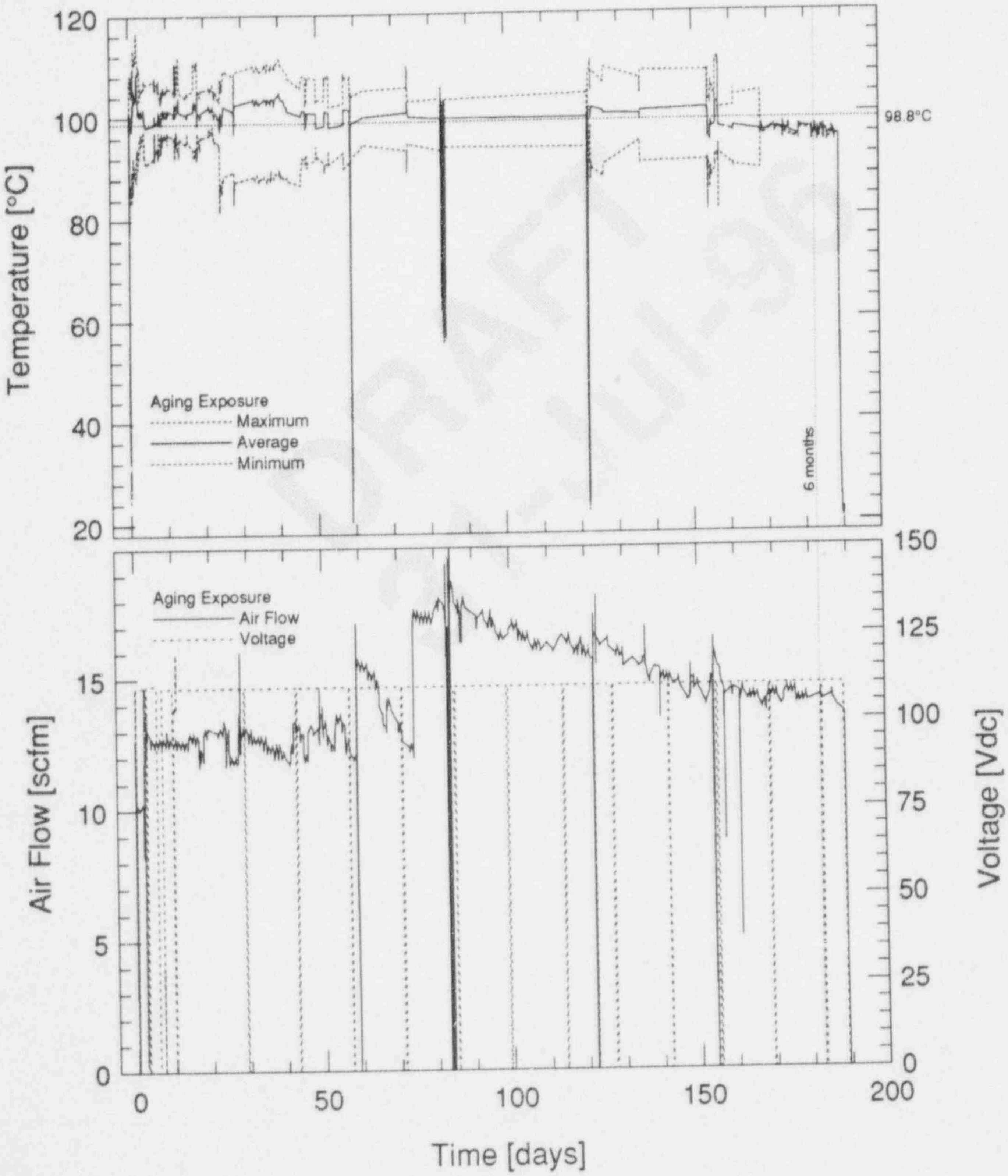

Figure 2.9: Temperature, airflow, and cable excitation during the simultaneous radiation and thermal aging exposure.

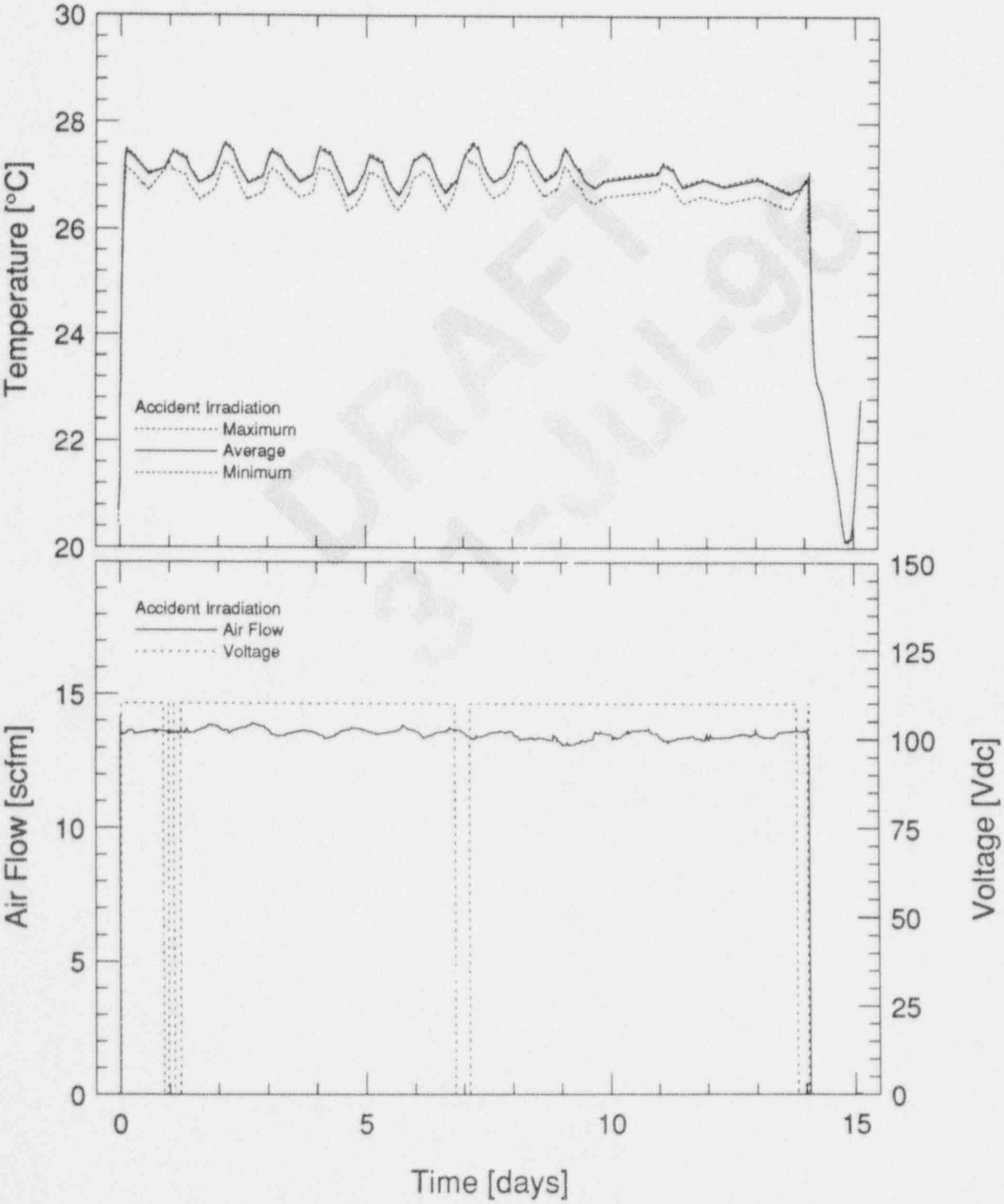

Figure 2.10: Temperature, airflow, and cable excitation during the accident radiation exposure.

Accident Steam Exposure

The accident steam exposure was performed after the accident radiation exposure. The steam exposure consisted of simulated LOCA transient temperature and pressure conditions. The same test chamber used for the aging exposure and accident irradiation was used for the accident steam exposure.

The desired accident steam temperature and pressure profiles are given in Table 2.5 (this is the same profile used in [16, 17, 18]). The only significant difference between the desired profile and the "generic" profile given in Appendix A of IEEE Std 323-1974[2] [15, Fig. A1] is that the final portion of the current test is at a higher temperature and for a shorter duration than the appendix to IEEE Std 323-1974 suggests. Note that the test profile has superheated steam conditions (*i.e.*, $P < P_{sat}$ for a given T) during the initial ramp and until 6 hours after the start of the second transient. After this, the profile continues as saturated steam. Note that the IEEE profile has a pure steam environment; previous research [13, 14] has shown that the presence or lack of oxygen is an important parameter for LOCA simulations. The test chamber temperature and pressure were controlled manually. No chemical spray was used during the steam exposure.

During the accident steam exposure, the non-terminal block conductors were energized at approximately 110 Vdc, 0 mA to allow for on-line measurement of insulation resistance. One conductor in each connection (or the shield, if present) was grounded as indicated in Table 2.2.

The actual and target pressure and temperature during the accident steam exposure are shown in Figure 2.11. The pressure shown in Fig. 2.11 was measured using a single Heise 710B pressure transducer with a range of 0–1380 kPa gauge (0–200 psig). The temperature shown in Fig. 2.11 is the average value calculated from the 20 thermocouples in the test chamber.

Two problems occurred during the accident steam exposure. The first occurred at the start of the first transient when a port on the test chamber was left open, causing steam to be vented into the laboratory when steam was introduced into the chamber. The valve controlling steam flow into the test chamber was immediately closed, the open port was then closed and the first transient was restarted approximately 24 min later. This can be seen in the Figure 2.11 temperature plot which shows that the test chamber temperature reached approximately 102°C (216°F) prior to the start of the first transient. The second problem was a slow drop in the test chamber temperature that occurred during days 4 and 5. This was due to steam condensate slowly beginning to fill the test chamber after a steam trap failed so that condensate no longer drained from the test chamber. The pressure remained on target because it was manually set by a pressure regulator, however as more and more condensate collected in the bottom of the test chamber, the steam injected into the test chamber was no longer able to keep it at the saturation temperature and thus the test chamber temperature began to cool.

[2] The newer standard, IEEE Std 323-1983, has never been endorsed by the NRC. It also does not include a "generic" steam condition profile like that found in Appendix A of IEEE Std 323-1974.

2.4 Electrical Measurement Techniques

All the measurements performed were electrical in nature — electrical measurements were performed to detect if the connections had failed. It is unclear what type of mechanical, physical, or chemical testing could be non-destructively performed on an installed connection. Note that previous test programs regarding the aging degradation of cables [16, 17, 18] have indicated that electrical measurements are not good at detecting degradation of cables.

2.4.1 High Potential

The high potential testing measured the ac leakage current. When an ac voltage is applied to a device, the resulting leakage current gives an indication of the device's reactive impedance (at the excitation frequency of the applied ac voltage).

Using the system shown schematically in Figure 2.12, a Hipotronics Model 750-2 AC Dielectric Test Set (Hipotronics, Inc., Brewster, NY) was used to perform leakage current measurements on the connectors. Data were acquired for dry connections at voltages of 600 and 1000 Vac rms (60 Hz) and for submerged

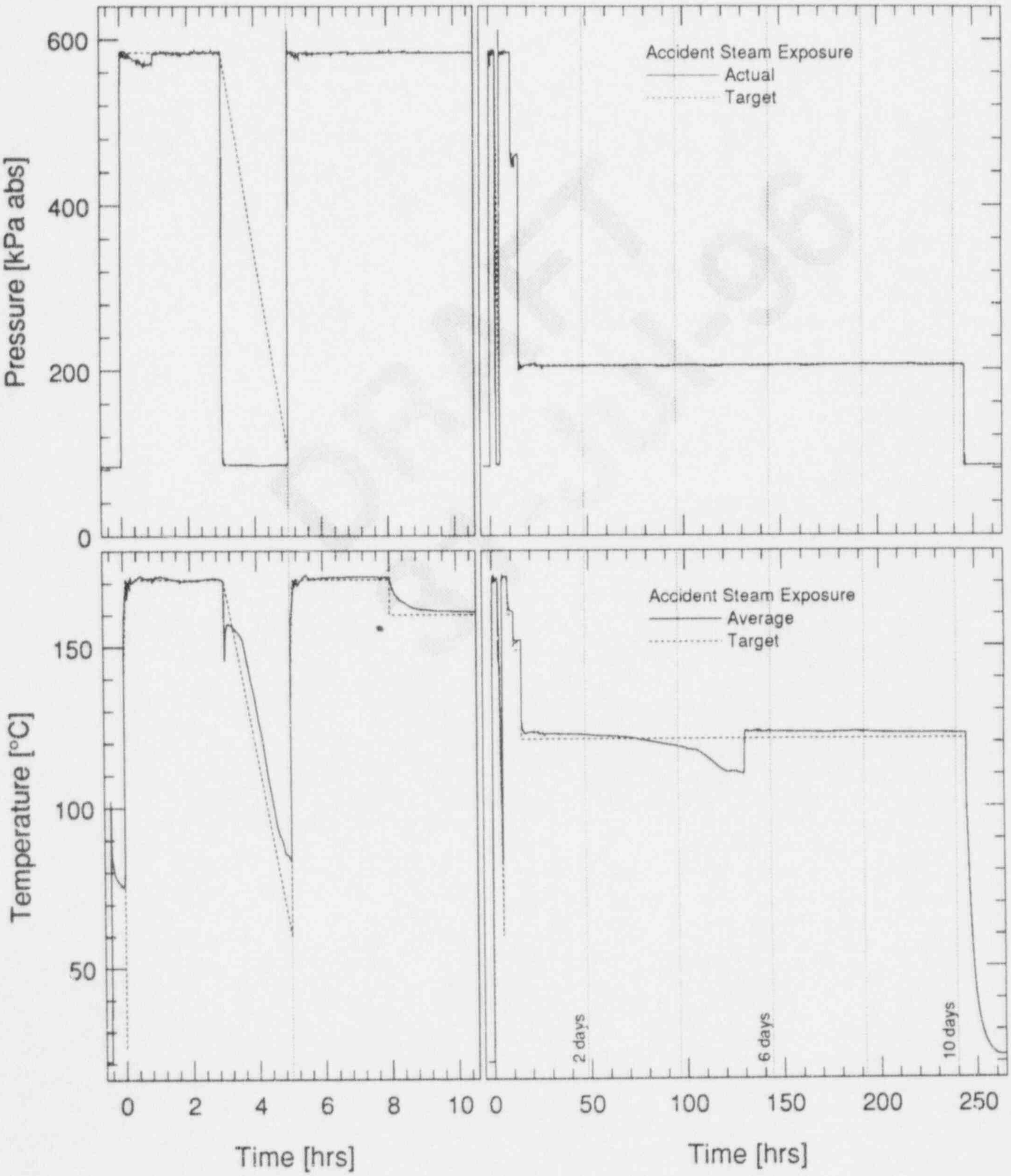

Figure 2.11: Pressure and temperature during the accident steam exposure.

Table 2.5: Target Accident Steam Exposure Profile and IEEE Std 323-1974 Combined PWR/BWR Profile.

Time	Intended Test Profile		IEEE Std 323-1974 Profile	
	Temperature [°C]	Absolute Pressure [kPa]	Temperature [°C]	Absolute Pressure[a] [kPa]
0–10 s	Ambient–137.8	Ambient–583.9	57.2–137.8	101.3–583.9
10 s–5 min	137.8–171.1	583.9	137.8–171.1	583.9
5 min–3 hr	171.1	583.9	171.1	583.9
3–5 hr	171.1–60.0	583.9–101.3	171.1–60.0	583.9–101.3
Reset time to 0 for the next portion of the profile				
0–10 s	60.0–137.8	101.3–583.9	60.0–137.8	101.3–583.9
10 s–5 min	137.8–171.1	583.9	137.8–171.1	583.9
5 min–3 hr	171.1	583.9	171.1	583.9
3–6 hr	160.0	583.9	160.0	583.9
6–10 hr	148.9	461.8	148.9	583.9
10–91 hr	121.1	205.6	121.1	273.7
91–240 hr	121.1	205.6		
91 hr–100 days			93.3	170.2

[a] Assuming an ambient pressure of 101.325 kPa (sea level); note that the laboratory elevation is approximately 1646 m (5400 ft) for which the standard ambient pressure is 83.057 kPa [23, p. 121].

connections at 600 and 2400 Vac rms (60 Hz) — the 600 Vac is a nominal value because the Hipotronics test set cannot precisely control such low ac voltages. The conductor under test was connected to the dielectric test set and all other conductors were electrically grounded before applying the ac voltage. The opposite ends of the conductors were allowed to float electrically.

The Hipotronics dielectric test set outputs dc voltages proportional to the ac excitation voltage and ac leakage current. These two dc voltage outputs were acquired using two HP 3478A Multimeters, one acquired the excitation voltage and the other the leakage current. Data acquisition utilized the following procedure:

1. Start the acquisition program, the two streams of data are acquired every half second by the multimeters and sent to the computer for storage.
2. Ramp the excitation voltage up to the desired voltage using a voltage ramp rate of 500 Vac/sec.
3. Hold at the desired excitation voltage for 1 minute.
4. Ramp the excitation voltage back down.
5. Stop the acquisition program.

The leakage current data point was calculated by the program based on the acquired values during the 1 minute hold at the desired excitation voltage.

2.4.2 Insulation Resistance

Insulation resistance (IR) gives a measure of the resistive component of dielectric impedance. The IR value calculated from the applied dc voltage and measured current only includes resistive impedance—any initial ac effects due to the sudden application of the dc voltage are effectively gone by the time the IR measurement is taken. IR values are typically used by the utility industry as a go/no-go test of insulation—however, no technical basis is available to set an IR acceptance criteria for age-related degradation. Typically, an IR test is used to assist detection of locally damaged cable (*i.e.*, insulation windings that are wet, or a gouged cable that is "sufficiently close" to the ground plane in the test).

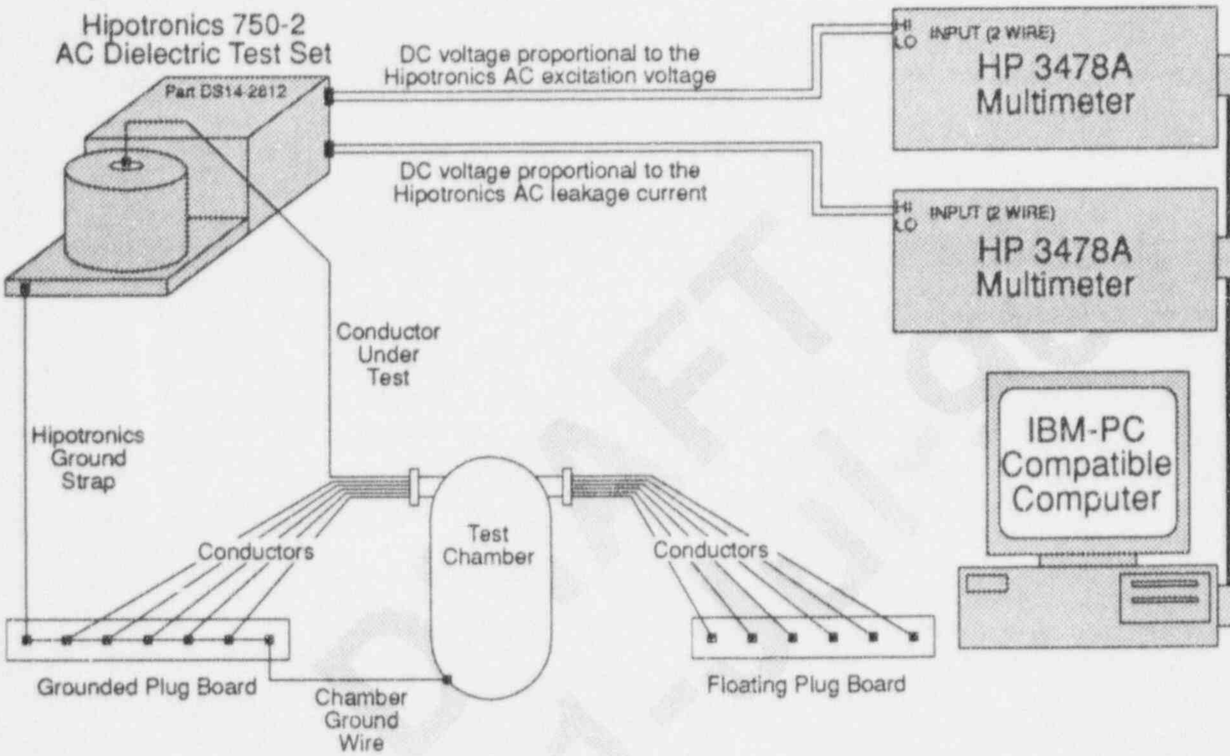

Figure 2.12: Schematic of the system used to measure ac leakage currents.

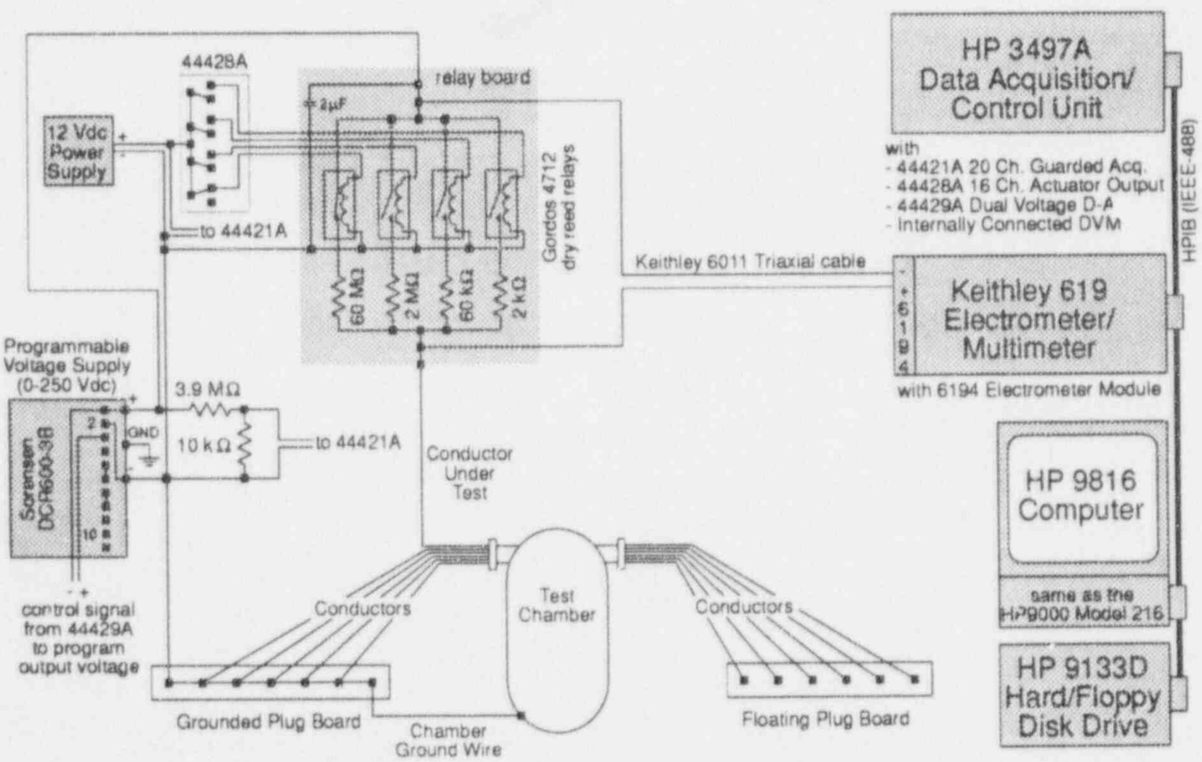

Figure 2.13: Schematic of the system used to measure insulation resistance.

The IR of the complete cable samples was measured at discrete times using the system shown schematically in Figure 2.13—a detailed discussion of this system appears in Ref. [16, Section A.2]. The conductor (or shield) under test was connected to the dc power supply through a resistor—all other conductors (and shields) were grounded before applying the dc voltage. The opposite ends of all the cables were allowed to float electrically. The majority of IR measurements were performed at 100 Vdc, however some data were also acquired at 50 and 250 Vdc. A single IR measurement consisted of acquiring 15 samples of the voltage across the resistor at times ranging from 2 seconds to 1 minute after the application of the power supply voltage. For each of the 15 samples, the conductor's IR was calculated using the measured voltage across the known resistance and the power supply voltage. To reduce the effect of measurement noise, the IR values were fit using a least-squares polynomial regression and the value from the fit, rather than the actual measured value, was used as the IR at 1 minute.

During the accident steam exposure, IR measurements were performed using the circuit shown in Figure 2.14 in addition to the discrete IR measurements. These IRs are referred to as "continuous" IRs, even though they were not truly continuous—these measurements were performed at intervals ranging from 10–300 seconds. The conductor numbers in the figure correspond to the numbers in Table 2.2. As indicated in Fig. 2.14 and Table 2.2, one conductor or shield from each cable was connected to ground to provide a ground plane—no continuous IR measurements are available for these grounded conductors. The continuous system could measure IR values up to approximately 10^8 Ω which is several orders of magnitude less than what could be measured with the discrete IR system. The continuous IR system is most useful for identifying short-term drops in IR values, such as during the initial transient of the accident steam exposure, that would otherwise be missed by the discrete IR system. A more complete discussion of the measurement limits of the continuous IR system appears in Ref. [16, Section 2.4.3].

Because of limitations in the accuracy of the measuring equipment, discrete IR measurements were cut off above 2.0×10^{12} Ω and continuous IR measurements were cut-off above 1.0×10^8 Ω.

2.4.3 Time Domain Reflectometry

A Tektronix 1502B Time Domain Reflectometer (Tektronix, Inc., Wilsonville, OR) was used to perform time domain reflectometry (TDR) measurements on the conductors. The TDR data were sent to an IBM PC-compatible computer for storage via a serial port (RS-232) connection using a Tektronix SP232 serial interface. Measurements were performed before and after the accident steam exposure.

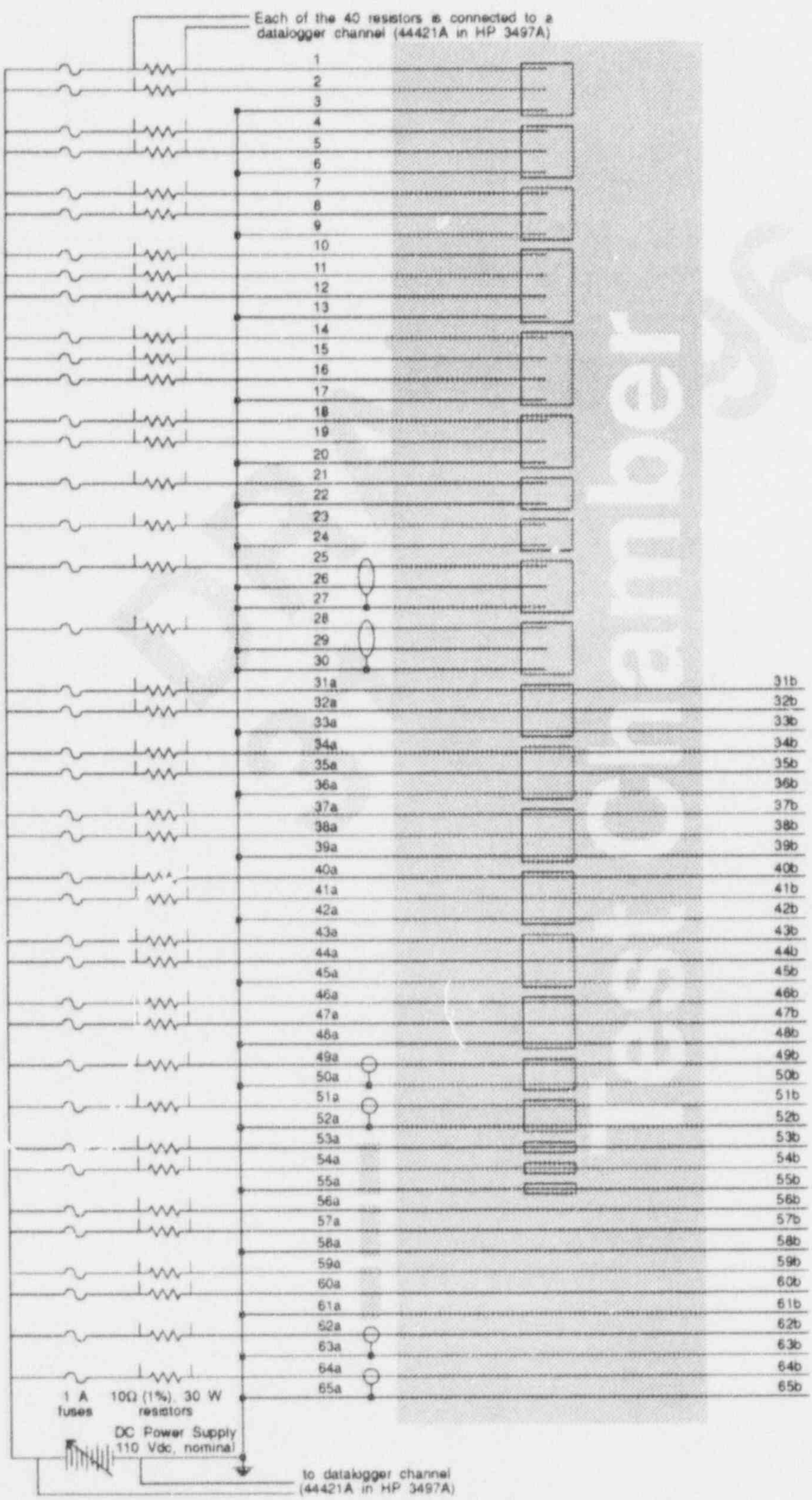

Figure 2.14: Circuitry used to measure continuous insulation resistance during the accident steam exposure.

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3 Experimental Results

This section presents the experimental data[1] acquired for the 10 different types of non-terminal block connections and the 2 types of cables that were tested.

All the measurements performed were electrical in nature. It is unclear what type of mechanical, physical, or chemical testing could be non-destructively performed on an installed connection. Previous test programs on electrical cables have shown that electrical property measurements typically do not show significant changes with aging; mechanical measurements, most notably elongation at break, generally provide a better indication of aging degradation [16, 17, 18]. However, electrical measurements are simple to perform and can be performed without destroying the device under test.

A dominant failure mechanism for low-voltage instrumentation and control cables is cracking of the conductor's insulation after it has become embrittled due to thermal and/or radiation exposures. A cable with no residual elongation at break has often been found capable of performing its intended function in an accident scenario as long as no cracks already exist in the insulation. However, any handling of the cable, something dropping on it, or even movement of the cable tray or conduit could cause the cable to crack. An electrical test might indicate that a cable is good even though it has no remaining elongation and any movement will cause the cable to crack and fail in the event of an accident.

This same type of failure mechanism does not typically occur in connections because the conductors are often encased in some sort of rigid shell that protects the conductors and makes the insulation less susceptible to mechanical damage even after the insulation has become embrittled. Thus, the ability of a connection to perform its intended function is less dependent on the mechanical state of the conductor insulation. While electrical testing provides a direct indication of connection functionality, it must be remembered that electrical testing has not been shown to indicate connection degradation or predict imminent connection failure.

[1] In addition to the figures and tables included in this section, all the raw data are available upon request from the author.

3.1 Aging Exposure

Only IR data were acquired during the simultaneous thermal and radiation aging exposure, these data are plotted versus radiation dose in Figures 3.1–3.12, these figures also include the accident irradiation IR data. Each plotted point is the average and the plotted bars show the sample standard deviation for the IR measurements of all the conductors for the given type of connection. The IR measurements during the aging exposure were performed with the test chamber and cable leads submerged in the LICA pool. Measurements at ambient temperature were performed with the test chamber and cable leads out of the LICA pool before the start of the aging exposure and between the aging exposure and accident irradiation. The ambient IR measurements were typically greater than those acquired at the higher temperatures present during aging exposure.

The measured average IR values typically remained above 10^9 Ω for the duration of the aging exposure, however the following observations should be noted:

- During the baseline IR testing prior to the start of aging, one of the Rosemount 353C conduit seals was found to have an internal short circuit between its two conductors (25 and 26). There was no short to either the shield (27) or the body of the conduit seal. The defective conduit seal was replaced with a spare which was used for the test program.
- The lowest IR values during the aging exposure were for the Rosemount 353C conduit seal (see Figure 3.12). The measured IR of conductor 28 fell immediately from an initial value of 8.4×10^{10} Ω to 1.9×10^6 Ω and then slowly increased to approximately 2×10^7 Ω during the remainder of the aging exposure. The other 3 conductors and 2 shields typically had IR values in the range of 5×10^8 Ω and above.
- Conductor 22 from a Conax ECSA conduit seal also had reduced IR values (see Figure 3.2); the 8.3×10^9 Ω measurement at 60 kGy fell to 7.0×10^6 Ω at 75 kGy and remained at these low levels for the remainder of the aging exposure. The other 3 conductors typically had IR values near 10^{10} Ω.

- Two of the three EGS Grayboot connectors were installed with a snap-on plastic cover intended to prevent the connector from pulling apart — only one of the two covered connectors was cycled. After 2 months of aging, the plastic cover was very brittle and broke apart when it was removed to cycle the connector (conductor 54). The test was continued without a plastic cover over this connector. When the 2 Grayboot connectors were cycled after 4 months of aging, the lubricant between the mating halves of the connections was dried out and had the appearance of rolled-up rubber cement. However, enough lubricant remained that the two connectors could be cycled easily. These issues had no negative effect on the measured IR data (see Figure 3.5) which were in the range of 10^{11} Ω and above.

3.2 LOCA Exposure

The LOCA simulation consisted of an accident radiation exposure followed by an accident steam exposure.

3.2.1 Accident Irradiation

Only IR data were acquired during the accident radiation exposure, these data are plotted versus radiation dose in Figures 3.1–3.12 along with the simultaneous aging IR data. Each plotted point is the average and the plotted bars show the sample standard deviation for the IR measurements of all the conductors for the given type of connection. The IR measurements during the accident irradiation were performed with the test chamber and cable leads submerged in the LICA pool. Measurements at ambient temperature were performed with the test chamber and cable leads out of the LICA pool between the aging exposure and accident irradiation and after the accident irradiation. The ambient IR measurements were typically greater than those acquired during the accident irradiation.

The measured average IR values typically remained above 10^9 Ω for the duration of the accident irradiation, however the following observations should be noted:

- In all cases, the measured IR values during the accident irradiation remained relatively constant as the dose increased.
- Just as for the aging exposure, the lowest IR values during the accident irradiation were for the Rosemount 353C conduit seal (see Figure 3.12). Conductor 25 had measured IR values in the range of 3×10^5 to 1×10^6 Ω and conductor 28 had IR values near 2×10^7 Ω. The other 2 conductors and 2 shields typically had IR values in the range of 5×10^6 Ω and above.
- Conductor 22 from a Conax ECSA conduit seal (see Figure 3.2) also had reduced IR values of approximately 2×10^6 Ω for the duration of the accident irradiation. The other 3 conductors had IR values near 2×10^9 Ω.

3.2.2 Accident Steam Exposure

A TDR measurement was performed on each of the conductors prior to the start of the accident steam exposure. The purpose of this measurement was to provide a baseline for a post-steam TDR measurement. These results will be discussed with the post-LOCA results.

IR data during the accident steam exposure are plotted versus time from the start of the first steam transient for both cable conductors and shields in Figures 3.13–3.24. Each plotted point is the average and the plotted bars show the sample standard deviation for the IR measurements of all the conductors for the given type of connection. All the IR measurements were performed with the test chamber and cable leads out of the LICA pool. Measurements at ambient temperature were performed before and after the accident steam exposure. The remainder of the IR measurements were acquired at the pressures and temperatures indicated in Table 2.5 and Figure 2.11.

In general, the IR measurements inversely mirrored the environmental conditions (*i.e.*, IR decreased as temperature and pressure increased, and IR increased when temperature and pressure decreased). For all the conductors, the measured IR decreased by at least two orders of magnitude during the transients at the start of the accident steam exposure.

Several of the connections were used with Rockbestos Firewall III cable. Of these, the measured IR of the EGS conduit seal (Figure 3.16), EGS Grayboot connector (Figure 3.17), Okonite tape splice (Figure 3.22), and the Raychem heat shrink splice (Figure 3.23) were all very similar to that of the Rockbestos Firewall III cable in Figure 3.19. This indicates that these connections had IR values that were comparable or better than the Rockbestos cable. The measured IR of the NAMCO EC210 connector (Figure 3.21) was also very similar even though it used a different type of cable.

The IR results for the Litton-VEAM connector (Figure 3.20), which also used the Rockbestos Firewall III cable, would have also given similar results except that conductors 43 and 47 had IR values several orders of magnitude less than the other four conductors.

The IR results for the Rosemount 353C conduit seal (Figure 3.24) during the accident steam exposure were only slightly degraded, if any, from the values seen during the aging exposure and accident irradiation (Figure 3.12) — the reason for this "recovery" in IR is unknown.

The average IR values of the EGS quick disconnect connector (Figure 3.18) remained relatively constant near 10^8 Ω during the steam exposure after the initial drop due to the steam transients.

The IR of the Conax ECSA conduit seal (Figure 3.14) remained high during the first and most of the second steam transient, but then dropped rather quickly to the 10^6 Ω range about 9 hours into the steam exposure (4 hours into the second steam transient). The IR measurements then remained in the 10^5–10^6 Ω range until approximately 52 hours, after which the IR values began to fall steadily. The discrete IR measurements at 94, 171, 194, 219, and 242 hours had IR values of less than 10^3 Ω. The low IR values caused the 1 A fuses for conductors 21 and 23 on the continuous IR measurement circuits to blow repeatedly as shown in Table 3.1 and Figure 3.14. There was a period of slight recovery in the discrete IR values; at 132 and 146 hours the IR recovered to approximately 2.3×10^4 Ω, however the IR had fallen again by the 171 hour measurement.

The Rockbestos coaxial cable was only used in the Amphenol coaxial connector. The coaxial cable's IR remained very high throughout the accident steam exposure, as shown in Figure 3.15. The IR of the Amphenol coaxial connector (Figure 3.13) was very high during the two transients at the start of the steam exposure, but dropped precipitously during the second day of the steam exposure and remained at values between 10^4–10^5 Ω for the duration of the exposure.

3.3 Post-LOCA Measurements

After the completion of the accident steam exposure, several types of measurements were performed, they included:

- IR measurements (1 min at 100 Vdc)
- TDR measurements
- Submerged IR measurements (1 min at 100 Vdc)
- Dielectric withstand measurements (1-min hold at 1000 Vac rms for conductors, 600 Vac rms for shields)
- Submerged dielectric withstand measurements (1-min hold at 2400 Vac rms for conductors, 600 Vac rms for shields)

A set of IR measurements was performed quickly (3 days) after the completion of the accident steam exposure, these data are tabulated in Tables 3.2 and 3.3 and are also plotted as the ambient data at approximately 245 hr in Figures 3.13–3.24. In general, these data show a recovery in IR from that during the steam exposure.

At this same time, TDR measurements were performed on all the conductors. These data are plotted with the results obtained prior to the start of the accident steam exposure in Appendix B as Figures B.1–B.12. The pre- and post-steam TDR measurements were performed with identical test parameters and the connections were located at a distance of approximately 9.14 m (30 ft) down the cable. In general, the reflection coefficient, ρ, of the post-steam TDR measurements was less than that of the pre-steam measurements, which indicates that the impedance of the connection or cable had been reduced. One possible cause of the decreased post-steam impedance could be moisture present in the cable and connection from the steam exposure. Also, the cable in the post-steam measurements appears "longer" than that of the pre-steam measurements. Since both measurements

Table 3.1: Conax ECSA conduit seal Conductor Fuses Replaced During the Accident Steam Exposure.

Time [hrs]	Conductor	Description
73	23	blown fuse
74	23	replaced fuse, blew instantly
93	21	blown fuse
98	21	replaced fuse, blew instantly
131	21, 23	replaced fuses, fuses okay
139	23	blown fuse
147	21	blown fuse
147	21, 23	replaced fuses, blew instantly
167	21, 23	replaced fuses, blew instantly
215	21, 23	replaced fuses, 21 blew within 20 min, 23 blew immediately
245	21, 23	replaced fuses, 21 blew immediately, 23 okay
267	21	replaced fuse, blew immediately
285	21	replaced fuse, blew immediately

were performed assuming the same propagation velocity on the same cable and connection, this indicates that the actual propagation velocity was slower for the post-steam measurements than for the pre-steam measurements. The effect of the high temperature and pressure during the accident steam exposure might have affected the cable propagation velocity. It is difficult to identify if changes between the pre- and post-steam TDR measurements are due to cable or connection degradation, or to some other effect such as moisture or water intrusion.

Because of the possibility that moisture still remained in and on the connections, the IR was retested approximately 13 months later which provided sufficient time to ensure that everything had dried out. The results are shown in Tables 3.2 and 3.3, and are similar to those obtained immediately after the accident steam exposure, except for the following observations. The IR of several NAMCO EC210 connector conductors fell substantially; the IR of conductor 7 fell by over 5 orders of magnitude and the IR of conductors 9 and 10 fell by over 2 orders of magnitude. In contrast, the IR of all the EGS quick disconnect connector conductors increased markedly to values above 10^{10} Ω, those of Conax ECSA conduit seal conductors 21 and 22 increased by at least 4 orders of magnitude, those of Rosemount 353C conduit seal conductors 28 and 29 increased by 2 orders of magnitude, and those of Amphenol coaxial connector conductors 49 and 50 increased by a factor of 40. The IR of the Litton-VEAM connector conductors showed no consistent trend as the IR of conductors 43 and 45 increased at least 2 orders of magnitude and conductors 47 and 48 increased by at least 6 orders of magnitude; however, the IR of conductor 44 actually decreased by almost 4 orders of magnitude.

Once the dry IR test was completed, the test chamber was flooded with tap water and two additional sets of IR measurements were performed. As shown in Tables 3.2 and 3.3, these IR measurements were performed after a soak period of at least 30 min for one set, and a minimum soak period of 3 hr for the second set. Again, the submerged IR results were similar to those of the previous (dry) IR measurements, except for the following observations. The submerged IR of all the EGS quick disconnect connector conductors decreased from values above 10^{10} Ω to less than 10^6 Ω. The submerged IR values of all the Conax ECSA conduit seal conductors decreased at least 2 orders of magnitude to values of 3×10^4 Ω and below. The submerged IR values of all the Litton-VEAM connector conductors decreased at least 3 orders of magnitude to values of 6.9×10^4 Ω and below. The submerged IR values of the Amphenol coaxial connector shield conductors (50 and 52) decreased to values in the 1×10^4 to 4×10^4 Ω range. There were no substantial differences between the data for minimum soak times of 30 min and 3 hr except for

the Rosemount 353C conduit seal where the IR of several conductors decreased by over 3 orders of magnitude between the 30 min and 3 hr soak times.

Following the submerged IR tests, the connections were allowed to fully dry and then dielectric withstand testing was performed. An initial withstand testing on the dry cables was performed at 1000 Vac rms for the conductors and 600 Vac rms for the shields to get an indication of operability before performing submerged dielectric withstand testing. As shown in Tables 3.2 and 3.3, most of the connections did not trip[2] the dielectric test set (8 of 55 connection conductors and 0 of 10 cable conductors tripped the test set). The individual conductors either had essentially constant current during the 1-min long hold, or tripped the dielectric test set immediately during the initial ramp up to the desired voltage; none of the conductors held at the desired voltage for some period of time and then caused the dielectric test set to fault. All the Conax ECSA conduit seal conductors and approximately half of the Litton-VEAM connector and Amphenol coaxial connector conductors tripped the dielectric test set during the dry dielectric withstand test.

Following the dry dielectric withstand tests, the test chamber was flooded again with tap water and submerged dielectric withstand tests were performed after a minimum submergence of 2 hrs. The dielectric withstand testing on the submerged cables was performed at 2400 Vac rms for the conductors and 600 Vac rms for the shields. As shown in Tables 3.2 and 3.3, half of the 10 connection types tripped[3] the dielectric test set (22 of 55 connection conductors and 0 of 10 cable conductors tripped the test set). Just as for the dry withstand testing, individual conductors either had essentially constant current during the 1-min long hold, or tripped the dielectric test set immediately during the initial ramp up to the desired voltage; none of the conductors held at the desired voltage for some period of time and then caused the dielectric test set to fault. Essentially all of the EGS quick disconnect connector, Conax ECSA conduit seal, Rosemount 353C conduit seal, Litton-VEAM connector, and Amphenol coaxial connector conductors tripped the dielectric test set.

If a typical cable is assumed to have a capacitance of roughly 98.4 pF/m (30 pF/ft) and the cable specimens are approximately 18.3 m (60 ft) long, then the cable impedance for 60 Hz excitation would be:

$$\begin{aligned} Z &= \frac{1}{\omega C} = \frac{1}{(2\pi f)C} \\ &= \frac{1}{(2\pi \times 60)(30 \times 10^{-12} \times 60)} = 1.47 \times 10^6 \Omega. \end{aligned}$$

For a 2400 Vac conductor excitation voltage, this results in a capacitive charging current of 1.6 mAac. The ac charging and leakage current measurement is the sum of the current actually leaking from the conductor through the insulation to a ground outside the cable plus the current necessary to charge and discharge the capacitance of the cable dielectric (insulation) as the applied cable voltage changes. This differs from an IR measurement, which only gives the dc leakage of current from the conductor through the insulation to a ground outside the cable (assuming the dc voltage has been applied long enough for initial transients to die off). At 2400 Vac, the cable IR must be less than approximately 2×10^6 Ω before leakage through the conductor is comparable to a typical capacitive charging current. Because typical measured IRs are greater than 10^8 Ω (see Figures 3.1–3.24), the capacitive charging current accounts for a substantial portion of the ac charging and leakage current shown in Tables 3.2 and 3.3. Increased ac charging and leakage current is caused by a combination of increased cable capacitance or substantial decreases in the cable IR.

For the dry 1000 Vac rms excitation, typical currents were 0.4 mAac and 0.8 mAac for the 30-ft long conductors (1–30) and 60-ft long conductors (30–65), respectively. This is consistent with a 60 Hz cable impedance of 2.5×10^6 Ω for the 30-ft long conductors and 1.25×10^6 Ω for the 60-ft long conductors; these impedances correspond to a cable capacitance of approximately 35 pF/ft.

For the submerged 2400 Vac rms excitation, typical currents were 1.1 mAac and 2.2 mAac for the 30-ft long conductors (1–30) and 60-ft long conductors (30–65), respectively. This is consistent with a 60 Hz cable impedance of 2.2×10^6 Ω for the 30-ft long conductors and 1.1×10^6 Ω for the 60-ft long conductors; these impedances correspond to a cable capacitance of approximately 40 pF/ft.

[2] For the dry dielectric withstand testing, the Hipotronics test set was adjusted to trip at a current of approximately 8 mAac.

[3] For the submerged dielectric withstand testing, the Hipotronics test set was adjusted to trip at a current of approximately 20 mAac.

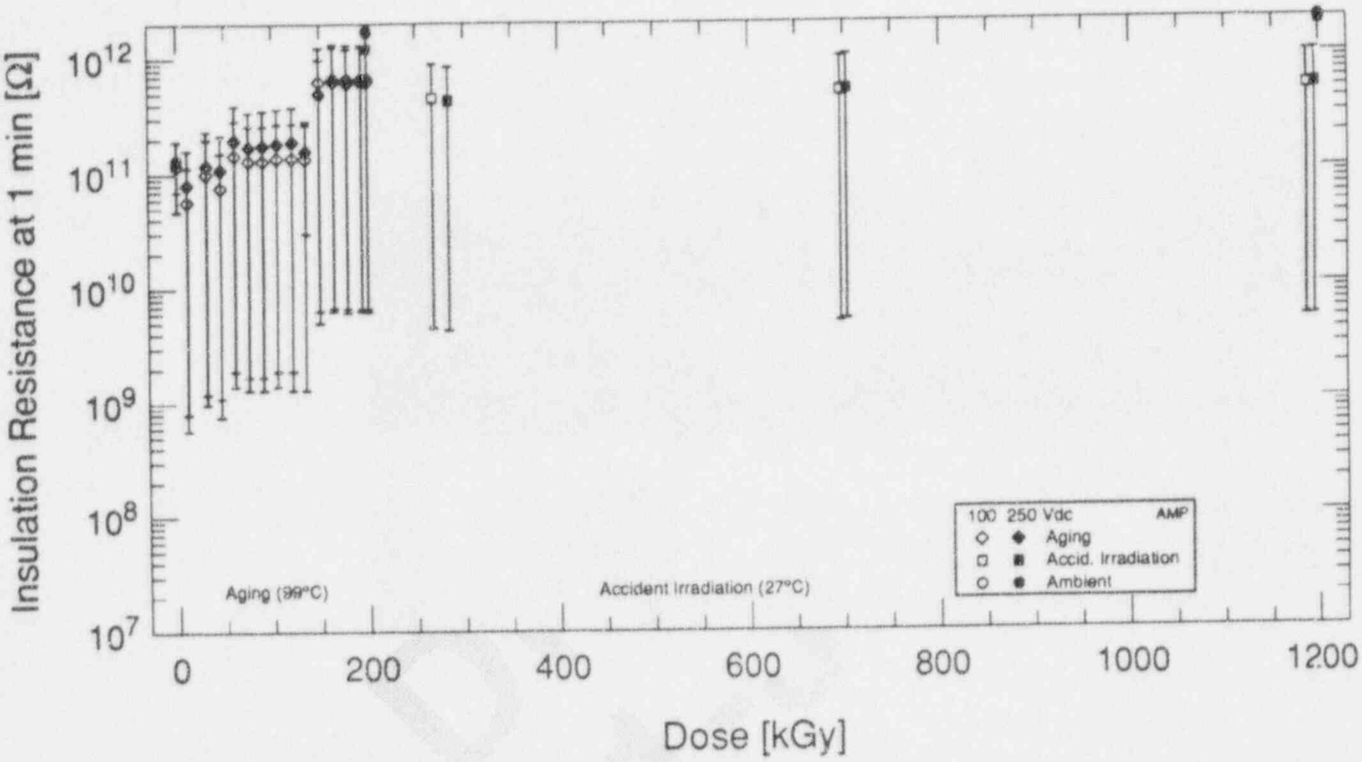

Figure 3.1: IR of Amphenol coaxial connector during aging and accident irradiation.

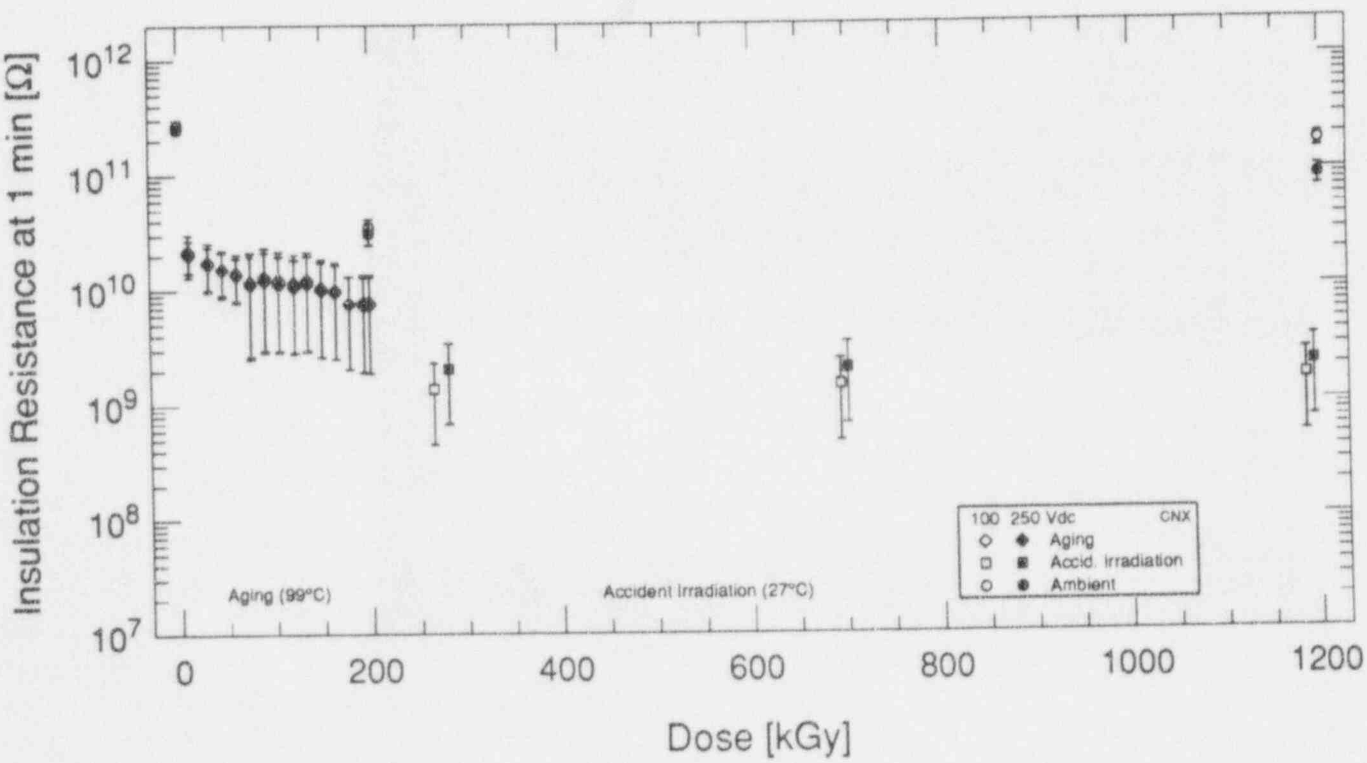

Figure 3.2: IR of Conax ECSA conduit seal during aging and accident irradiation.

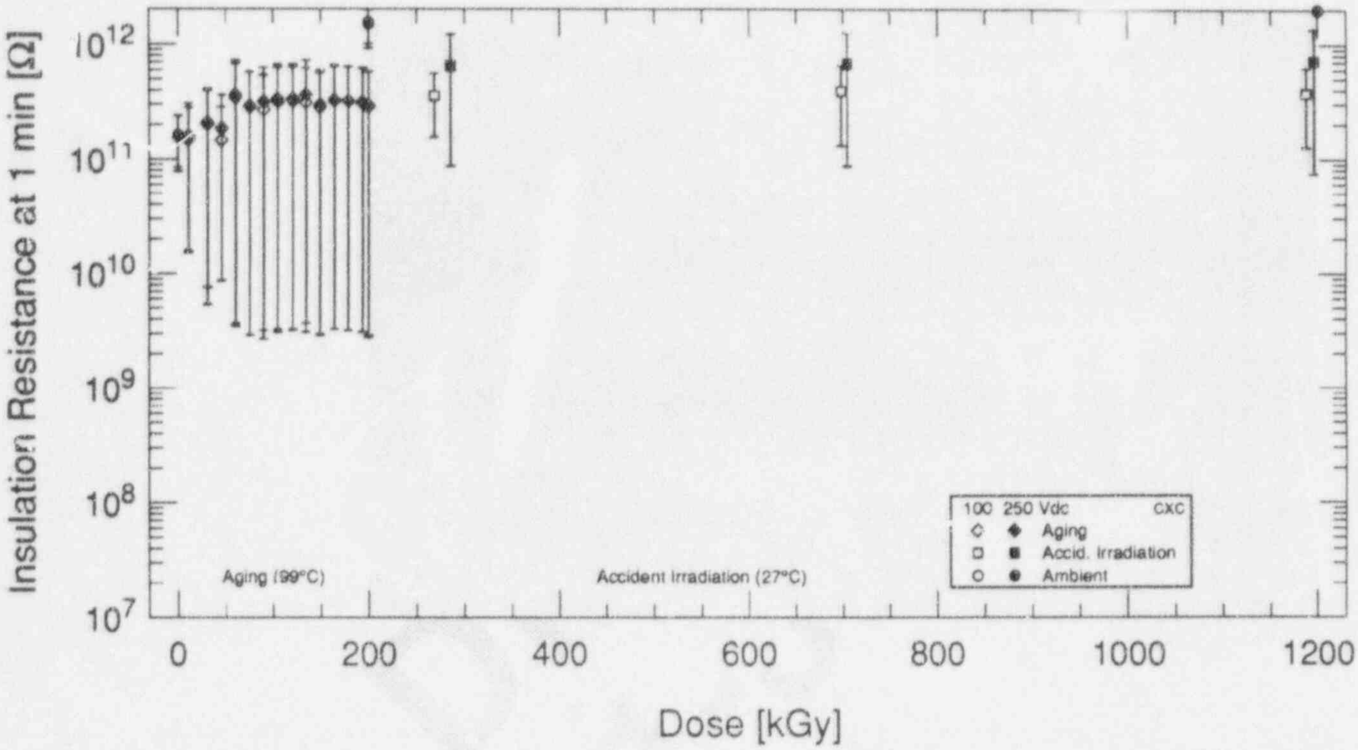

Figure 3.3: IR of Rockbestos coaxial cable during aging and accident irradiation.

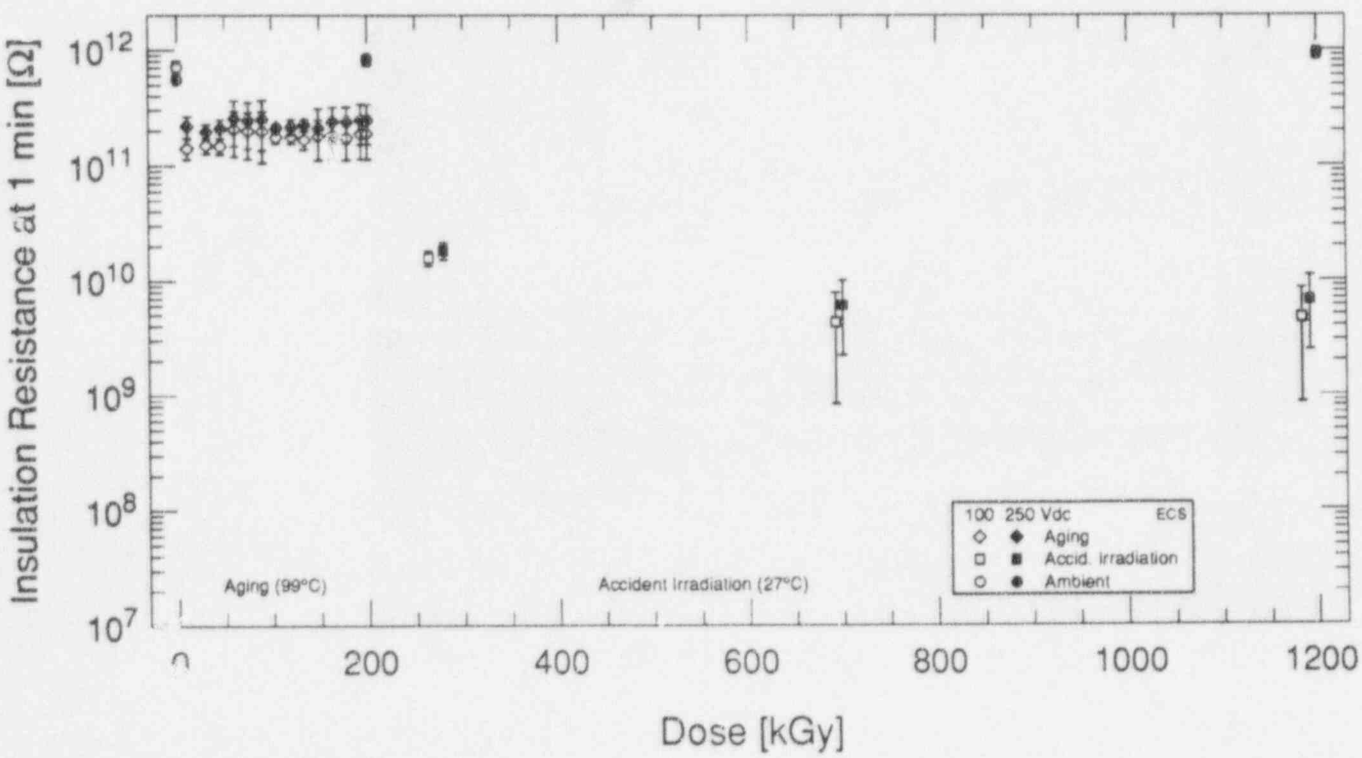

Figure 3.4: IR of EGS conduit seal during aging and accident irradiation.

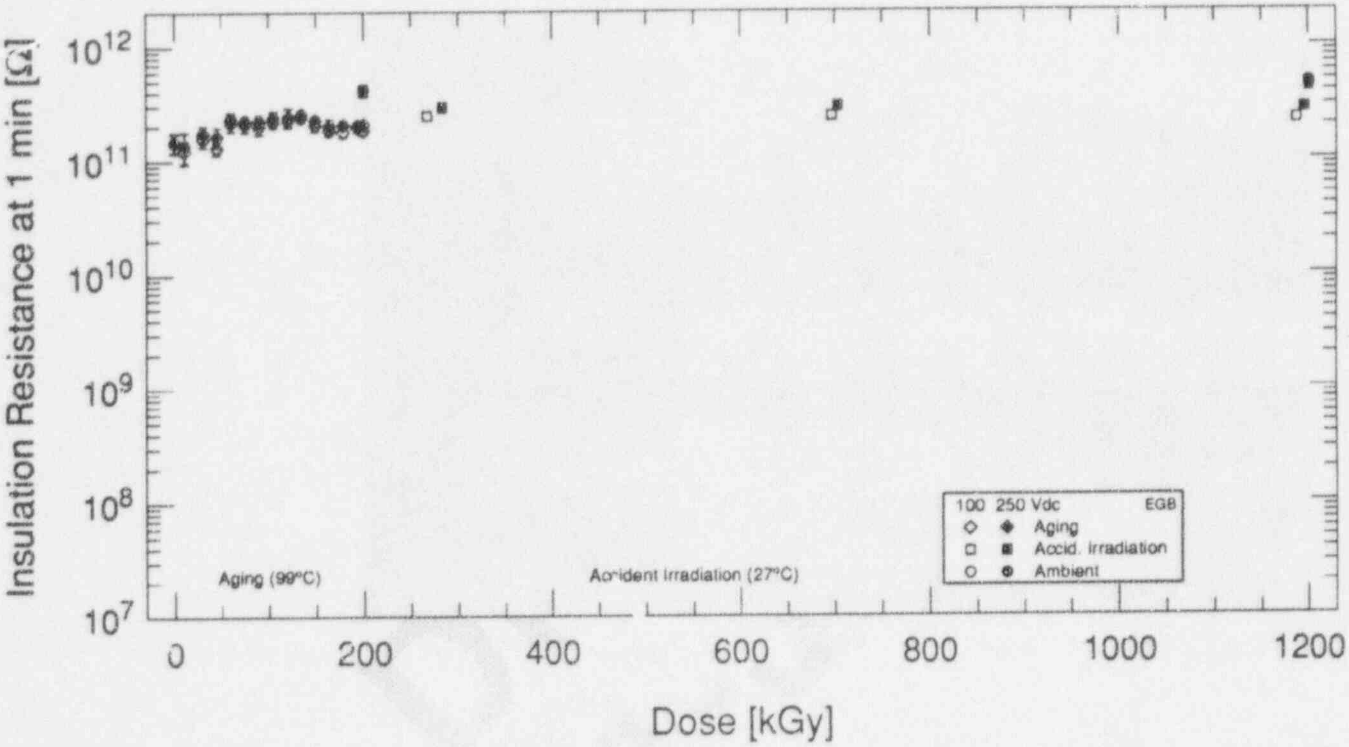

Figure 3.5: IR of EGS Grayboot connector during aging and accident irradiation.

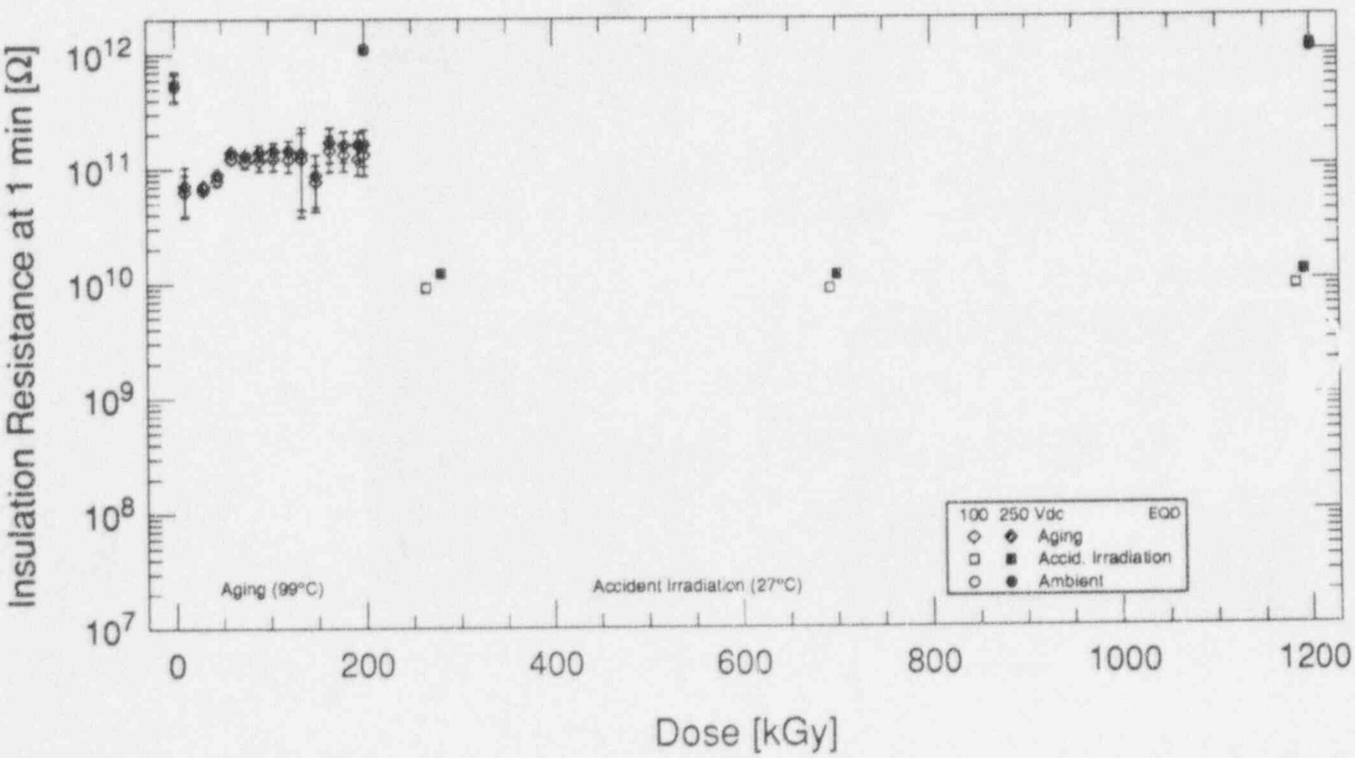

Figure 3.6: IR of EGS quick disconnect connector during aging and accident irradiation.

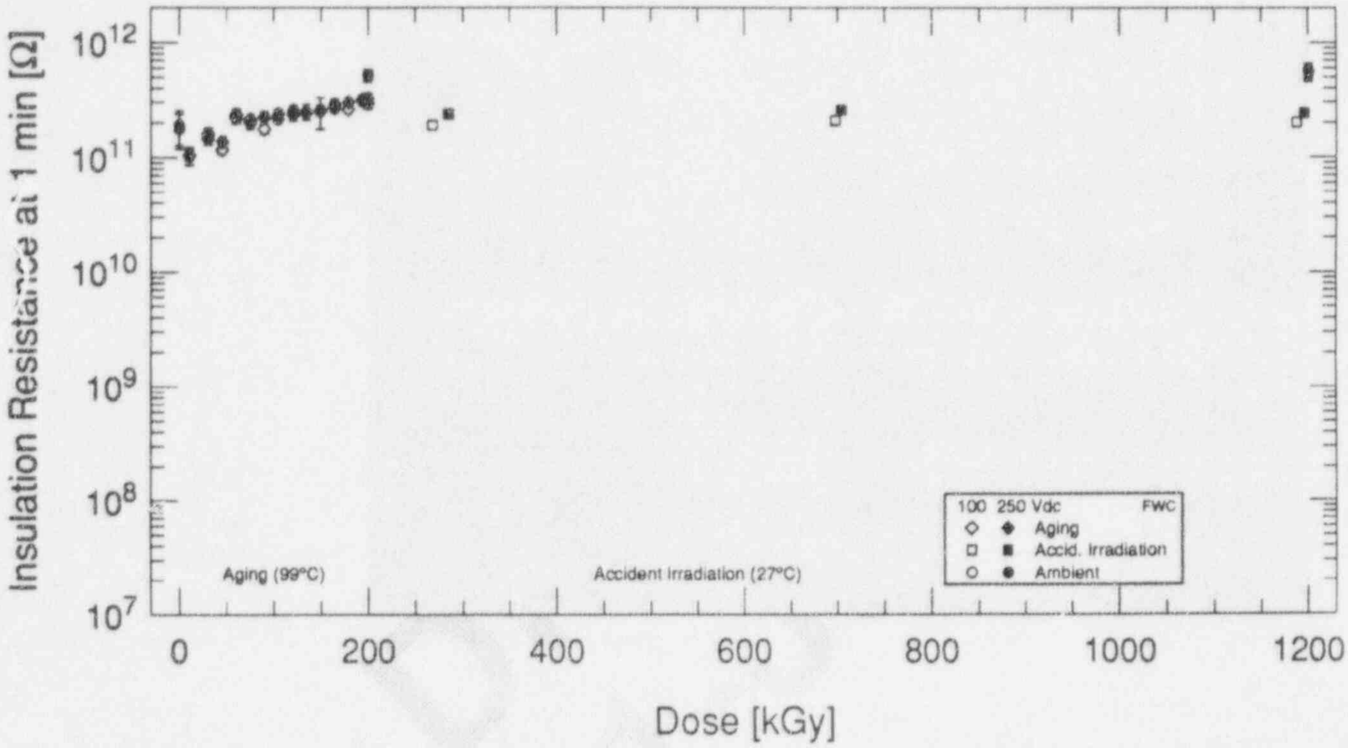

Figure 3.7: IR of Rockbestos Firewall III cable during aging and accident irradiation.

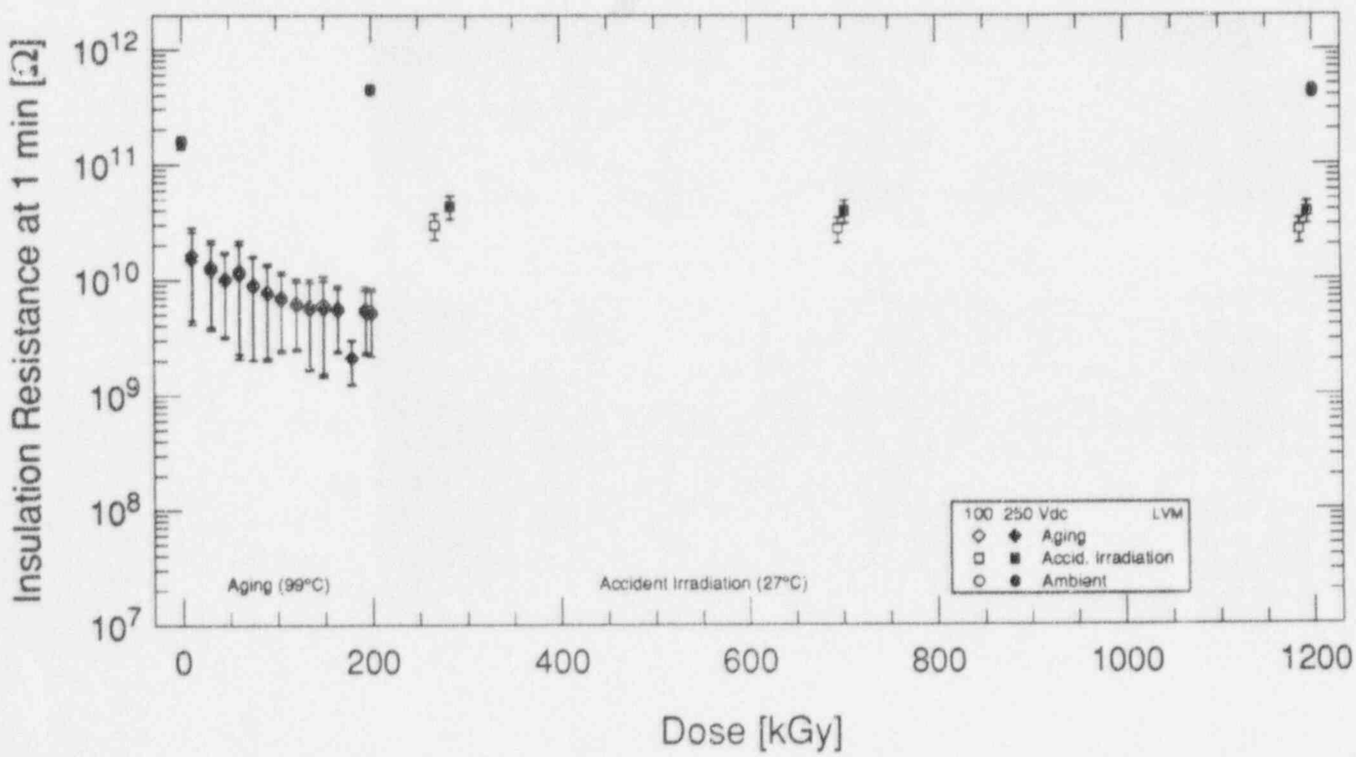

Figure 3.8: IR of Litton-VEAM connector during aging and accident irradiation.

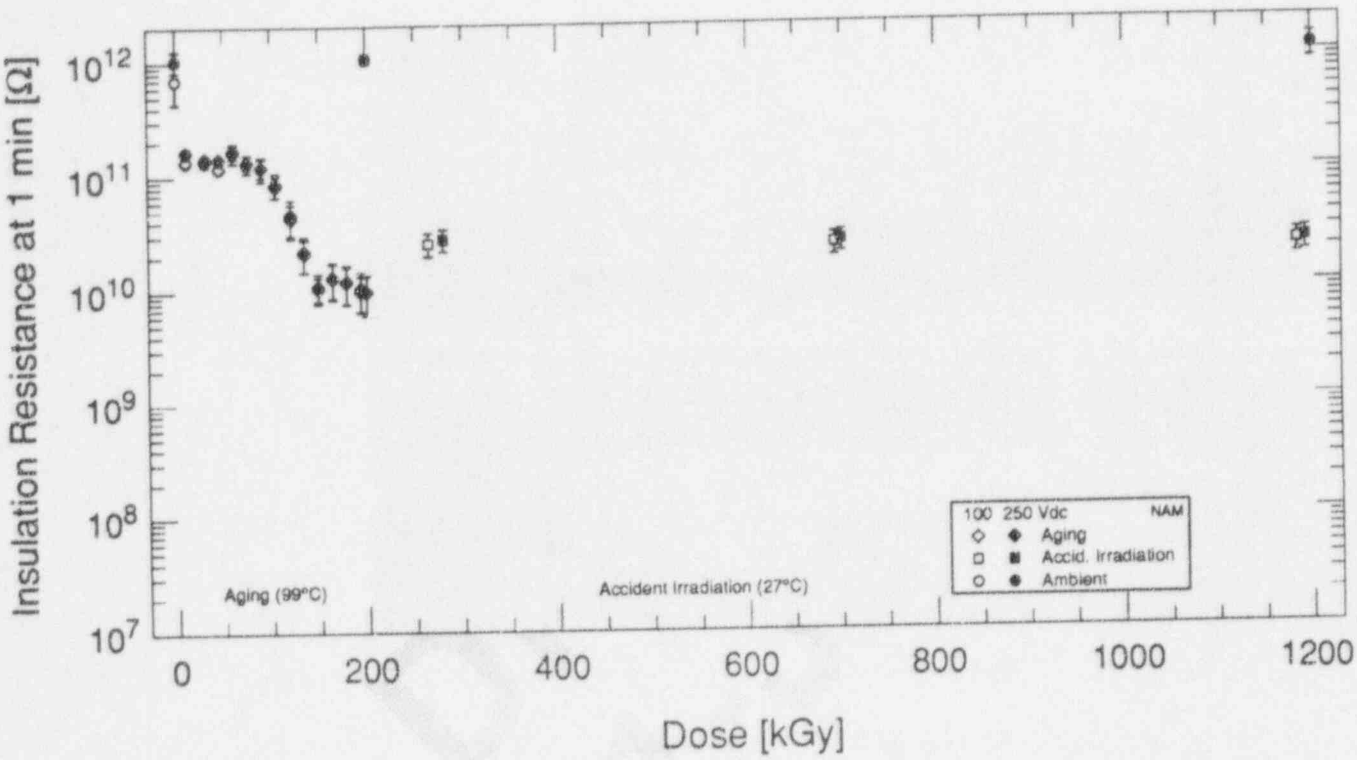

Figure 3.9: IR of NAMCO EC210 connector during aging and accident irradiation.

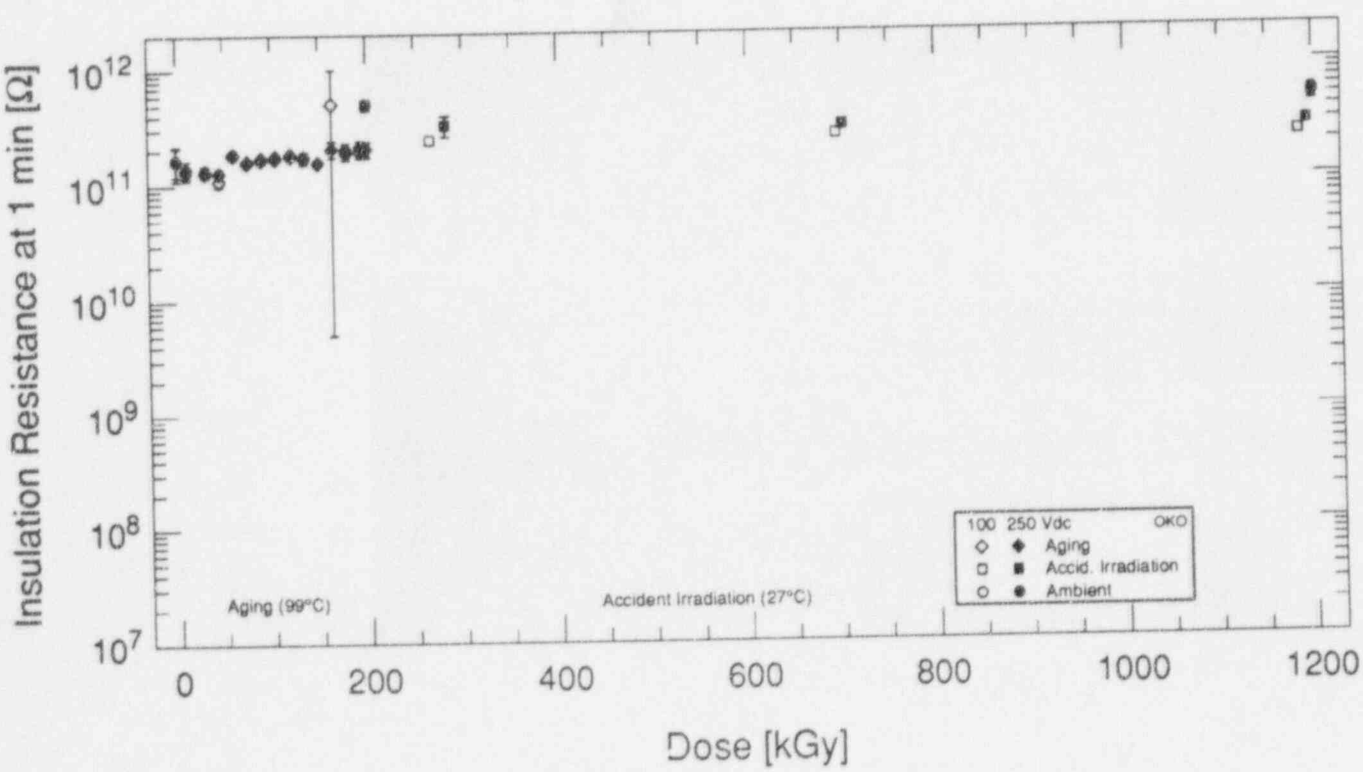

Figure 3.10: IR of Okonite tape splice during aging and accident irradiation.

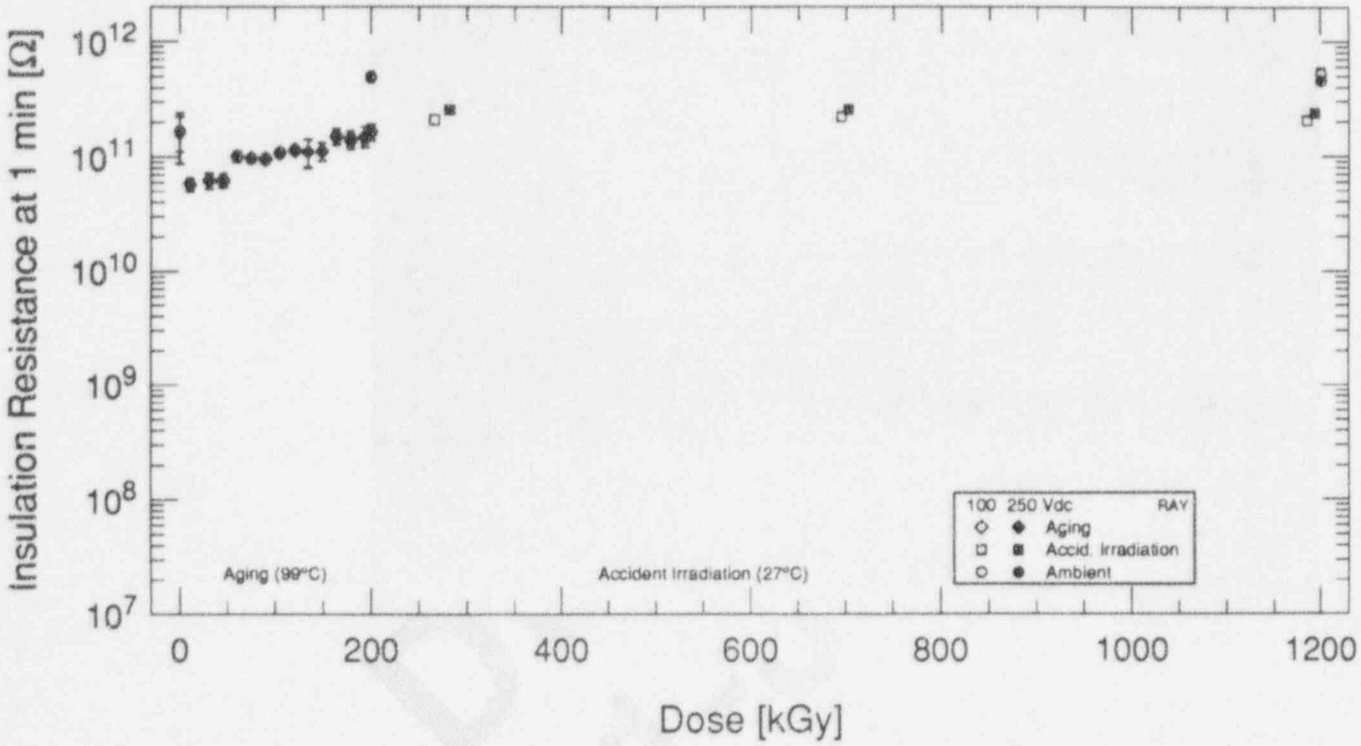

Figure 3.11: IR of Raychem heat shrink splice during aging and accident irradiation.

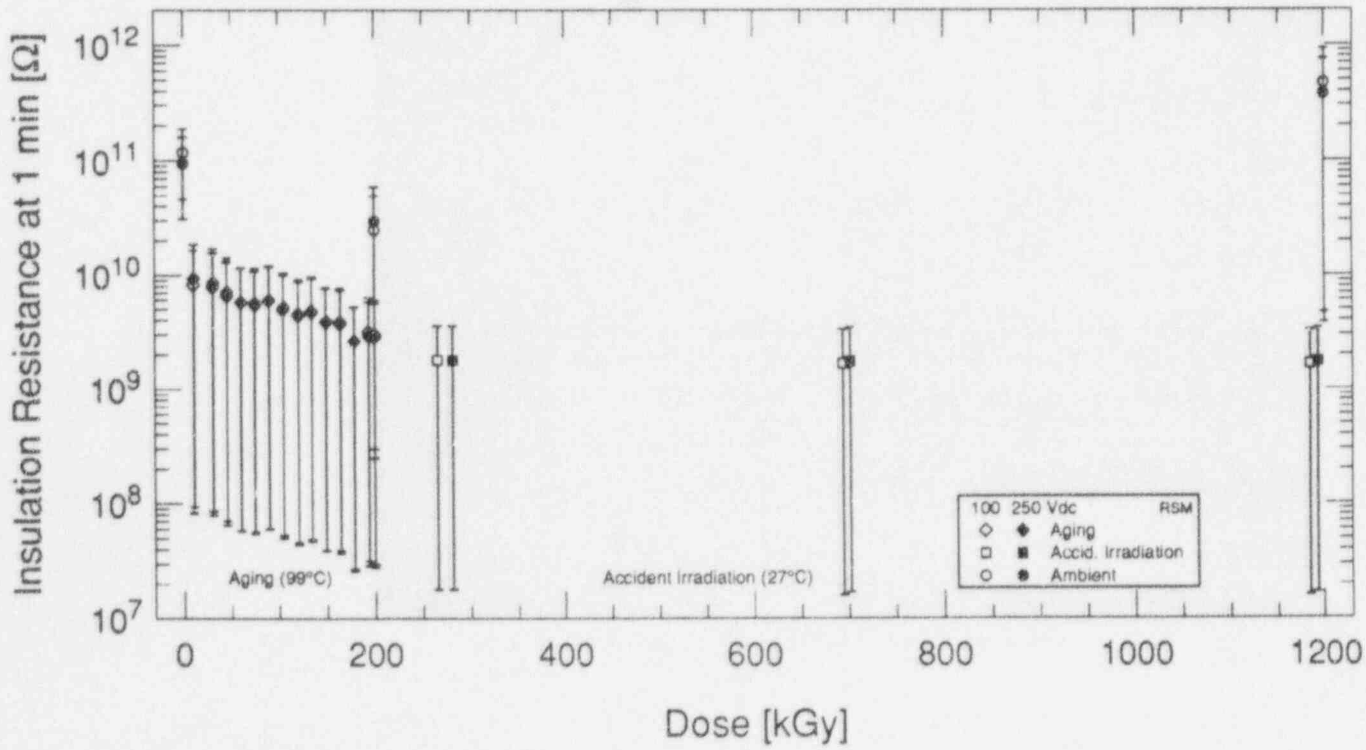

Figure 3.12: IR of Rosemount 353C conduit seal during aging and accident irradiation.

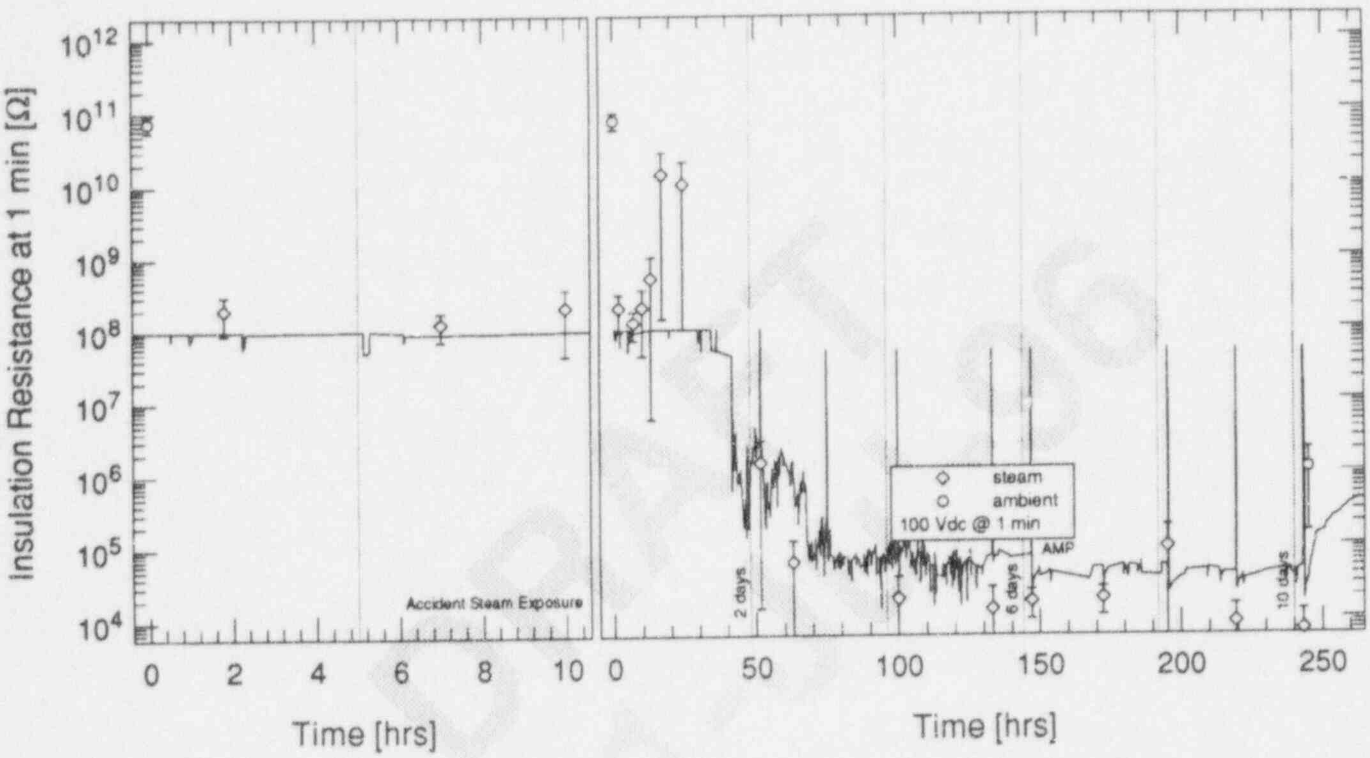

Figure 3.13: IR of Amphenol coaxial connector during accident steam exposure.

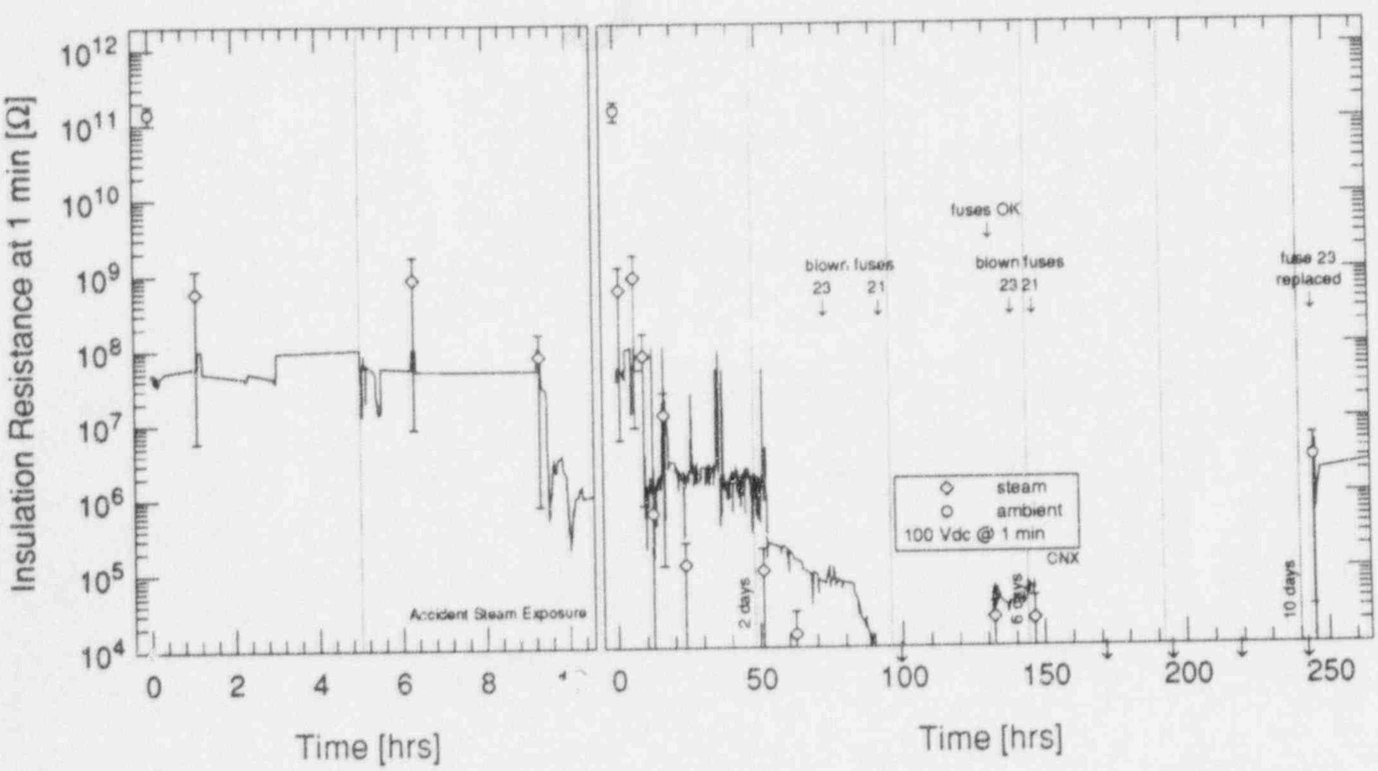

Figure 3.14: IR of Conax ECSA conduit seal during accident steam exposure.

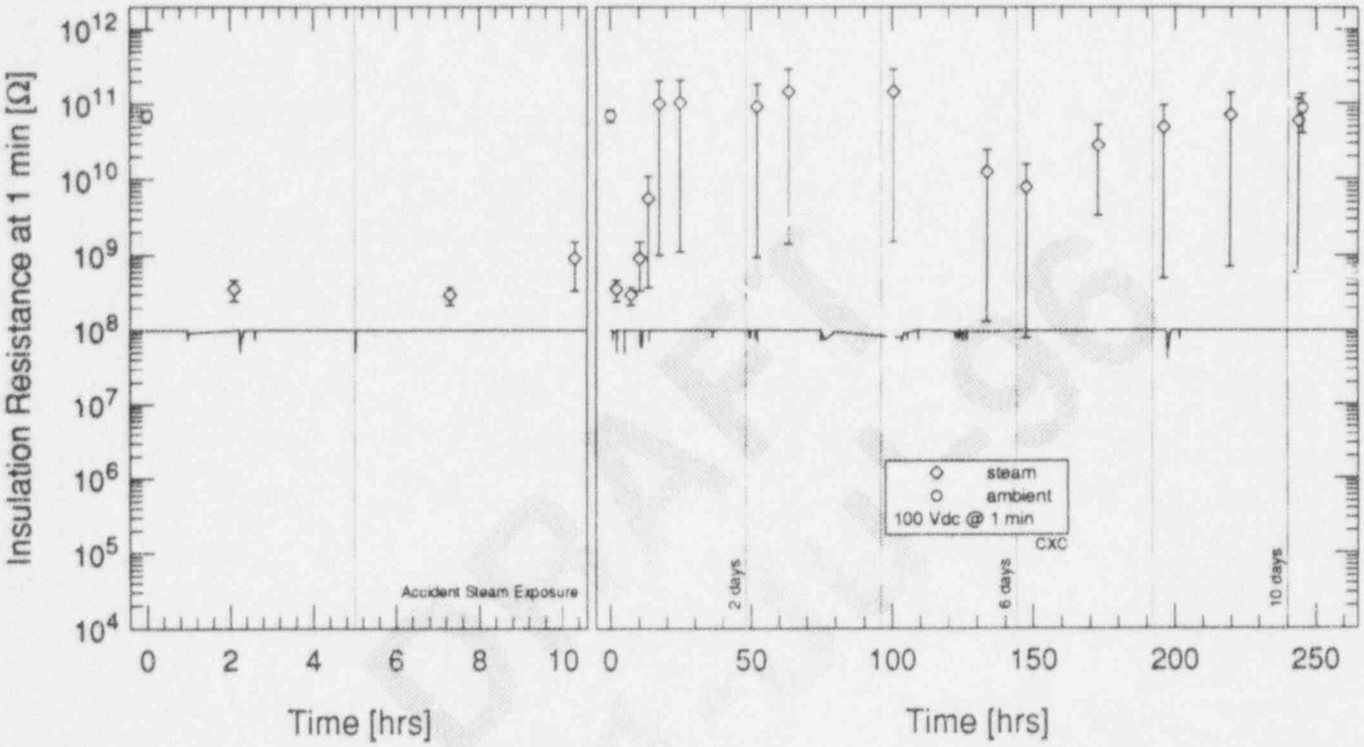

Figure 3.15: IR of Rockbestos coaxial cable during accident steam exposure.

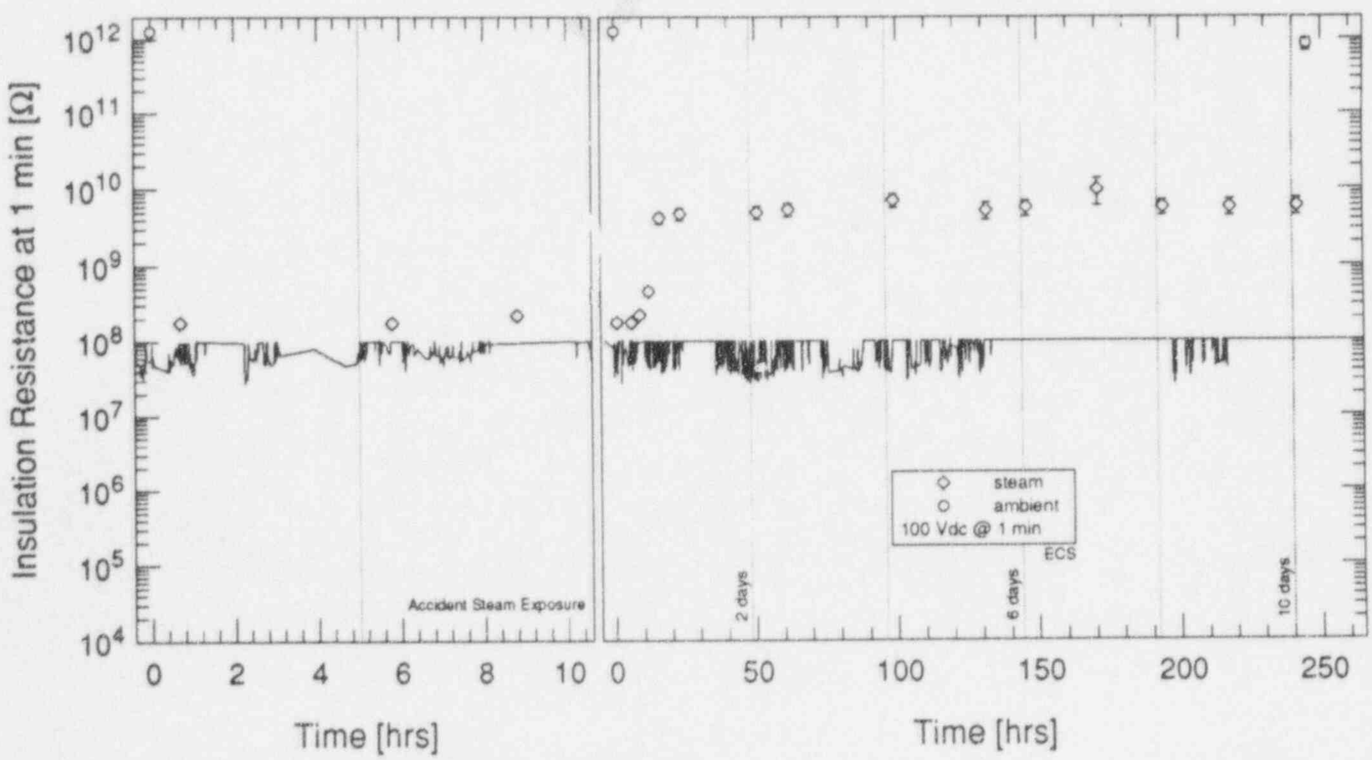

Figure 3.16: IR of EGS conduit seal during accident steam exposure.

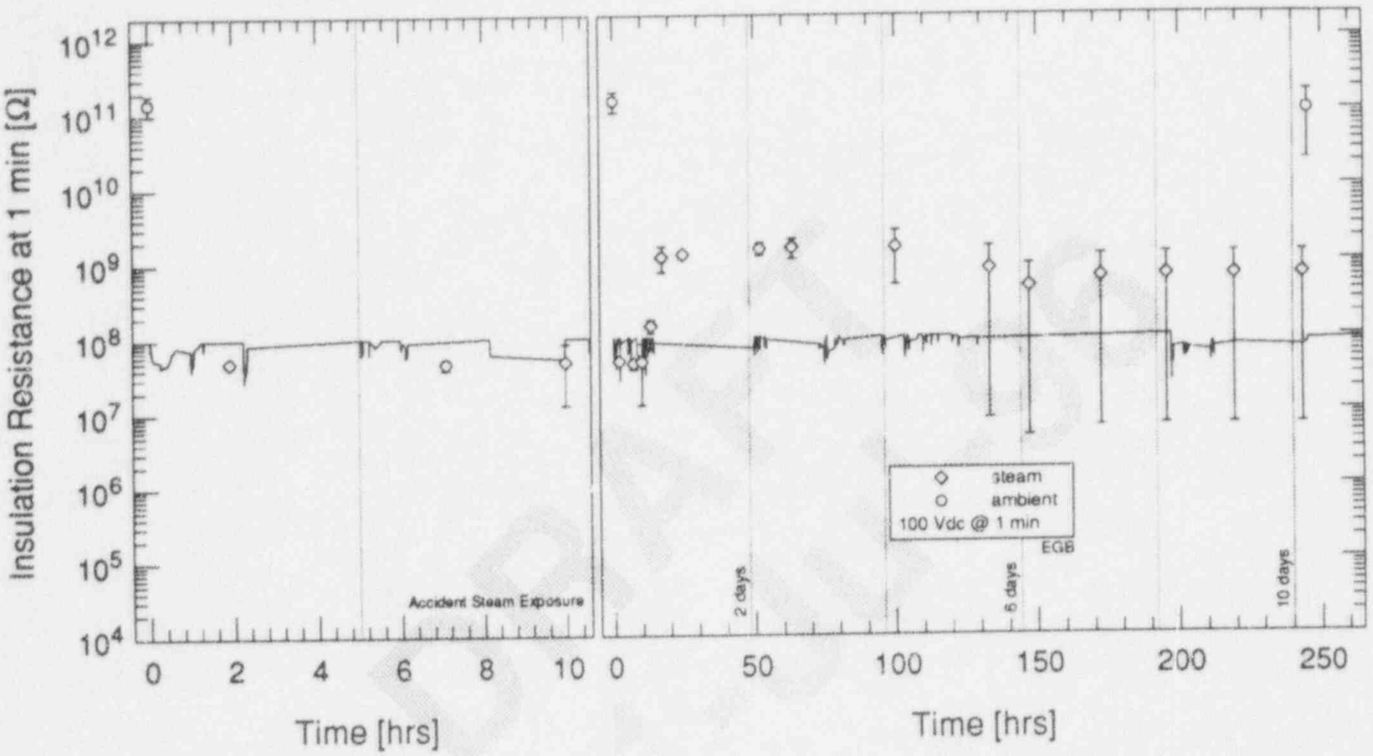

Figure 3.17: IR of EGS Grayboot connector during accident steam exposure.

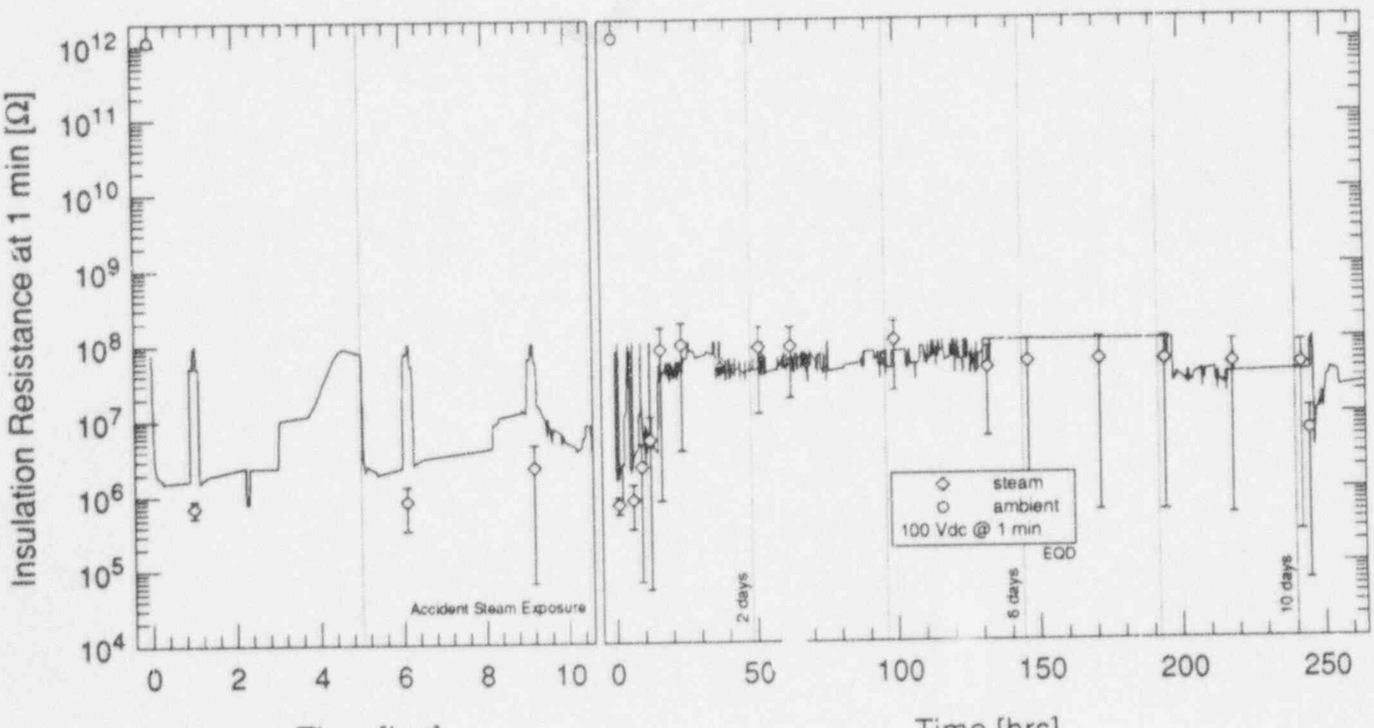

Figure 3.18: IR of EGS quick disconnect connector during accident steam exposure.

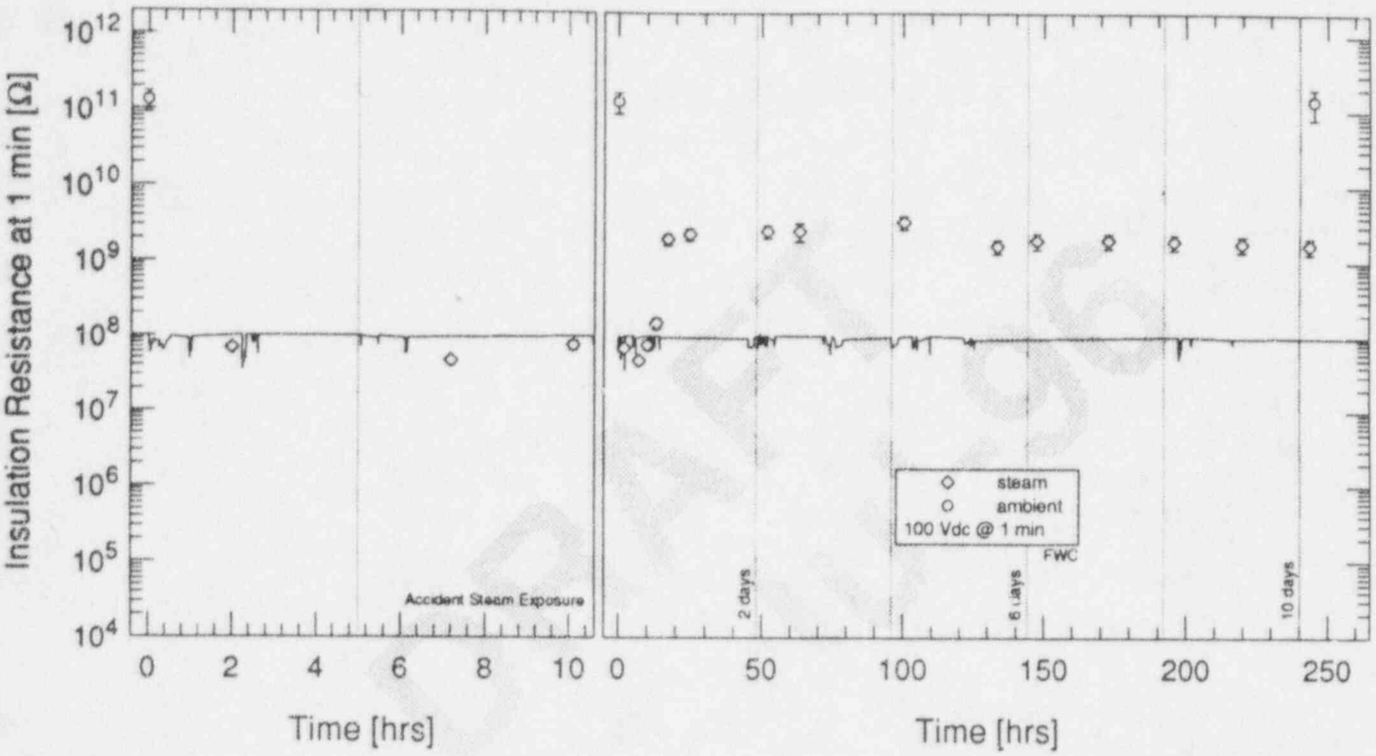

Figure 3.19: IR of Rockbestos Firewall III cable during accident steam exposure.

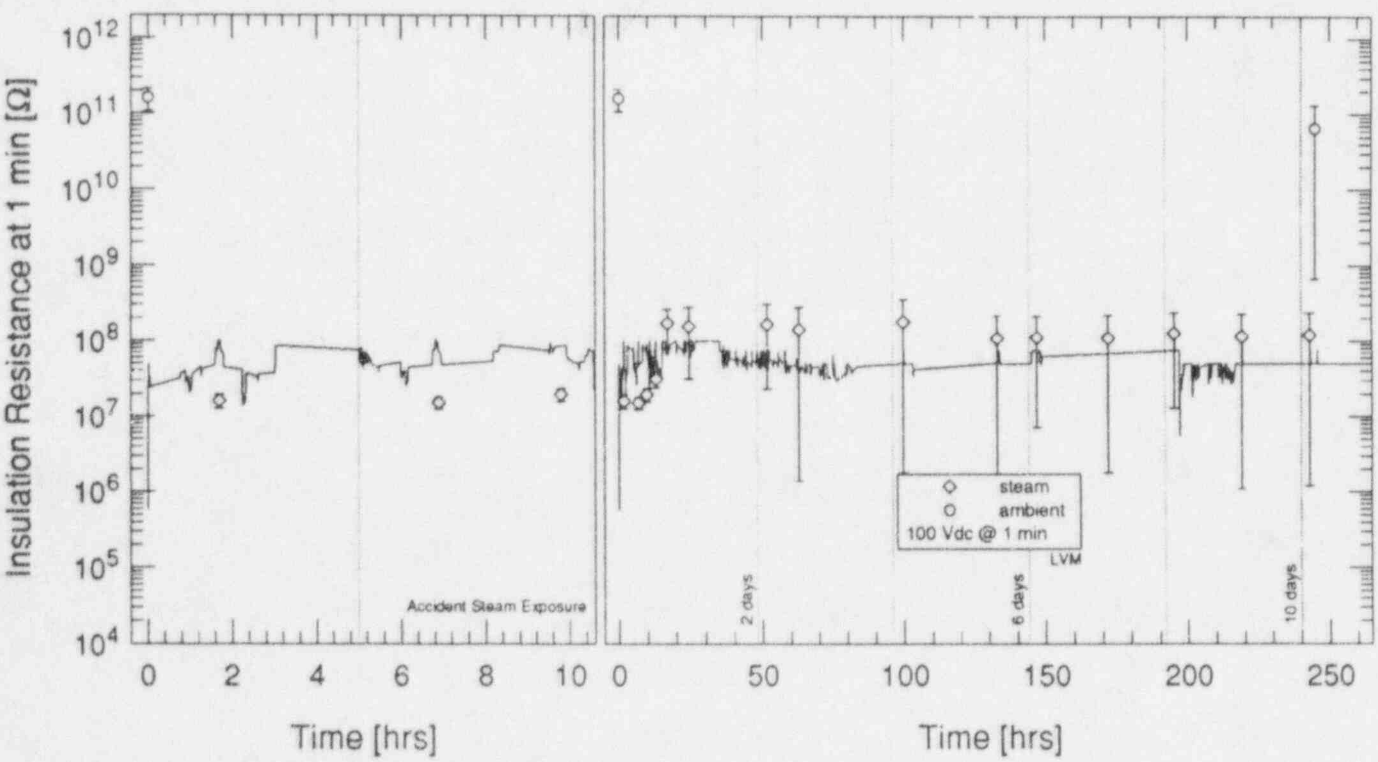

Figure 3.20: IR of Litton-VEAM connector during accident steam exposure.

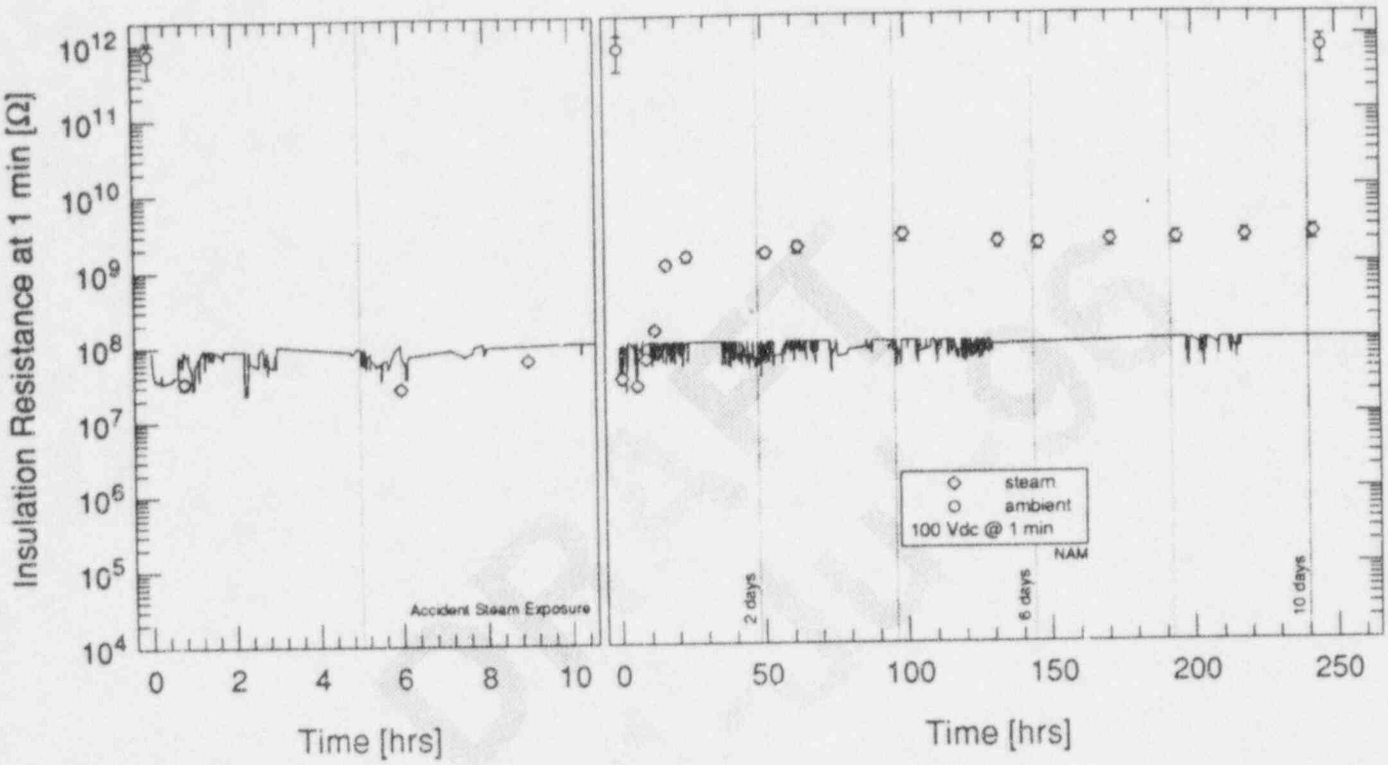

Figure 3.21: IR of NAMCO EC210 connector during accident steam exposure.

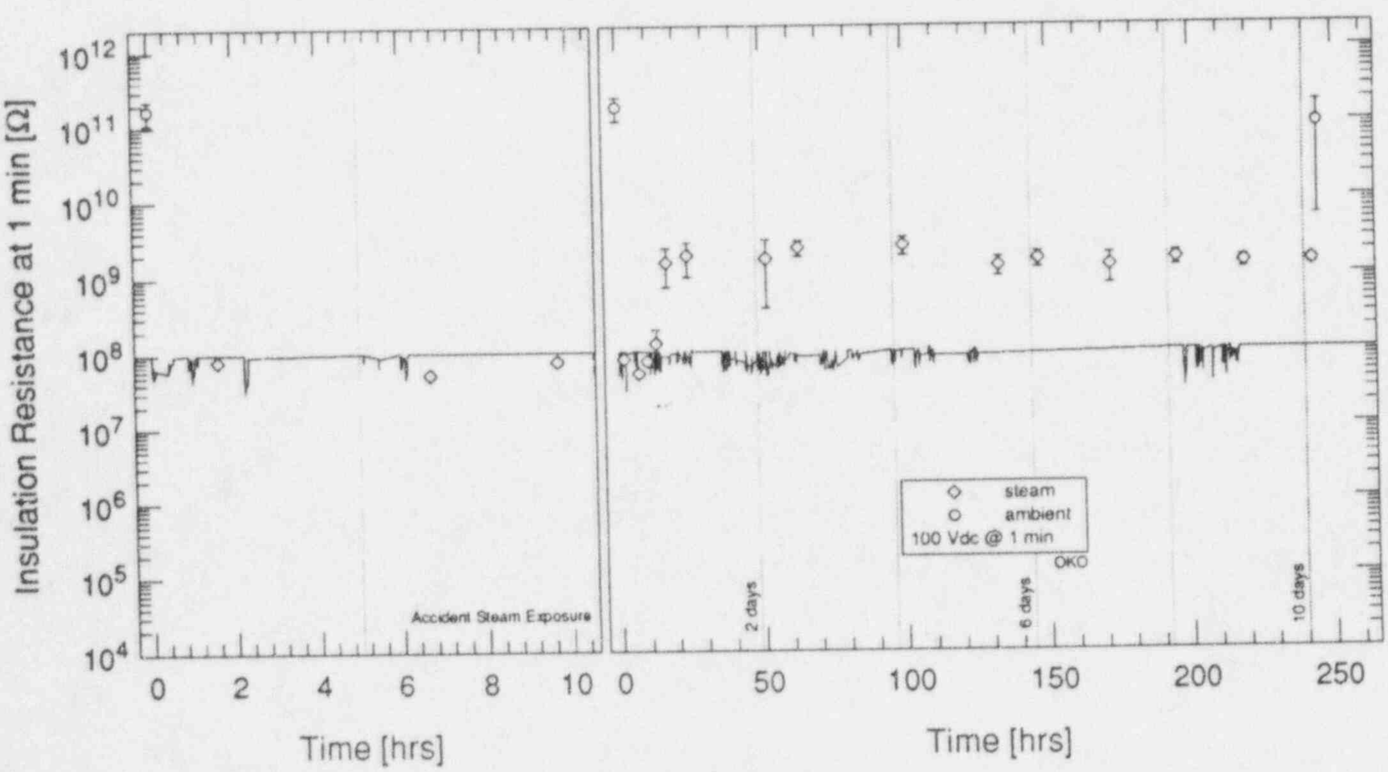

Figure 3.22: IR of Okonite tape splice during accident steam exposure.

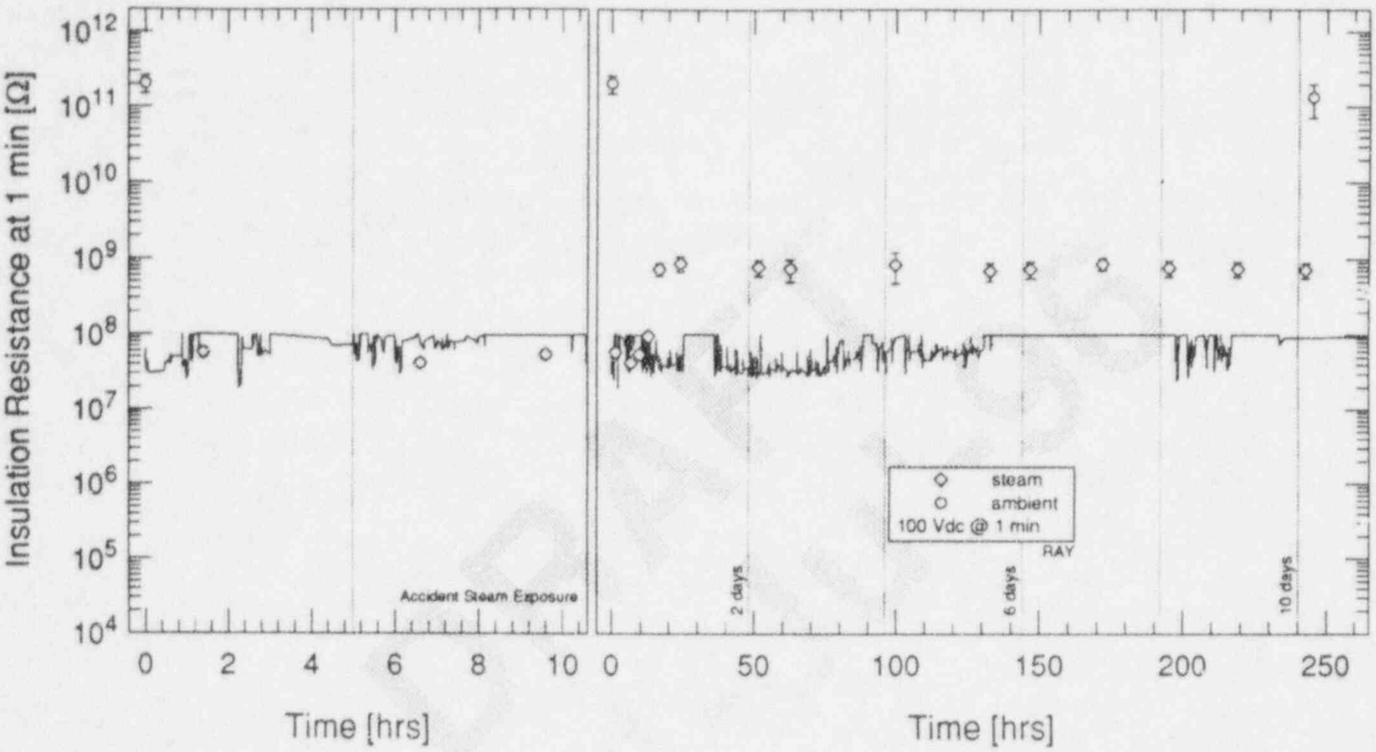

Figure 3.23: IR of Raychem heat shrink splice during accident steam exposure.

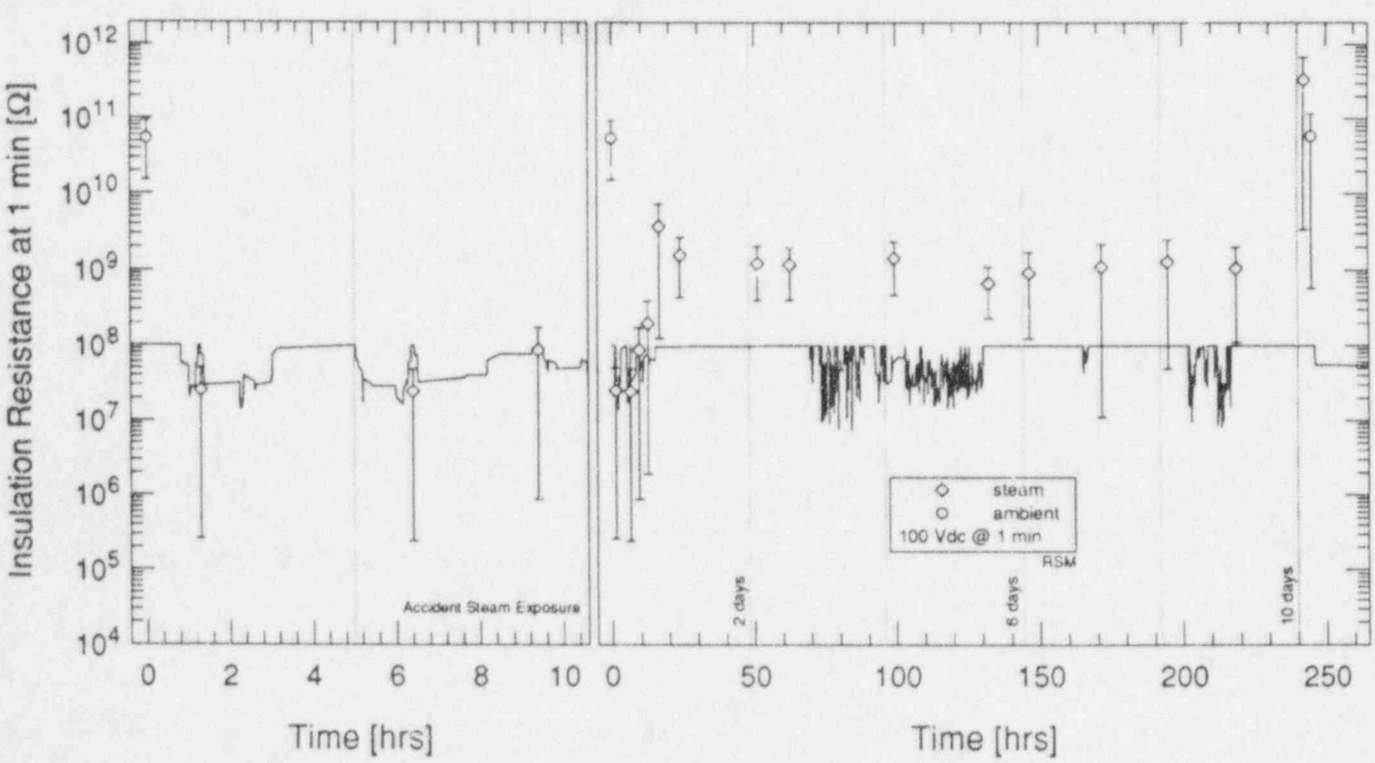

Figure 3.24: IR of Rosemount 353C conduit seal during accident steam exposure.

Table 3.2: Post-LOCA Test Results (1 of 2).

	100 Vdc IR at 1 min				Dielectric Withstand (1 min hold period)			
	LOCA	LOCA + 13 months			LOCA + 23 months			
	+ 3 days		Submerged		Dry		2 hr Submergence	
	Dry	Dry	30 min	3 hr	Voltage	Current	Voltage	Current
Conductor[a]	[Ω]	[Ω]	[Ω]	[Ω]	[kVac]	[mAac]	[kVac]	[mAac]
EGS conduit seal								
1	5.7e11	9.0e11	7.0e11	7.0e11	1.0	0.4	2.4	1.0
2	7.9e11	1.1e12	9.1e11	9.2e11	1.0	0.4	2.4	1.0
3	9.2e11	1.2e12	6.7e11	7.9e11	1.0	0.4	2.4	1.0
5	8.0e11	1.2e12	1.7e12	1.5e12	1.0	0.4	2.4	1.1
6	9.4e11	1.1e12	1.6e12	1.7e12	1.0	0.4	2.4	1.1
NAMCO EC210 connector								
7	7.7e11	2.5e06	4.2e06	1.0e07	1.0	0.4	2.4	1.1
8	7.4e11	2.7e11	1.9e11	1.7e11	1.0	0.4	2.4	1.2
9	5.3e11	2.0e09	7.6e08	6.2e08	1.0	0.4	2.4	1.2
10	6.9e11	1.9e09	8.8e08	7.3e08	1.0	0.4	2.4	1.1
11	4.7e10	3.1e11	1.3e11	1.3e11	1.0	0.4	2.4	1.1
12	8.3e11	4.9e11	3.2e11	3.3e11	1.0	0.4	2.4	1.1
13	9.1e11	1.4e11	3.2e10	5.1e10	1.0	0.4	2.4	1.1
14	9.3e11	3.8e11	2.1e11	2.2e11	1.0	0.4	2.4	1.1
EGS quick disconnect connector								
15	5.0e05	3.3e11	3.9e04	1.1e05	1.0	0.4	2.4	Trip
16	1.0e06	2.0e10	2.8e04	9.1e04	1.0	0.4	2.4	Trip
17	1.1e07	2.5e10	2.0e04	6.5e04	1.0	0.4	2.4	Trip
18	4.9e05	1.9e10	1.7e05	7.1e04	1.0	0.4	2.4	1.0
19	2.1e06	2.6e10	6.3e04	3.3e04	1.0	0.4	2.4	Trip
20	2.1e07	1.2e10	6.7e05	3.5e05	1.0	0.4	2.4	Trip
Conax ECSA conduit seal								
21	5.2e01	8.8e05	3.6e03	2.4e03	1.0	Trip	2.4	Trip
22	1.5e01	1.2e06	2.2e03	2.0e03	1.0	Trip	2.4	Trip
23	6.5e06	5.4e06	3.0e04	3.2e04	1.0	Trip	2.4	Trip
24	5.7e06	6.2e06	8.1e03	7.5e03	1.0	Trip	2.4	Trip
Rosemount 353C conduit seal								
25	2.9e11	1.8e11	2.4e11	3.0e11	1.0	0.4	2.4	1.1
26	1.8e10	3.4e10	8.1e10	1.9e07	1.0	0.4	2.4	Trip
27	3.8e10	6.5e10	1.6e11	1.7e11	0.6	0.4	0.6	0.4
28	6.7e07	5.2e09	3.5e09	4.7e05	1.0	0.4	2.4	Trip
29	5.6e07	1.1e10	6.4e10	6.0e05	1.0	0.4	2.4	Trip
30	8.4e09	1.4e10	6.3e10	4.1e06	0.6	0.4	0.6	0.6
Raychem heat shrink splice								
31	1.3e11	2.5e11	2.7e11	3.1e11	1.0	0.8	2.4	2.1
32	5.2e10	2.0e11	2.7e11	3.2e11	1.0	0.8	2.4	2.1
33	1.6e11	2.5e11	3.9e11	3.8e11	1.0	0.8	2.4	2.1
34	2.2e11	3.2e11	3.3e11	3.8e11	1.0	0.9	2.4	2.3
35	7.4e10	9.4e10	1.5e11	2.1e11	1.0	0.9	2.4	2.2
36	1.8e11	2.2e11	3.1e11	3.0e11	1.0	0.9	2.4	2.3

[a]See Table 2.2.

Table 3.3: Post-LOCA Test Results (2 of 2).

	100 Vdc IR at 1 min				Dielectric Withstand (1-min hold period)			
	LOCA + 3 days	LOCA + 13 months			LOCA + 23 months			
			Submerged		Dry		2 hr Submergence	
Conductor[a]	Dry [Ω]	Dry [Ω]	30 min [Ω]	3 hr [Ω]	Voltage [kVac]	Current [mAac]	Voltage [kVac]	Current [mAac]
Okonite tape splice								
37	2.3e11	1.9e11	4.8e11	4.8e11	1.0	0.9	2.4	2.3
38	3.6e10	1.0e11	2.3e11	3.0e11	1.0	0.8	2.4	2.3
39	1.3e10	1.3e11	2.5e11	3.1e11	1.0	0.9	2.4	2.3
40	1.8e10	1.0e11	1.9e11	2.3e11	1.0	0.9	2.4	2.4
41	1.1e11	1.1e11	2.5e11	3.0e11	1.0	0.9	2.4	2.3
42	1.5e11	2.1e11	5.1e11	4.4e11	1.0	0.9	2.4	2.4
Litton-VEAM connector								
43	1.0e03	9.2e05	2.2e02	7.0e01	1.0	Trip	2.4	Trip
44	2.8e11	3.6e07	5.6e03	7.9e03	1.0	0.7	2.4	Trip
45	6.0e03	6.5e05	8.8e01	6.9e01	1.0	Trip	2.4	Trip
46	1.1e11	1.2e11	6.9e04	6.0e04	1.0	0.7	2.4	Trip
47	1.5e04	2.0e10	4.0e03	4.4e03	1.0	0.7	2.4	Trip
48	1.5e05	2.1e11	1.2e04	2.1e04	1.0	0.7	2.4	Trip
Amphenol coaxial connector								
49	1.9e06	7.6e07	7.9e07	8.8e07	1.0	0.6	2.4	Trip
50	1.9e06	8.0e07	3.6e04	3.6e04	0.6	0.8	0.6	Trip
51	3.2e05	3.9e05	3.6e05	4.1e05	1.0	Trip	2.4	Trip
52	2.4e05	7.7e05	1.3e04	1.1e04	0.6	Trip	0.6	Trip
EGS Grayboot connector								
53	4.1e10	1.9e11	3.2e11	4.1e11	1.0	0.7	2.4	2.1
54	6.8e10	2.4e11	2.1e11	2.2e11	1.0	0.7	2.4	2.1
55	1.9e11	2.5e11	1.9e11	1.9e11	1.0	0.7	2.4	2.1
Rockbestos Firewall III cable								
56	2.3e11	3.2e11	5.8e11	4.9e11	1.0	0.8	2.4	2.0
57	1.0e11	2.1e11	3.8e11	4.0e11	1.0	0.8	2.4	2.0
58	2.0e11	2.4e11	4.1e11	3.9e11	1.0	0.8	2.4	2.0
59	8.8e10	2.2e11	3.9e11	4.7e11	1.0	0.8	2.4	2.1
60	1.1e11	1.9e11	3.2e11	3.7e11	1.0	0.8	2.4	2.1
61	1.0e11	3.3e11	4.9e11	4.1e11	1.0	0.8	2.4	2.1
Rockbestos coaxial cable								
62	1.3e11	2.5e11	9.7e11	5.8e11	1.0	0.7	2.4	1.7
63	1.2e11	2.1e11	3.4e11	3.0e11	0.6	0.9	0.6	1.0
64	2.1e10	9.2e10	2.9e11	2.3e11	1.0	0.7	2.4	1.7
65	9.1e10	2.1e11	3.8e11	3.5e11	0.6	0.8	0.6	1.0

[a]See Table 2.2.

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4 Summary and Conclusions

This report has presented the results of an experimental program regarding the aging and loss-of-coolant accident (LOCA) behavior of electrical connections. In all, 10 different types of non-terminal block connections commonly used in nuclear power plants were tested. These included 3 types of conduit seals, 2 types of connectors for installation in a device, and 5 in-line splices and connectors.

The conclusions of this experimental program with regard to the specific objectives of the program are addressed below.

Objective: To assess the accident performance of electrical connections aged more slowly (*i.e.*, at lower temperatures and radiation dose rates) than in typical industry tests and under simultaneous conditions.

- In general, there was no meaningful degradation in the measured IR of the connections during the simultaneous aging exposure and accident irradiation; only the IR of a few of the Conax ECSA conduit seal and Rosemount 353C conduit seal conductors fell below 10^7 Ω[1].
- Prior to starting the aging, one Rosemount 353C conduit seal was found to have an internal short circuit between its two conductors; this defective device was replaced with a spare.
- The snap-on plastic covers used on the EGS Grayboot connector quickly became very brittle during aging and will easily break apart and fall off. This had no effect on the measured IR values and the covers are not required by the manufacturer. However, if the covers are required for seismic reasons or to simply prevent the connector from pulling apart, then the premature aging of the covers could lead to problems.
- While the IR measurements for most of the connections remained high during the accident steam exposure, 3 of 6 Litton-VEAM connector and all 4 Amphenol coaxial connector conductors had IR values that fell below 10^7 Ω. All 4 Conax ECSA conduit seal conductors gave extremely low IR values (< 100 Ω) and the 2 non-grounded conductors repeatedly blew 1 A fuses when energized at 110 Vdc.
- Half of the 10 connection types did not pass a post-LOCA, submerged dielectric withstand test:
  - Essentially all the Conax ECSA conduit seal, Rosemount 353C conduit seal, EGS quick disconnect connector, Amphenol coaxial connector, and Litton-VEAM connector conductors tripped the dielectric test set.
  - None of the EGS conduit seal, NAMCO EC210 connector, EGS Grayboot connector, Okonite tape splice, and Raychem heat shrink splice conductors tripped the test set.

Objective: To investigate the performance of connections aged to a 60-year life to determine their suitability for life extension beyond the current nominal 40-year qualified life.

- Because 50% of the connection types were unable to successfully pass the submerged dielectric withstand test following a simulated life of 60-years and a LOCA exposure, further investigation of electrical connections related to life extension seems warranted.
- It is interesting to note that the problems are not limited to any one family of electrical connections. At least one connection from each family (conduit seals, connections for installation into a device, and in-line splices and connections) was unable to pass the submerged dielectric withstand test.

[1] Whether or not degraded IR values will impact the operability of an electrical circuit is plant and circuit dependent, and is thus beyond the scope of this report.

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[41] Phone call to Douglas A. Coe (216)946-9900, Sales Application Engineer for Namco Controls, on 13-Dec-1991. He gave the minimum activation

energy for Namco EC210 connectors as 0.8 eV for the replaceable o-rings; the next lowest activation energy was 1.13 eV for the lead wire jacket (these values are from Namco Report No. QTR 145, Rev. 2).

[42] Facsimile from A.J. Bernardini, General Manager for Litton-VEAM, on 23-Aug-1991 (TF# 8690/91). Activation energy of 1.15 eV is for the silicon elastomers used in the connector.

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A Terminal Blocks

This section describes the 2 types of tested terminal blocks; the experimental apparatus, techniques, and test conditions used to perform terminal block measurements; and the results of the terminal block measurements[1].

The terminal blocks were chosen to address issues related to a previous study of terminal blocks by Craft [5, 6], namely

1. the terminal blocks were not aged before the LOCA test in the previous study, and
2. the terminal blocks were constantly powered in the previous study. The heat caused by this probably reduced the amount of surface moisture on the blocks during the accident test. To more closely mimic the behavior of a typical safety system, it would be useful to see what happens if the initially unpowered terminal blocks have power suddenly applied after the accident has started.

A.1 Experimental Apparatus and Technique

A.1.1 Tested Terminal Blocks

As shown in Table 2.1, two types of terminal blo s were tested:

- Marathon 1604 NUC
- States ZWM-25004

The two types of terminal blocks are Class 1E qualified and were supplied with a Certificate of Compliance or Conformance that indicates the standards to which they have been qualified, the relevant qualification documents, and the manufacturing lot and date. Two of each type of terminal block were installed in the test chamber using 6 cables (18 conductors) as indicated in Table A.1. Of these 18 conductors, 4 supplied power to the 4 terminal blocks, 4 were the return legs for the power, and the remaining 10 were connected to adjacent terminal block terminals or the terminal block ground planes to serve as possible leakage paths.

[1] In addition to the figures and tables included in this section, all the raw data are available upon request from the author.

Rockbestos Firewall III XLPE multiconductor cable (12 AWG, 3 conductor) was used for all the terminal block connections. This cable is nuclear qualified and has been previously tested to the equivalent of 60 years [16]. This cable was used to make the connections to help ensure that the testing isolated the effects of aging on the connections, rather than simply failing the cable. However, to provide a baseline for the effect of the test exposures on the cables, two of the Rockbestos cables without any connections were also included in the test chamber for the entire duration of the test.

A.1.2 Test Conditions

All environmental exposures were performed in the same test chamber and at the same time as the other connections as described in Section 2.

Figure 2.5 shows a top view of the arrangement of connections in the test chamber. Two Hoffman A-806CHNF enclosures, each containing one Marathon and one States terminal block, were mounted inside the mandrel; the top of each enclosure was located at the centerline of the cobalt-60 sources. As shown in Figure A.1, the Marathon terminal block was installed at the top of each of the two enclosures. A 0.25 inch diameter weep hole was located at the bottom of each enclosure. The cables entered and exited each enclosure through an elbow and a short section of conduit located inside the test chamber.

During the aging and accident radiation exposures, the terminal blocks were energized with 110 Vdc and no current; all other terminal block conductors were grounded as indicated in Table A.1. During the accident steam exposure, the terminal block conductors were energized using the circuit shown in Figure A.2 as follows:

- The Marathon terminal block in enclosure 1 and the States terminal block in enclosure 2 were energized continuously with 45–110 Vdc. The actual dc energization is shown in Figure A.3.
- The States terminal block in enclosure 1 and the Marathon terminal block in enclosure 2 were switched between 110 Vac, 220 Vac, and no current. This allowed the measurement of transient terminal block leakage currents during

Table A.1: Terminal Block Conductor Numbers.

Enclosure 1	red conductor	white conductor	black conductor
cable 1	66[a]	71a	72a
cable 2	67	71b[b]	**68**
cable 3	69	72b	**70**
Enclosure 2	**red conductor**	**white conductor**	**black conductor**
cable 4	73	78a	79a
cable 5	74	78b	**75**
cable 6	76	79b	**77**

[a]Conductor numbers listed in bold were electrically grounded during aging, accident irradiation, and the accident steam exposure.

[b]Conductors numbered with a "b" suffix were left as an open circuit; they are the return legs of the 4 "a" suffix conductors used to energize the 4 terminal blocks.

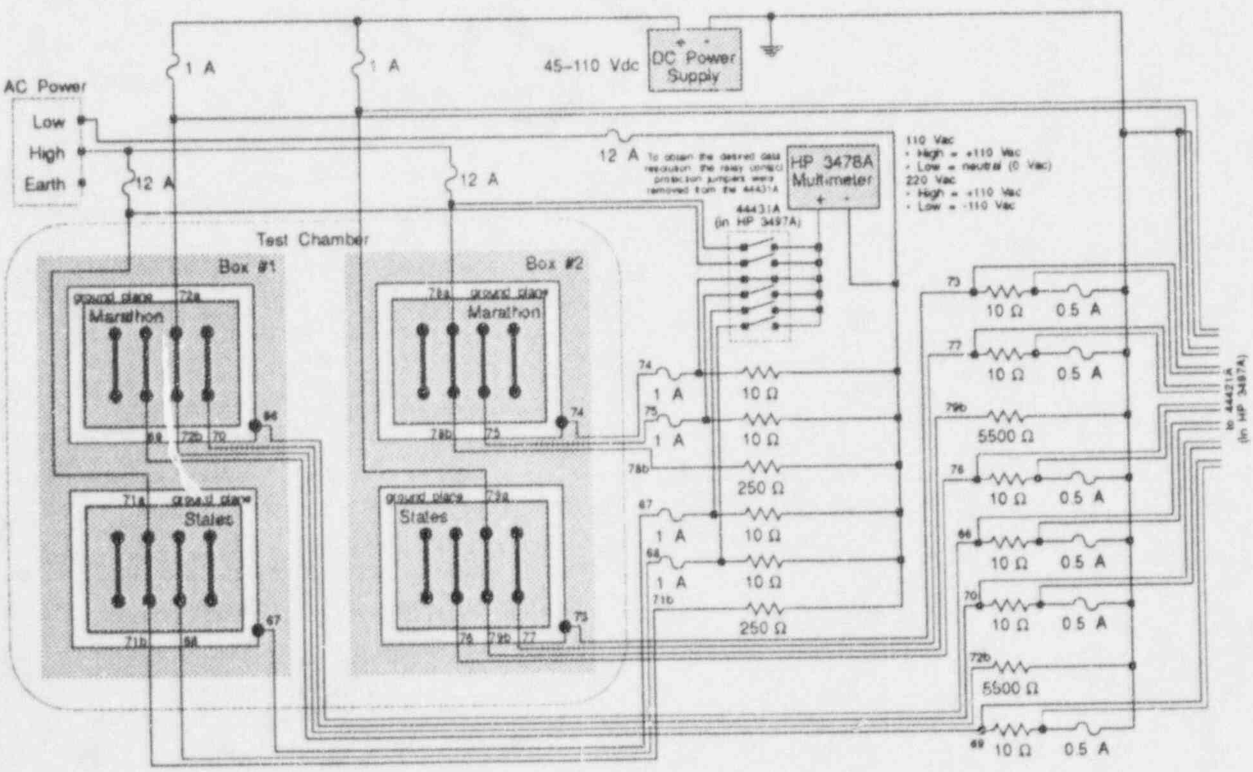

Figure A.2: Circuit used for dc and ac excitation of the terminal block conductors and to measure their "continuous" IRs during the accident steam exposure.

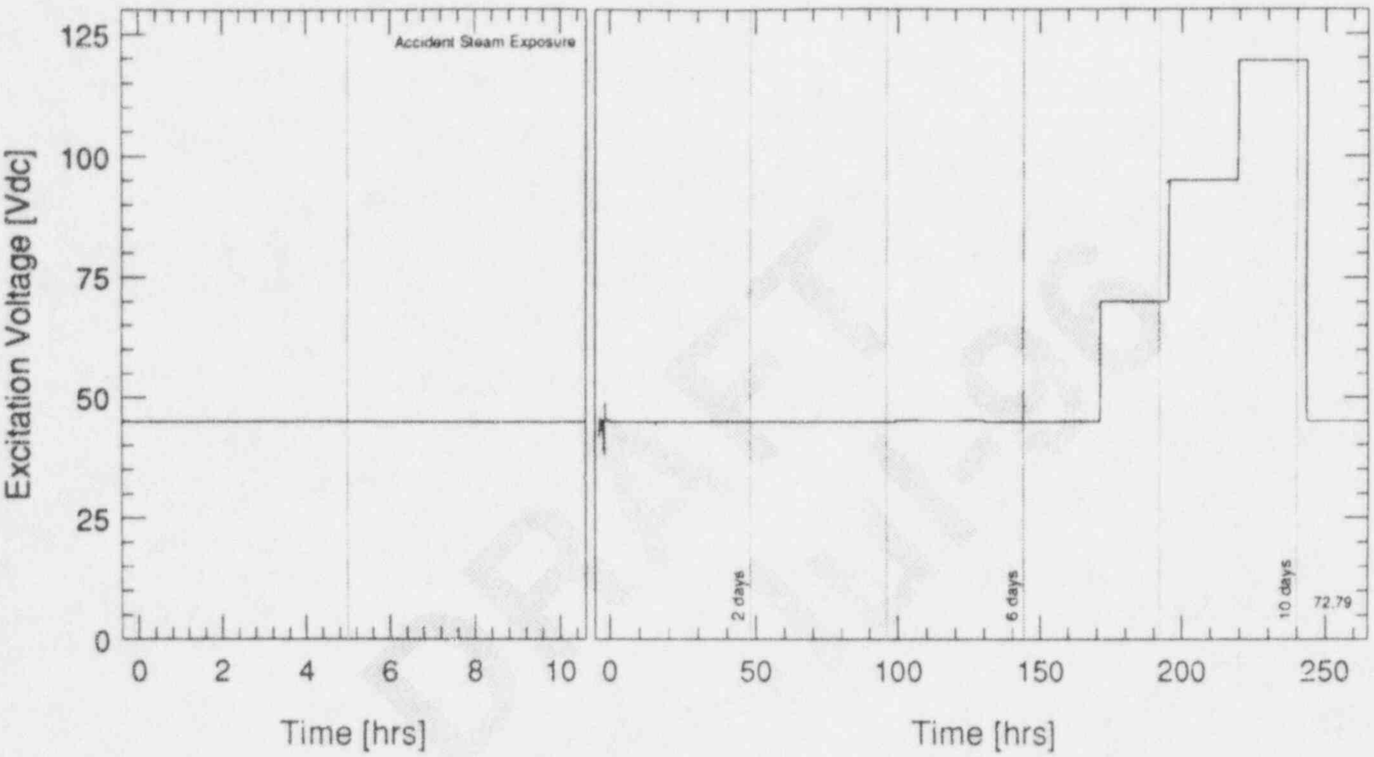

Figure A.3: DC excitation for the terminal block conductors during the accident steam exposure.

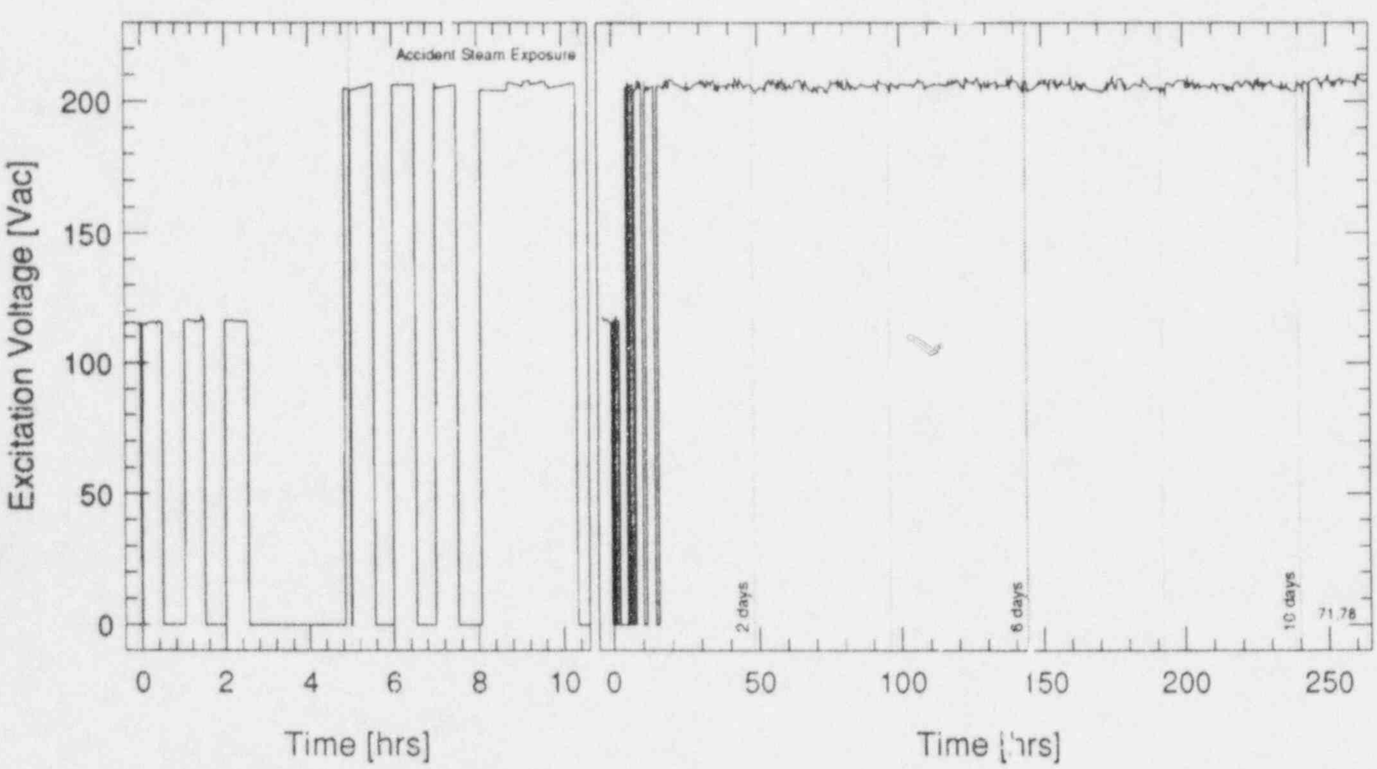

Figure A.4: AC excitation for the terminal block conductors during the accident steam exposure.

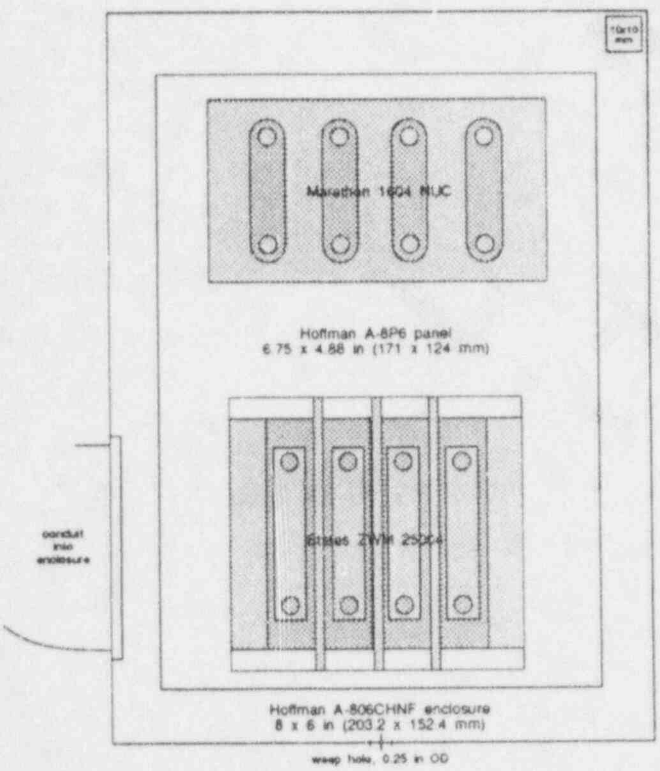

Figure A.1: Sketch of the two terminal blocks inside an enclosure (to scale).

the accident steam exposure. The actual ac energization is shown in Figure A.4.

A.1.3 Electrical Measurement Techniques

In addition to the discrete IR measurements described in Section 2.4.2, the continuous IR of the terminal block conductors was measured using the circuit shown in Figure A.2. Continuous IR measurements were performed for all terminal block conductors except for the 4 conductors that energized the terminal blocks.

Note that all the discrete IR measurements were dc measurements. However, only the continuous IR measurements for the conductors from the dc energized terminal blocks were dc measurements. The continuous IR measurements for the conductors from the ac energized terminal blocks were ac measurements; thus, these measurements really measure the leakage and charging current for these conductors, much like an ac dielectric test set measurement.

A.2 Experimental Results

Measured IR values during aging and accident irradiation are shown in Figures A.5 and A.6 for the Marathon and States terminal block conductors, respectively. For all the conductors, the IR remained essentially unchanged during the aging exposure and the ambient IR values measured at the end of aging were all higher than those measured prior to aging. The IR values during the accident irradiation were somewhat lower than the values during the aging exposure; however, similar to the aging results, the IR values were essentially constant[2]. The ambient IR values measured at the end of the accident irradiation were all higher than those measured prior to aging.

Measured terminal block conductor IR data during the accident steam exposure are shown in Figures A.7–A.20. The IR values fell to low values due to the presence of moisture during the steam exposure. The slow test chamber flooding that occurred through day 5 caused even larger reductions in the measured

[2] The very high IR for the States terminal block conductor 73 at a dose of 698 kGy was considered a test anomaly.

IR values because water could enter the terminal block enclosures through the weep hole and unsealed conduit entry and submerge the bare terminal blocks. The terminal block enclosures were also mounted lower in the test chamber than the other connections, which caused the terminal blocks to be submerged before the other connections. The data does not show any change in the measured IR when an initially unpowered terminal block has power suddenly applied while in a steam environment; it had been hypothesized that this might cause electrical shorting because of surface moisture that might form on the cold terminal block. Previous testing had utilized continuously powered terminal blocks and the resulting I^2R heat generation might have reduced the amount of surface moisture that formed on the terminal blocks.

A post-LOCA IR measurement was performed 3 days after completion of the accident steam exposure; these data are tabulated in Table A.2 and are also plotted as the ambient data at approximately 245 hr in Figures A.7–A.20. These data show a recovery in IR from that of the steam exposure.

Because of the possibility that moisture still remained in and on the terminal block enclosures, the IR was retested approximately 13 months later which provided sufficient time to ensure that everything had dried out; these results are also shown in Table A.2. The IR of all the terminal block conductors had increased by several orders of magnitude to values near 10^9 Ω and above.

Once the dry IR test was completed, the test chamber was flooded with tap water and additional IR measurements were performed. As expected, the IR of the uncovered terminal block conductors fell to low levels for measurements performed after a minimum soak time of 30 min (see Table A.2). No measurements were performed on the terminal block conductors after a minimum soak time of 3 hr.

Following the submerged IR tests, the connections were allowed to fully dry and then dielectric withstand testing was performed. An initial withstand test on the dry conductors was performed at 1000 Vac rms; all of the terminal block conductors had a resulting current of less than 1 mAac as shown in Table A.2. No submerged dielectric withstand testing was performed on the terminal block conductors.

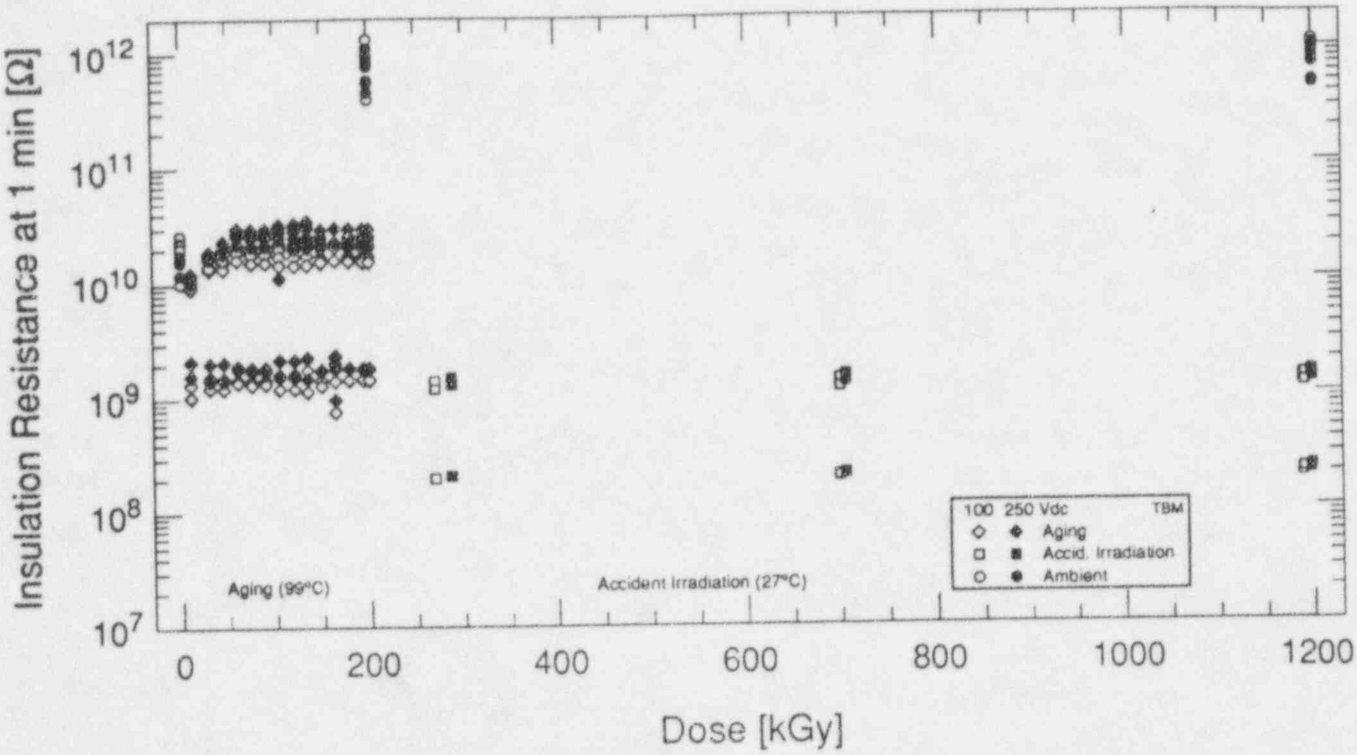

Figure A.5: IR of the 7 Marathon terminal block conductors during aging and accident irradiation.

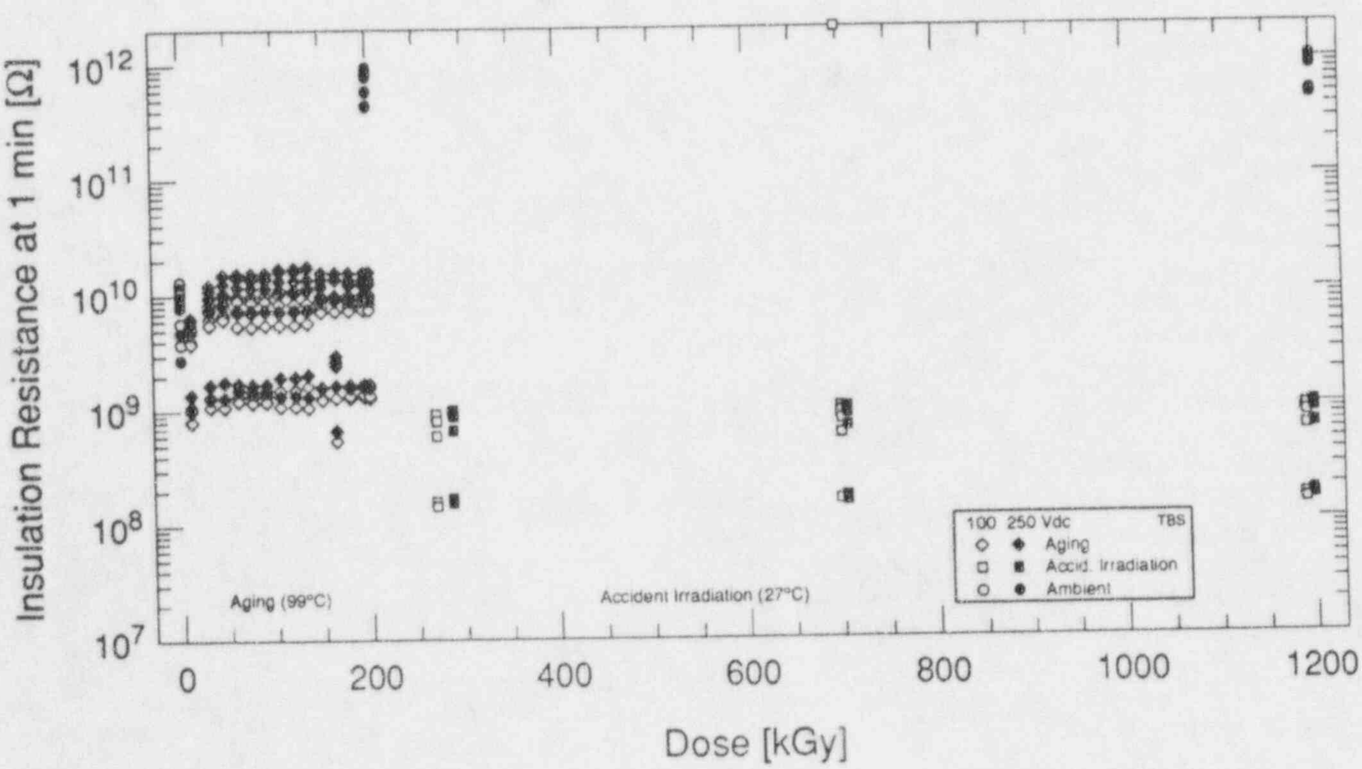

Figure A.6: IR of the 7 States terminal block conductors during aging and accident irradiation.

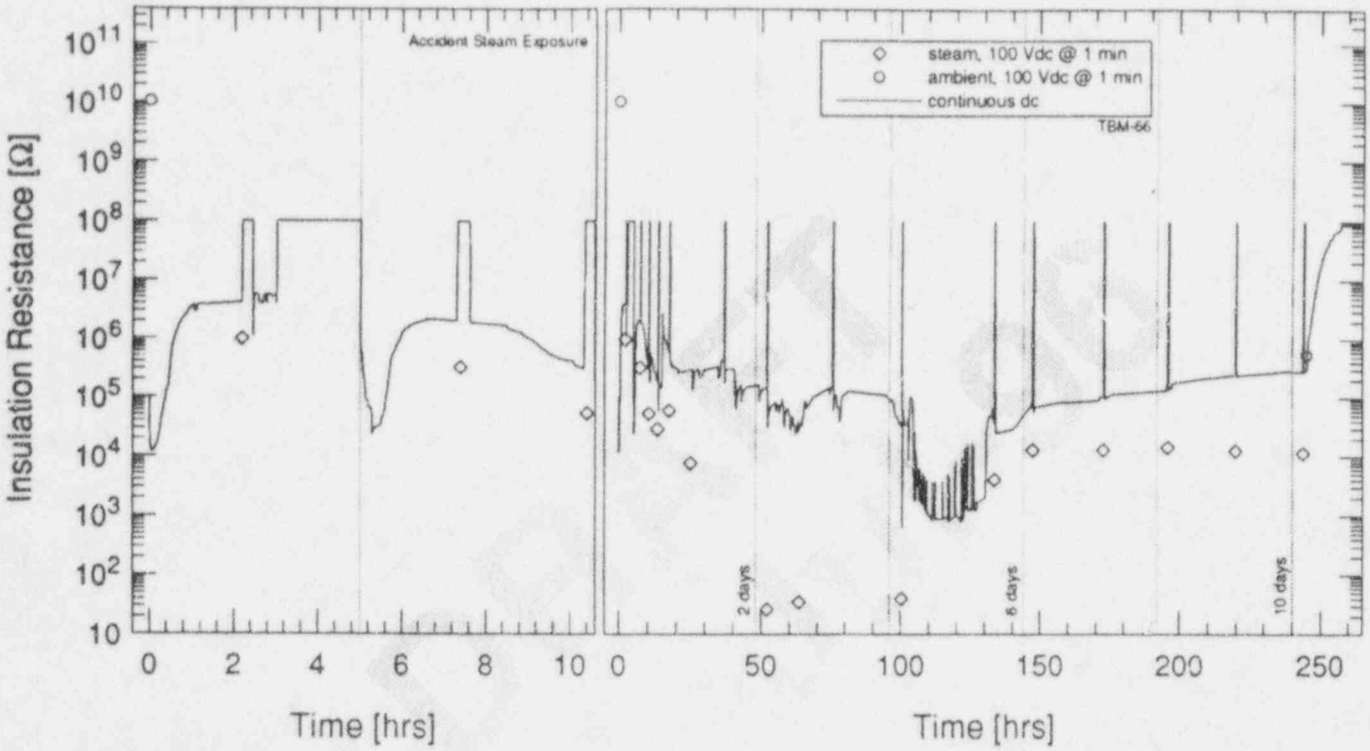

Figure A.7: IR of conductor 66 during the accident steam exposure (Marathon dc ground plane, enclosure 1).

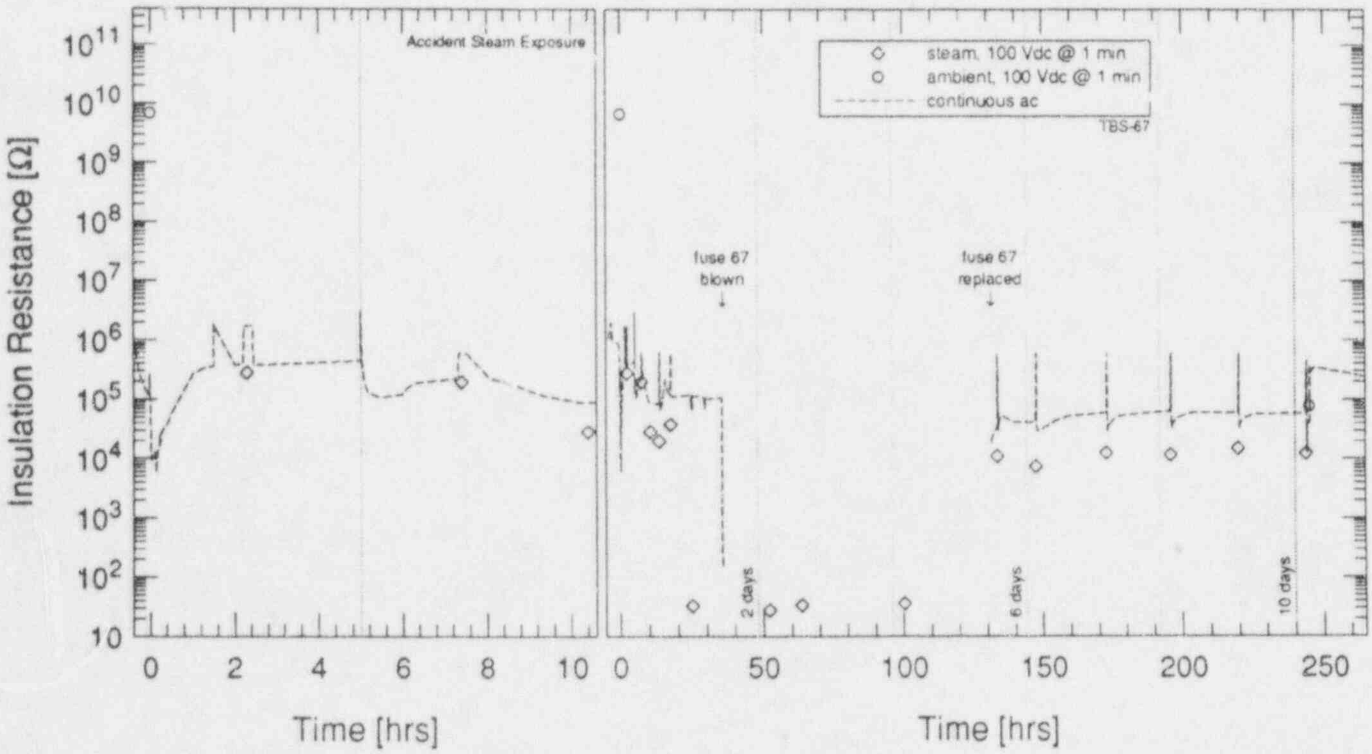

Figure A.8: IR of conductor 67 during the accident steam exposure (States ac ground plane, enclosure 1).

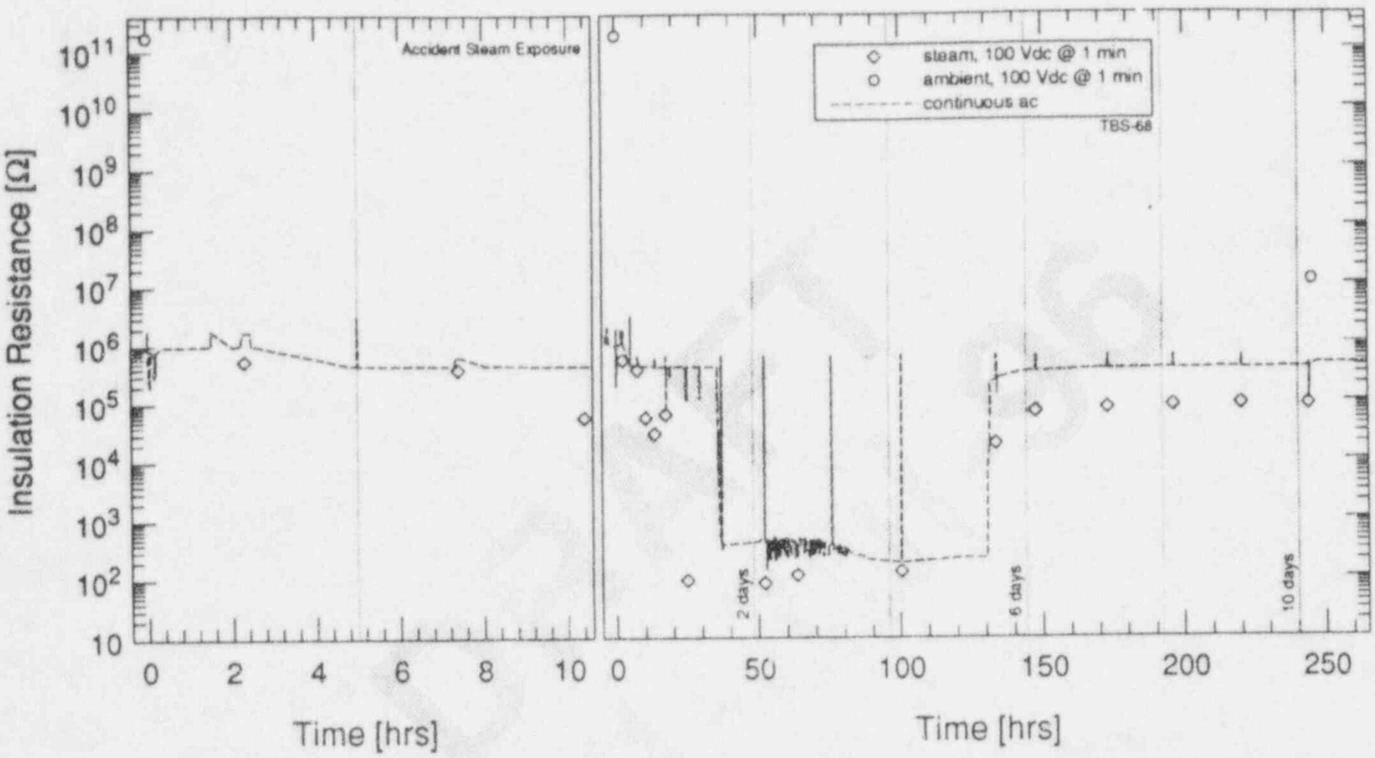

Figure A.9: IR of conductor 68 during the accident steam exposure (States ac adjacent terminal, enclosure 1).

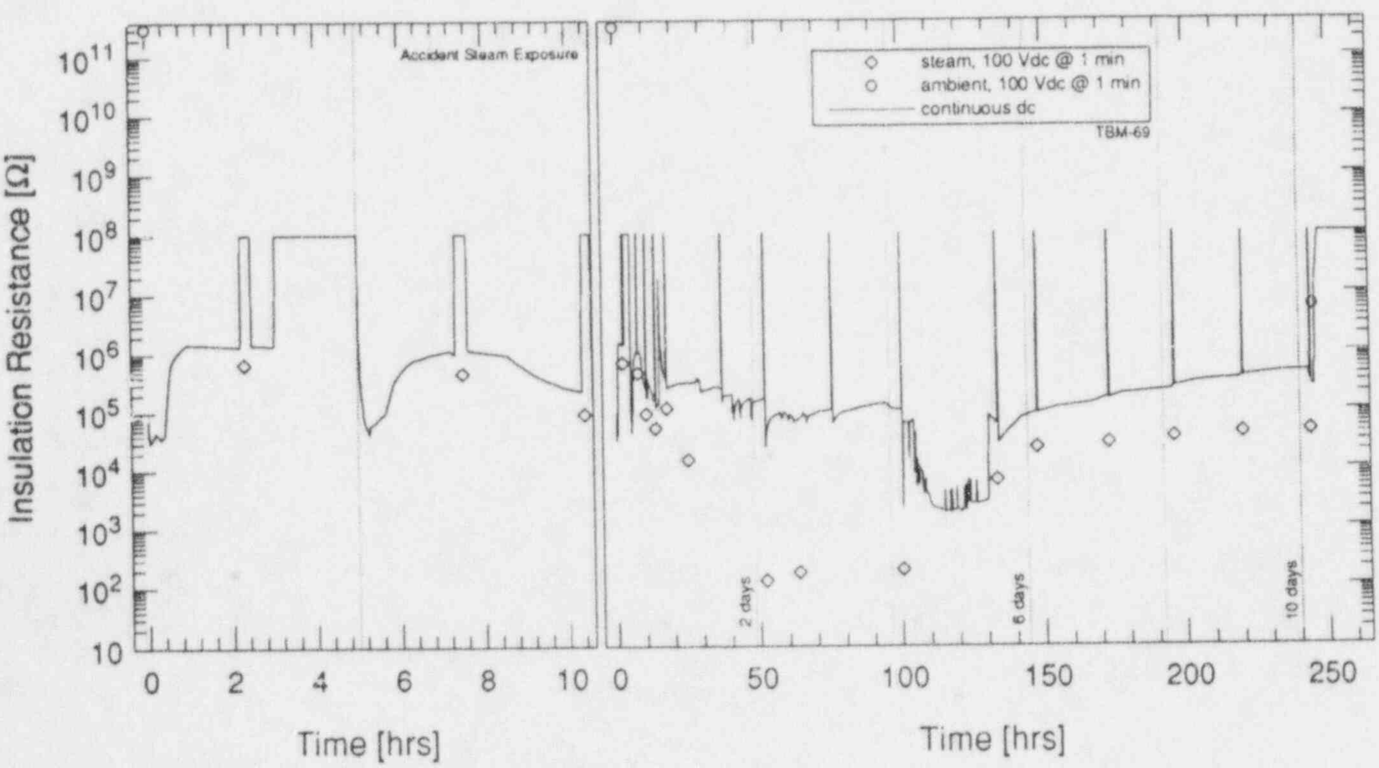

Figure A.10: IR of conductor 69 during the accident steam exposure (Marathon dc adjacent terminal, enclosure 1).

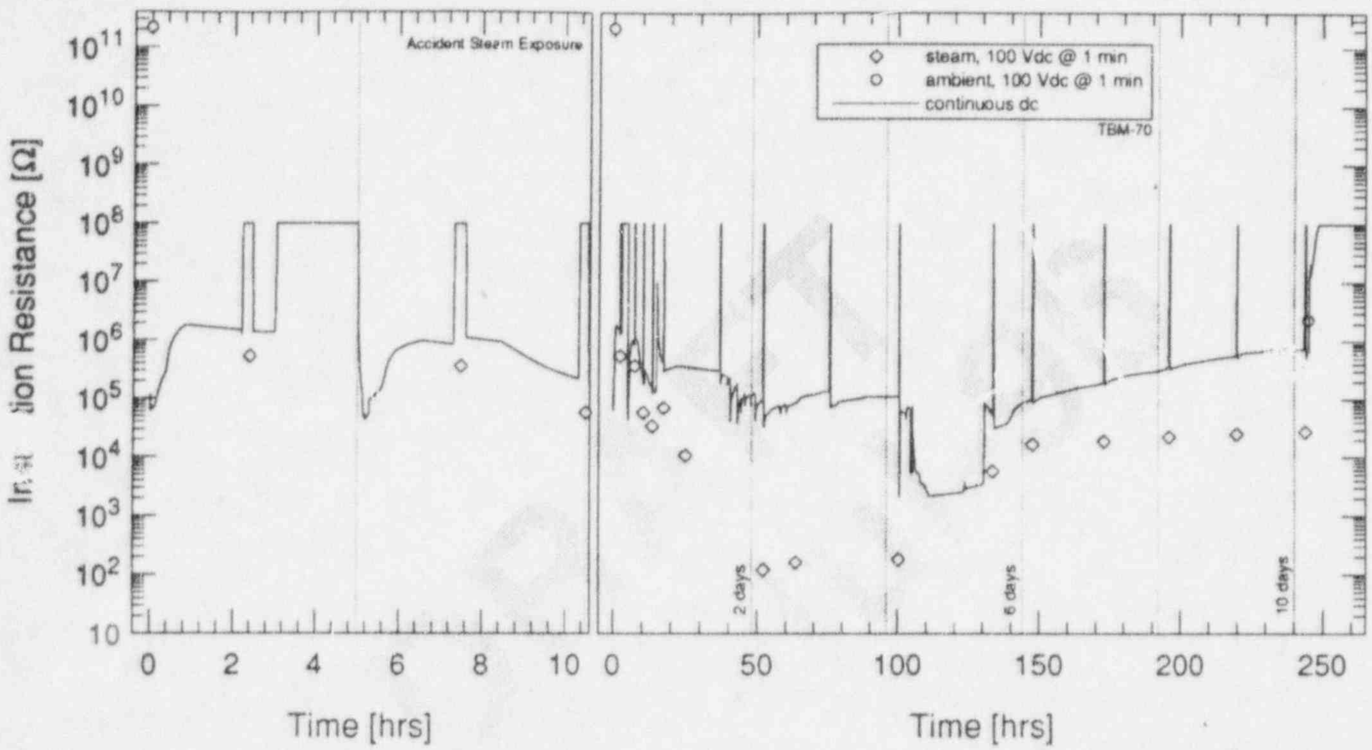

Figure A.11: IR of conductor 70 during the accident steam exposure (Marathon dc adjacent terminal, enclosure 1).

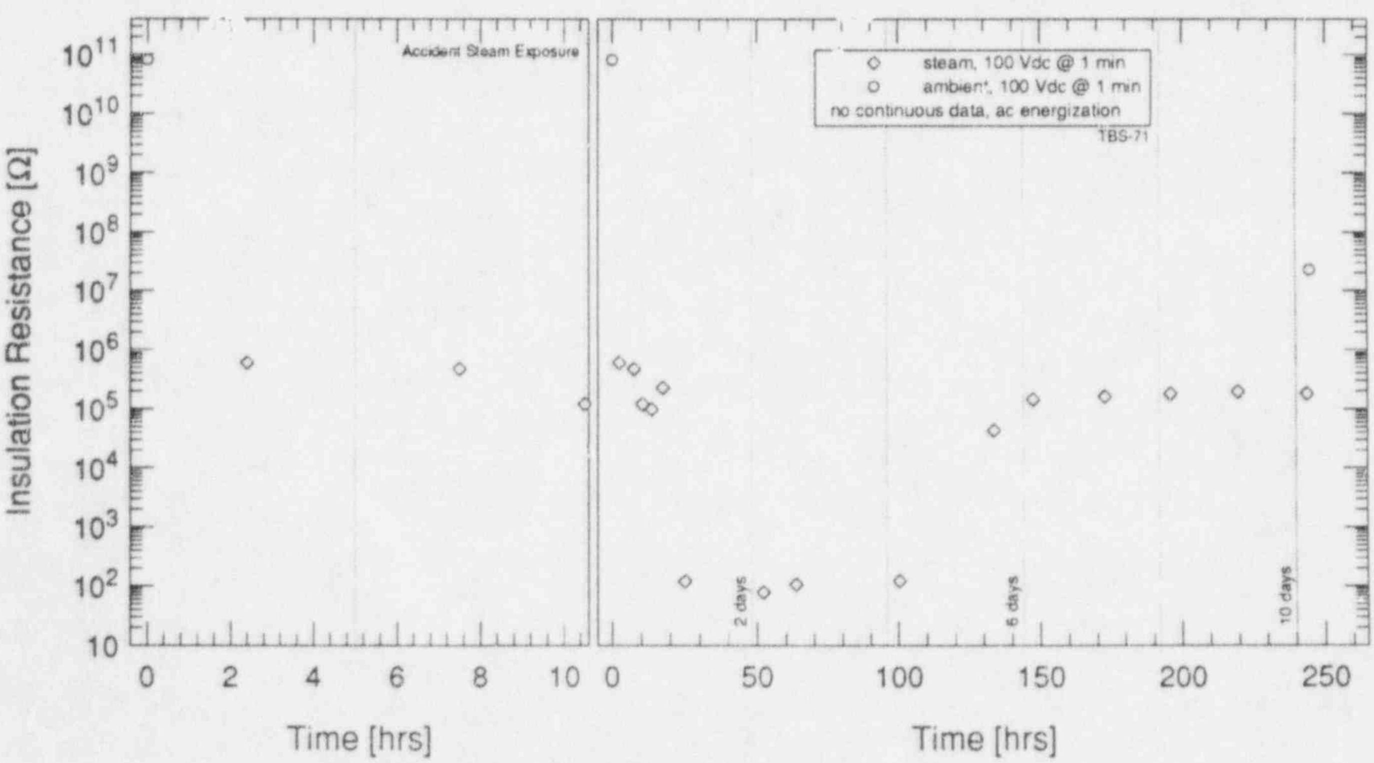

Figure A.12: IR of conductor 71 during the accident steam exposure (States ac energization, enclosure 1).

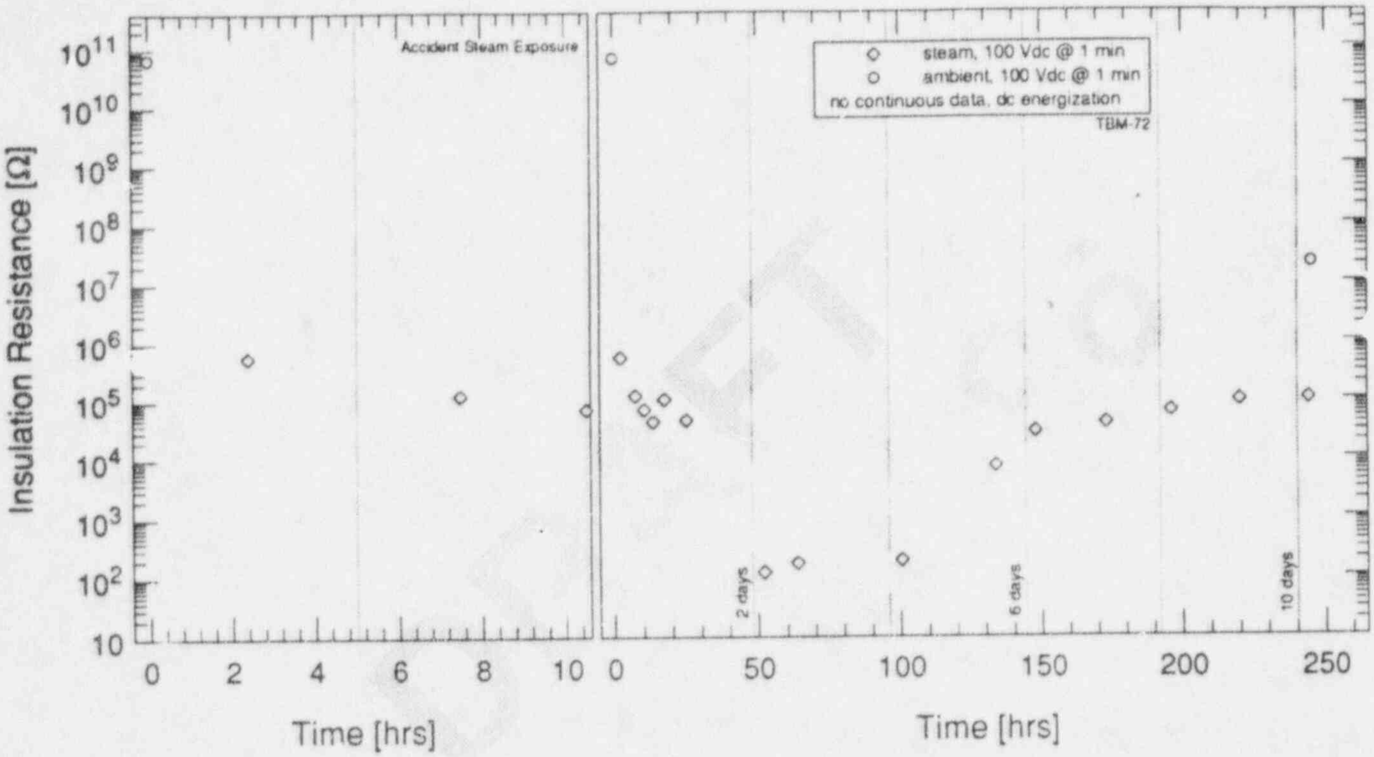

Figure A.13: IR of conductor 72 during the accident steam exposure (Marathon dc energization, enclosure 1).

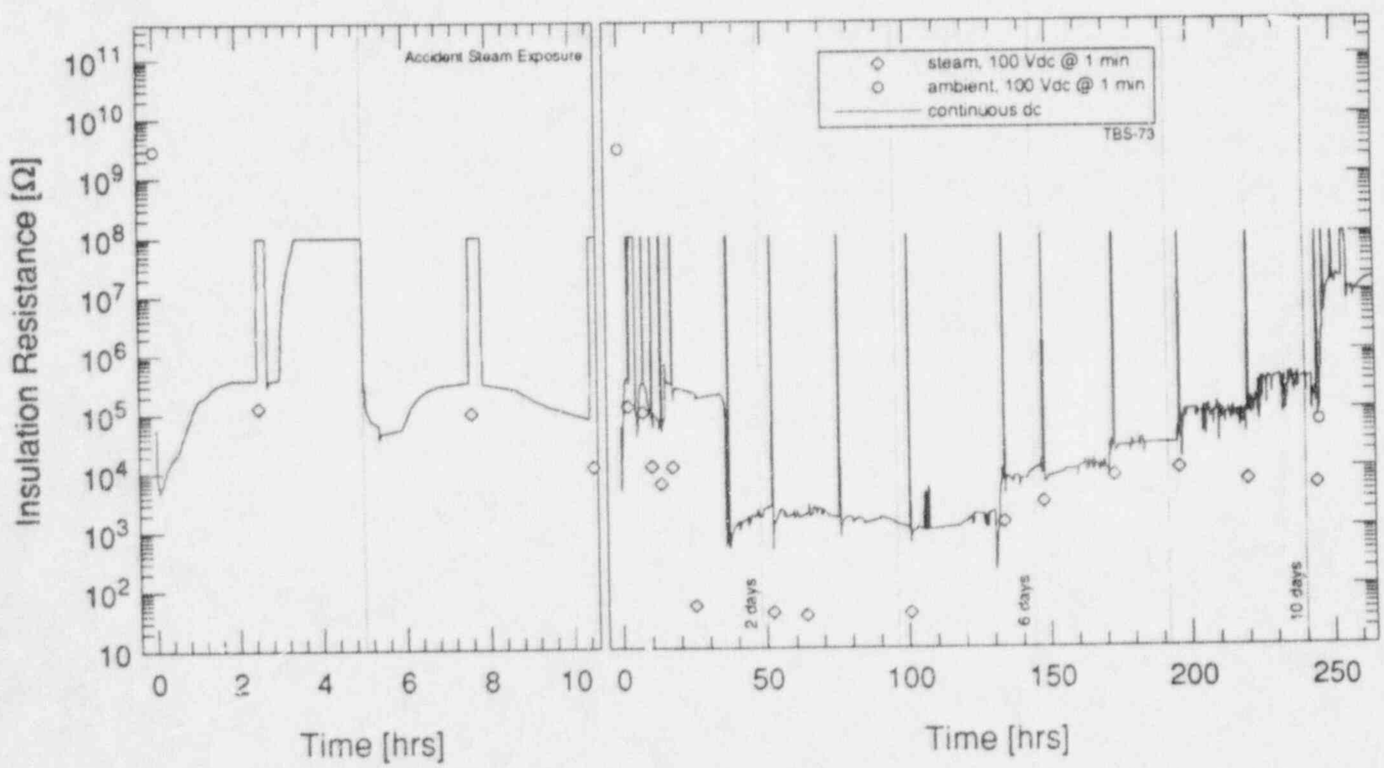

Figure A.14: IR of conductor 73 during the accident steam exposure (States dc ground plane, enclosure 2).

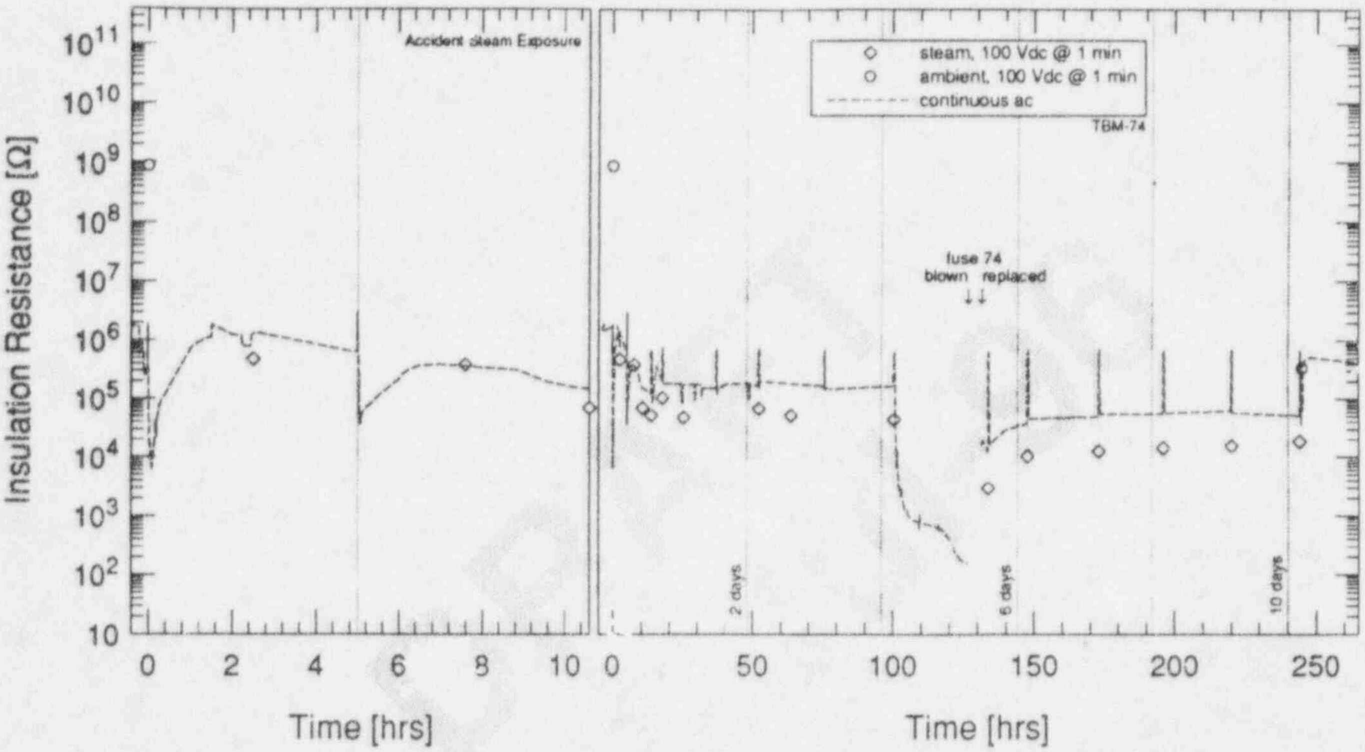

Figure A.15: IR of conductor 74 during the accident steam exposure (Marathon ac ground plane, enclosure 2).

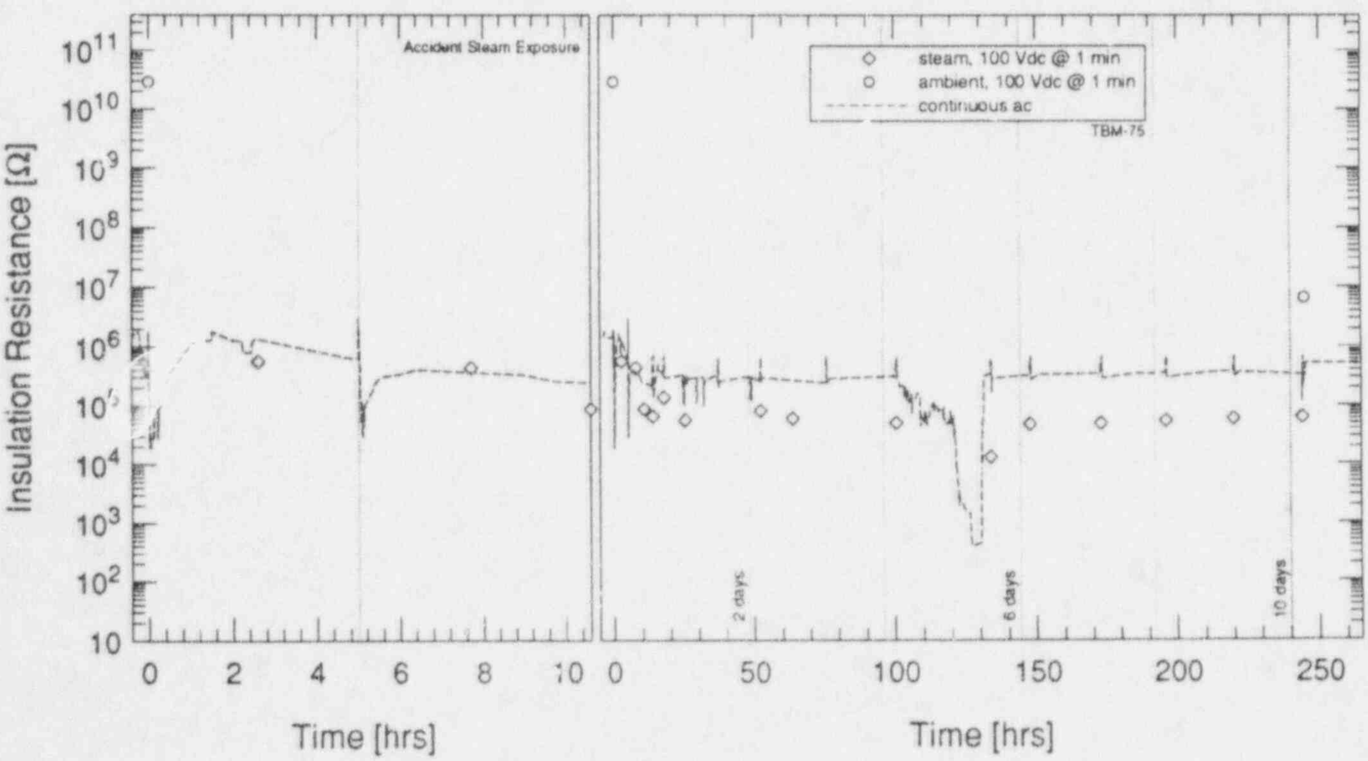

Figure A.16: IR of conductor 75 during the accident steam exposure (Marathon ac adjacent terminal, enclosure 2).

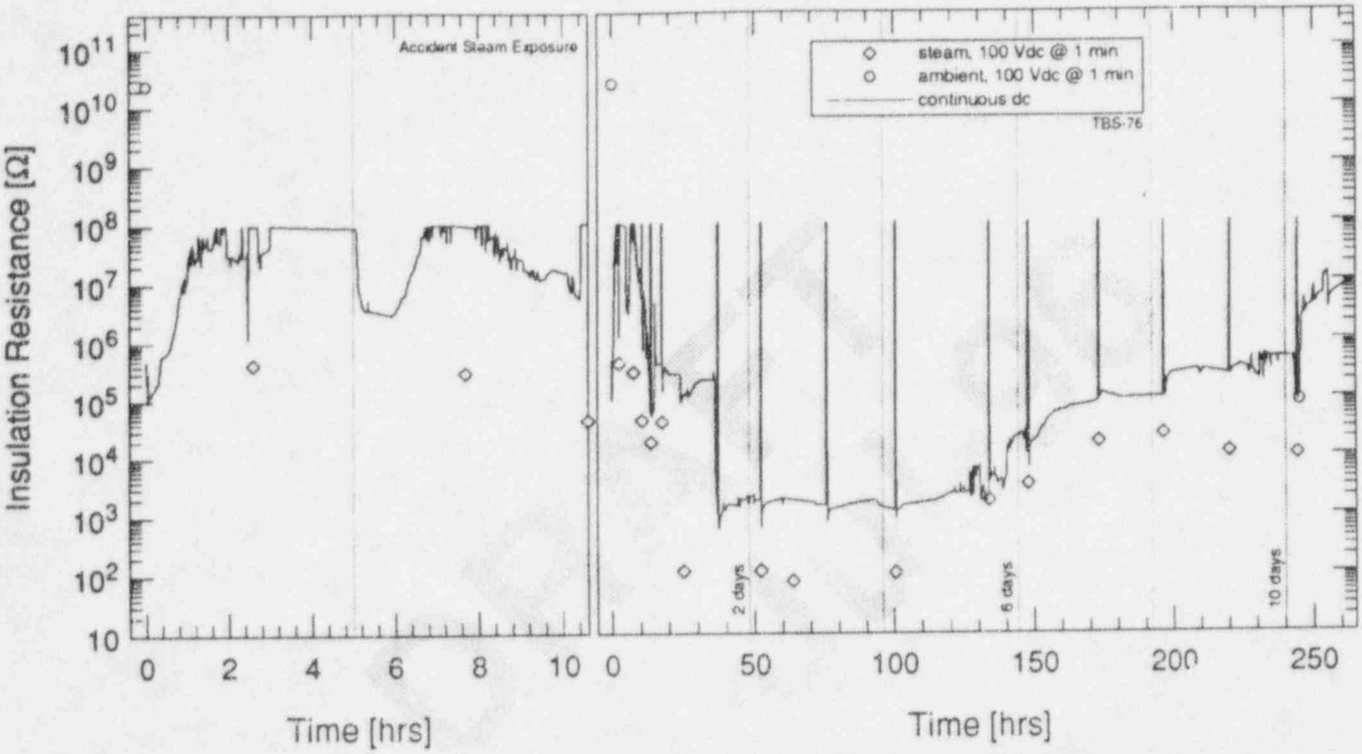

Figure A.17: IR of conductor 76 during the accident steam exposure (States dc adjacent terminal, enclosure 2).

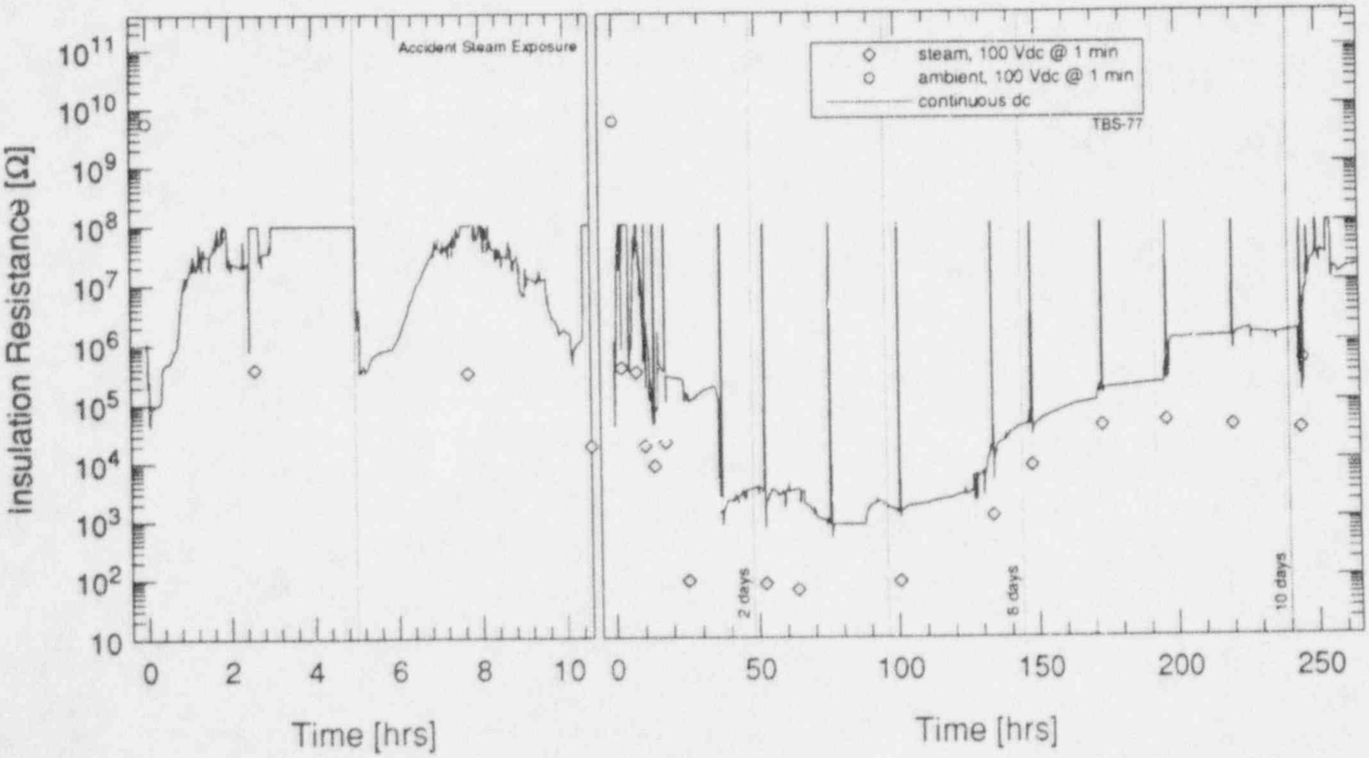

Figure A.18: IR of conductor 77 during the accident steam exposure (States dc adjacent terminal, enclosure 2).

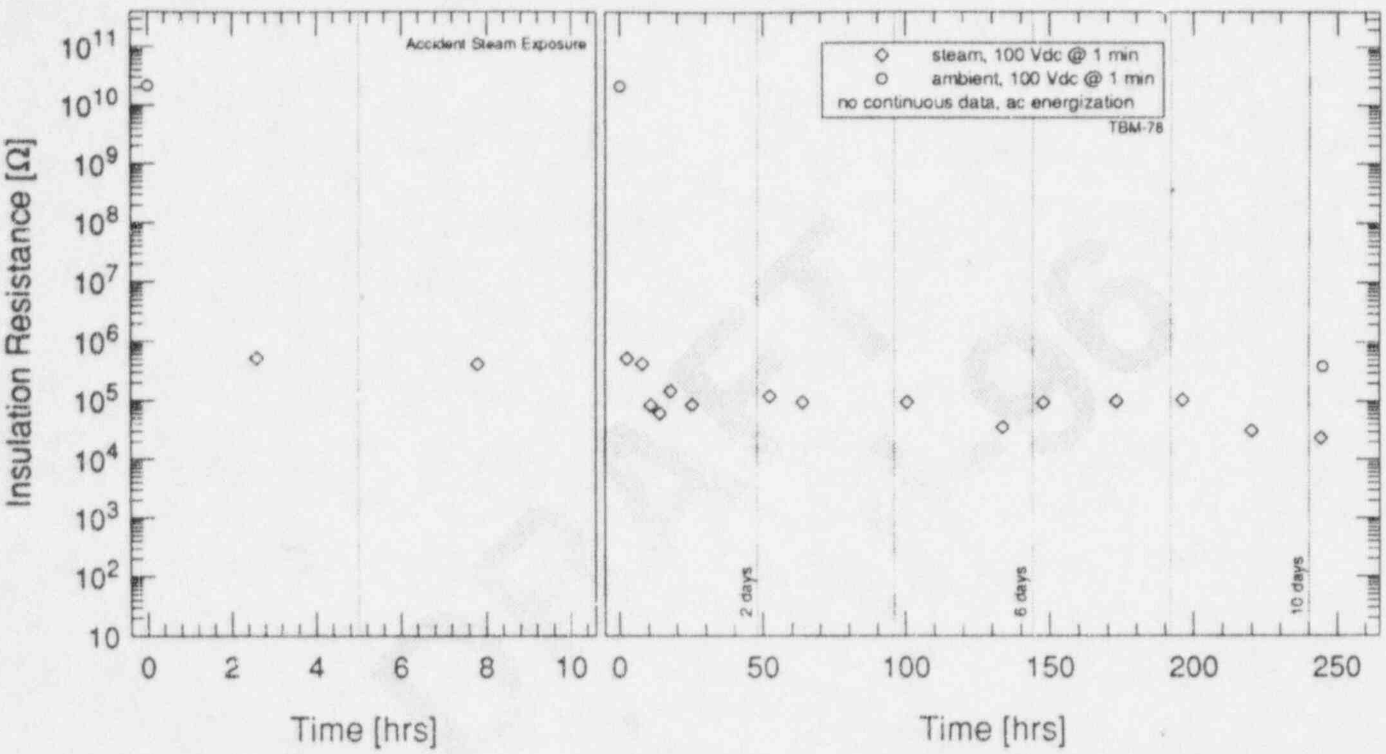

Figure A.19: IR of conductor 78 during the accident steam exposure (Marathon ac energization, enclosure 2).

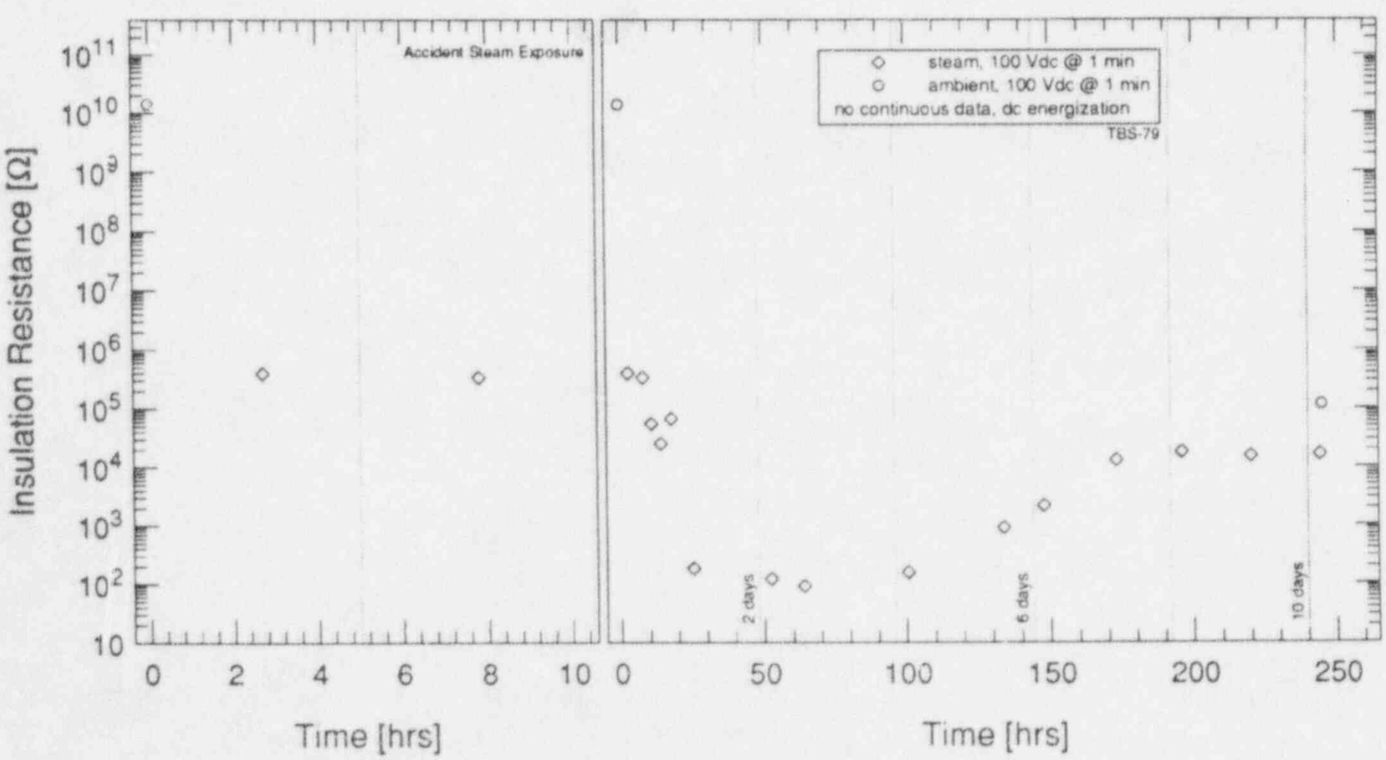

Figure A.20: IR of conductor 79 during the accident steam exposure (States dc energization, enclosure 2).

Table A.2: Post-LOCA, Terminal Block Test Results.

	100 Vdc IR at 1 min				Dielectric Withstand (1-min hold period)			
	LOCA	LOCA + 13 months			LOCA + 23 months			
	+ 3 days		Submerged		Dry		2 hr Submergence	
	Dry	Dry	30 min	3 hr	Voltage	Current	Voltage	Current
Conductor[a]	[Ω]	[Ω]	[Ω]	[Ω]	[kVac]	[mAac]	[kVac]	[mAac]
Enclosure 1, Marathon terminal block, dc excitation during accident steam exposure								
66	5.5e05	5.0e09	1.1e02	—	1.0	0.4	—	—
69	5.9e06	6.8e09	3.6e02	—	1.0	0.4	—	—
70	2.3e06	7.9e09	3.6e02	—	1.0	0.4	—	—
72	2.1e07	6.5e09	5.2e02	—	1.0	0.4	—	—
Enclosure 1, States terminal block, ac excitation during accident steam exposure								
67	7.7e04	6.3e09	6.6e01	—	1.0	0.4	—	—
68	1.1e07	1.1e10	3.2e02	—	1.0	0.4	—	—
71	2.3e07	1.5e10	2.7e02	—	1.0	0.7	—	—
Enclosure 2, States terminal block, dc excitation during accident steam exposure								
73	6.2e04	1.5e09	5.2e01	—	1.0	0.5	—	—
76	8.6e04	4.5e09	1.9e02	—	1.0	0.4	—	—
77	4.9e05	4.3e09	1.5e02	—	1.0	0.4	—	—
79	1.2e05	1.4e10	1.3e04	—	1.0	0.5	—	—
Enclosure 2, Marathon terminal block, ac excitation during accident steam exposure								
74	3.4e05	7.6e08	6.4e01	—	1.0	0.5	—	—
75	6.6e06	9.6e08	3.9e02	—	1.0	0.5	—	—
78	3.9e05	1.5e09	3.5e02	—	1.0	0.9	—	—

[a]See Table A.1.

B Time Domain Reflectometry Results

This section presents the experimental time domain reflectometry (TDR) data[1] acquired for the 10 different types of non-terminal block connections and the 2 types of cables that were tested.

TDR measurements were performed before and after the accident steam exposure with identical test parameters. The connections were located at a distance of approximately 9.14 m (30 ft) down the cable.

The figures in this section are plots of reflection coefficient, ρ, versus distance down the cable, where:

$$\rho = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \frac{Z_L - Z_0}{Z_L + Z_0}, \qquad \text{(B.1)}$$

which can be rewritten as,

$$Z_L = Z_0 \frac{1+\rho}{1-\rho}, \qquad \text{(B.2)}$$

where

- ρ = reflection coefficient,
- Z_0 = characteristic impedance of cable (transmission line),
- Z_L = load impedance.

The reflection coefficient is the ratio of the voltage applied to the cable divided by the voltage reflected back from the cable or circuit due to cable faults or changes in impedance. If there is an open circuit ($Z_L = \infty$) in the cable, nearly all the energy will be reflected back when a pulse is sent down the cable. The reflected voltage will equal the incident pulse voltage and ρ will be +1. If there is a short circuit ($Z_L = 0$) in the cable, nearly all the energy will be delivered back to the instrument through a ground or return conductor instead of being sent on to the load. The polarity of the reflected pulse will be the opposite of the incident pulse and ρ will be -1. If there is no mismatch between the cable and the load ($Z_L = Z_0$), almost no energy will be reflected back and ρ will be 0. In general, a load or fault with higher impedance tha the cable will return a ρ measurement of 0 to +1, and a load or fault with a lower impedance will return a ρ measurement of 0 to -1.

[1] In addition to the figures included in this section, all the raw data are available upon request from the author.

For most of the figures, a vertical scale of 25, 50, or 100 mρ/division was used. A value of 25, 50, or 100 mρ (-25, -50, or -100 mρ) corresponds to an impedance increase (decrease) of 5.1, 10.5, and 22.2% (4.9, 9.5, and 18.2%), respectively.

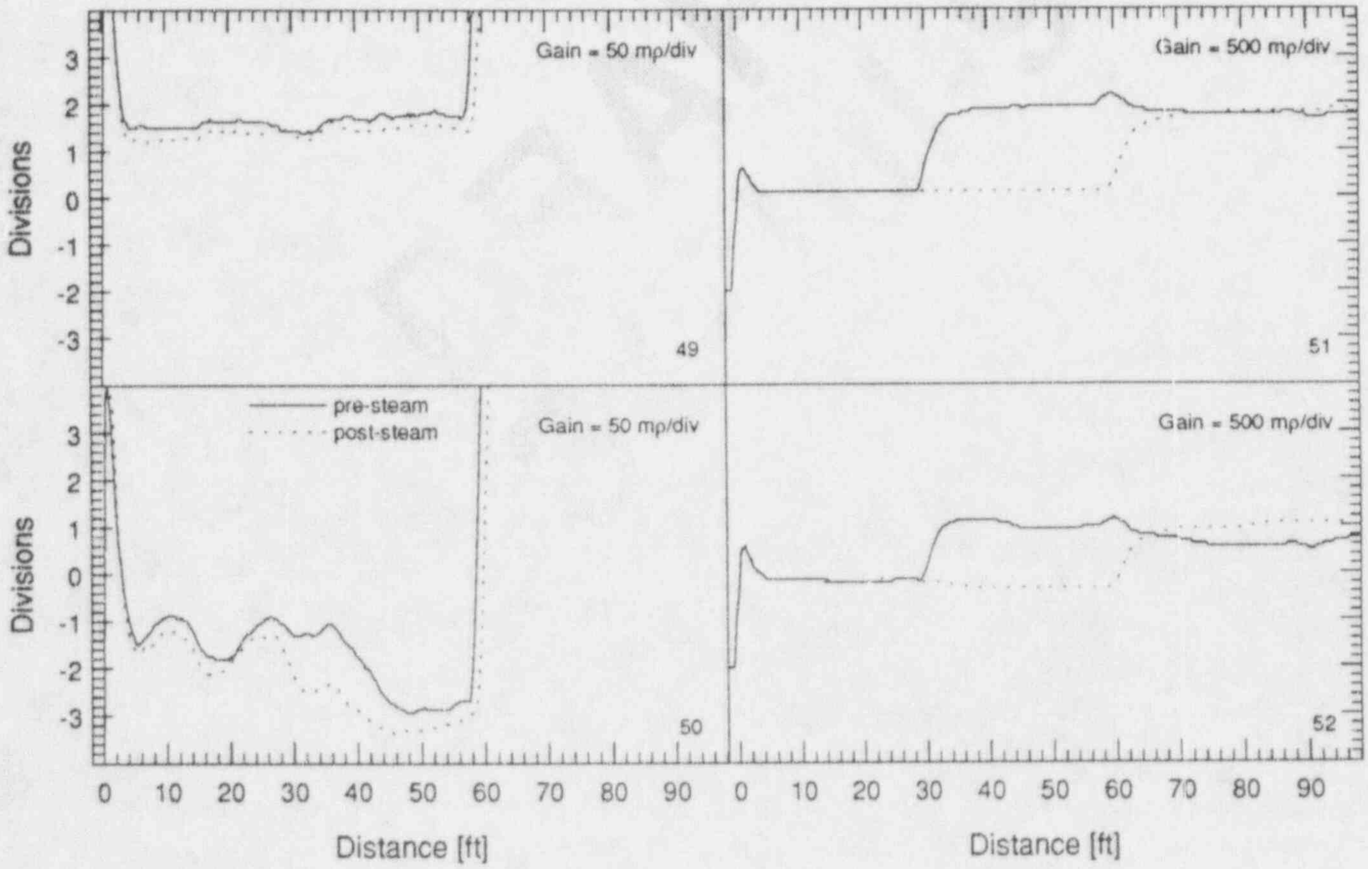

Figure B.1: TDR of the Amphenol coaxial connector conductors before and after the accident steam exposure.

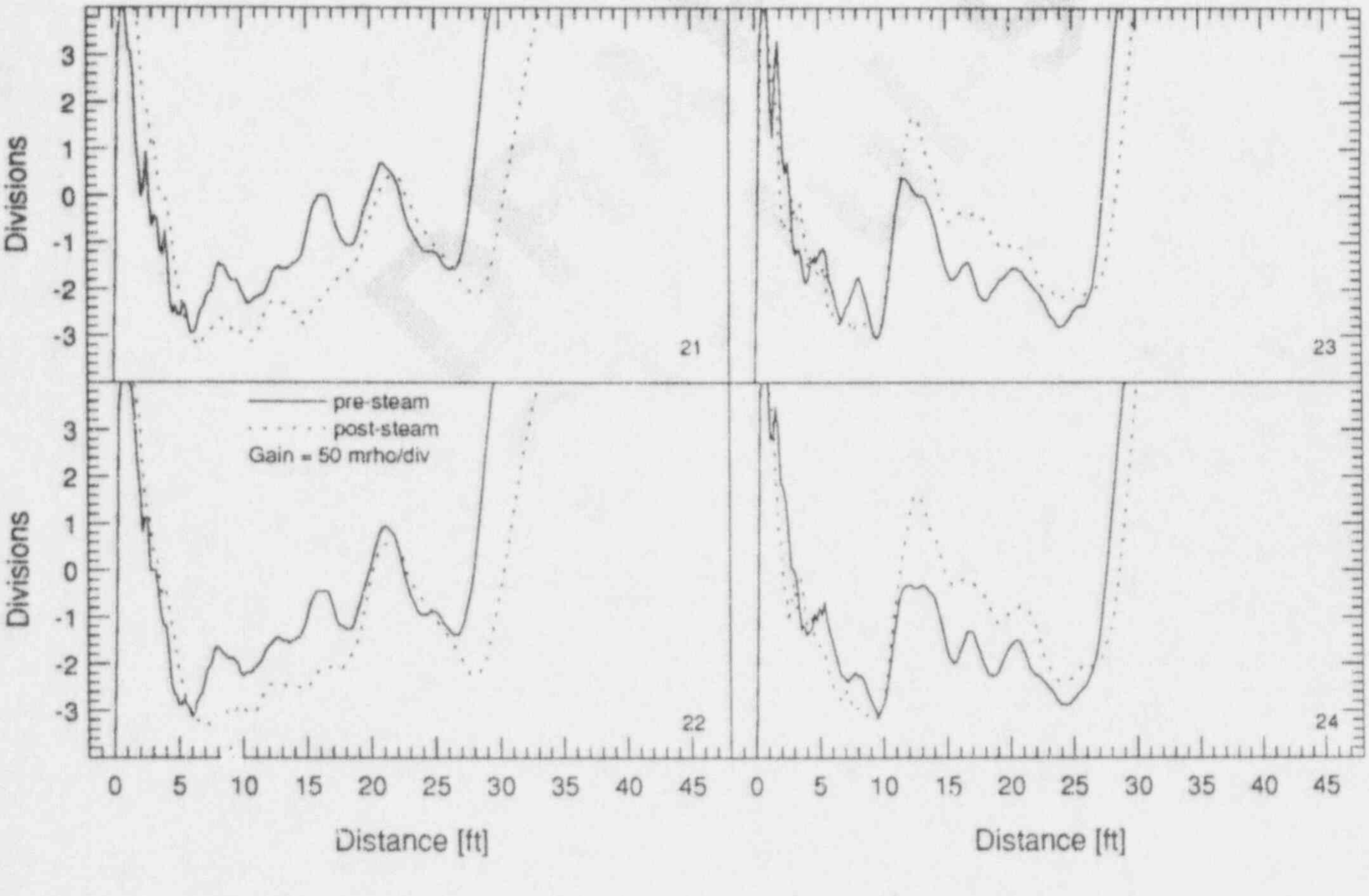

Figure B.2: TDR of the Conax ECSA conduit seal conductors before and after the accident steam exposure.

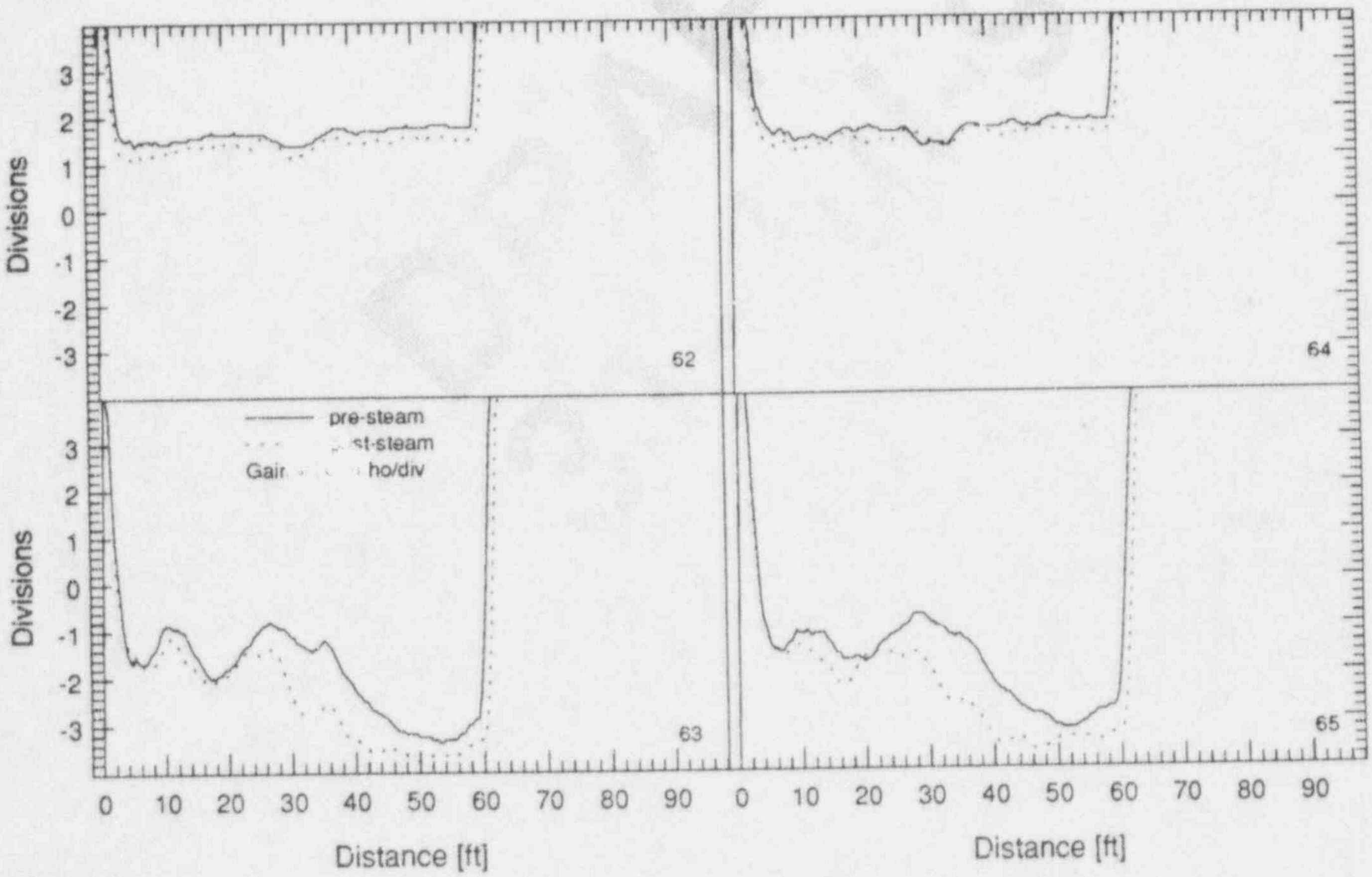

Figure B.3: TDR of the Rockbestos coaxial cable conductors before and after the accident steam exposure.

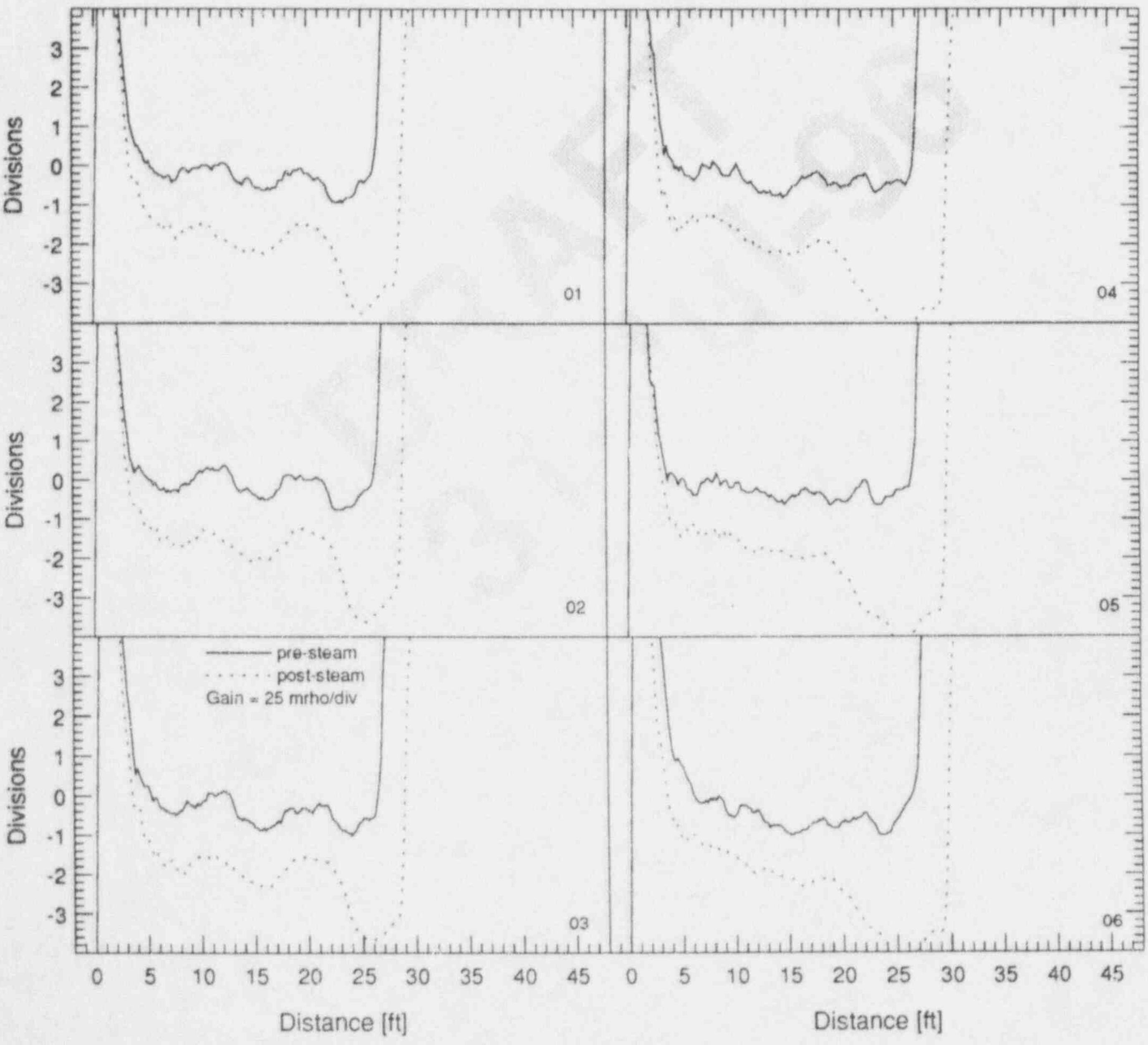

Figure B.4: TDR of the EGS conduit seal conductors before and after the accident steam exposure.

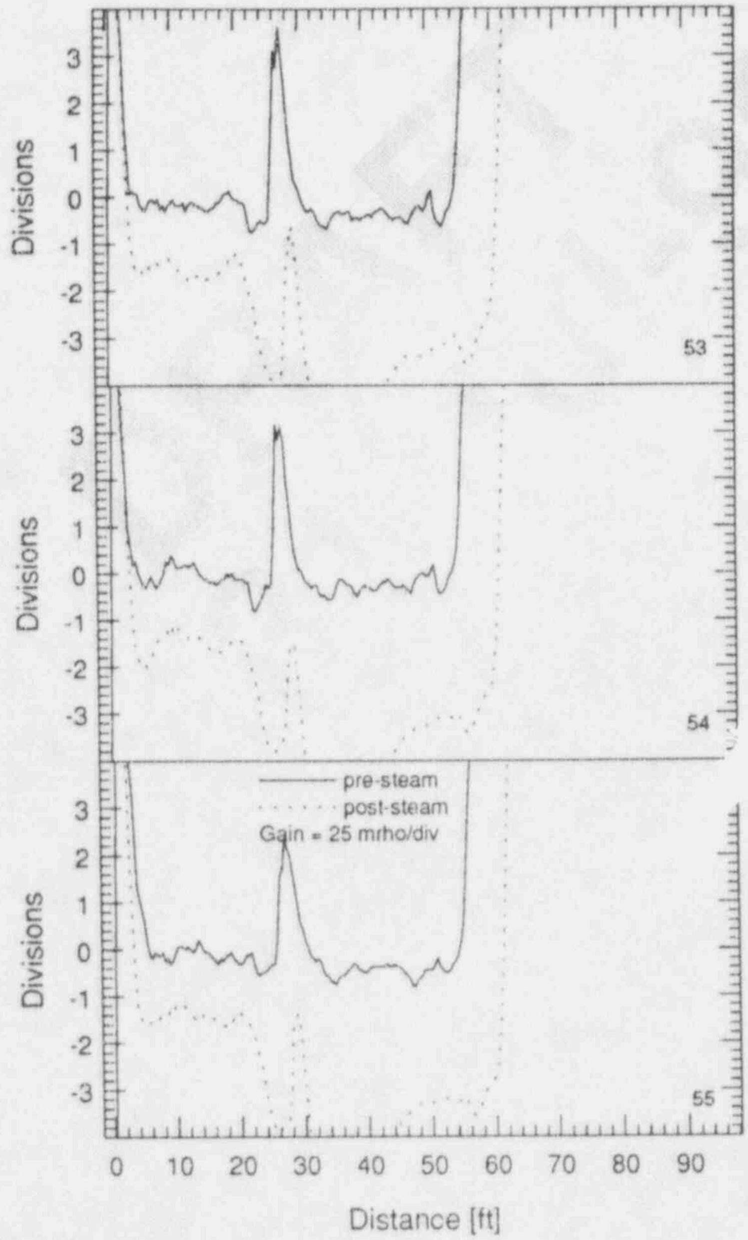

Figure B.5: TDR of the EGS Grayboot connector conductors before and after the accident steam exposure.

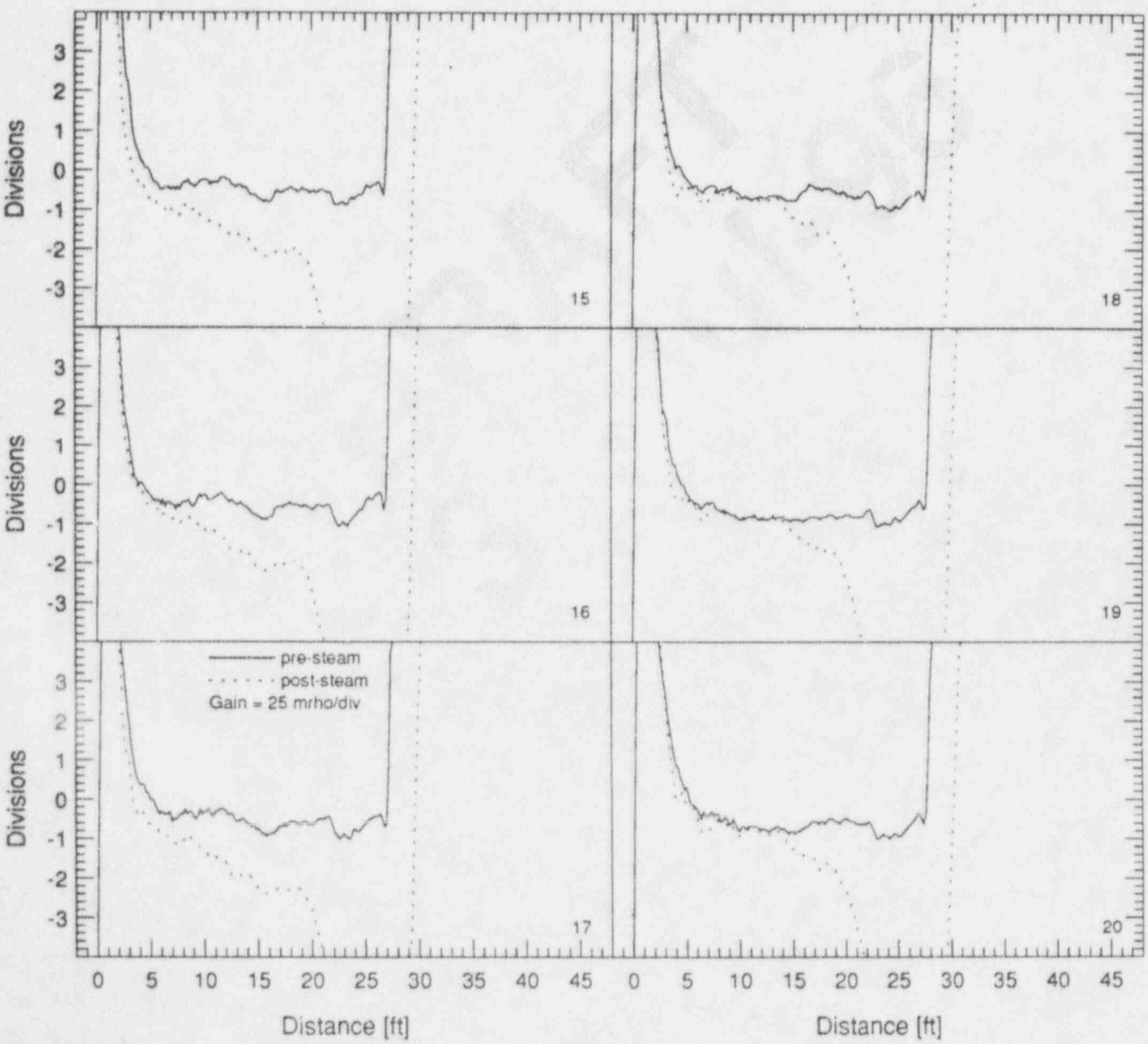

Figure B.6: TDR of the EGS quick disconnect connector conductors before and after the accident steam exposure.

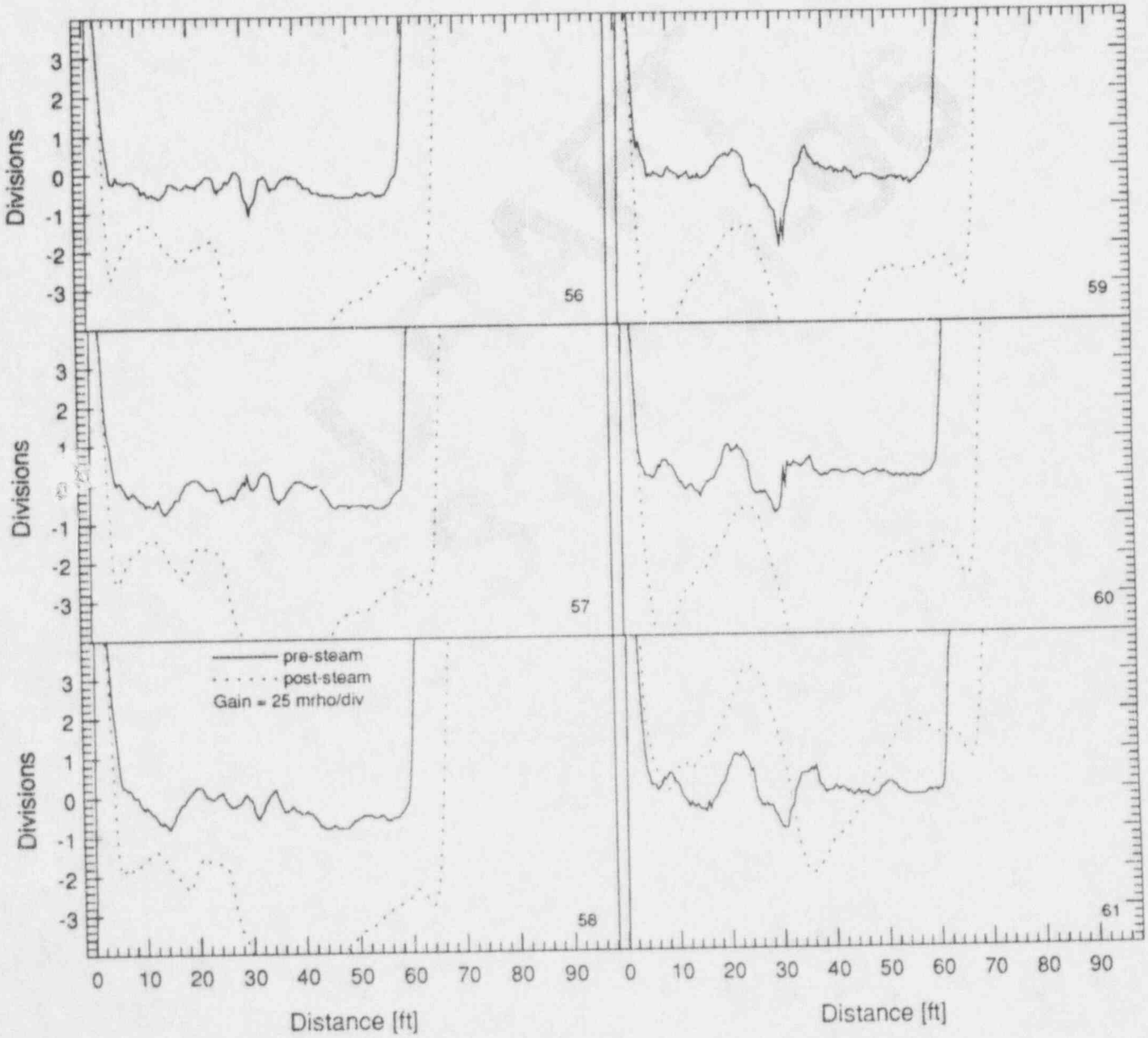

Figure B.7: TDR of the Rockbestos Firewall III cable conductors before and after the accident steam exposure.

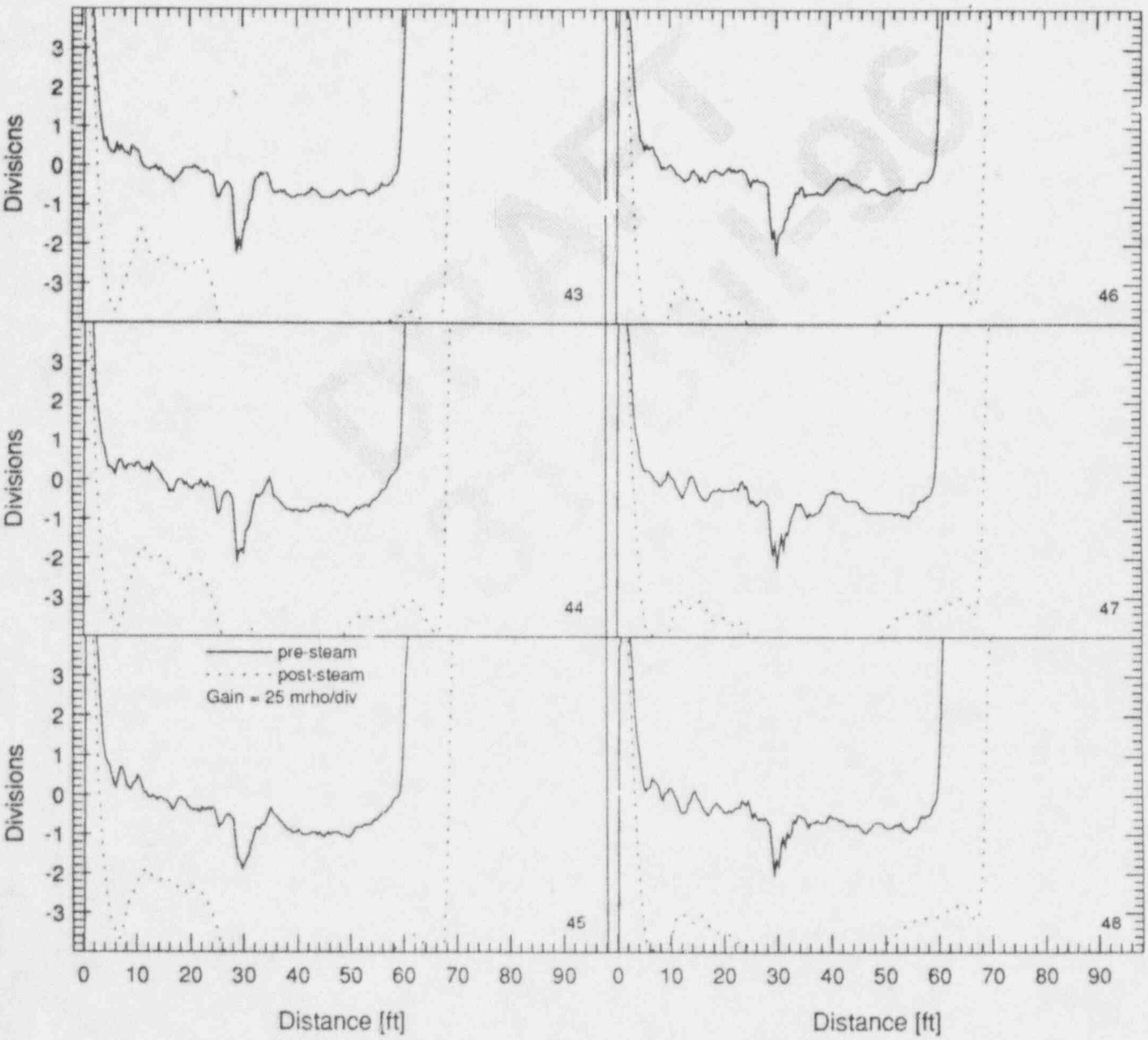

Figure B.8: TDR of the Litton-VEAM connector conductors before and after the accident steam exposure.

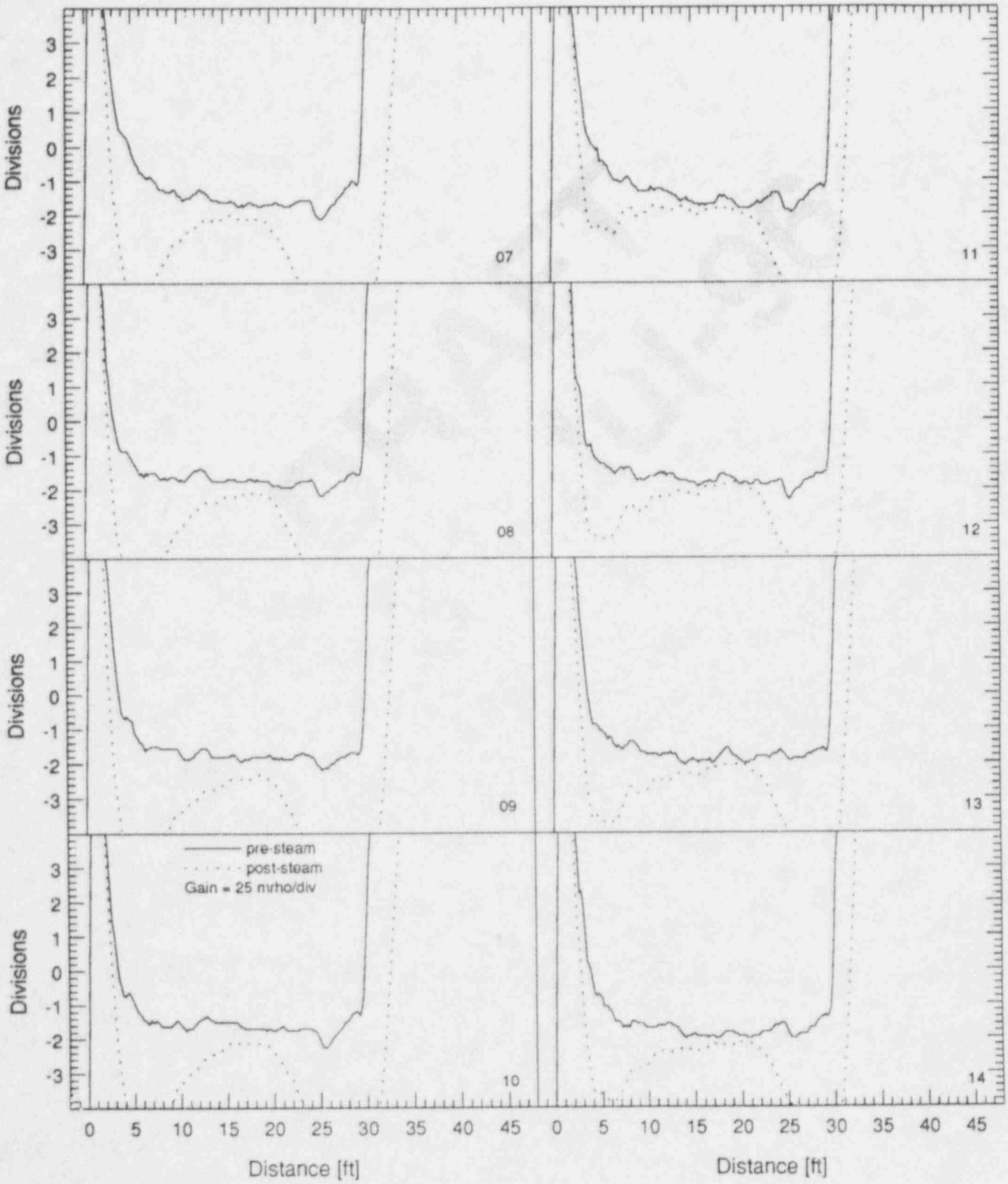

Figure B.9: TDR of the NAMCO EC210 connector conductors before and after the accident steam exposure.

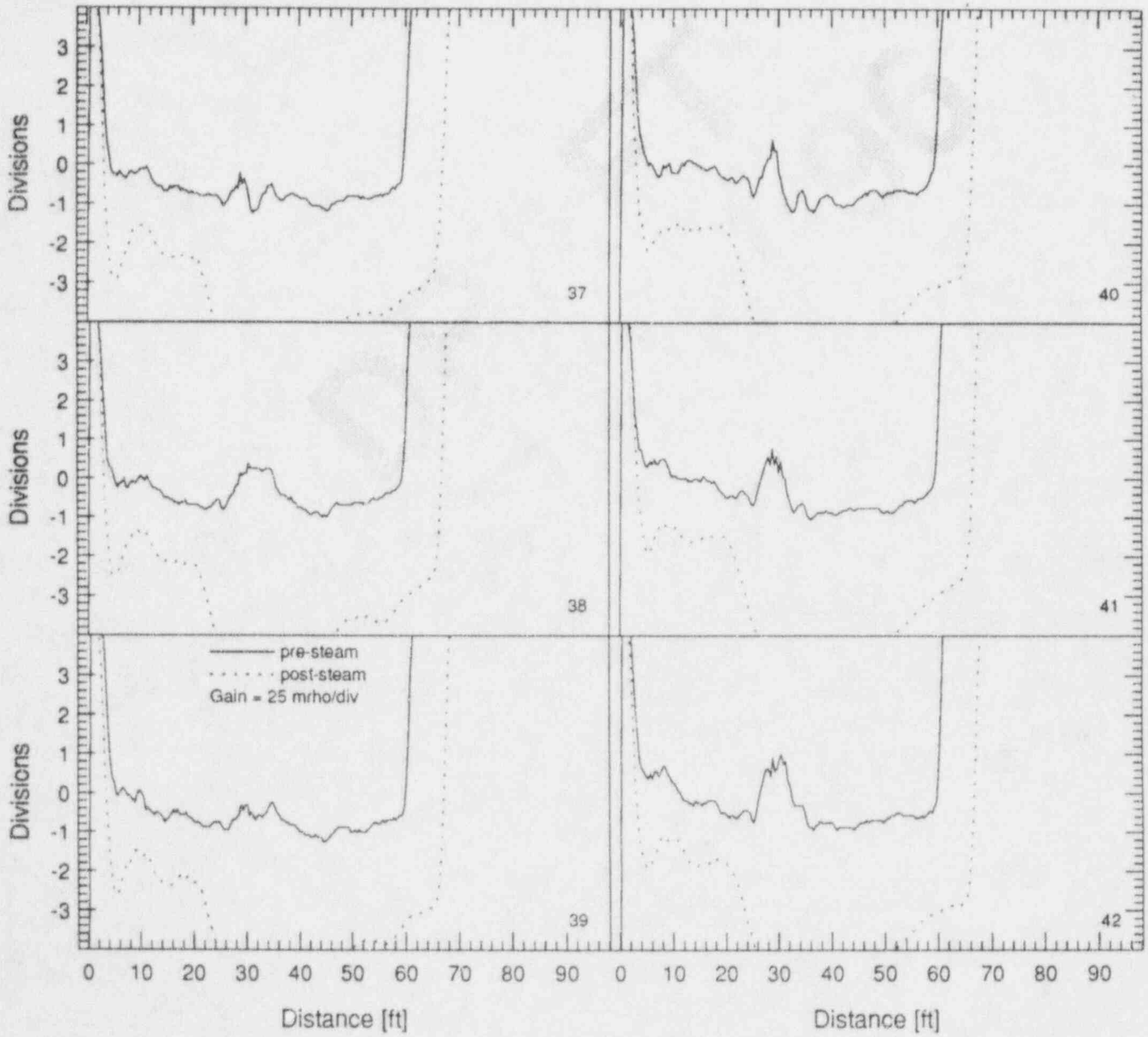

Figure B.10: TDR of the Okonite tape splice conductors before and after the accident steam exposure.

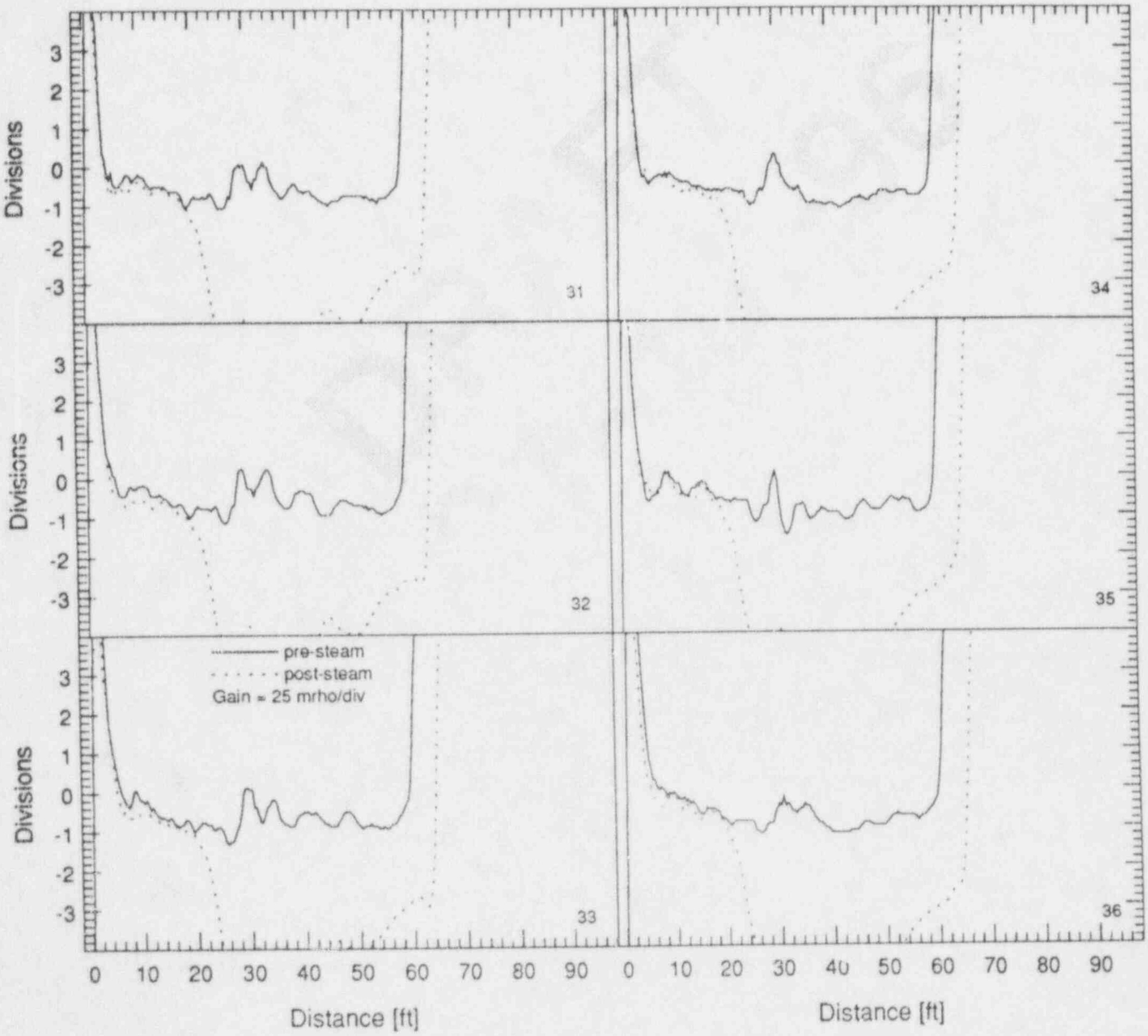

Figure B.11: TDR of the Raychem heat shrink splice conductors before and after the accident steam exposure.

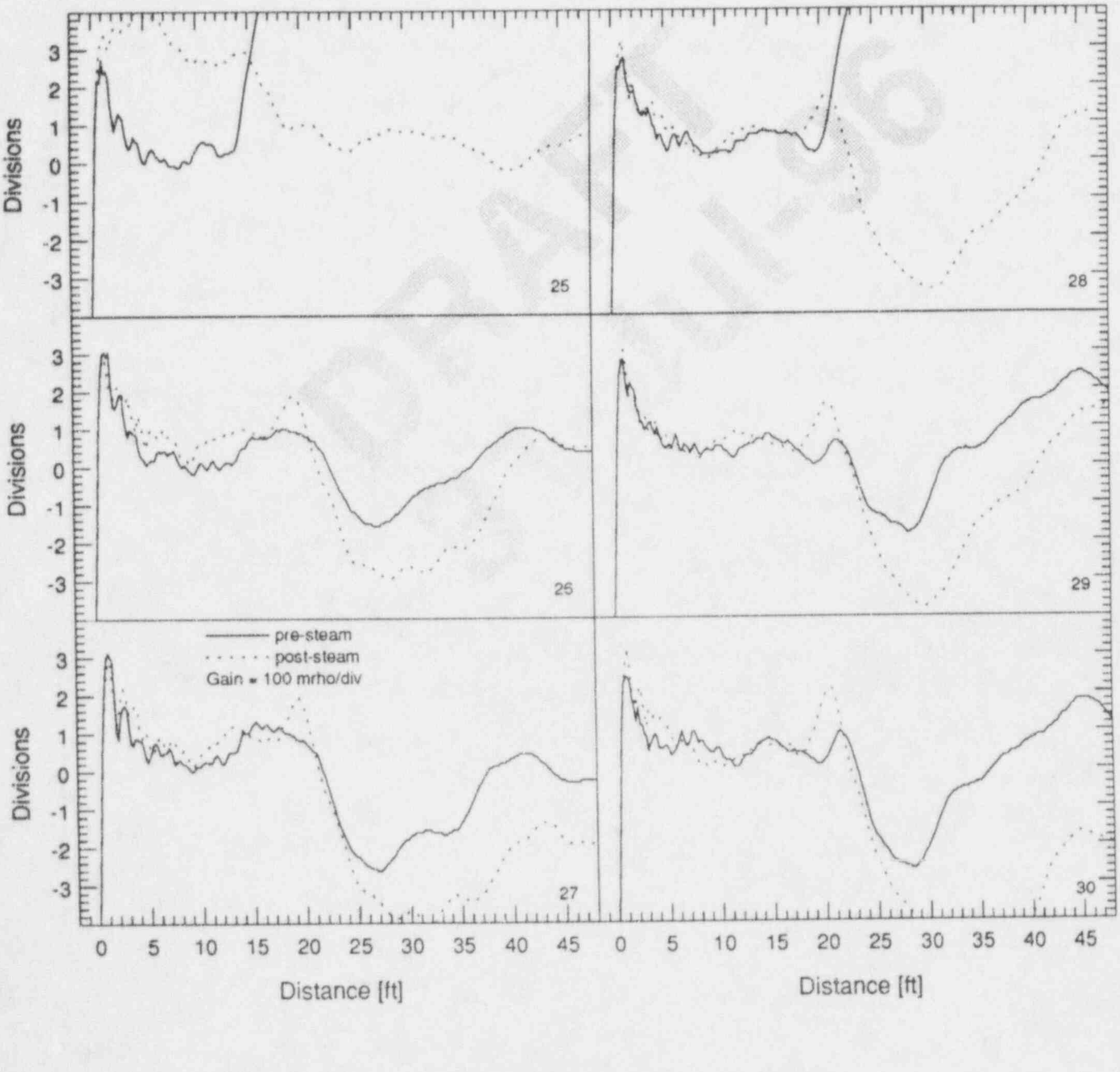

Figure B.12: TDR of the Rosemount 353C conduit seal conductors before and after the accident steam exposure.

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