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Submergence and High Temperature Steam Testing of Class 1E Electrical Cables

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Sandia National Laboratories
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Submergence and High Temperature Steam Testing of Class 1E Electrical Cables

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Abstract

This report describes the results of high temperature steam testing and submergence testing of 12 different cable products that are representative of typical cables used inside containments of U.S. light water reactors. Both tests were performed after the cables were exposed to simultaneous thermal and radiation aging, followed by exposure to loss-of-coolant accident simulations. The results of the high temperature steam test indicate the approximate thermal failure thresholds for each cable type. The results of the submergence test indicate that a number of cable types can withstand submergence at elevated temperature, even after exposure to a loss-of-coolant accident simulation.

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Keywords

3-month chamber	Refers to the cables aged for 3 months or the associated test chamber
6-month chamber	Refers to the cables aged for 6 months or the associated test chamber
AT3	Refers to the accident (LOCA) test performed on the cables aged for 3 months
AT6	Refers to the accident (LOCA) test performed on the cables aged for 6 months
HTS3	Refers to the high temperature steam test performed on the cables aged for 3 months
LOCA	Loss-of-Coolant Accident; a hypothesized design basis event for nuclear power plants
IR	Insulation Resistance
Keithley IR	IR measured using the Keithley electrometer apparatus
XLPO	Cross-linked polyolefin
XLPE	Cross-linked polyethylene, a specific type of XLPO
CSPE	Chlorosulfonated polyethylene
AWG	American Wire Gauge
/C	number of conductors
FR-EP	Flame retardant ethylene propylene
CPE	Chlorinated polyethylene
EPR	Ethylene propylene rubber
EPDM	Ethylene propylene diene monomer
TSP	Twisted, shielded pair
FR	Flame retardant
BIW	Boston Insulated Wire

EXECUTIVE SUMMARY

Many types of cable are used throughout nuclear power plants in a wide variety of applications. Cable qualification typically includes thermal and radiation aging intended to put the cable into a defined "end-of-life" condition prior to a simulated design basis accident exposure. In some instances, cables must be qualified for submergence conditions. High temperature steam testing of cables (beyond the design basis) is not required for qualification.

This report describes the results of high temperature steam testing and submergence testing of 12 different cable products. The cable products tested are representative of typical cables used inside containments of U.S. light water reactors and include primary insulations of cross-linked polyolefin (XLPO), ethylene propylene rubber (EPR), silicone rubber (SR), polyimide, and chlorosulfonated polyethylene (CSPE).

The testing described in this report was part of a larger test program that included four separate test chambers, each containing cables that were aged to a different extent prior to accident testing. Cables were aged for 3 months in the first chamber, 6 months in the second chamber, and 9 months in the third chamber. The fourth chamber contained unaged cables. Following aging, each set of cables was exposed to a loss-of-coolant accident (LOCA) simulation.

The submergence test was performed on the cables that had been aged for 6 months and accident tested, and the high temperature steam test was performed on the cables that had been aged for 3 months and accident tested. Both of these tests were added to the scope of the test program since the aged cables had completed all planned testing and many of the cables had not yet failed. Because they were involved in neither the submergence testing nor the high temperature steam testing, the unaged cables and the cables aged for 9 months are not discussed in detail in this report.

The submergence test solution was close to that specified by IEEE 383-1974 for chemical spray during LOCA simulations. The solution was maintained at about 95°C during the exposure, which lasted a total of 1000 hours. The high temperature steam test was a steam exposure at temperatures as high as 400°C (750°F). Cable insulation resistances (IRs) were monitored throughout the high temperature steam test and at discrete times during the submergence test. Dielectric withstand testing was performed before the submergence and high temperature steam tests and at the end of the submergence test. The cables that passed the post-submergence dielectric test were subsequently wrapped around a mandrel with a diameter 40 times that of the cable and exposed to a final dielectric withstand test.

The conclusions from this study are as follows:

a) EPR cables generally survived to higher temperatures than XLPO cables in the high temperature steam exposure. The XLPO-insulated conductors had no insulation remaining at the end of the high temperature steam test.

b) XLPO cables generally performed better than EPR cables in the submergence test and in the post-submergence dielectric testing. By the end of the final dielectric test (after a 40xD mandrel bend), only 1 of 11 XLPO-insulated conductors had failed, while 17 of 20 EPR-insulated conductors had failed.

c) A number of cables that performed well during the submergence test failed post-submergence dielectric withstand testing (either before or after the mandrel bend). This indicates that the IEEE 383 dielectric withstand tests and mandrel bends can induce failure of otherwise functional cables. Note that this conclusion does not imply a criticism of the IEEE 383 requirements, which are intended to provide a level of conservatism in the testing.

d) The IEEE 383 dielectric withstand tests are very severe even if a mandrel bend is not performed. This is evidenced by the failure of 9 conductors and the near failure of 3 more conductors in the post-submergence dielectric withstand test, only 2 of which were showing a strong indication of degradation during the submergence test.

1.0 INTRODUCTION

Many types of cable are used throughout nuclear power plants in a wide variety of applications. Cable qualification typically includes thermal and radiation aging intended to put the cable in a defined "end-of-life" condition prior to a simulated design basis accident exposure. In some instances, cables must be qualified for submergence conditions. High temperature steam testing (e.g., severe accident conditions) of cables is not required for qualification.

This report describes the results of high temperature steam testing and submergence testing of 12 different cable products. The cable products tested are representative of typical cables used inside containments of U.S. light water reactors [1].

This report is part of a series of reports on the results of an NRC-sponsored cable aging research program. The objectives of the overall experimental program were:

a) to determine the life extension potential of popular cable products used in nuclear power plants and

b) to determine the potential of condition monitoring (CM) for residual life assessment.

To accomplish these objectives, an experimental program consisting of simultaneous thermal (≈95°C) and radiation aging (≈0.09 kGy/hr) exposure, followed by a sequential accident exposure, was performed. The accident exposure included high dose rate irradiation (≈6 kGy/hr) followed by a simulated loss-of-coolant accident (LOCA) steam exposure. Our test program generally followed the guidance of IEEE 383-1974, but we used much lower accelerated aging rates than those typically employed in industry qualification tests. The accelerated aging conditions were chosen to equate a 6-month exposure to a 40-year life, assuming an activation energy of 1.15, a plant ambient of 55°C, and a 40-year radiation dose of 400 kGy.

We included four separate test chambers in the overall program, each containing cables that were aged to a different extent prior to accident testing. Cables were aged for 3 months in the first chamber, 6 months in the second chamber, and 9 months in the third chamber. A fourth chamber contained unaged cables.

Submergence and high temperature steam tests were added to the scope of the experimental program because of the limited amount of publicly available data on these topics. The submergence test was performed on the cables that had been aged for 6 months and accident tested, and the high temperature steam test was performed on the cables that had been aged for 3 months and accident tested. The LOCA test of the cables aged for 3 months will be denoted AT3, the LOCA test of the cables aged for 6 months will be denoted AT6, the submergence test of the cables aged for 6 months will be denoted SUB6, and the high temperature steam test of the cables aged for 3 months will be denoted HTS3. Both HTS3 and SUB6 were easily added to the scope of the test program since the aged cables had completed all planned testing and many of the cables had not yet failed. Because they were involved in neither the submergence testing nor the high temperature steam testing, the unaged cables and the cables aged for 9 months will not be discussed further in this report.

2.0 TESTING PRIOR TO HIGH TEMPERATURE STEAM AND SUBMERGENCE TESTS

2.1 Test Specimens

A list of the cables included in this program is given in Table 1. The overall length of each cable specimen was 23-m (76-ft). The middle 3.0 m (10 ft) of each sample was wrapped around a mandrel to be inserted in a test chamber. A typical test chamber and mandrel are shown in Figure 1. The total cable length of each cable specimen inside the test chamber was 4.5-6 m (15-20 ft), with the remainder of the cable used for external connections. Where both single and multiconductors samples of the same cable were tested, the single conductors were obtained by stripping the jacket from multiconductor cable and removing all filler materials.

Table 2 gives a list of the cables that were tested in each of the two chambers, their locations in the test chambers, and the associated conductor numbers that will be used in the remainder of this report.

2.2 Age Conditioning

The age conditioning consisted of simultaneous thermal and radiation aging of the cables. The aging was performed in Sandia's Low Intensity Cobalt Array (LICA) facility. Two sets of specimens are described in this report, one aged to a nominal lifetime of 20 years (3 months of artificial aging) and a second to 40 years (6 months of artificial aging). The lifetimes actually simulated for each cable type vary greatly because of different activation energies of the specimens (a single activation energy of 1.15 was assumed for all cables in aging calculations); because of the assumed plant ambient temperature; and because of test temperature gradients. The aging conditions assumed a plant ambient temperature of 55°C with no conductor heat rise. The use of a single value of activation energy was necessary in the aging calculations to keep aging times and temperatures constant for different cables, which were all located in common test chambers for each exposure. Based on the Arrhenius equation, the aging temperature was calculated to be 95°C. The total dose desired for the 20-year cables was 200 kGy and the total dose desired for the 40-year cables was 400 kGy. These total doses required an accelerated aging dose rate of about 90 Gy/hr. As a result of shielding effects of the tested specimens, the actual dose rates were somewhat lower than desired.

The temperature in each of the three test chambers was normally maintained at 97±5°C during the aging exposure. The pressure in each chamber during aging and accident radiation exposure was maintained slightly above ambient to prevent water leakage into the chamber. The actual absolute pressure in the test chamber was very near ambient pressure at sea level. Complete temperature profiles for each of the chambers will be given in a future publication.

The radiation dose rates to the cables during the aging exposures are given in Table 3. The estimated uncertainty in the radiation aging exposure data is ±20%. The 3-month chamber aging was all performed in a

Table 1 Cable Products Included in the Test Program

Supplier	Description
1. Brand Rex	XLPE Insulation, CSPE Jacket, 12 AWG, 3/C, 600 V
2. Rockbestos	Firewall 3, Irradiation XLPE, Neoprene Jacket, 12 AWG, 3/C, 600 V
3. Raychem	Flamtrol, XLPE Insulation, 12 AWG, 1/C, 600 V
4. Samuel Moore	Dekoron Polyset, XLPO Insulation, CSPE Jacket, 12 AWG, 3/C and Drain
5. Anaconda	Anaconda Y Flame-Guard FR-EP, EPR Insulation, CPE Jacket, 12 AWG, 3/C, 600 V
5a. Anaconda *	Anaconda Flame-Guard EP, EPR Insulation, Individual CSPE Jacket, CSPE Jacket, 12 AWG, 3/C, 1000 V
6. Okonite	Okonite Okolon, EPR Insulation, CSPE Jacket, 12 AWG, 1/C, 600 V
7. Samuel Moore	Dekoron Dekorad Type 1952, EPDM Insulation, Individual CSPE Jackets, Overall CSPE Jacket, 16 AWG, 2/C TSP, 600 V
8. Kerite **	Kerite 1977, FR Insulation, FR Jacket, 12 AWG 1/C, 600 V
8a. Kerite **	Kerite 1977, FR Insulation, FR Jacket, 12 AWG 1/C, 600 V
9. Rockbestos	RSS-6-104/LE Coaxial Cable, 22 AWG, 1/C Shielded
10. Rockbestos	Firewall Silicone Rubber Insulation, Fiberglass Braided Jacket, 16 AWG, 1/C, 600 V
11. Champlain	Polyimide (Kapton) Insulation, Unjacketed, 12 AWG, 1/C
12. BIW	Bostrad 7E, EPR Insulation, Individual CSPE Jackets, Overall CSPE Jacket, 16 AWG, 2/C TSP, 600 V

* This cable was only used for the multiconductor samples in the 3-month chamber.

** Because of a shortage of Kerite cable, two different reels of Kerite were used in the tests. The only difference between them was the thicknesses of the insulation and jacket. Cable 8 had a thicker insulation with a thinner jacket; cable 8a had a thinner insulation with a thicker jacket.

Note: See keyword list for abbreviations.

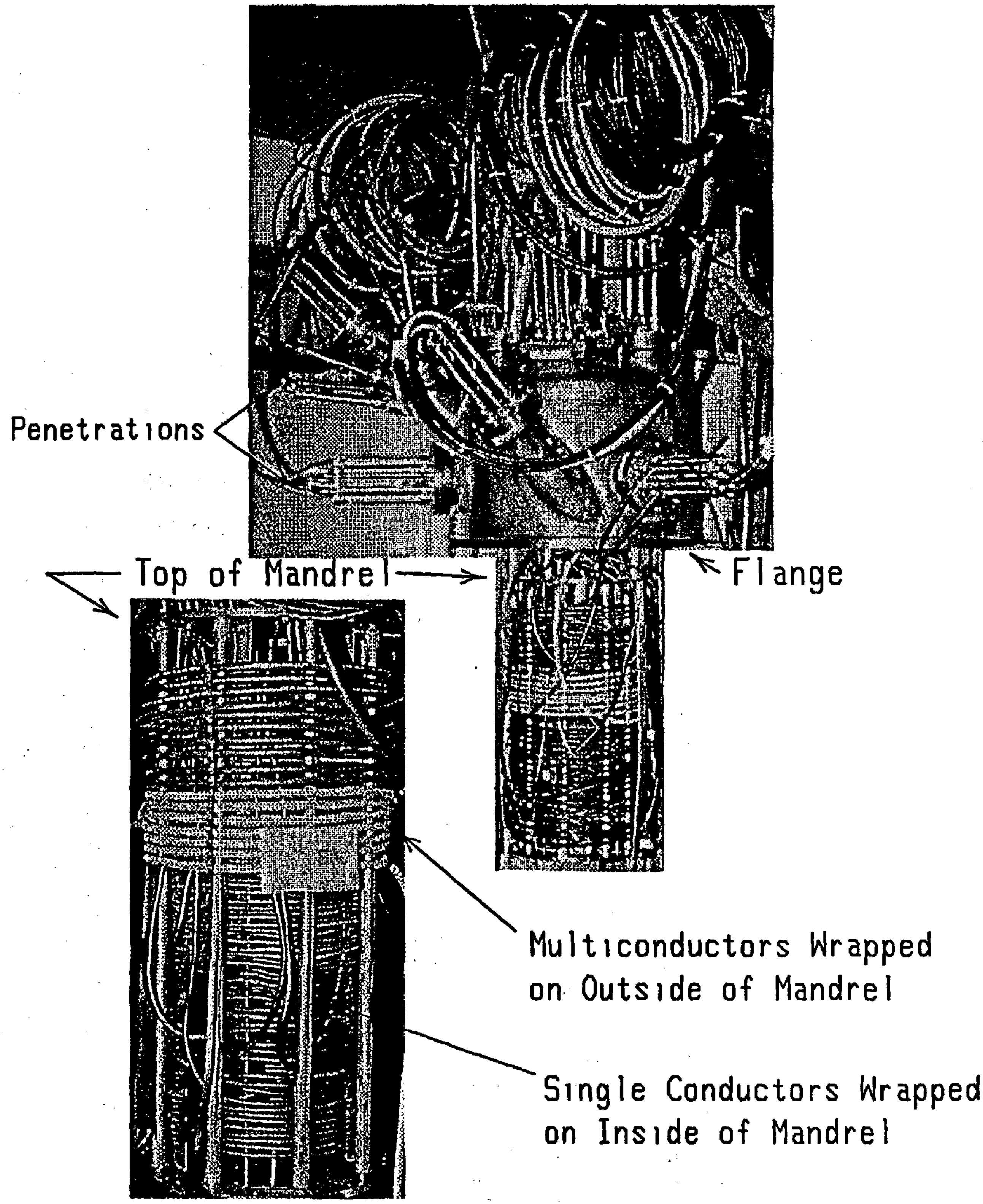

Figure 1 Typical Test Chamber and Mandrel

Table 2 Cables Tested in Each Chamber and Conductor Identification

Three Month Chamber

Cable Type (see Table 1)	Conductor Number	Tested Length	Location on Mandrel * (from chamber flange)
Brand Rex--1	1* (Red)	5.2 m (17 ft)	28 cm (11 in)
	2 (White)		
	3 (Black)		
Anaconda--5a	4 (Red)	5.2 m (17 ft)	33 cm (13 in)
	5 (White)		
	6 (Black)		
Anaconda--5a	7 (Red)	5.8 m (19 ft)	38 cm (15 in)
	8 (White)		
	9 (Black)		
BIW--12	10 (White)	5.3 m (18 ft)	43 cm (17 in)
	11 (Black)		
Firewall III--2	12 White)	5.3 m (18 ft)	48 cm (19 in)
	13 (Black)		
	14 (Red)		
Dekorad--7	15 (White)	5.7 m (19 ft)	53 cm (21 in)
	16 (Black)		
Dekorad--7	17 (White)	6.2 m (20 ft)	58 cm (23 in)
	18 (Black)		
Polyset--4	19 (#1)	5.8 m (19 ft)	64 cm (25 in)
	20 (#2)		
	21 (#3)		
Silicone Rubber--10	22	4.1 m (13 ft)	25 cm (10 in)
Silicone Rubber--10	23	4.1 m (13 ft)	28 cm (11 in)
Kapton--11	24	4.5 m (15 ft)	30 cm (12 in)
Kapton--11	25	4.1 m (13 ft)	33 cm (13 in)
Anaconda--5	26	4.4 m (14 ft)	36 cm (14 in)
Raychem--3	27	4.5 m (15 ft)	38 cm (15 in)
Raychem--3	28	4.5 m (15 ft)	41 cm (16 in)
BIW Single--12	29 (White)	4.5 m (15 ft)	43 cm (17 in)
BIW Single-12	30 (White)	4.5 m (15 ft)	46 cm (18 in)
Okolon--6	31	4.6 m (15 ft)	48 cm (19 in)
Okolon--6	32	4.6 m (15 ft)	51 cm (20 in)
Okolon--6	33	4.6 m (15 ft)	53 cm (21 in)
Dekorad--7	34 (White)	4.8 m (16 ft)	56 cm (22 in)
Dekorad--7	35 (White)	4.8 m (16 ft)	58 cm (23 in)
Kerite--8a (Thin)	36	5.0 m (16 ft)	61 cm (24 in)
Kerite--8 (Thick)	37	5.4 m (18 ft)	64 cm (25 in)
Coaxial--9	38	5.6 m (18 ft)	69 cm (27 in)
Coaxial--9	39	5.3 m (17 ft)	71 cm (28 in)
Shield for cond. 10-11	40		
Shield for cond. 19-21	41		
Shield for cond. 38	42		
Shield for cond. 39	43		
Shield for cond. 15-16	44		
Shield for cond. 17-18	45		

* Conductors 1-21 wrapped on outside of mandrel (see Figure 1).
Conductors 22-39 wrapped on inside of mandrel.

Table 2 Cables Tested in Each Chamber
and Conductor Identification (cont.)

Six Month Chamber

Cable Type (see Table ?)	Conductor Number	Tested Length	Location on Mandrel ** (from chamber flange)
Brand Rex--1	1* (Red)	4.6 m (15 ft)	28 cm (11 in)
	2 (White)		
	3 (Black)		
Anaconda--5	4 (Red)	4.8 m (16 ft)	33 cm (13 in)
	5 (White)		
	6 (Black)		
Anaconda--5	7 (Red)	5.2 m (17 ft)	38 cm (15 in)
	8 (White)		
	9 (Black)		
BIW--12	10 (White)	5.6 m (18 ft)	41 cm (16 in)
	11 (Black)		
Firewall III--2	12 White)	5.0 m (16 ft)	46 cm (18 in)
	13 (Black)		
	14 (Red)		
Dekorad--7	15 (White)	5.7 m (19 ft)	51 cm (20 in)
	16 (Black)		
Dekorad--7	17 (White)	5.4 m (18 ft)	56 cm (22 in)
	18 (Black)		
Polyset--4	19 (#1)	5.9 m (19 ft)	61 cm (24 in)
	20 (#2)		
	21 (#3)		
Silicone Rubber--10	22	4.5 m (15 ft)	25 cm (10 in)
Silicone Rubber--10	23	4.6 m (15 ft)	28 cm (11 in)
Kapton--11	24	4.7 m (15 ft)	30 cm (12 in)
Kapton--11	25	4.6 m (15 ft)	30 cm (12 in)
Anaconda--5	26	4.9 m (16 ft)	33 cm (13 in)
Raychem--3	27	4.7 m (15 ft)	36 cm (14 in)
Raychem--3	28	4.9 m (16 ft)	38 cm (15 in)
BIW Single--12	29 (Black)	4.8 m (16 ft)	41 cm (16 in)
BIW Single-12	30 (White)	4.7 m (15 ft)	43 cm (17 in)
Okolon--6	31	4.8 m (16 ft)	46 cm (18 in)
Okolon--6	32	4.8 m (16 ft)	48 cm (19 in)
Okolon--6	33	4.9 m (16 ft)	53 cm (21 in)
Dekorad--7	34(White)	5.0 m (16 ft)	56 cm (22 in)
Dekorad--7	35(Black)	4.9 m (16 ft)	58 cm (23 in)
Kerite--8 (Thick)	36	4.9 m (16 ft)	61 cm (24 in)
Kerite--8 (Thick)	37	5.4 m (18 ft)	64 cm (25 in)
Coaxial--9	38	5.4 m (18 ft)	69 cm (27 in)
Coaxial--9	39	5.6 m (18 ft)	71 cm (28 in)
Shield for cond. 10-11	40		
Shield for cond. 19-21	41		
Shield for cond. 38	42		
Shield for cond. 39	43		
Shield for cond. 15-16	44		
Shield for cond. 17-18	45		

* Conductors 1-21 wrapped on outside of mandrel (see Figure 1).
Conductors 22-39 wrapped on inside of mandrel.

Table 3 Average Aging and Accident Radiation Exposure Data

Three-Month Chamber

Conductors	Aging Dose Rate (Gy/hr)	Accident Dose Rate (Gy/hr)	Total Integrated Dose (kGy)
Brand Rex 1-3	72	5000	1190
Anaconda 1 kV 4-6	75	5200	1260
Anaconda 1 kV 7-9	77	5400	1290
BIW 10-11	77	5400	1300
Rockbestos 12-14	78	5400	1290
Dekorad 15-16	77	5200	1260
Dekorad 17-18	76	5000	1200
Polyset 19-21	75	4600	1130
Silicone 22	70	4800	1150
Silicone 23	72	5000	1190
Kapton 24	74	5100	1230
Kapton 25	75	5200	1260
Anaconda FR-EP 26	76	5300	1280
Raychem 27	77	5400	1290
Raychem 28	77	5400	1300
BIW 29	77	5400	1300
BIW 30	78	5400	1300
Okolon 31	78	5400	1290
Okolon 32	77	5300	1280
Okolon 33	77	5200	1260
Dekorad 34	77	5100	1230
Dekorad 35	76	5000	1200
Kerite 36	75	4800	1170
Kerite 37	75	4600	1130
Coaxial 38	73	4200	1050
Coaxial 39	72	4000	1000

Table 3 Average Aging and Accident Radiation Exposure Data (cont)

Six-Month Chamber

Cable Type and Conductors	Aging Dose Rate 1 (Gy/hr)	Aging Dose Rate 2 (Gy/hr)	Accident Dose Rate (Gy/hr)	Total Integrated Dose (kGy)
Brand Rex 1-3	63	61	5200	1280
Anaconda FR-EP 4-6	64	62	5500	1340
Anaconda FR-EP 7-9	65	63	5700	1380
BIW 10-11	65	63	5700	1390
Rockbestos 12-14	66	63	5700	1390
Dekorad 15-16	65	63	5600	1360
Dekorad 17-18	64	62	5400	1320
Polyset 19-21	63	61	5100	1250
Silicone 22	62	60	5000	1240
Silicone 23	63	61	5200	1280
Kapton 24	64	62	5400	1320
Kapton 25	64	62	5400	1320
Anaconda FR-EP 26	64	62	5500	1340
Raychem 27	65	63	5600	1360
Raychem 28	65	63	5700	1380
BIW 29	65	63	5700	1390
BIW 30	66	63	5700	1390
Okolon 31	66	63	5700	1390
Okolon 32	65	63	5700	1380
Okolon 33	65	63	5500	1340
Dekorad 34	64	62	5400	1320
Dekorad 35	64	62	5200	1290
Kerite 36	63	61	5100	1250
Kerite 37	63	61	4900	1220
Coaxial 38	62	60	4500	1130
Coaxial 39	61	59	4200	1090

single orientation, while the 6-month chamber, to achieve a more uniform exposure, was rotated 180° after 3 months, resulting in two different dose rates for each location. The effects of the rotation are not evident in Table 3 because Table 3 only gives average dose rate data for each exposure.

2.3 Accident Exposure

Following aging, the cables were exposed to accident radiation at the dose rates given in Table 3. The cables in the 3-month chamber were exposed to the accident radiation for 210 hr, and the cables in the 6-month chamber were exposed to the accident radiation for 193 hr. The estimated uncertainty in the accident exposure dose rates is ±10%. The total integrated dose that each cable was exposed to is also reported in Table 3.

After the accident irradiations, the cables were then exposed to a high temperature and pressure steam LOCA environment using Sandia's Area I steam facility. The test profile was similar to the one given in IEEE 323-1974 for "generic" qualification, except that the post-accident exposure was at a higher temperature and for a shorter time. The actual temperature and pressure profiles during AT3 are shown in Figure 2 and the actual temperature and pressure profiles during AT6 are shown in Figure 3. The cables were energized at 110 Vdc during the steam exposure, with insulation resistance measurements performed on-line throughout the test. No chemical spray was used during the steam exposure, providing another motivation for the post-LOCA submergence test.

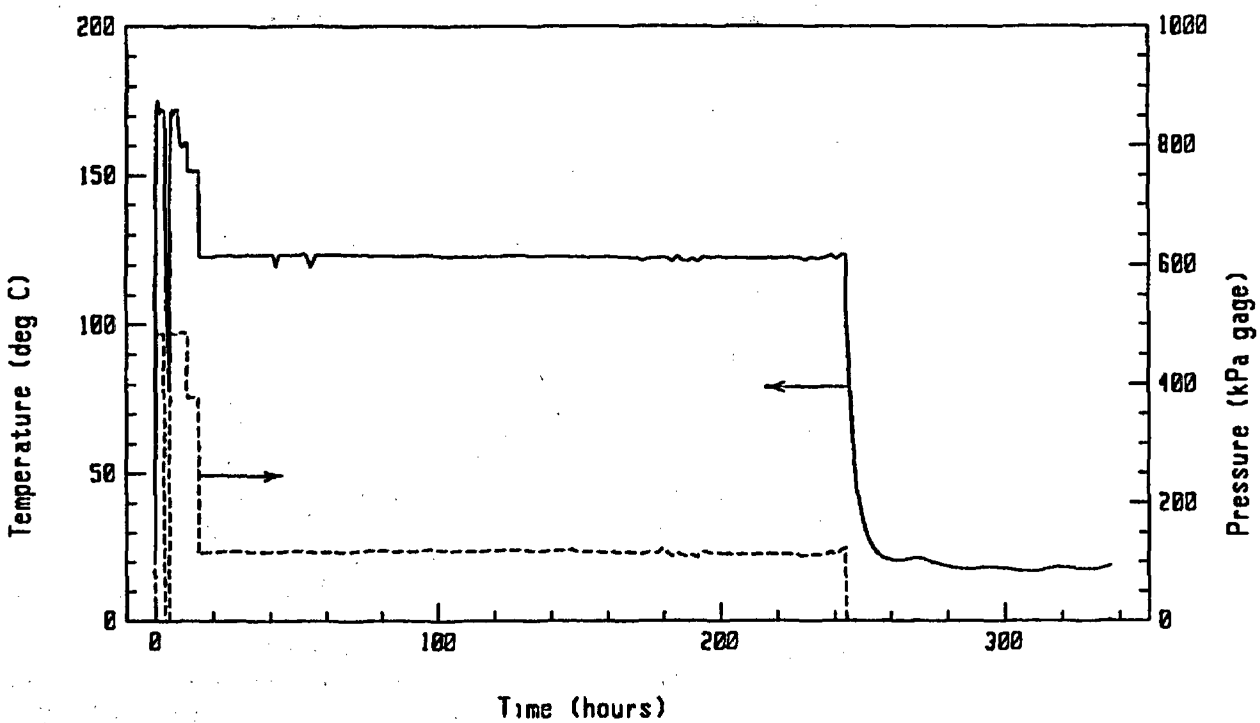

Figure 2 Actual Temperature and Pressure Profiles During AT3

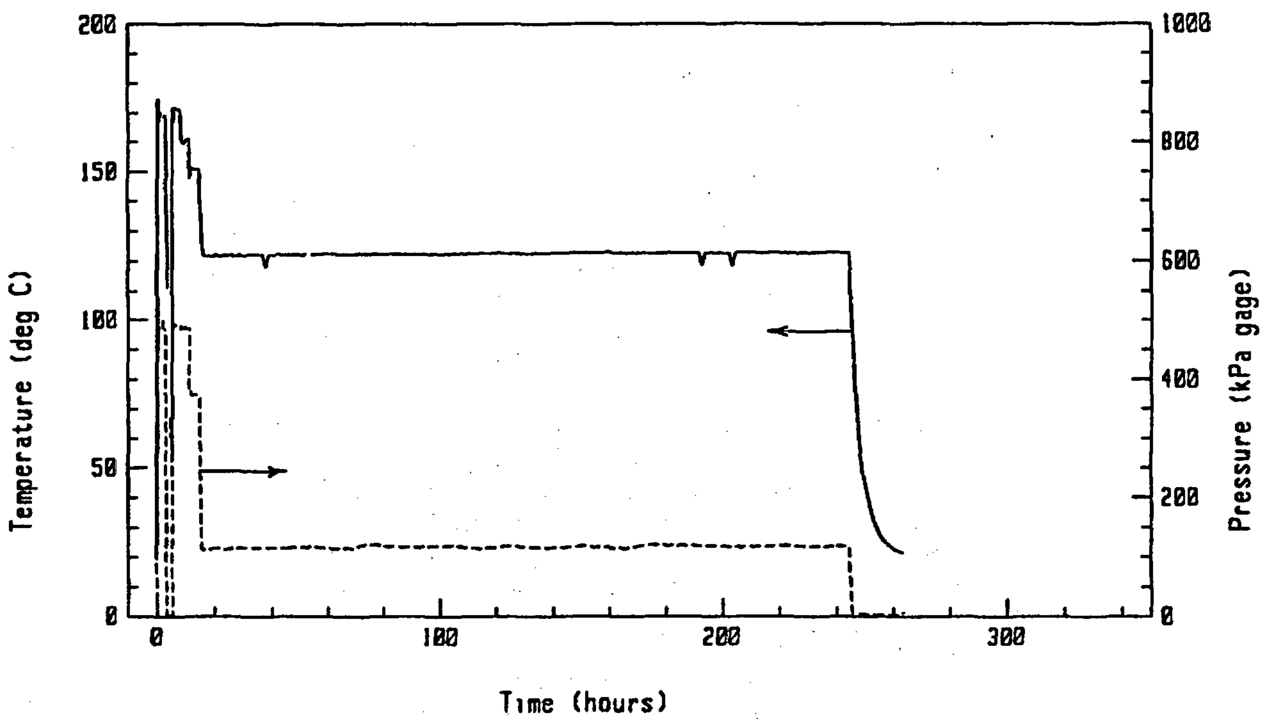

Figure 3 Actual Temperature and Pressure Profiles During AT6

3.0 HIGH TEMPERATURE STEAM EXPOSURE OF CABLES AGED FOR 3 MONTHS

Following completion of AT3 and dielectric withstand testing (see Section 5.0), failed cables were removed from the test chamber and then the high temperature steam exposure (HTS3) was conducted on the remaining cables. The objective of the high temperature steam exposure was to obtain some quantitative information on the failure thresholds of cables exposed to high temperature steam conditions.

3.1 Environmental Profile

The intended profile for HTS3 was to increase the temperature by about 10 C° every 15 minutes until all of the cables failed. The actual temperature and pressure profiles during the high temperature steam exposure are shown in Figures 4 and 5. Because of a problem in the steam system, the initial attempt at HTS3 had to be aborted when the temperature reached about 210°C (420°F). Following repair of the steam system, the test was restarted the next day, beginning with an initial rapid temperature rise to approximately where the test finished the previous day. The peak conditions attained in the second attempt were 400°C (752°F) at 806 kPag (117 psig), although the pressure was only above 690 kPag (100 psig) for 11 minutes. Conditions were maintained at saturation until the temperature exceeded about 165°C (329°F); superheated steam was used above this temperature.

3.2 Cable Monitoring During High Temperature Steam Exposure

The cables were energized at a nominal voltage of 110 Vdc throughout the high temperature steam exposure, with IRs measured at intervals ranging from 10 seconds to 5 minutes. During the first 2.5 hours of the high temperature steam test, IR measurements (leakage currents) were monitored using the circuitry shown in Figure 6. The maximum IR that can be measured using this circuitry is primarily limited by the data logger accuracy and response time. For purposes of this report, it suffices to note that the IRs are very accurate at any level below 1 MΩ-100 m. For values above 1 MΩ-100 m, no adverse effects of reduced IR would normally be experienced in actual applications, with the possible exception of circuits using coaxial cables.

For each three conductor cable, one of the conductors was connected to the ground bus to help provide an effective ground plane. Because of experience in previous testing, we decided (during the high temperature steam test) that a reasonable ground plane was available through the metal mandrel, even when all three conductors were powered. Thus, at 2.5 hours into the test, we connected the insulated conductors that had been previously grounded (#3, 6, 9, 14, and 21) into the power circuitry of Figure 6 through five additional 10 Ω resistors. To measure IRs, the voltage across the 10 Ω resistors was monitored with a Hewlett Packard Model 3497A data logger, which was connected to a Hewlett Packard Model 216 computer for permanent storage of the data.

The connection of conductors 3, 6, 9, 14, and 21 to the power circuitry had two effects. The positive effect was that all conductors were

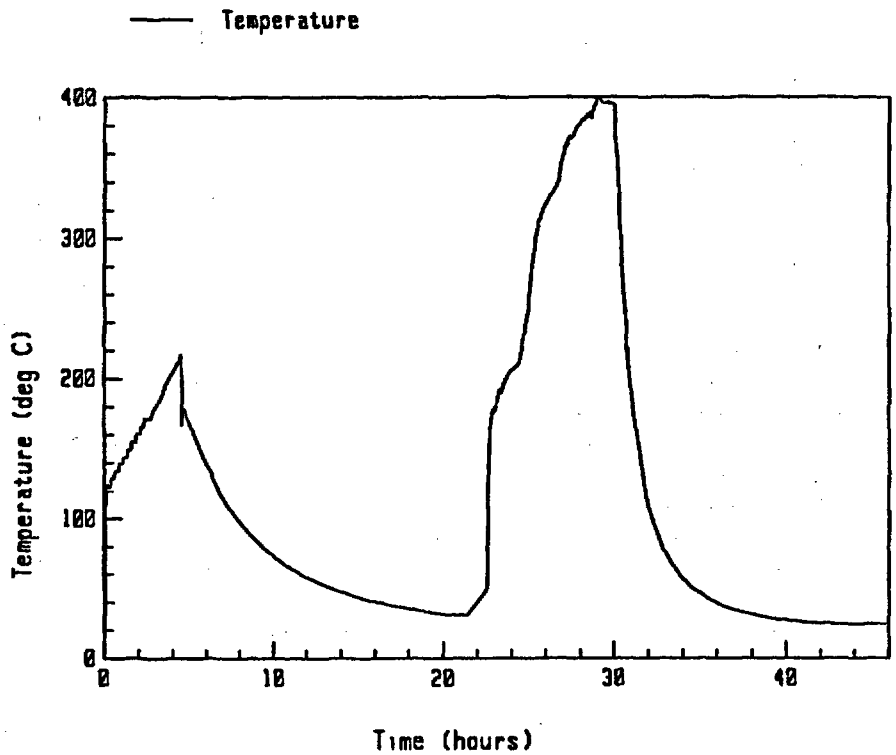

Figure 4 Temperature Profile During HTS3

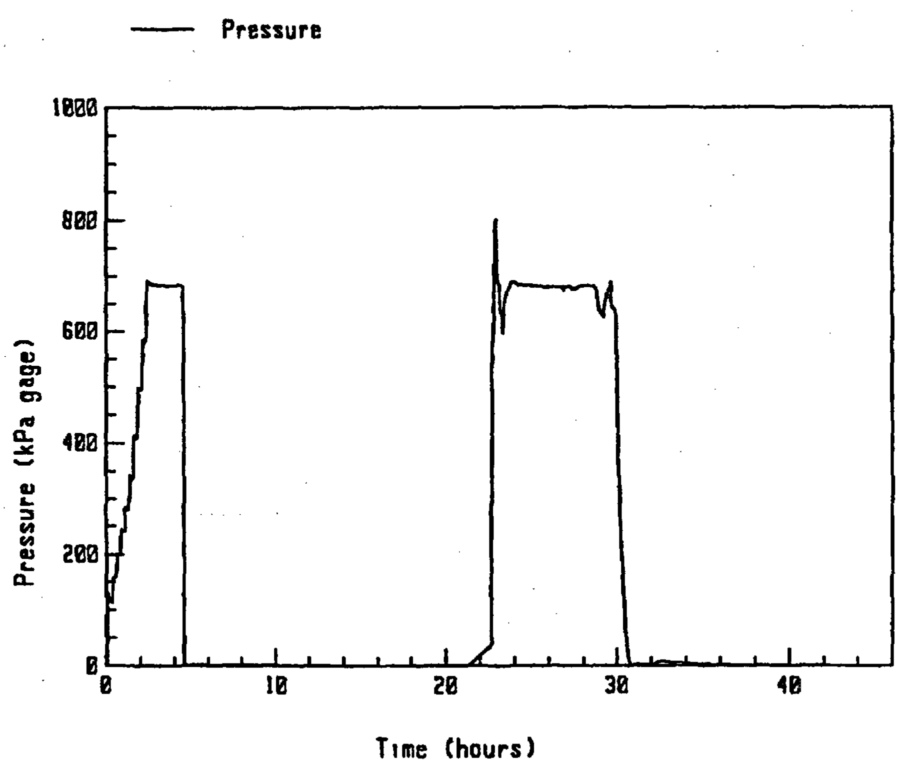

Figure 5 Pressure Profile During HTS3

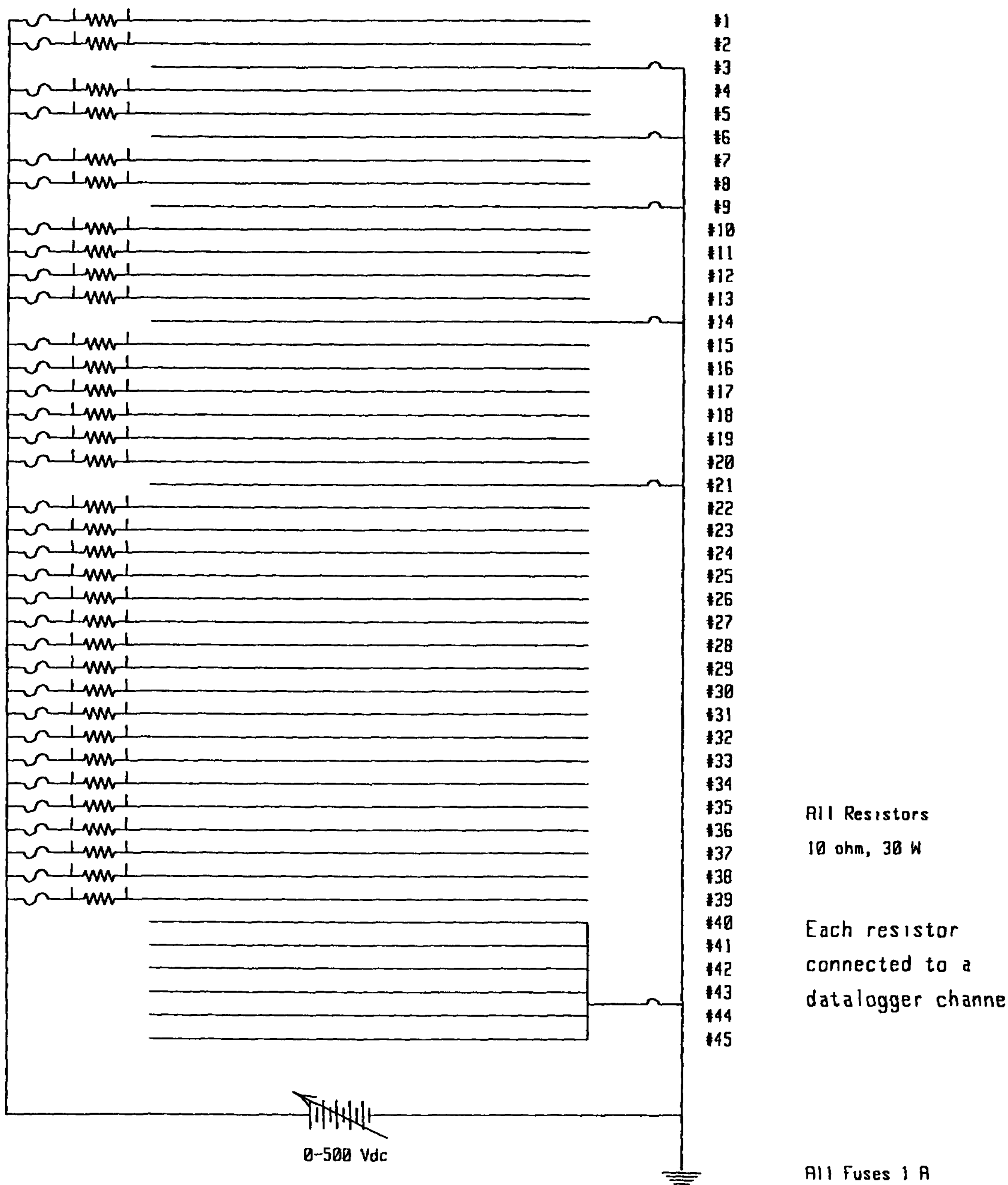

Figure 6 Circuitry Used to Monitor Leakage Currents During the First 2.5 Hours of the High Temperature Steam Test

subsequently monitored for shorting to ground. The negative effect was that the ground plane along the multiconductors was not as good as it was with one of the insulated conductors grounded, particularly under superheated steam conditions. Possible results of the less effective ground plane include higher cable IRs and longer times (i.e. possibly higher temperatures) to failure of the associated cables, although there is evidence indicating that neither of these was actually a significant factor.

3.3 Insulation Resistance Behavior

Appendix A contains plots of the IR of each cable as a function of time into HTS3. For convenience, the temperature profile is repeated in each figure. As a basis for comparison of cable performance in this test, Table 4 provides the temperature where each cable first fell below certain IRs. Conductors that did not fall below a given IR are listed as "did not fail" (DNF). The various IR criteria were chosen in the range of where unacceptable circuit degradation might occur in some actual nuclear plant circuits [2]. For any specific application, other values might be more appropriate. For coaxial cables, the range of values listed in Table 4 is below that where unacceptable accuracy could occur in some circuits.

Table 4 indicates that EPR conductors generally survived to higher temperatures than XLPO cables. After completion of the high temperature steam test, inspection of the cable specimens revealed that the XLPO insulation had been completed disintegrated, leaving only bare conductors. In contrast, the EPR insulations were still largely intact.

Based on Table 4 and using a failure criterion of 1 kΩ-100 m, the following is a summary of the failure temperature ranges for each material (note that the Dekorad multiconductors had all failed prior to beginning HTS3):

XLPO (based on 13 samples)	254-378°C (489-712°F)
EPR (based on 16 samples)	235-400+°C (454-752+°F)
Silicone Rubber (based on 2 samples)	396-400+°C (744-752+°F)
Kerite FR (based on 2 samples)	153-171°C (307-340°F)
Polyimide (based on 1 sample)	399°C (751°F).

If the failure criterion is relaxed to 0.1 kΩ-100 m, then the failure temperature ranges are as follows:

XLPO (based on 13 samples)	299-388°C (569-730°F)
EPR (based on 16 samples)	370-400+°C (698-752+°F)
Silicone Rubber (based on 2 samples)	396-400+°C (744-752+°F)
Kerite FR (based on 2 samples)	372-382°C (702-720°F)
Polyimide (based on 1 sample)	399°C (751°F).

Based on the above data, it is obvious that an order of magnitude change in the failure criterion causes the EPRs and the Kerite FR to "survive" to considerably higher temperatures. This data emphasizes the need to assess cable performance in terms of circuit requirements for a given application.

Table 4 Failure Temperature of Cables in HTS3 Based on Various Criteria for a 100-Meter Cable Length

Conductor	≤ 100 kΩ °C (°F)	≤ 10 kΩ °C (°F)	≤ 1 kΩ °C (°F)	≤ 0.1 kΩ °C (°F)	
1	212 (413)	262 (503)	309 (588)	385 (725)	
2	165 (329)	270 (517)	313 (595)	385 (725)	Brand Rex
3	225 (437)	267 (512)	312 (594)	385 (725)	
4	234 (454)	389 (732)	391 (735)	DNF	
5	247 (477)	395 (744)	DNF	DNF	
6	234 (453)	389 (732)	DNF	DNF	Anaconda 1 kV
7	234 (453)	385 (725)	394 (742)	394 (742)	
8	249 (480)	394 (742)	394 (742)	394 (742)	
9	234 (453)	393 (740)	395 (743)	399 (751)	
10	147 (297)	203 (398)	235 (454)	375 (707)	BIW
11	143 (289)	203 (398)	245 (473)	375 (707)	
12	211 (412)	269 (516)	293 (559)	321 (610)	
13	211 (412)	270 (517)	294 (562)	320 (608)	Rockbestos
14	211 (412)	268 (515)	291 (557)	322 (611)	
15	NS	NS	NS	NS	
16	NS	NS	NS	NS	Dekorad
17	NS	NS	NS	NS	
18	NS	NS	NS	NS	
19	209 (408)	207 (405)	254 (489)	304 (580)	
20	213 (415)	225 (436)	267 (513)	299 (569)	Polyset
21	211 (412)	225 (436)	266 (510)	307 (585)	
22	394 (742)	396 (744)	396 (744)	396 (744)	Silicone
23	399 (750)	396 (745)	***	DNF	
24	NS	NS	NS	NS	Kapton
25	395 (743)	399 (750)	399 (751)	399 (751)	
26	285 (546)	316 (601)	381 (717)	381 (717)	Anaconda FR-EP
27	331 (628)	333 (631)	374 (705)	388 (730)	Raychem
28	330 (627)	333 (631)	378 (712)	385 (726)	
29	134 (273)	169 (337)	384 (723)	384 (723)	BIW Single
30	134 (273)	171 (340)	DNF	DNF	
31	246 (475)	357 (675)	368 (694)	387 (729)	
32	160 (320)	356 (673)	368 (694)	395 (744)	Okonite Okolon
33	265 (508)	355 (671)	366 (691)	DNF	
34	247 (476)	372 (702)	372 (702)	372 (702)	Dekorad Single
35	246 (474)	369 (695)	370 (698)	370 (698)	
36	115 (238)	134 (273)	171 (340)	382 (720)	Kerite
37	103 (218)	120 (248)	153 (307)	372 (702)	
38	222 (432)	271 (520)	316 (601)	378 (712)	Coaxial
39	221 (430)	269 (515)	316 (600)	378 (712)	

DNF Did not fail according to this criterion.
NS No sample was available because of prior test failure.
*** This conductor fell below 1 kΩ-100 m during the final cooldown.

Reference 3 provides some indication of possible peak temperatures under severe accident conditions prior to containment failure. The temperature estimates cited in Reference 3 range up to 260°C (500°F). Comparisons with the above data show that a number of typical cable materials might survive the high temperature exposure during such severe accidents, although the limitations and assumptions used to derive the temperature data in Reference 3 must be considered.

4.0 SUBMERGENCE TEST OF CABLES AGED FOR 6 MONTHS

The submergence test was performed on the cables that had been aged for 6 months using the same test chamber that was used during aging. This chamber had a free volume of about 303 ℓ.

4.1 Environmental Profile

The desired temperature during the submergence test was 95±5°C, with a slightly positive pressure and a chemical solution in accordance with IEEE 323-1974 recommendations for chemical spray solution, consisting of the following:

0.28 molar H_3BO_3 (3000 parts per million boron)
0.064 molar $Na_2S_2O_3$
NaOH to make a pH of 10.5 at 25°C (77°F) (about 0.59%).

The chemical solution was made as follows (a mixer was used to dissolve the chemicals):

a. The chamber was filled with 180 ℓ of tap water.
b. 5.24 kg of H_3BO_3 was added.
c. 3.25 kg of NaOH was added.
d. 4.82 kg of $Na_2S_2O_3 \cdot 5H_2O$ was added.
e. Tap water was added to bring the volume to 303 ℓ.
f. A check of the pH gave 10.21.
g. An additional 0.68 kg of NaOH was added.
h. A check of the pH gave 11.94. (This was considered satisfactory since it was ≥10.5 pH.)

The test chamber head was inserted into the chemical solution (which had been preheated to about 60°C) and then the solution was heated to the desired temperature. Band heaters surrounding the bottom half of the chamber were used for temperature control. The pressure in the chamber was increased to 5.5 psig using a dry nitrogen source. During the test the pressure ranged from 1 to 5.5 psig, generally at the lower end of this range. The chemical solution was continuously circulated by a pump that took solution from the bottom of the chamber and pumped it to the top of the chamber. Table 5 gives the temperature at the center of the chamber during the submergence exposure. A second thermocouple, at the bottom of the chamber, normally followed the thermocouple at the center of the chamber within ±0.3 C°. A third thermocouple, located just above the liquid level in the chamber, had readings that were normally 5-10 C° below the readings of the two thermocouples in the liquid. The total test time was 1000 hr, but two separate equipment failures reduced the effective time at the desired temperature (less than 60 hours below 90°C--see Table 5).

4.2 Cable Monitoring During Submergence

The cables were not powered during the submergence test, but cable IRs during submergence were measured periodically using a Keithley electrometer apparatus described in Reference 4. This apparatus was

Table 5 Temperature at Center of Chamber During Submergence

Time from start (hours)	Temperature (°C)	Time from start (hours)	Temperature (°C)
1	93.0	463	93.6
9	98.0	482	93.5
17	97.8	510	94.7
25	93.6	530	94.6
33	93.9	552	95.9
41	93.6	584	95.1
53	93.3	608	94.9
77	92.0	632	95.0
101	92.1	656	92.6
109	92.0	680	92.3
117	92.2	704	92.2
125 *	77.4	728	92.1
133	61.7	752	93.5
139	61.0	776	92.2
147	92.0	785	91.7
155	93.1	**	**
163	93.8	816	91.7
186	93.6	848	93.5
210	93.5	872	92.2
234	92.9	896	91.6
258	92.7	920	92.4
282	92.5	944	91.6
316	92.5	968	91.0
340	92.4	992	91.1
356	93.8	1000	91.1
383	92.9	1008	41.5
407	91.9	1016	30.2
439	92.2		

* Between 117 and 147 hours, failure of band heaters caused the temperature to fall. Heaters were repaired and the test was continued.

** Between 785 and 816 hours, failure of a Diesel generator caused the temperature to fall and data logger readings to be lost. The amount that the temperature fell is unknown.

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used to measure each cable IR individually and it has a much higher upper range (about $5 \times 10^{12}\ \Omega$, or about $2.5 \times 10^{11}\ \Omega \cdot 100$ m for a 5 m cable length) than the monitoring method of Figure 6. These IRs will be subsequently referred to as Keithley IRs. The Keithley IR measurements were performed at nominal voltages of 50 V, 100 V, and 250 V. The actual applied voltage during a given measurement can be approximated from Table 6. Details of the calculations to support Table 6 will be included in a future report. In general, the actual applied voltage was not more than 10% below the nominal except for cables with IRs below

Table 6 Actual Applied Voltage as a Function of Sample IR and Nominal Applied Voltage

Sample IR (kΩ)	Sample IR * (kΩ-100 m)	Nominal Applied Voltage (V) 50	100	250
1000	50	≥45	≥90	≥225
500	25	≥45	≥90	223
250	12.5	≥45	≥90	200
100	5	≥45	≥90	155
50	2.5	≥45	≥90	112
25	1.25	≥45	≥90	72
15	0.75	44	88	**
10	0.5	42	83	**
5	0.25	36	71	**
4	0.20	33	67	**
3	0.15	30	60	**
2	0.10	25	50	**
1	0.05	17	33	**

* Assuming a sample length in the test chamber of 5 m.
** At 250 V, no measurement was possible at these conditions.

18 kΩ at 50 V, 18 kΩ at 100 V, or 540 kΩ at 250 V. For a typical length of 5 m in the test chamber, these values correspond to 0.9 kΩ-100 m at 50 V, 0.9 kΩ-100 m at 100 V, and 27 kΩ-100 m at 250 V.

4.3 Insulation Resistance Behavior

The IR of each cable during the submergence test is given in Table 7. For convenience, plots of this data are included as Appendix B. Note that the initial and final IR measurements were performed in a dry environment, while the others were performed with the cables submerged in the chemical solution. Most of the cables performed reasonably well (IRs generally above 10^5 Ω-100 m) during the submergence test, with the exception of the Dekorad single and multiconductors, the Kapton single conductors, and possibly the Kerite single conductors (depending on the application). One of the Kapton conductors failed the post-LOCA dielectric withstand test (see section 5.0), and the other was failed when the first set of IR measurements was performed during the submergence test. One Kerite conductor had failed the post-LOCA dielectric withstand test; the other Kerite conductor exhibited low IRs that decreased throughout the submergence exposure, with a minimum reading of 502 Ω-100 m. Five of the six Dekorad conductors failed somewhere between the measurements at 42-47 hours and 166-168 hours. The remaining conductor failed somewhere between the measurements at 166-168 hours and 355-358 hours. None of the XLPO cables had IRs below 10^5 Ω-100 m during the submergence test, and many XLPO cables remained above 10^8 Ω-100 m.

Table 7 Insulation Resistance During Submergence
(all values in ohm-100 meter)

	Conductor	Prior to Test			Time=21-25 hr.	
		50 V	100 V	250 V	100 V	250 V
	1	1.61E+11	4.37E+10	2.96E+10	2.92E+08	2.29E+08
Brand Rex	2	7.88E+10	3.90E+10	3.14E+10	3.58E+08	2.95E+08
	3	6.48E+10	5.06E+10	3.57E+10	3.35E+08	2.68E+08
	4	1.03E+10	7.41E+09	7.15E+09	2.68E+07	1.55E+07
Anaconda FR-EP	5	5.91E+09	4.50E+09	3.61E+09	7.81E+06	2.41E+06
	6	4.47E+09	4.19E+09	3.33E+09	6.55E+06	1.64E+06
	7	1.02E+10	7.77E+09	6.62E+09	2.45E+07	1.40E+07
	8	6.03E+09	4.48E+09	3.51E+09	5.66E+06	1.53E+06
	9	4.97E+09	4.39E+09	3.72E+09	4.81E+06	1.15E+06
BIW	10	1.53E+09	1.21E+09	9.94E+08	2.91E+06	2.04E+06
	11	1.84E+09	1.44E+09	1.18E+09	3.17E+06	2.27E+06
	12	5.51E+10	3.81E+10	3.34E+10	1.43E+08	1.24E+08
Rockbestos	13	6.69E+10	4.01E+10	3.74E+10	1.60E+08	1.40E+08
	14	6.44E+10	4.84E+10	3.95E+10	1.34E+08	1.17E+08
	15	6.60E+09	5.63E+09	4.51E+09	7.58E+06	3.97E+06
Dekorad	16	9.07E+09	7.18E+09	5.65E+09	9.95E+06	5.17E+06
	17	6.46E+09	5.29E+09	4.18E+09	6.67E+06	1.53E+06
	18	7.91E+09	6.73E+09	5.20E+09	9.49E+06	3.13E+06
	19	8.48E+08	7.30E+08	6.44E+08	2.34E+05	2.15E+05
Polyset	20	6.06E+09	3.98E+09	3.25E+09	2.86E+06	2.71E+06
	21	1.63E+09	1.41E+09	1.25E+09	5.64E+05	5.28E+05
Silicone	22	3.52E+06	1.73E+06	3.87E+05	3.44E+06	2.46E+06
	23	5.09E+09	3.96E+09	3.35E+09	1.00E+08	9.89E+07
Kapton	24	6.80E+05	4.41E+05	1.57E+05	****	****
	25	4.42E+07	****	****	****	****
Anaconda FR-EP	26	1.61E+10	1.37E+10	1.13E+10	2.06E+08	1.66E+08
Raychem	27	2.85E+10	3.64E+10	3.69E+10	5.73E+09	5.13E+09
	28	4.36E+10	3.96E+10	2.69E+10	5.58E+09	4.99E+09
BIW	29	7.77E+08	6.42E+08	4.50E+08	1.68E+06	1.20E+06
	30	4.76E+08	3.82E+08	2.50E+08	1.17E+06	8.39E+05
Okolon	31	1.71E+10	1.68E+10	1.51E+10	1.40E+08	1.28E+08
	32	1.86E+10	1.60E+10	1.48E+10	1.40E+08	1.27E+08
	33	1.23E+06	1.19E+06	9.86E+05	3.48E+05	2.19E+05
Dekorad	34	4.83E+07	3.25E+07	1.75E+07	2.69E+04	6.17E+04
	35	1.60E+09	9.56E+08	3.28E+08	2.38E+06	3.91E+05
Kerite	36	1.30E+07	9.42E+06	4.89E+06	4.60E+03	4.21E+03
	37	1.99E+05	1.46E+05	9.17E+04	****	****
Coaxial	38	####	5.25E+11	3.37E+11	1.22E+10	1.22E+10
	39	2.92E+11	2.32E+12	3.09E+11	1.17E+10	1.07E+10
BIW	40	4.14E+04	1.74E+04	1.46E+04	****	****
Polyset	41	1.54E+08	9.26E+07	6.40E+07	****	****
Coaxial	42	3.92E+05	3.38E+05	3.18E+05	2.55E+05	4.46E+05
	43	8.48E+06	5.55E+05	2.19E+06	4.54E+05	5.90E+05
Dekorad	44	8.27E+05	5.55E+05	2.81E+05	****	****
	45	1.96E+05	2.18E+05	1.38E+05	****	****

**** IR too low to be measured at this voltage
IR too high to be measured at this voltage

Table 7 Insulation Resistance During Submergence (cont.)
(all values in ohm-100 meter)

	Conductor	Time=42-47 hr. 100 V	Time=42-47 hr. 250 V	Time=166-168 hr. 100 V	Time=166-168 hr. 250 V
	1	3.34E+08	2.96E+08	4.14E+08	3.20E+08
Brand Rex	2	4.25E+08	3.87E+08	5.15E+08	4.08E+08
	3	3.97E+08	3.54E+08	4.55E+08	3.34E+08
	4	2.91E+07	1.71E+07	3.70E+07	1.57E+07
Anaconda FR-EP	5	7.97E+06	2.40E+06	1.05E+07	2.69E+06
	6	6.72E+06	1.65E+06	9.00E+06	1.89E+06
	7	2.73E+07	1.55E+07	3.44E+07	1.43E+07
	8	5.87E+06	1.53E+06	7.38E+06	1.72E+06
	9	4.99E+06	1.14E+06	6.44E+06	1.33E+06
BIW	10	3.35E+06	2.49E+06	4.19E+06	2.72E+06
	11	3.70E+06	2.81E+06	4.72E+06	3.10E+06
	12	1.69E+08	1.60E+08	2.02E+08	1.76E+08
Rockbestos	13	1.92E+08	1.79E+08	2.25E+08	1.97E+08
	14	1.61E+08	1.52E+08	1.84E+08	1.66E+08
	15	8.34E+06	3.08E+06	****	****
Dekorad	16	1.11E+07	5.06E+06	7.96E+06	5.19E+05
	17	7.30E+06	1.19E+06	****	****
	18	1.08E+07	2.41E+06	****	****
	19	2.68E+05	2.53E+05	2.56E+05	2.41E+05
Polyset	20	3.12E+06	3.06E+06	2.66E+06	2.64E+06
	21	6.37E+05	6.13E+05	5.84E+05	5.72E+05
Silicone	22	3.99E+06	2.57E+06	5.51E+06	3.97E+06
	23	1.09E+08	1.15E+08	1.16E+08	1.09E+08
Kapton	24	****	****	****	****
	25	****	****	****	****
Anaconda FR-EP	26	3.01E+08	2.67E+08	3.83E+08	----
Raychem	27	7.03E+09	6.92E+09	7.46E+09	----
	28	6.83E+09	6.63E+09	7.24E+09	----
BIW	29	1.73E+06	1.29E+06	1.42E+06	----
	30	1.17E+06	8.68E+05	9.17E+05	----
Okolon	31	1.83E+08	1.80E+08	2.63E+08	----
	32	1.85E+08	1.83E+08	2.69E+08	----
	33	1.27E+06	1.02E+06	2.56E+06	2.30E+06
Dekorad	34	1.42E+04	****	****	****
	35	1.95E+06	3.96E+05	****	****
Kerite	36	4.20E+03	4.07E+03	2.71E+03	2.68E+03
	37	****	****	****	****
Coaxial	38	1.20E+10	1.16E+10	1.38E+10	1.30E+10
	39	1.05E+10	1.13E+10	1.11E+10	1.19E+10
BIW	40	****	****	****	****
Polyset	41	****	****	****	****
Coaxial	42	5.99E+05	5.69E+05	4.72E+04	8.72E+04
	43	2.89E+06	2.01E+06	1.46E+06	2.98E+06
Dekorad	44	****	****	****	****
	45	****	****	****	****

**** IR too low to be measured at this voltage
---- No reading due to data acquisition problem

Table 7 Insulation Resistance During Submergence (cont.)
(all values in ohm-100 meter)

	Conductor	Time=355-358 hr. 50 V	Time=355-358 hr. 100 V	Time=572-575 hr. 50 V	Time=572-575 hr. 100 V
Brand Rex	1	3.63E+08	3.60E+08	2.91E+08	2.65E+08
	2	4.52E+08	4.46E+08	3.65E+08	3.35E+08
	3	3.73E+08	3.44E+08	3.04E+08	2.60E+08
Anaconda FR-EP	4	4.47E+07	3.44E+07	2.93E+07	2.23E+07
	5	2.02E+07	1.19E+07	1.54E+07	9.76E+06
	6	2.06E+07	1.09E+07	1.55E+07	9.21E+06
	7	4.18E+07	2.96E+07	2.51E+07	1.89E+07
	8	1.75E+07	8.38E+06	1.24E+07	6.90E+06
	9	1.82E+07	7.77E+06	1.28E+07	6.61E+06
BIW	10	4.82E+06	3.63E+06	2.82E+06	2.43E+06
	11	5.48E+06	4.13E+06	3.21E+06	2.77E+06
Rockbestos	12	2.62E+08	2.13E+08	1.81E+08	1.83E+08
	13	2.93E+08	2.36E+08	2.01E+08	2.02E+08
	14	2.45E+08	1.95E+08	1.68E+08	1.68E+08
Dekorad	15	****	****	****	****
	16	****	****	****	****
	17	****	****	****	****
	18	****	****	****	****
Polyset	19	3.33E+05	2.77E+05	3.23E+05	2.82E+05
	20	2.79E+06	2.37E+06	2.28E+06	2.05E+06
	21	7.21E+05	6.16E+05	7.11E+05	6.27E+05
Silicone	22	5.63E+06	5.62E+06	5.02E+06	4.93E+06
	23	9.58E+07	8.93E+07	5.15E+06	3.27E+06
Kapton	24	****	****	****	****
	25	****	****	****	****
Anaconda FR-EP	26	4.45E+08	4.03E+08	4.25E+08	3.64E+08
Raychem	27	8.72E+09	7.68E+09	7.84E+09	7.20E+09
	28	7.47E+09	7.39E+09	7.68E+09	6.66E+09
BIW	29	1.62E+06	1.31E+06	1.43E+06	1.09E+06
	30	1.01E+05	1.25E+05	6.02E+04	1.33E+05
Okolon	31	3.32E+08	3.35E+08	3.95E+08	3.59E+08
	32	3.34E+08	3.44E+08	3.96E+08	3.64E+08
	33	1.27E+06	2.07E+06	1.44E+06	1.96E+06
Dekorad	34	****	****	****	****
	35	****	****	****	****
Kerite	36	1.96E+03	1.70E+03	1.37E+03	1.12E+03
	37	****	****	****	****
Coaxial	38	1.45E+10	1.62E+10	1.71E+10	1.86E+10
	39	1.23E+10	1.13E+10	1.41E+10	1.28E+10
BIW	40	****	****	****	****
Polyset	41	****	****	****	****
Coaxial	42	4.28E+05	1.51E+05	4.90E+05	3.99E+05
	43	1.17E+06	1.11E+06	3.36E+06	1.83E+06
Dekorad	44	****	****	****	****
	45	****	****	****	****

**** IR too low to be measured at this voltage

Table 7 Insulation Resistance During Submergence (cont.)
(all values in ohm-100 meter)

	Conductor	Time=665-671 hr. 50 V	Time=665-671 hr. 100 V	Time= 884-885 hr 100 V	After Test (Dry) 100 V
	1	3.34E+08	3.21E+08	3.22E+08	1.92E+10
Brand Rex	2	4.21E+08	4.13E+08	4.21E+08	2.87E+10
	3	3.47E+08	3.25E+08	3.29E+08	3.15E+10
	4	3.48E+07	2.81E+07	1.72E+07	1.09E+09
Anaconda FR-EP	5	1.96E+07	1.31E+07	1.38E+07	2.33E+09
	6	1.97E+07	1.25E+07	1.33E+07	2.09E+09
	7	2.94E+07	2.39E+07	2.22E+07	1.91E+09
	8	1.55E+07	9.10E+06	9.08E+06	1.97E+09
	9	1.58E+07	8.73E+06	8.64E+06	1.85E+09
BIW	10	3.06E+06	2.92E+06	2.54E+06	1.67E+09
	11	3.55E+06	3.44E+06	3.06E+06	1.90E+09
	12	2.56E+08	2.87E+08	3.50E+08	1.81E+10
Rockbestos	13	2.83E+08	3.17E+08	3.80E+08	2.17E+10
	14	2.37E+08	2.67E+08	3.20E+08	2.45E+10
	15	****	****	****	****
Dekorad	16	****	****	****	****
	17	****	****	****	****
	18	****	****	****	8.65E+03
	19	3.89E+05	4.03E+05	4.65E+05	1.21E+09
Polyset	20	2.55E+06	2.82E+06	2.87E+06	4.55E+09
	21	8.36E+05	8.94E+05	9.86E+05	2.64E+09
Silicone	22	4.56E+06	4.66E+06	6.94E+03	5.38E+08
	23	1.70E+06	4.19E+05	2.20E+03	1.03E+08
Kapton	24	****	****	****	****
	25	****	****	****	****
Anaconda FR-EP	26	4.74E+08	5.05E+08	4.39E+08	5.14E+09
Raychem	27	9.40E+09	1.02E+10	8.93E+09	1.94E+10
	28	8.55E+09	9.14E+09	8.27E+09	1.77E+10
BIW	29	1.49E+06	1.33E+06	1.05E+06	4.52E+08
	30	5.38E+04	5.59E+04	1.04E+05	1.36E+08
Okolon	31	4.81E+08	5.17E+08	4.84E+08	1.01E+10
	32	4.86E+08	5.15E+08	4.81E+08	8.94E+09
	33	9.66E+05	1.32E+06	1.13E+06	7.79E+09
Dekorad	34	****	****	****	****
	35	****	****	****	9.93E+03
Kerite	36	1.16E+03	1.08E+03	5.02E+02	5.42E+06
	37	****	****	****	1.52E+06
Coaxial	38	1.81E+10	2.02E+10	1.89E+10	4.81E+11
	39	1.16E+10	1.20E+10	1.45E+10	2.88E+11
BIW	40	****	****	****	3.34E+07
Polyset	41	****	****	****	6.73E+06
Coaxial	42	6.13E+05	6.10E+05	4.80E+05	5.24E+09
	43	7.53E+05	1.87E+06	1.44E+06	5.10E+09
Dekorad	44	****	****	****	****
	45	****	****	****	****

**** IR too low to be measured at this voltage

Following the submergence test, a dielectric withstand test (in tap water) was performed with the cables still wrapped on the mandrel. The conductors that passed the dielectric withstand test were then removed from the original mandrel, straightened, and recoiled around a mandrel with a diameter 40 times that of the cable and then subjected to a final dielectric withstand test (in tap water). The results of these tests are discussed in the next section, but it is interesting to note at this point that some of the cables that performed well during the submergence test could not survive the subsequent dielectric withstand tests.

5.0 DIELECTRIC WITHSTAND TESTING

Dielectric tests were performed using a Hipotronics Model 750-2 dielectric tester with a 40 mA maximum current and a 0-50 kVac capability. A voltage resolution of about 100 V was possible on the lowest voltage scale of the tester (0-10 kV). The following dielectric tests were performed:

a) Cables aged for 3 months were tested while still wrapped on the mandrel after the LOCA test. These cables were then exposed to high temperature steam conditions. Those cables that did not fail during the high temperature steam conditions were retested after the high temperature steam exposure, but none was able to maintain any applied ac voltage that was detectable on the lowest voltage scale of the dielectric tester (0-10 kV).

b) Cables aged for 6 months were tested while still wrapped on the mandrel after the LOCA test. These cables were then submergence tested (see Section 4.0). Following submergence, dielectric testing was again performed with the cables still wrapped on the mandrel. Finally, those cables that had not yet failed were removed from the test chamber and subjected to a 40xD mandrel bend per IEEE 383-1974, followed by another dielectric test.

Each dielectric test was performed on one conductor by setting the dielectric tester for automatic voltage rise to the peak voltage at 500 V/s, holding the voltage at the peak for 5 minutes, then returning to 0 V a rate of -500 V/s. In cases where the leakage current was increasing significantly, the applied voltage usually decreased in response. In the automatic mode of our dielectric tester, there is no provision for readjusting the voltage back to the desired peak. The discussions below indicate where the voltage varied significantly during the 5-minute hold period. All dielectric testing was performed with the cables submerged in tap water after a soak period of at least 1 hour. In some cases, a conductor is deemed to have failed a dielectric test by our criterion, but the conductor goes on to behave normally during some subsequent test. Because of the dielectric tester's response to increasing leakage currents, a conductor can fail the dielectric test by our criterion, but not experience a puncture of the insulation.

The test voltage for most cable types was nominally 80 V/mil of insulation thickness, not including the thickness of individual conductor jackets. Cables that were not tested at a nominal 80 V/mil include the Rockbestos coax cable (56 mil insulation thickness), which was tested at 2000 Vac; the Kerite cable (80 mil nominal insulation thickness), which was tested at 2400 Vac; the Kapton cable (5 mil nominal insulation thickness), which was tested at 1200 Vac; and all jackets (for cables with shields), which were tested at 600 Vac. Table 8 is a summary of the dielectric test results. For purposes of Table 8, a conductor was defined as failing if the maximum leakage/charging current exceeded 20 mA during any part of the test. This failure criterion is well above the normal charging currents for

Table 8
Maximum Leakage/Charging Current (mA) in Dielectric Tests
(PF denotes Previously Failed)

Cable ID	Desired Voltage (kV)	3-month Post-LOCA	6-month Post-LOCA	6-month Post-Submergence	6-month Post-Mandrel
Multiconductors					
Brand Rex	2.4	3.9 (2.4)*	3.4 (2.4)	3.3 (2.4)	1.0 (2.6)
Brand Rex	2.4	3.9 (2.4)	3.4 (2.4)	3.2 (2.4)	1.0 (2.6)
Brand Rex	2.4	4.0 (2.4)	3.4 (2.4)	3.3 (2.4)	1.2 (2.6)
Anaconda**	2.4	3.5 (2.6)	5.1 (2.3)	Fail (0.9)	PF
Anaconda	2.4	3.2 (2.5)	6.0 (2.2)	Fail (2.0)	PF
Anaconda	2.4	3.3 (2.5)	6.9 (2.0)	Fail (2.1)	PF
Anaconda	2.4	3.5 (2.5)	5.1 (2.4)	Fail (2.0)	PF
Anaconda	2.4	3.2 (2.5)	6.3 (2.4)	Fail (2.1)	PF
Anaconda	2.4	3.4 (2.5)	6.3 (2.4)	Fail (1.9)	PF
BIW	2.4	5.6 (2.5)	5.0 (2.5)	6.6 (3.0)	2.4 (2.7)
BIW	2.4	5.1 (2.5)	4.8 (2.5)	5.7 (2.7)	2.0 (2.7)
Rockbestos	2.4	3.6 (2.5)	3.5 (2.5)	5.0 (2.7)	Fail (2.7)
Rockbestos	2.4	3.7 (2.5)	3.4 (2.5)	5.0 (2.7)	2.6 (2.7)
Rockbestos	2.4	4.0 (2.6)	3.4 (2.5)	5.0 (2.7)	2.6 (2.7)
Dekorad	1.6	Fail (1.6)	7.0 (1.5)	Fail (0)	PF
Dekorad	1.6	Fail (1.6)	8.4 (1.4)	Fail (0)	PF
Dekorad	1.6	Fail (0)	7.7 (1.5)	Fail (0)	PF
Dekorad	1.6	Fail (1.6)	8.6 (1.3)	Fail (0)	PF
Polyset	2.4	6.4 (2.6)	5.2 (2.4)	7.5 (2.7)	1.8 (2.6)
Polyset	2.4	6.3 (2.6)	5.2 (2.4)	7.4 (2.7)	1.7 (2.6)
Polyset	2.4	6.4 (2.6)	5.3 (2.4)	7.5 (2.7)	1.7 (2.6)

* Numbers in parenthesis denote average sustained voltage for cables that passed or peak voltage for cables that failed (see additional information in text).

** Different Anaconda cables were used in the 3-month and 6-month chambers--see Table 1.

Table 8
Maximum Leakage/Charging Current (mA) in Dielectric Tests (cont)
(PF denotes Previously Failed)

Cable ID	Voltage (kV)	3-month Post-LOCA	6-month Post-LOCA	6-month Post-Submergence	6-month Post-Mandrel
Single Conductors					
Silicone	2.4	1.9 (2.6)	1.9 (2.4)	Fail (0.5)	PF
Silicone	2.4	1.9 (2.6)	1.8 (2.4)	Fail (0.5)	PF
Kapton	1.2	Fail (0)	3.2 (1.2)	Fail (0)	PF
Kapton	1.2	3.5 (1.3)	Fail (0)	PF	PF
Anaconda	2.4	2.3 (2.5)	2.2 (2.5)	3.1 (2.7)	1.9 (2.6)
Raychem	2.4	1.6 (2.5)	1.6 (2.4)	1.8 (2.6)	0.9 (2.6)
Raychem	2.4	1.6 (2.5)	1.6 (2.4)	2.0 (2.6)	0.9 (2.6)
BIW	2.4	2.6 (2.5)	2.0 (2.5)	3.2 (2.6)	Fail (0)
BIW	2.4	2.5 (2.5)	2.2 (2.5)	Fail (0.4)	PF
Okolon	2.4	2.3 (2.5)	2.2 (2.5)	14. (2.7)	Fail (0)
Okolon	2.4	Fail (1.3)	2.3 (2.4)	19. (2.7)	Fail (0)
Okolon	2.4	2.2 (2.5)	2.3 (2.5)	14. (2.7)	Fail (0)
Dekorad	1.6	15. (1.6)	Fail (1.4)	PF	PF
Dekorad	1.6	20. (1.6)	Fail (1.6)	PF	PF
Kerite	2.4	4.3 (2.5)	18. (2.1)	Fail (0)	PF
Kerite	2.4	Fail (1.1)	Fail (0.4)	PF	PF
Coax	2.0	1.6 (2.1)	1.6 (2.0)	1.6 (2.1)	0.4 (2.3)
Coax	2.0	1.5 (2.1)	1.6 (2.0)	1.6 (2.1)	0.4 (2.3)
Jackets					
BIW	0.6	Fail (0)	Fail (0)	PF	PF
Dekorad	0.6	Fail (0)	Fail (0.5)	Fail (0)	PF
Dekorad	0.6	Fail (0)	Fail (0.6)	Fail (0)	PF
Polyset	0.6	8.0 (0.7)	6.0 (0.7)	Fail (0)	PF
Coax	0.6	1.3 (0.6)	1.3 (0.6)	1.6 (0.7)	0.9 (0.9)
Coax	0.6	1.3 (0.6)	1.3 (0.6)	1.3 (0.6)	0.8 (0.9)

all cable types tested and therefore represents a level where significant leakage currents are occurring. The actual applied voltage at steady state is given in parenthesis for those cables that passed the test. For cables that failed, the number in parenthesis is the maximum voltage that was applied to the cables during the transient voltage rise. The peak voltages normally lasted 2 seconds or less. The discussion below gives details of some of the failures. For cables with a peak value of 0, no detectable voltage could be applied to the specimen, using the 0-10 kV scale on the dielectric tester.

Cables that passed the dielectric withstand test after a mandrel bend exhibited somewhat lower leakage/charging currents than they had previously exhibited (see Table 8). This resulted from the shorter length of cable tested in the final dielectric test. When the cables were removed from the test chamber prior to the mandrel bend tests, they were cut near the chamber penetrations at the inside of the test chamber, resulting in a cable length during the final dielectric test of 4.5-6.0 m (15-20 ft), rather than the previous test length of about 23 m (76 ft). In addition to the testing discussed below, dielectric withstand tests were also performed after accident tests on unaged cables and on cable aged for 9 months. These results will be discussed in a future report.

5.1 XLPO Cables

Table 8 indicates that all of the Brand Rex conductors and all of the Raychem Flamtrol conductors withstood all of the dielectric tests performed. (Note that no dielectric tests were performed on these cables after the high temperature steam exposure.) The insulated conductors of the Polyset cables also withstood all dielectric withstand tests performed. The shields of the Polyset cables passed the dielectric withstand tests after AT3 (prior to HTS3) and AT6 (1 sample each), but failed after the submergence exposure (1 sample). Two of the three Rockbestos Firewall III conductors aged for 6 months passed all of the dielectric tests; the third failed the dielectric withstand test after the 40xD mandrel bend. This latter conductor had a peak applied voltage of 2700 Vac, with the total test lasting about 10 seconds.

5.2 EPR Cables

Table 8 indicates that a number of EPR-insulated conductors failed dielectric withstand testing at various points in the testing, especially after the 6-month aging/LOCA/submergence exposure.

The Anaconda FR-EP multiconductor cables survived the post-LOCA dielectric withstand tests, but all six conductors failed the dielectric test after the submergence exposure. Each of the conductors had initial transients to about 2 kV. Three of the six maintained the voltage until failure at about 10 seconds. The other two conductors had voltage drops to 600-900 V after about 2 seconds, and then they held until failure at about 10 seconds. The remaining conductor had a voltage peak of 2100 V, but by 20 seconds, the voltage was fluctuating rapidly between 500 V and 1800 V. The peak leakage/charging current was 35 mA.

The single conductor BIW cables passed the dielectric tests after exposure to both AT3 and AT6, but one of two conductors failed after SUB6; the second conductor exposed to SUB6 failed dielectric testing after the 40xD mandrel bend. The conductor that failed after submergence maintained about 400 V for 10 seconds. None of the BIW jackets withstood any readable voltage application during any of the dielectric tests.

The multiconductor Dekoron Dekorad cables all passed the dielectric tests after AT6, while the comparable cables failed after AT3. The four conductors from AT6 that passed the dielectric test all went on to fail electrically prior to the end of the submergence exposure (see Section 4.0). One of the conductors that failed after AT3 withstood very little voltage. Another conductor that failed after AT3 initially held 1600 V with 16 mA leakage/charging current, but then the voltage degraded to about 1100 V at 5 minutes with 20 mA leakage/charging current. A repeat test of this conductor at 1600 V resulted in failure within several seconds. A third conductor that failed after AT3 held 1600 V for about 30 seconds with the leakage current steadily rising until failure. The final conductor that failed after AT3 had an initial transient to 1600 V, but was down to 600 V within 4 seconds and failed by 12 seconds.

In contrast to multiconductor results, the single conductor Dekoron Dekorad cables passed the dielectric withstand test following AT3, but the leakage currents were somewhat higher than similar multiconductor cables. Also in contrast to multiconductor results, both of the Dekorad single conductors failed the dielectric tests after AT6. One of the single conductors from AT6 was able to withstand 1200 V for 5 minutes with a leakage/charging current of 37 mA. The second was tested at 1500 V for 70 seconds with the current steadily increasing until the tester tripped. The test was repeated at 1200 V for 5 minutes with a leakage/charging current of 15 mA.

The Dekorad jackets failed the 600 V dielectric tests after AT3 and after AT6. The two jackets in AT6 did withstand 500 V and 600 V for 5 minutes with maximum leakage/charging currents of 38 mA and 22 mA, respectively, but these were above the chosen failure threshold of 20 mA.

The Okonite Okolon single conductor cables had one failure out of three conductors tested after AT3. This conductor withstood an initial transient for about 2 seconds to 2700 V, followed by a steady voltage of 1200 V. The leakage at 1200 V steadily increased until failure at 15 seconds. The one conductor that failed the dielectric test after AT3 (by our criterion) was functional during HTS3, and the IR of this conductor was similar to those of the other two conductors during HTS3.

All three Okonite Okolon conductors tested in AT6 passed the dielectric tests after LOCA and after SUB6, but leakage currents after submergence were an order of magnitude higher than before submergence. All of these conductors then failed the dielectric tests after the 40xD mandrel bend.

Severe cracking of the insulation, through to bare conductors, was noted during the mandrel bends.

5.3 Other Cable Types

Table 8 indicates that the Rockbestos coaxial cables and jackets passed all dielectric tests after all exposures. (Note that these cables were not tested after the high temperature steam exposure since they were destroyed.) The silicone rubber cables passed all dielectric withstand tests except after the submergence exposure, where both conductors failed. Each conductor withstood 500 V for less than 10 seconds. The Kapton cables had one conductor out of two tested fail after AT3 and one out of two fail after AT6. In each case, the dielectric tester tripped out very quickly. The one conductor that did pass after AT6 was shorted when the first IR measurement was conducted at the beginning of the submergence exposure. The polyimide was destroyed by the end of the submergence test. It should be noted that polyimide is subject to attach by high pH solutions and is not recommended for applications where it might become submerged in a high pH solution or where it might be subject to direct high pH spray solutions.

In dielectric tests after AT3 and AT6, one conductor out of two Kerite single conductors tested failed in each case. The conductor that passed after AT6 failed during the subsequent submergence test. (This conductor had abnormally high leakage current in the post-LOCA dielectric test.) The conductor that failed after AT3 had a brief transient to 1600 V and then settled at about 600 V until failure (by our criterion) at less than 20 seconds; however, this conductor was then exposed to HTS3 and it did not short to ground until well into the test (similar to the other Kerite conductor exposed to HTS3). The conductor that failed after AT6 had a maximum voltage of 400 V for less than 10 seconds.

5.4 Summary

Table 9 provides a summary of the results of dielectric testing on the cables in the six-month chamber. A number of cables that performed well during the submergence test failed post-submergence dielectric withstand testing, either before or after an IEEE 383 mandrel bend. This indicates that the dielectric withstand tests and mandrel bends can induce failures in cables that are otherwise functional. In our tests, we carefully avoided excessive handling of the cables during testing. In an actual nuclear plant, cables might be subjected to various types of damage and movement during operation and maintenance. The mandrel bends and dielectric withstand tests provide a margin of safety against such damage by assuring some remaining mechanical and electrical durability after the accident tests are completed.

It is very interesting that most of the cables that passed the dielectric test after submergence also survived the mandrel bend and final dielectric withstand test. In fact, if the criterion for failure of the dielectric tests were changed from 20 mA to 15 mA, only two

Table 9 Dielectric Test Failure Summary of Cables in 6-Month Chamber

	XLPO	EPR	Other *	Total
Failed Dielectric Test Prior to Submergence (i.e., after LOCA) **	0	2	2	4
Failed During Submergence Test ***	0	4	2	6
Failed Post-Submergence Dielectric Test **	0	7	2	9
Failed Dielectric Test after IEEE 383 Mandrel Bend **	1	4	0	5
Did not fail in any of the above	10	3	2	15
Total Number Tested	11	20	8	39

* Other includes Rockbestos silicone, Champlain Kapton, Kerite FR/FR, and Rockbestos coaxial cables.

** Failure during dielectric testing is defined as a leakage current exceeding 20 mA

*** Failure during submergence is defined as an IR < 1000 Ω-100 m

conductors would have been classified as having failed after the final dielectric test. The three Okonite Okolon conductors that are classified as passing the post-submergence test would be then classified as failing at that point, rather than failing after the final dielectric test.

Based on the above data, it is clear that the IEEE 383-1974 dielectric withstand tests are very severe, even when a mandrel bend test is not performed. This is evidenced by the failure of nine conductors and the near failure of three more conductors in the post-submergence dielectric withstand test, only two of which were showing strong indications of degradation during the submergence test. In addition, only two conductors that behaved normally (no indication of higher than expected leakage currents) during the dielectric test after SUB6 went on to fail the dielectric test after the mandrel bend.

6.0 CONCLUSIONS

The following conclusions may be drawn from the testing described in this report:

a) EPR cables generally survived to higher temperatures than XLPO cables in the high temperature steam exposure. The XLPO-insulated conductors had no insulation remaining at the end of the test.

b) XLPO cables generally performed better than EPR cables in the submergence test and in the post-submergence dielectric testing. By the end of the final dielectric test (after a 40xD mandrel bend), only 1 of 11 XLPO-insulated conductors had failed, while 17 of 20 EPR-insulated conductors had failed.

c) A number of cables that performed well during the submergence test failed post-submergence dielectric withstand testing (either before or after the mandrel bend). This indicates that the IEEE 383 dielectric withstand tests and mandrel bends can induce failure of otherwise functional cables. Note that this conclusion does not imply a criticism of the IEEE 383 requirements, which are intended to provide a level of conservatism in the testing.

d) The IEEE 383 dielectric withstand tests are very severe even if a mandrel bend is not performed. This is evidenced by the failure of 9 conductors and the near failure of 3 more conductors in the post-submergence dielectric withstand test, only 2 of which were showing strong indication of degradation during the submergence test.

The results presented in this report represent only a fraction of the data available from the tests performed. Additional results will be presented in a series of reports to be published in the future.

7.0 REFERENCES

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Appendix A Insulation Resistance of each Conductor During High Temperature Steam Test

The plots in this appendix present insulation resistance and temperature during the high temperature steam exposure. Where data appears absent from the plots, the insulation resistance is either below 100 Ω-100 m and the cable is considered failed or the insulation resistance is above the maximum measurable value. It is evident from each plot which of these two possibilities occurred. Those cables that were failed prior to the start of HTS3 do not have a corresponding plot in this appendix.

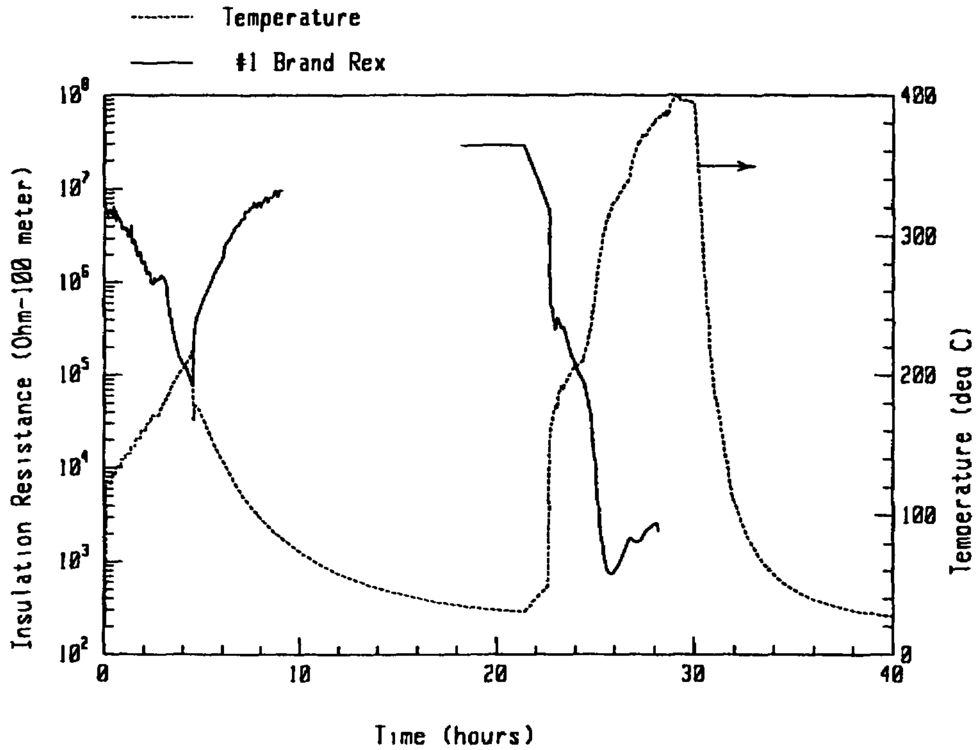

Figure A-1 IR of Brand Rex Conductor 20-1 During HTS3

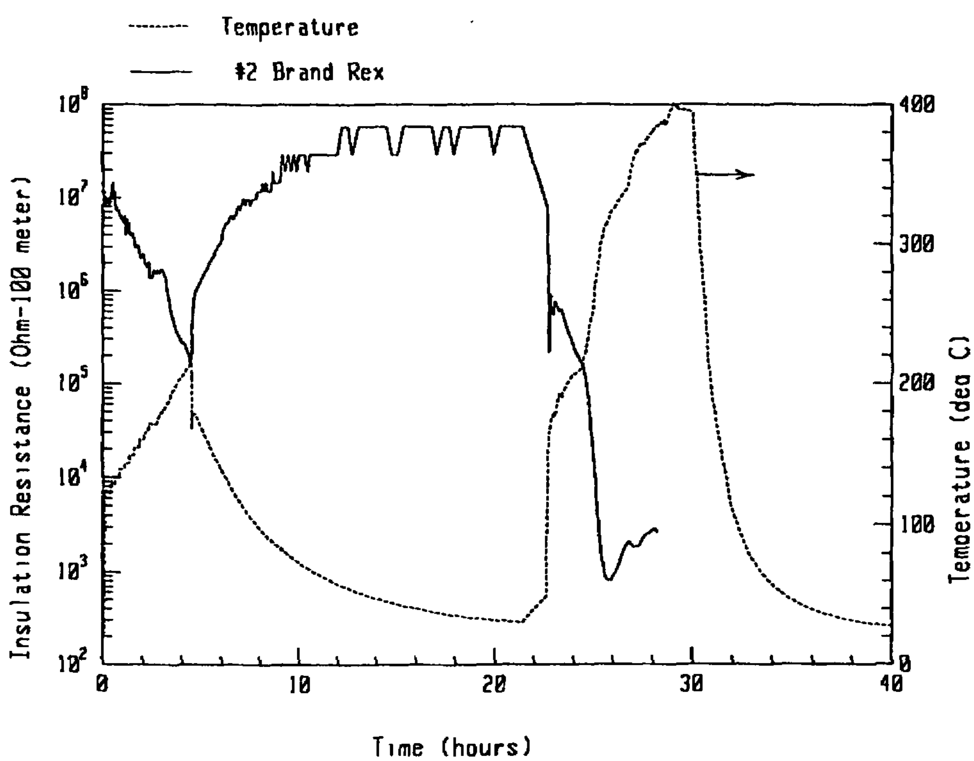

Figure A-2 IR of Brand Rex Conductor 20-2 During HTS3

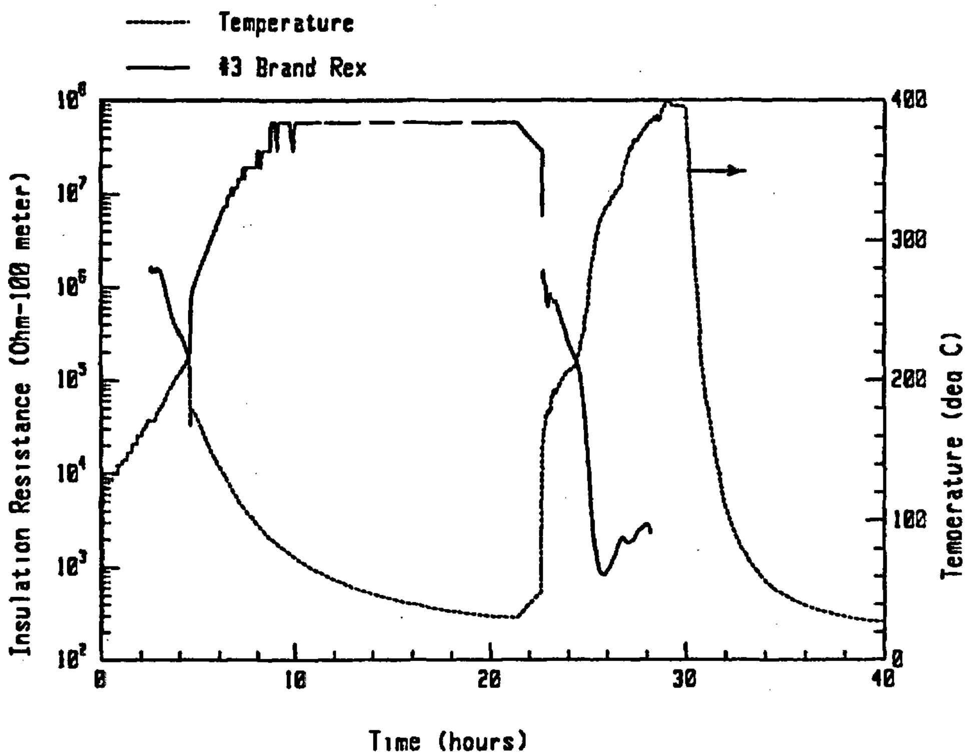

Figure A-3 IR of Brand Rex Conductor 20-3 During HTS3

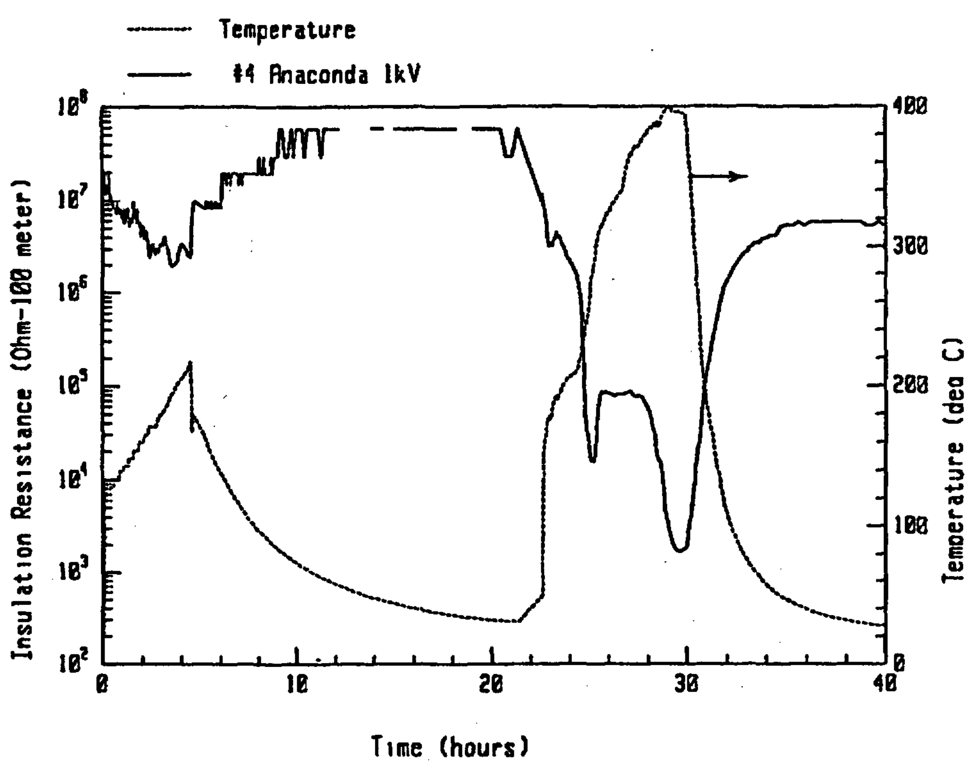

Figure A-4 IR of Anaconda 1 kV Conductor 20-4 During HTS3

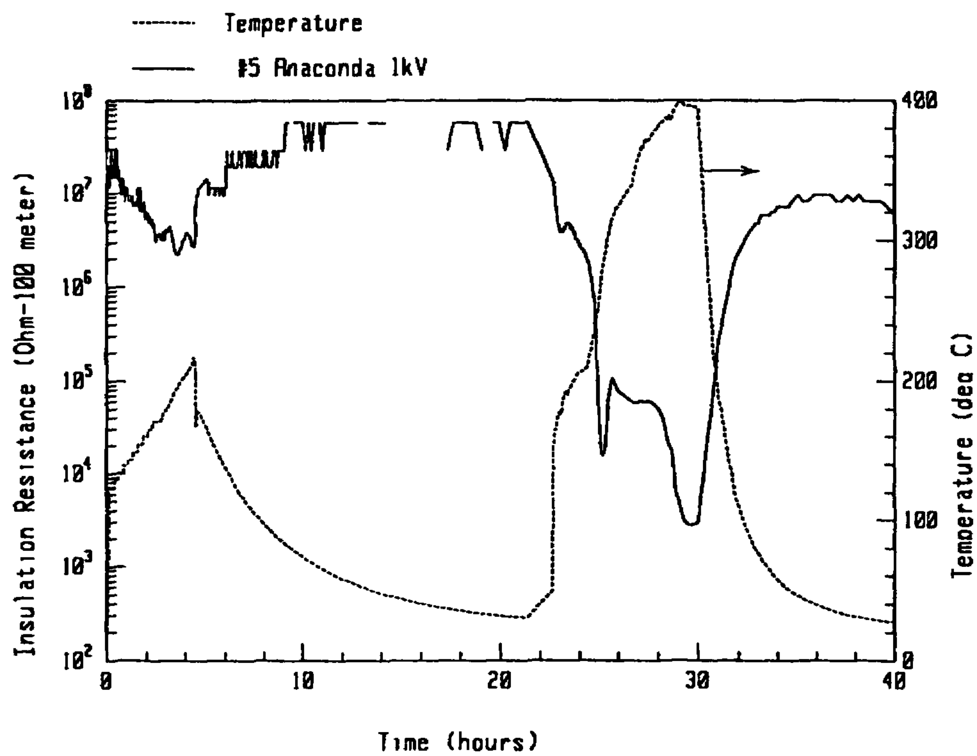

Figure A-5 IR of Anaconda 1 kV Conductor 20-5 During HTS3

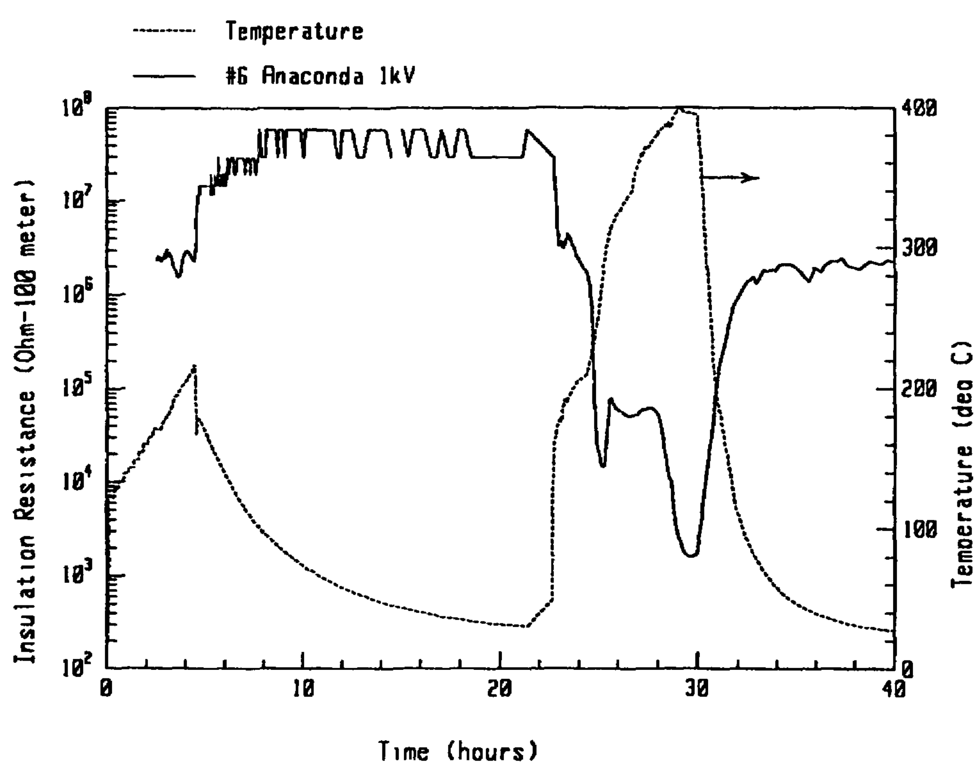

Figure A-6 IR of Anaconda 1 kV Conductor 20-6 During HTS3

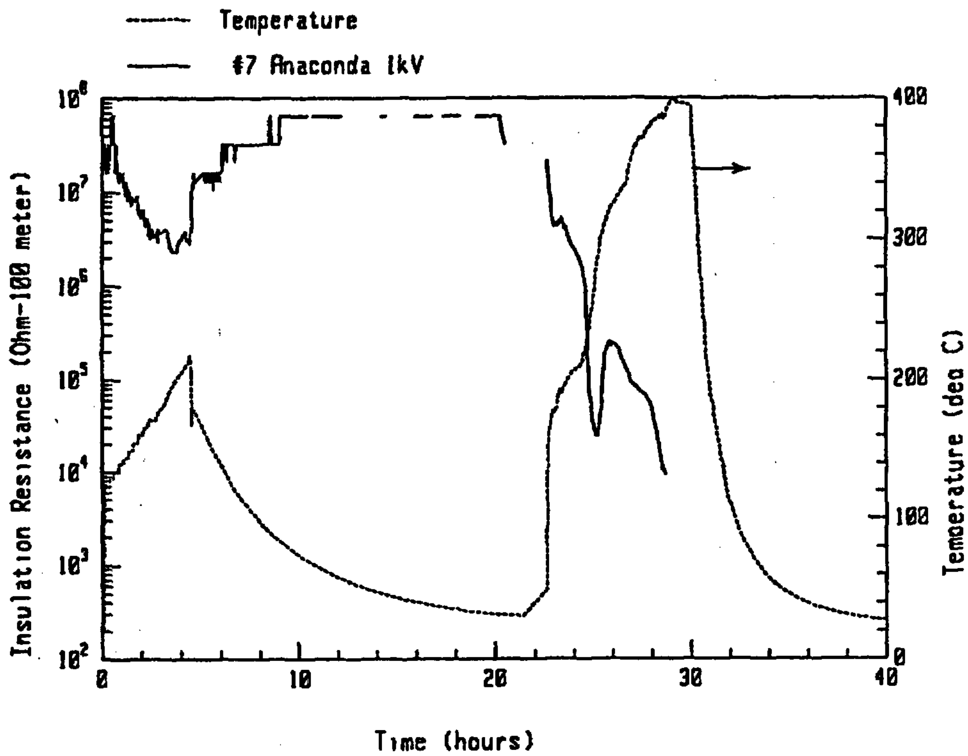

Figure A-7 IR of Anaconda 1 kV Conductor 20-7 During HTS3

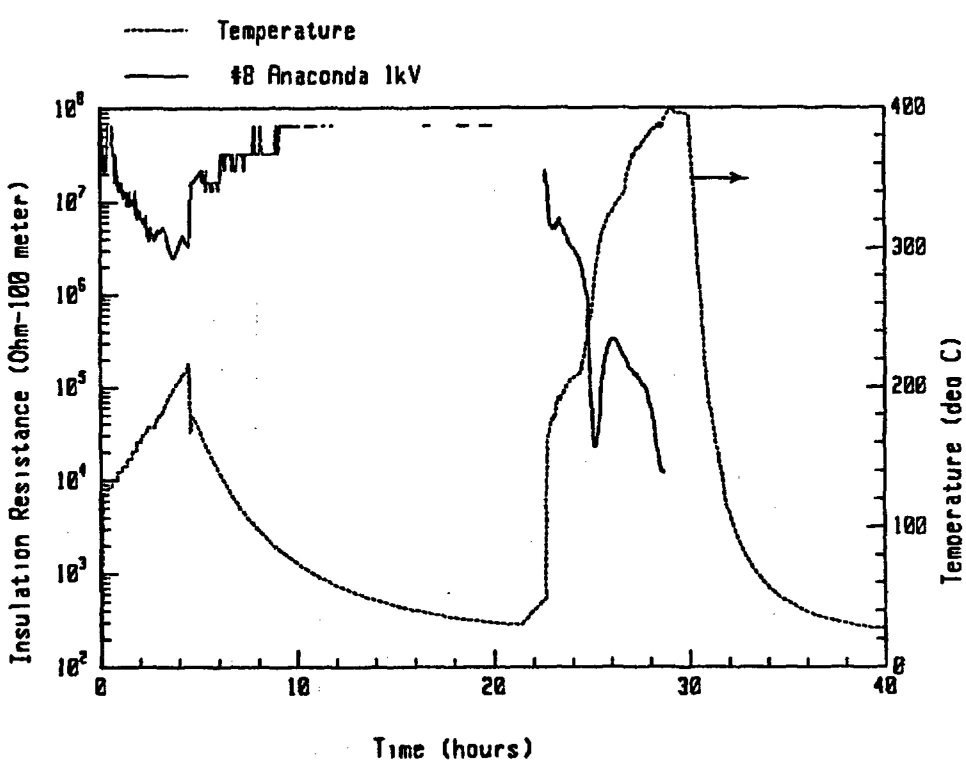

Figure A-8 IR of Anaconda 1 kV Conductor 20-8 During HTS3

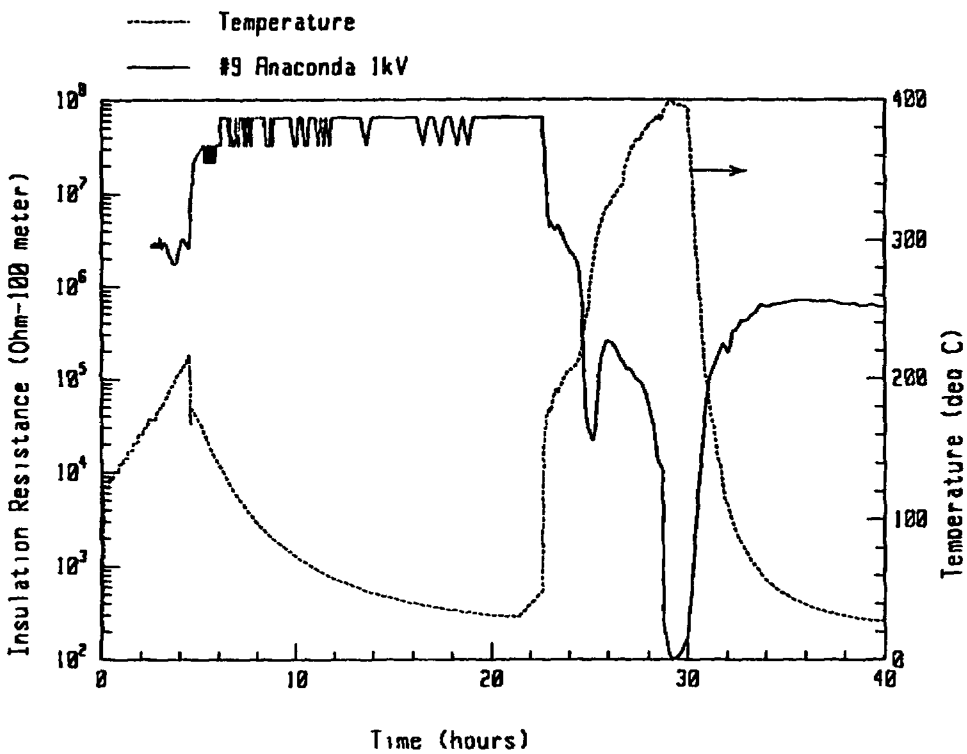

Figure A-9 IR of Anaconda 1 kV Conductor 20-9 During HTS3

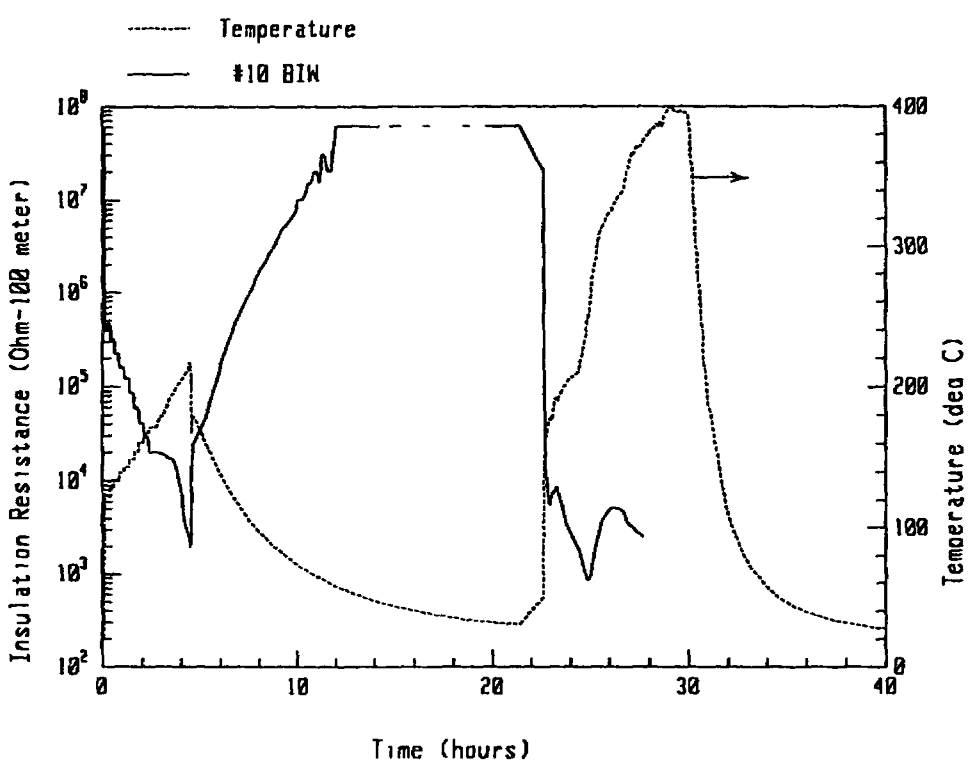

Figure A-10 IR of BIW Conductor 20-10 During HTS3

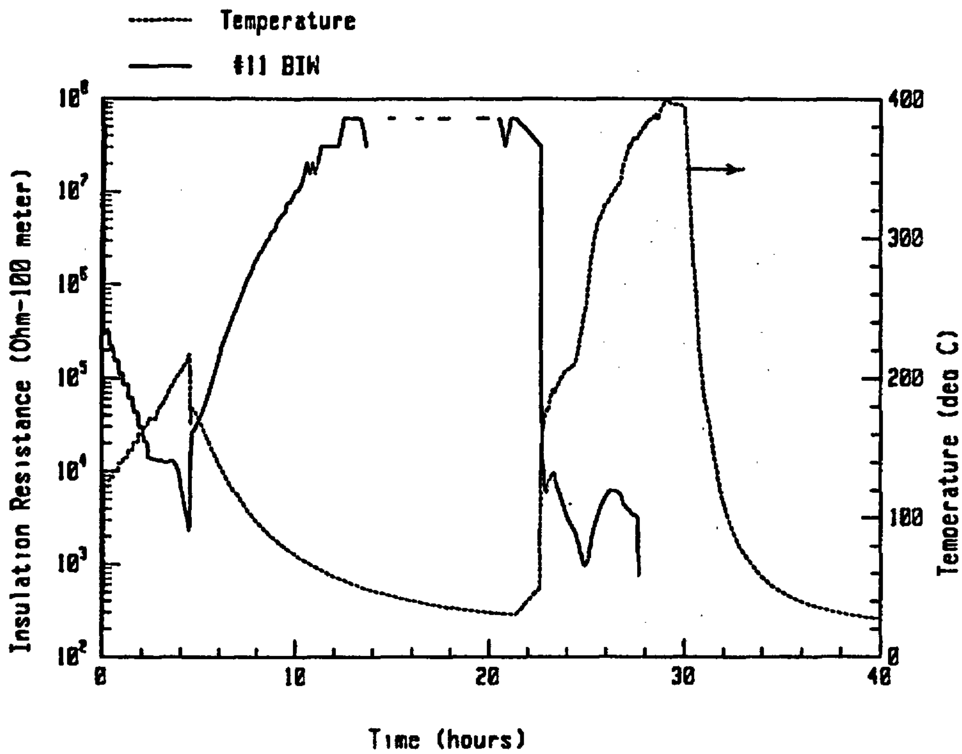

Figure A-11 IR of BIW Conductor 20-11 During HTS3

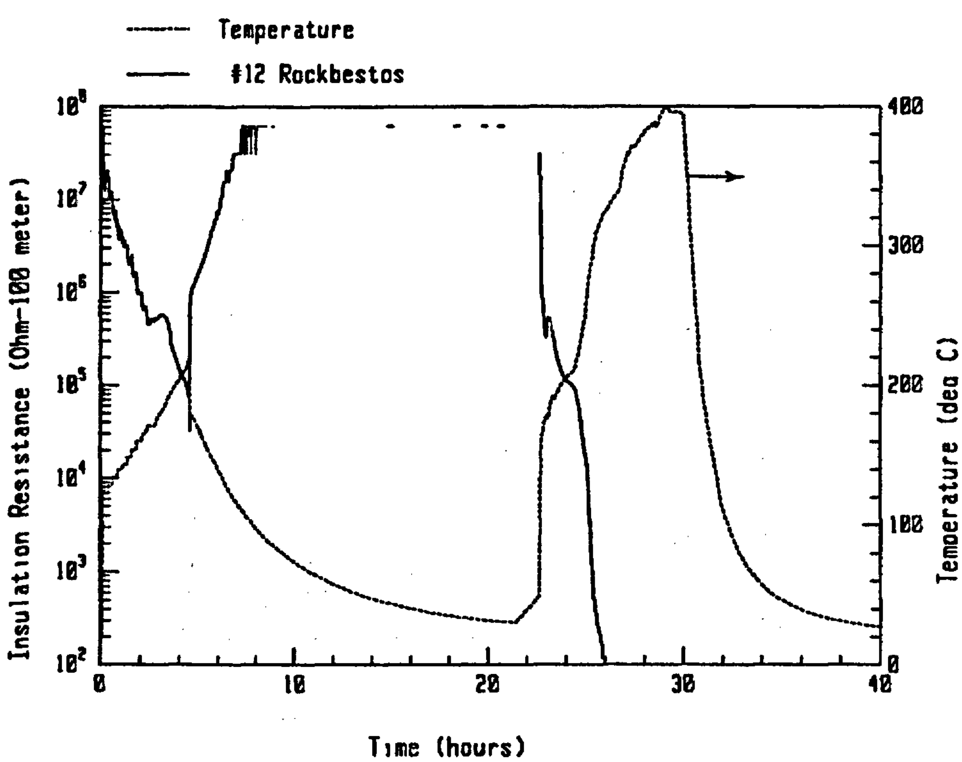

Figure A-12 IR of Rockbestos Conductor 20-12 During HTS3

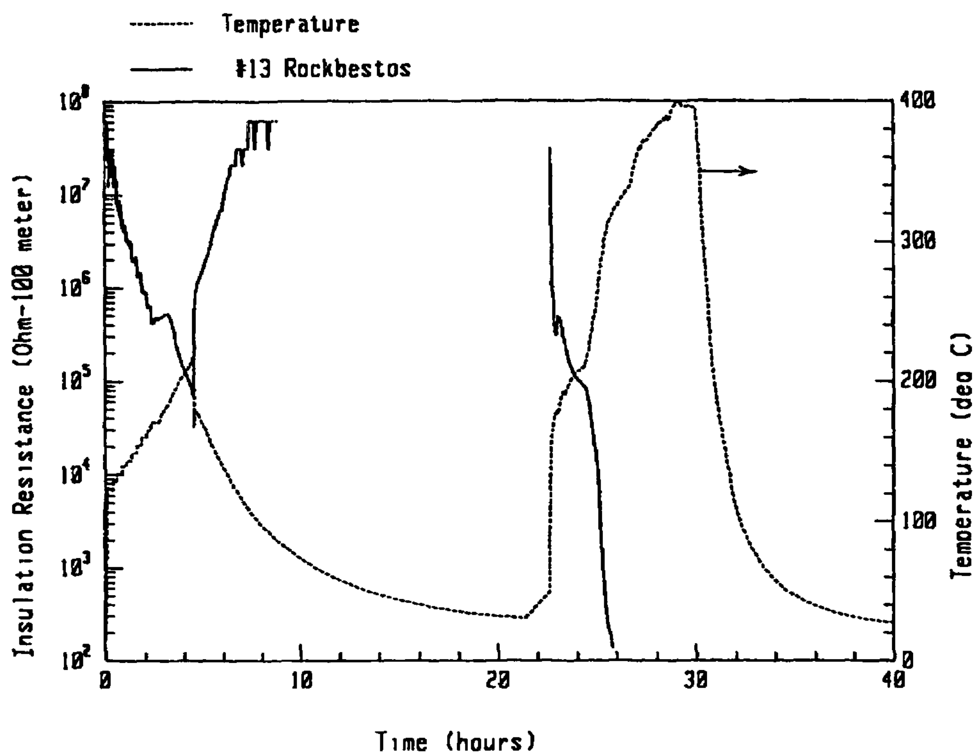

Figure A-13 IR of Rockbestos Conductor 20-13 During HTS3

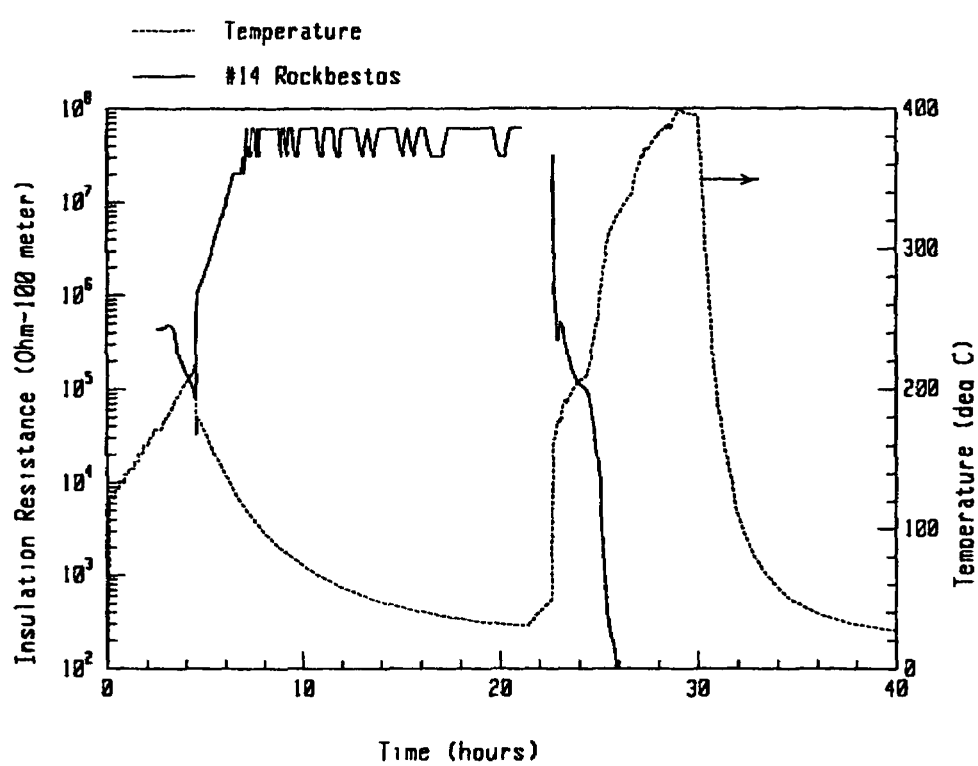

Figure A-14 IR of Rockbestos Conductor 20-14 During HTS3

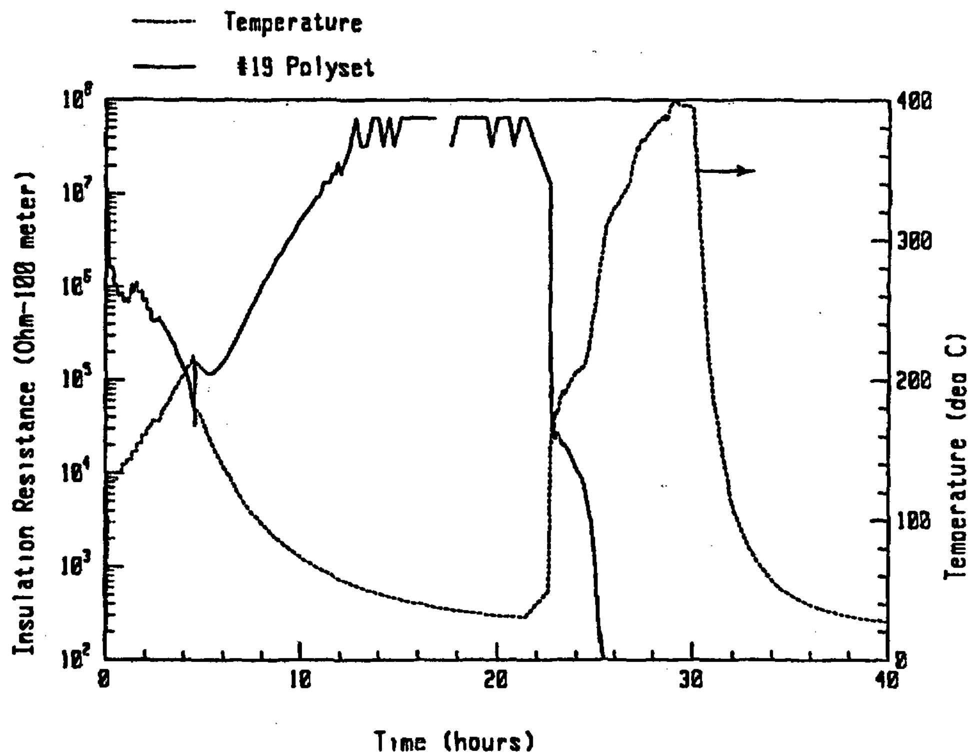

Figure A-15 IR of Dekoron Polyset Conductor 20-19 During HTS3

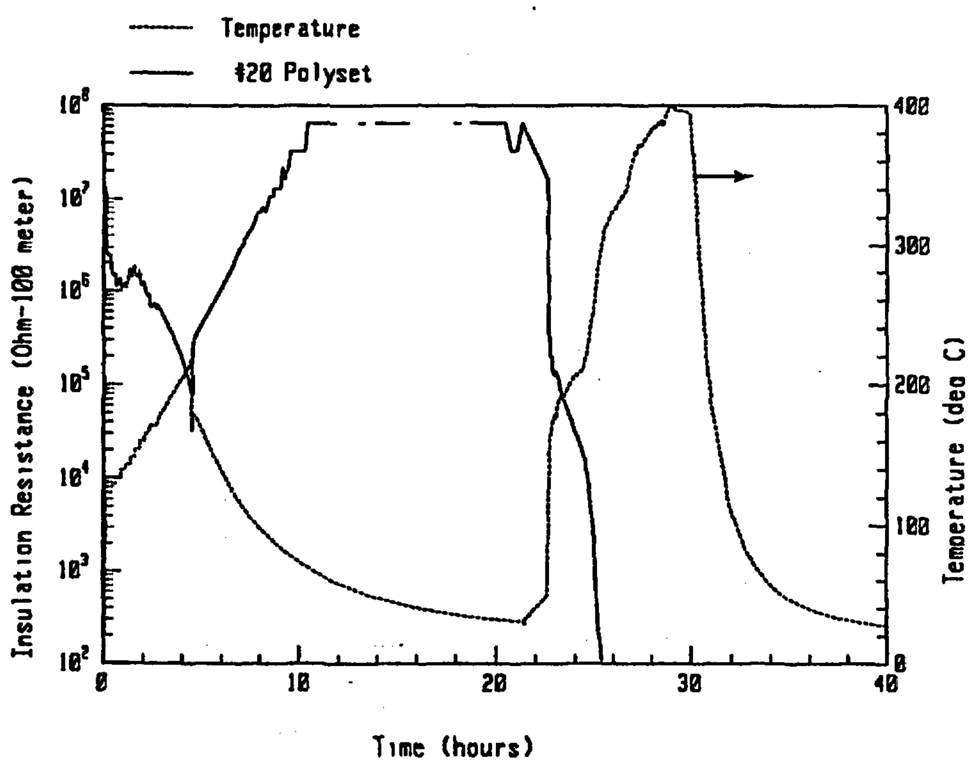

Figure A-16 IR of Dekoron Polyset Conductor 20-20 During HTS3

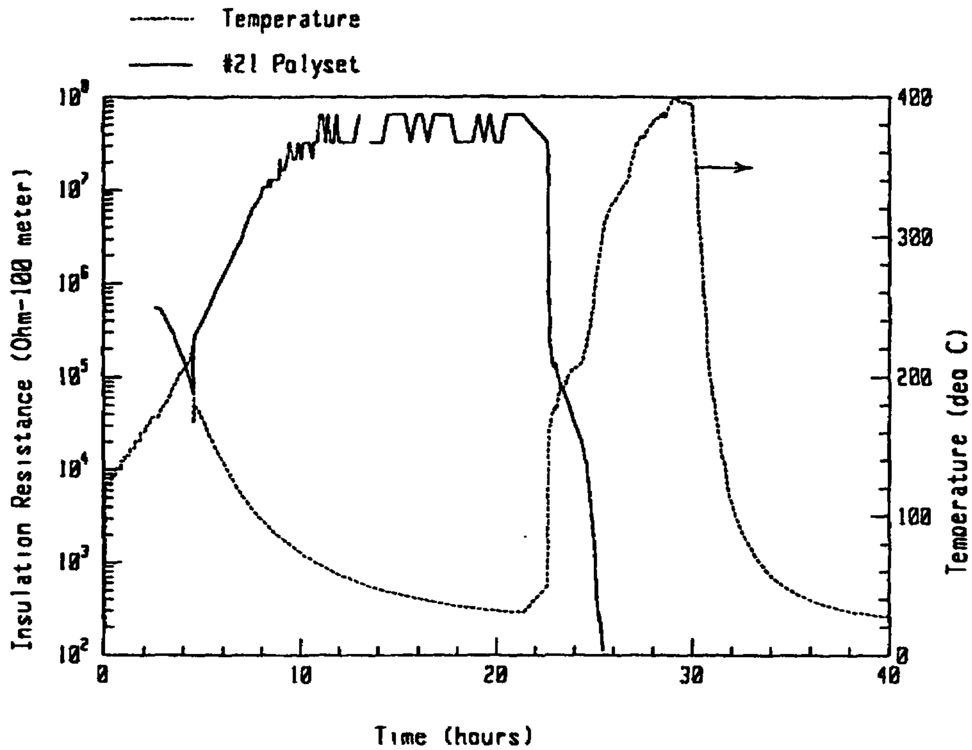

Figure A-17 IR of Dekoron Polyset Conductor 20-21 During HTS3

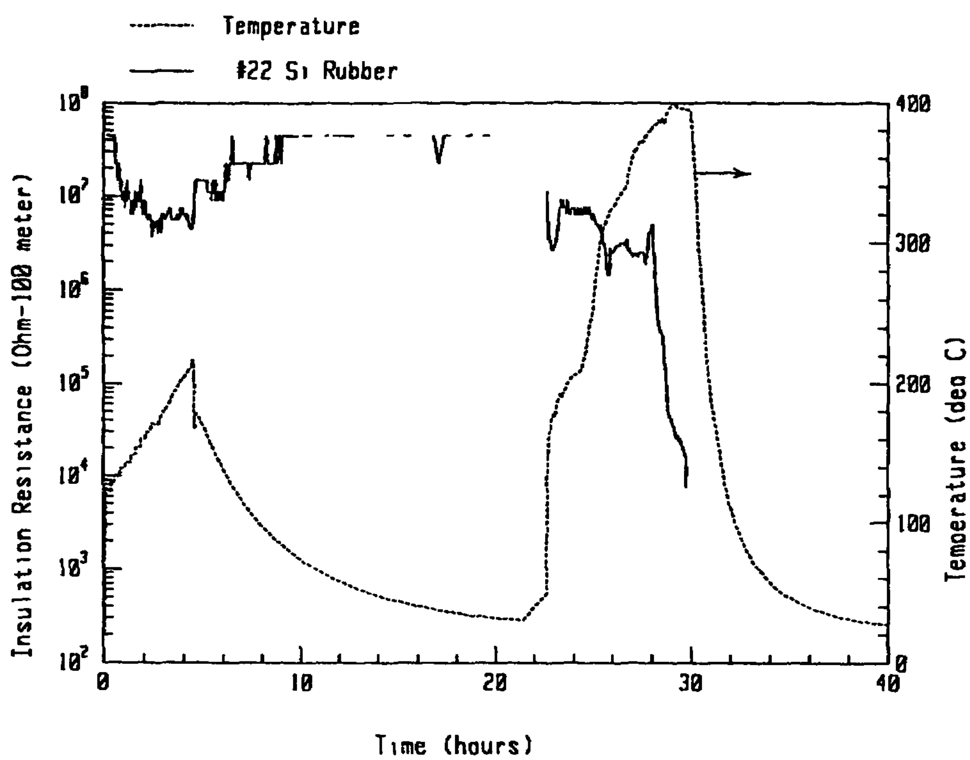

Figure A-18 IR of Rockbestos Silicone Conductor 20-22 During HTS3

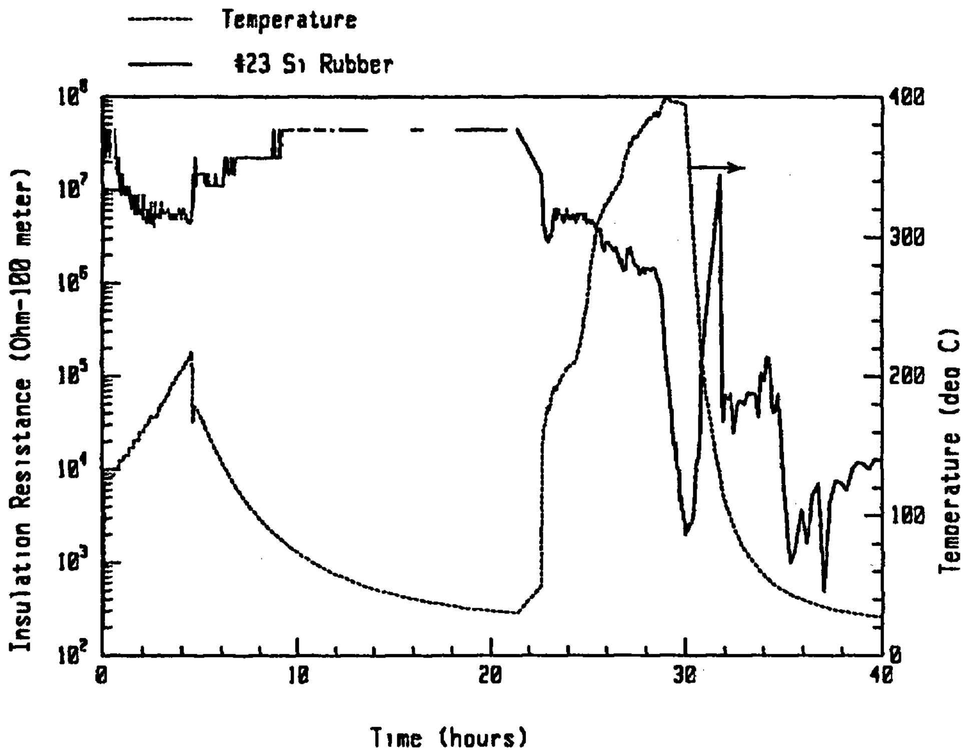

Figure A-19 IR of Rockbestos Silicone Conductor 20-23 During HTS3

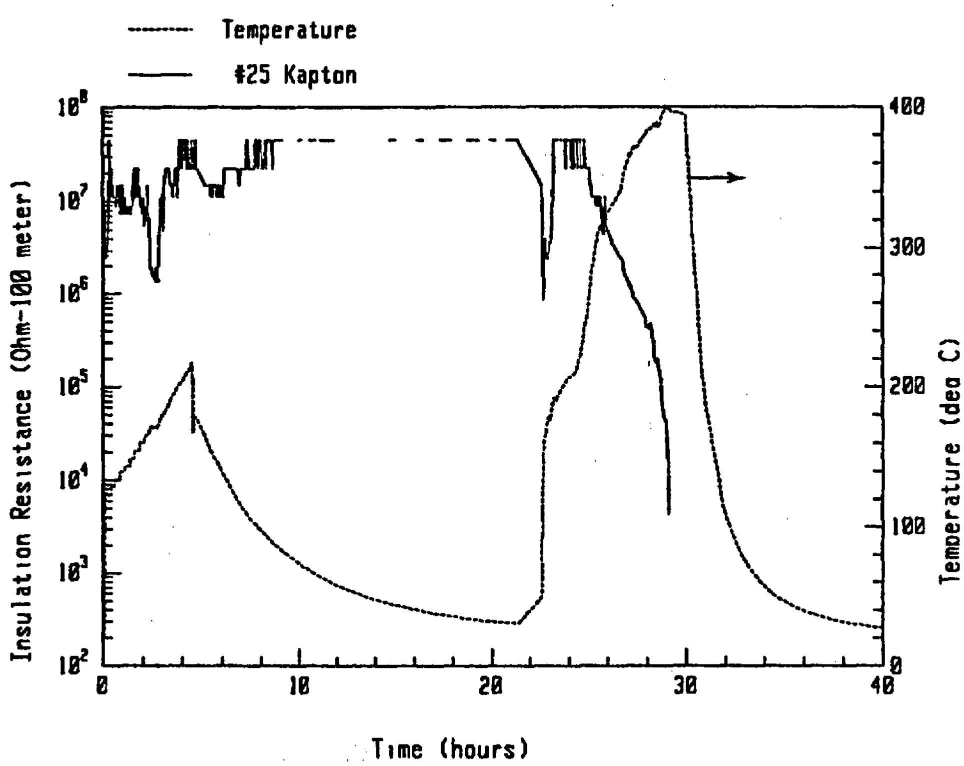

Figure A-20 IR of Champlain Kapton Conductor 20-25 During HTS3

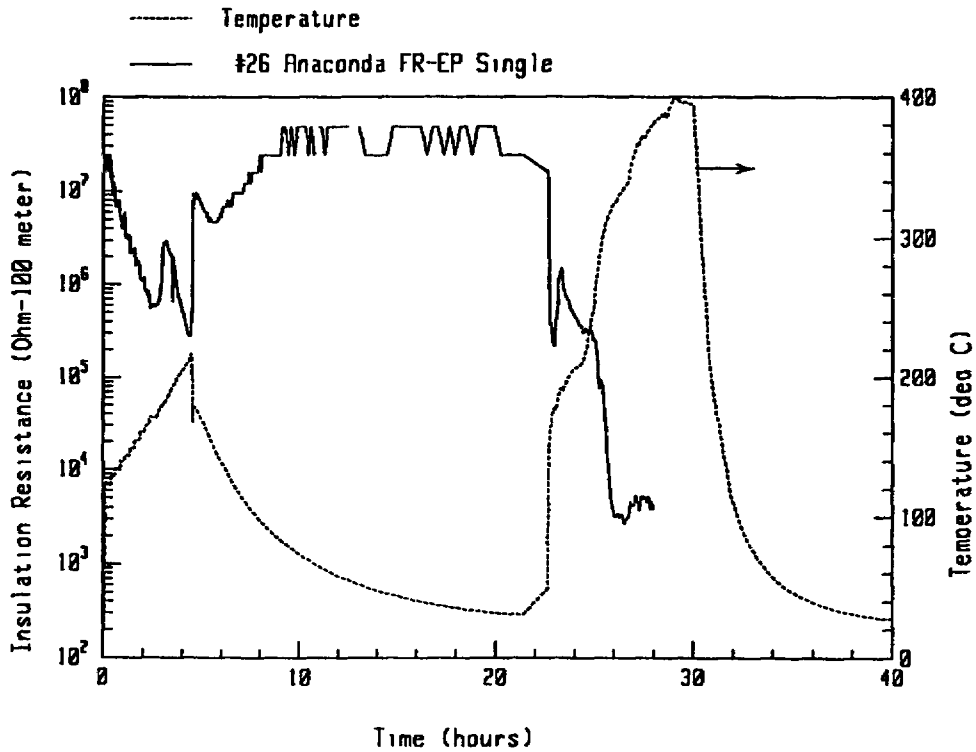

Figure A-21 IR of Anaconda FR-EP Single Conductor 20-26 During HTS3

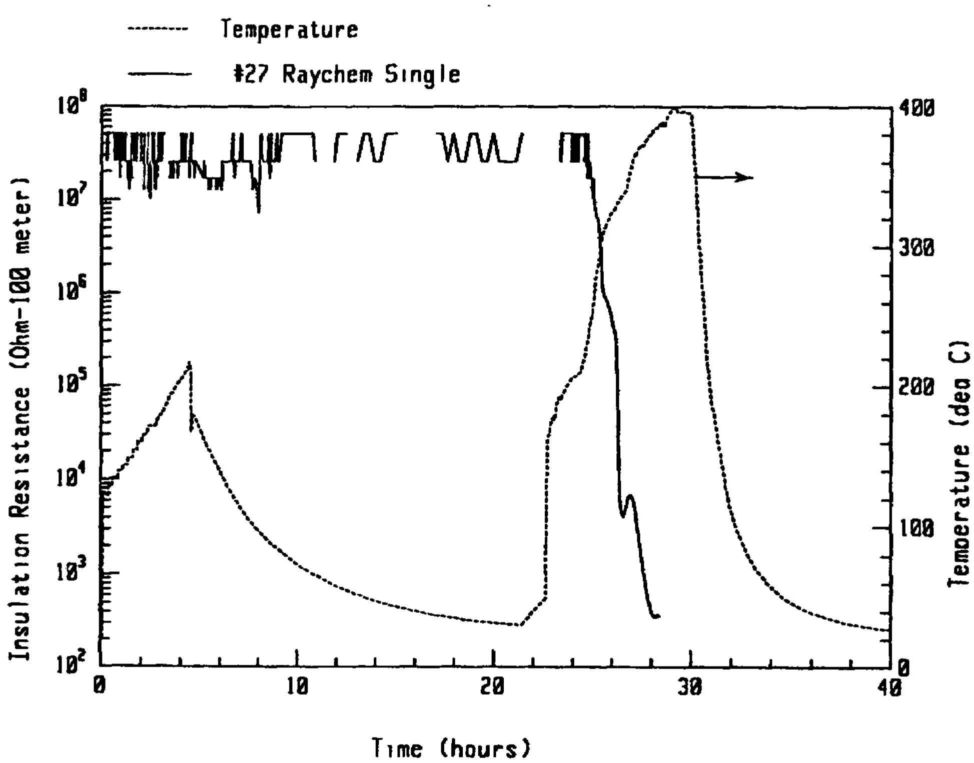

Figure A-22 IR of Raychem Flamtrol Conductor 20-27 During HTS3

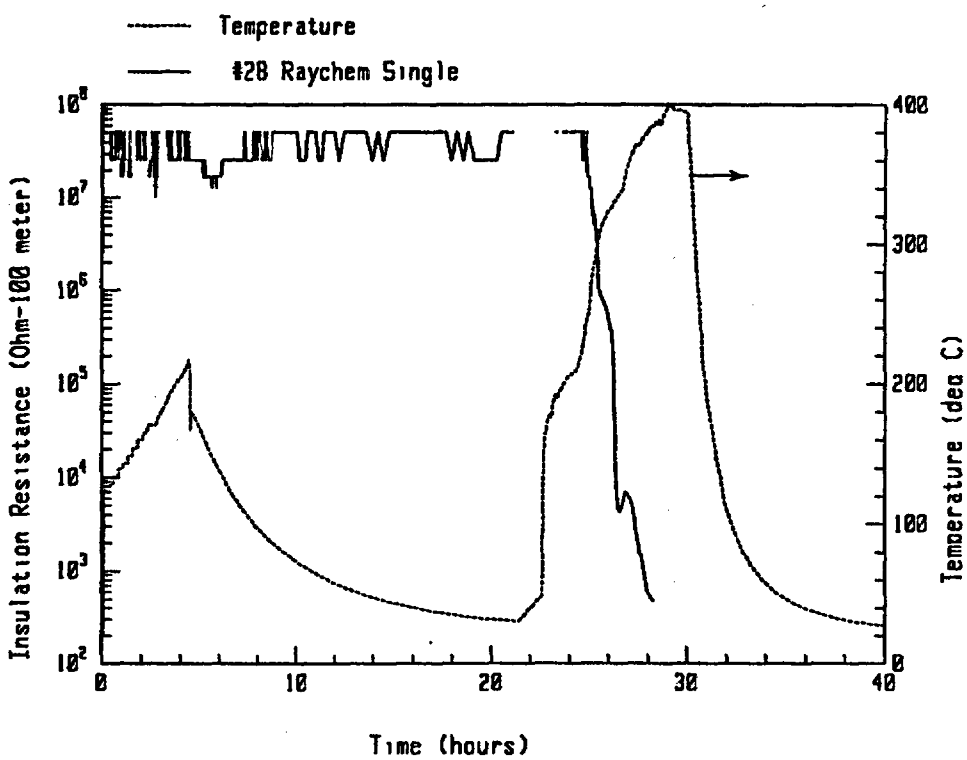

Figure A-23 IR of Raychem Flamtrol Conductor 20-28 During HTS3

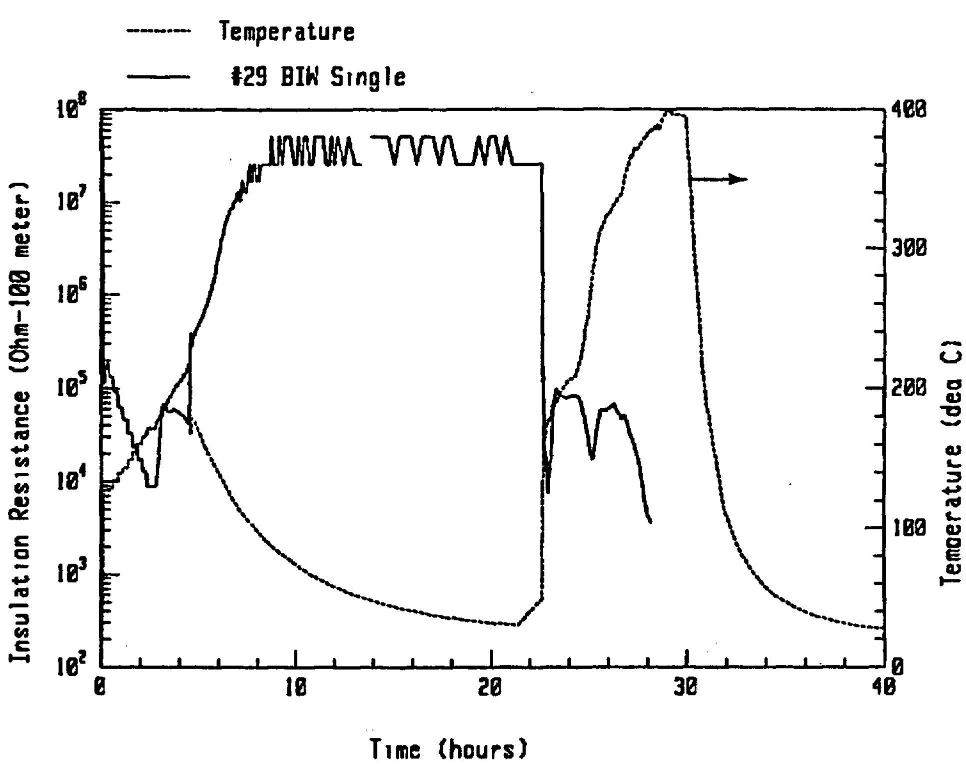

Figure A-24 IR of BIW Single Conductor 20-29 During HTS3

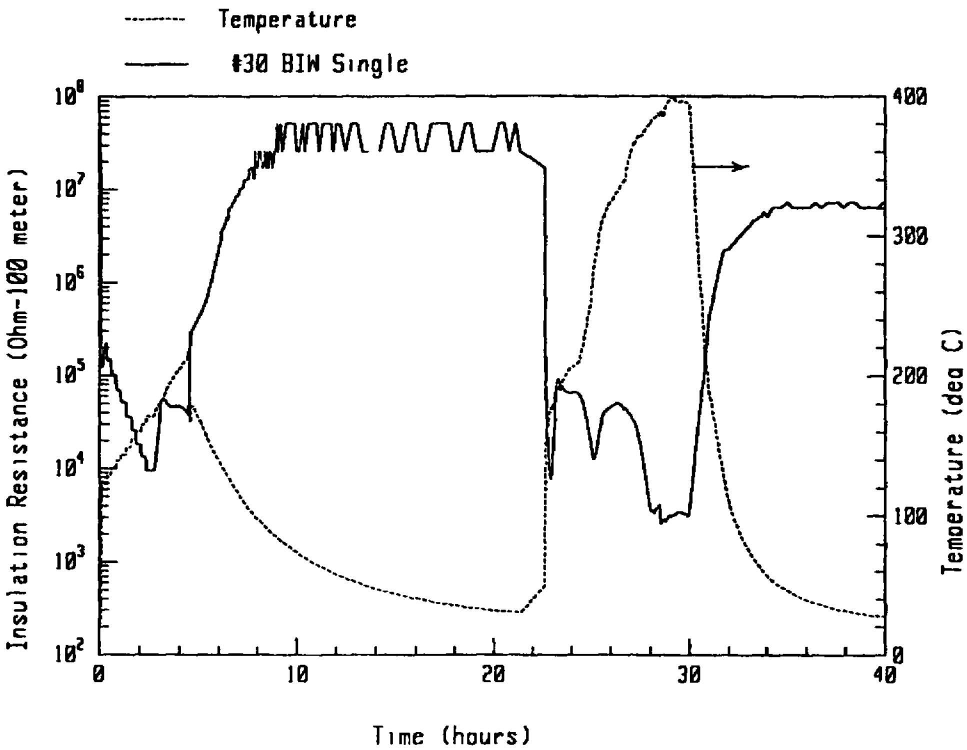

Figure A-25 IR of BIW Single Conductor 20-30 During HTS3

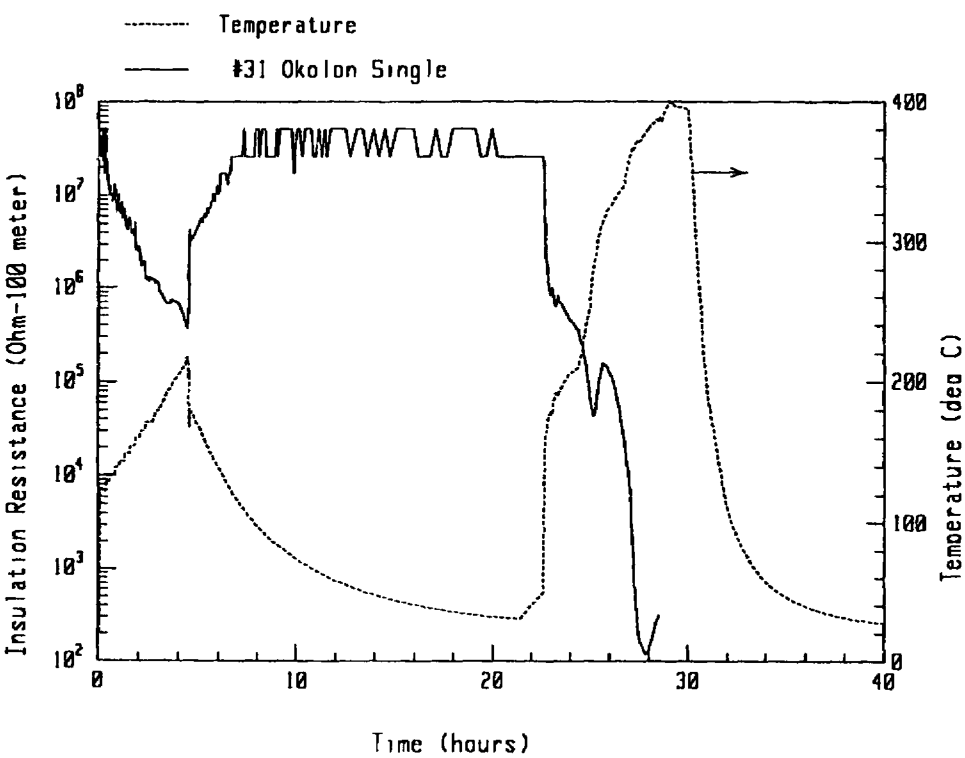

Figure A-26 IR of Okonite Okolon Conductor 20-31 During HTS3

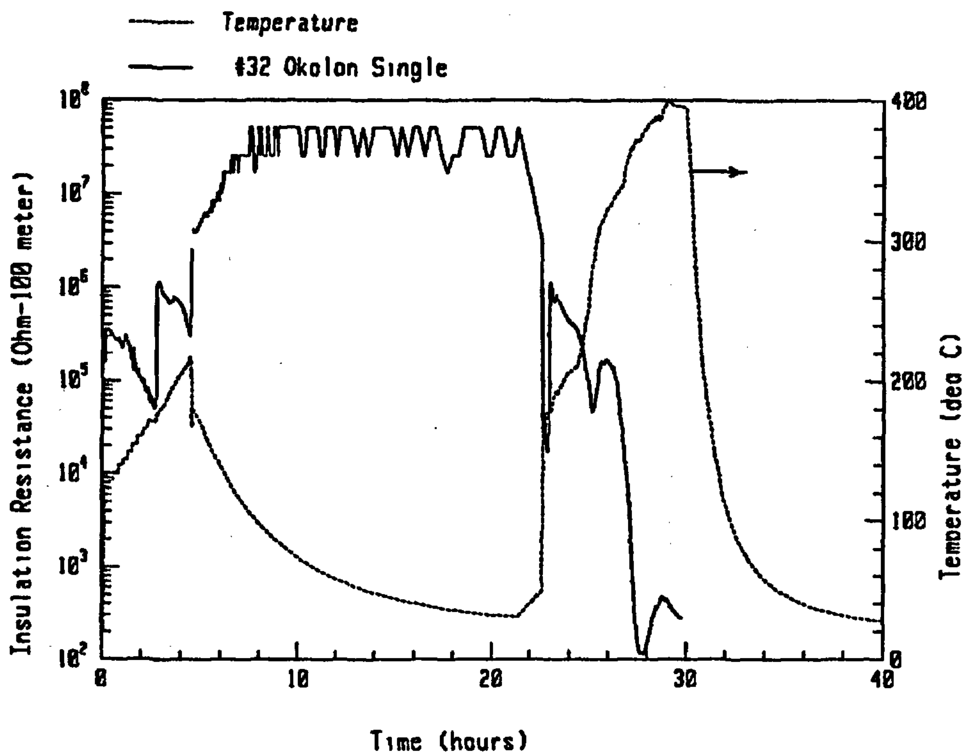

Figure A-27 IR of Okonite Okolon Conductor 20-32 During HTS3

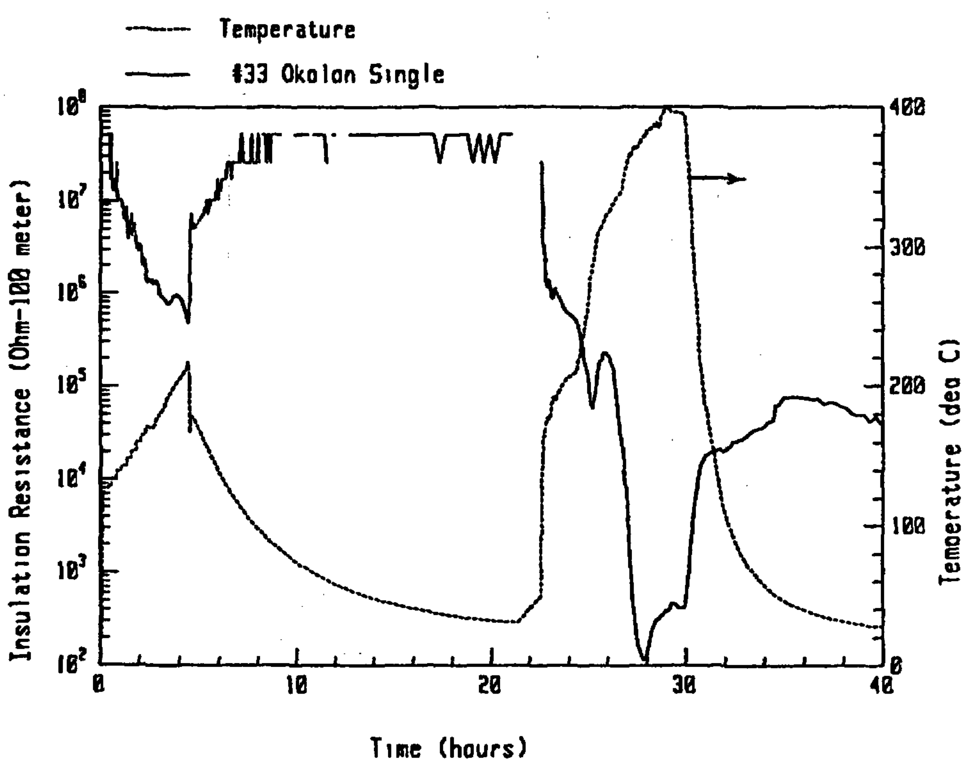

Figure A-28 IR of Okonite Okolon Conductor 20-33 During HTS3

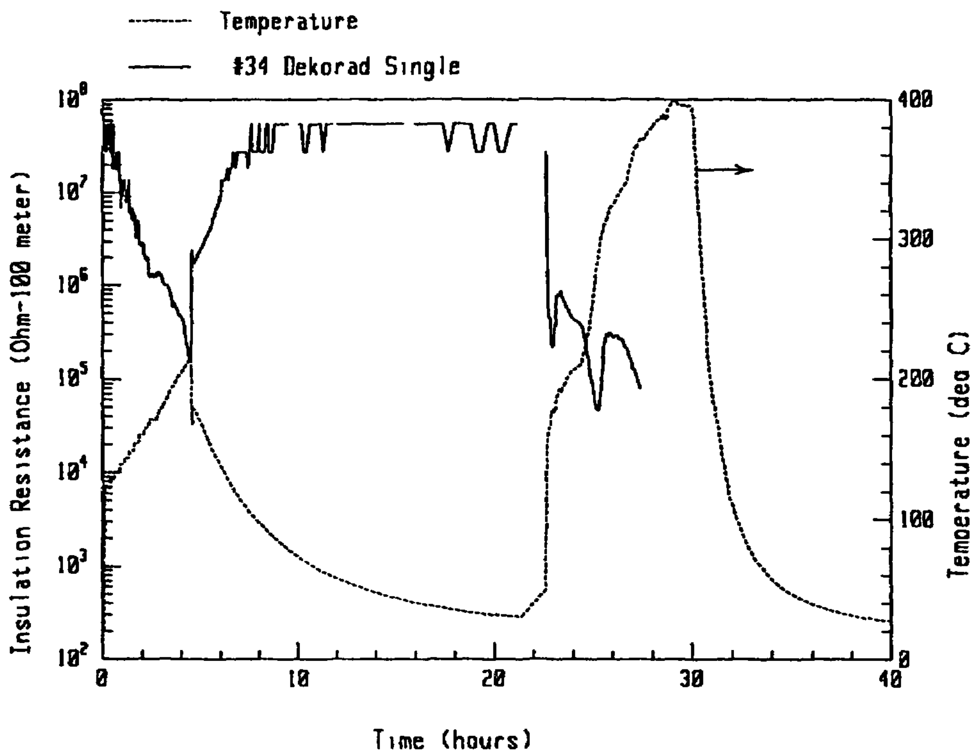

Figure A-29 IR of Dekoron Dekorad Single Conductor 20-34 During HTS3

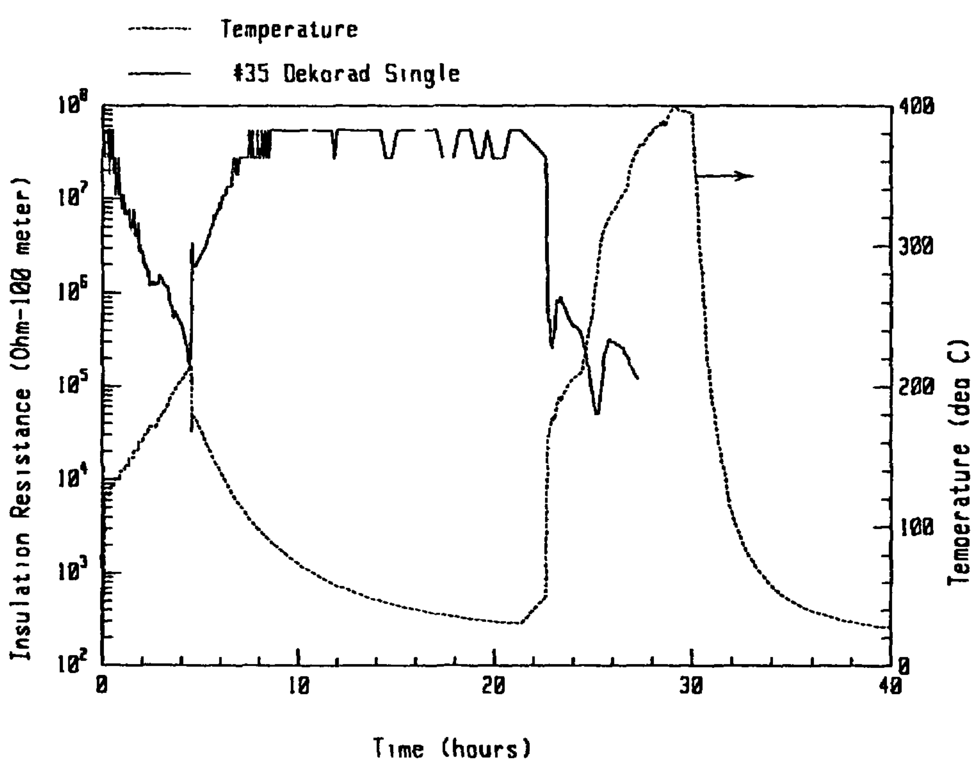

Figure A-30 IR of Dekoron Dekorad Single Conductor 20-35 During HTS3

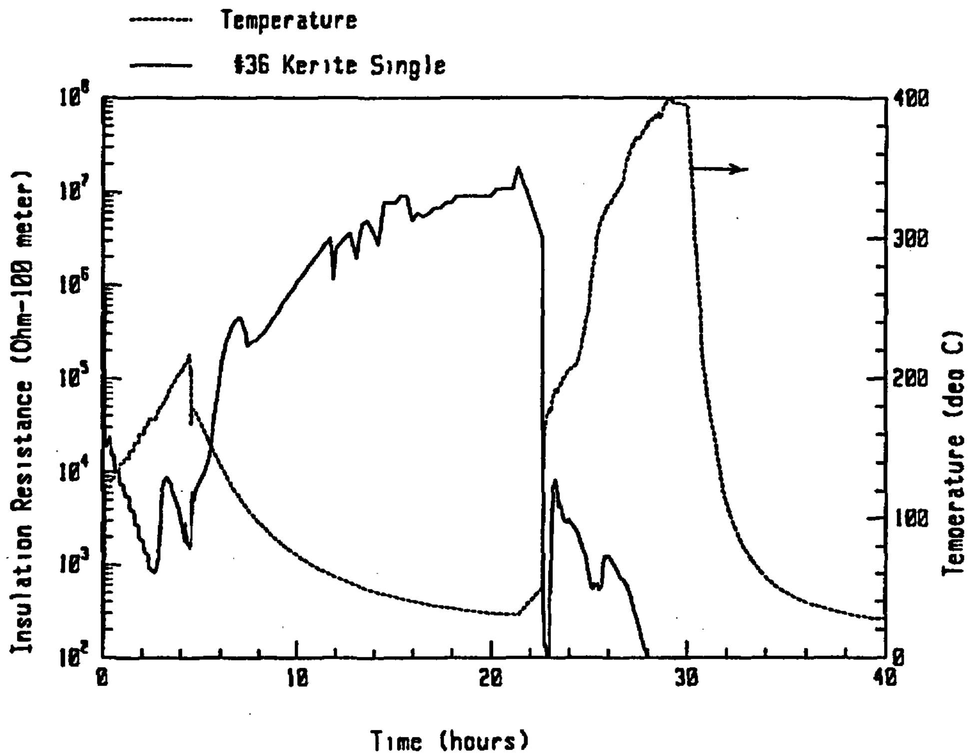

Figure A-31 IR of Kerite Conductor 20-36 During HTS3

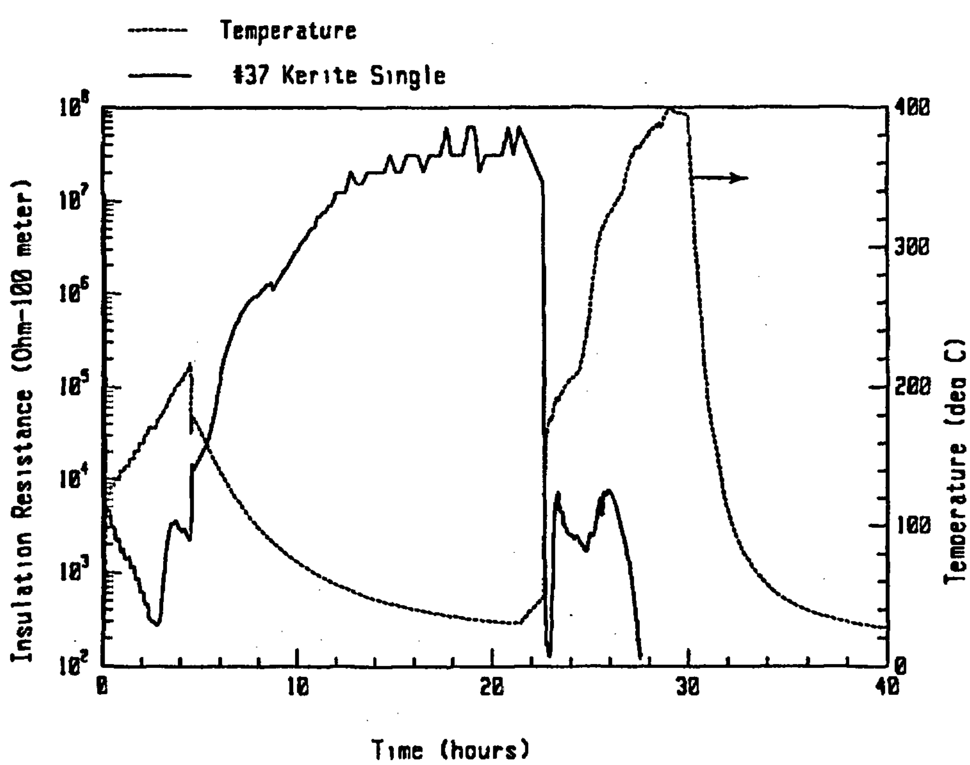

Figure A-32 IR of Kerite Conductor 20-37 During HTS3

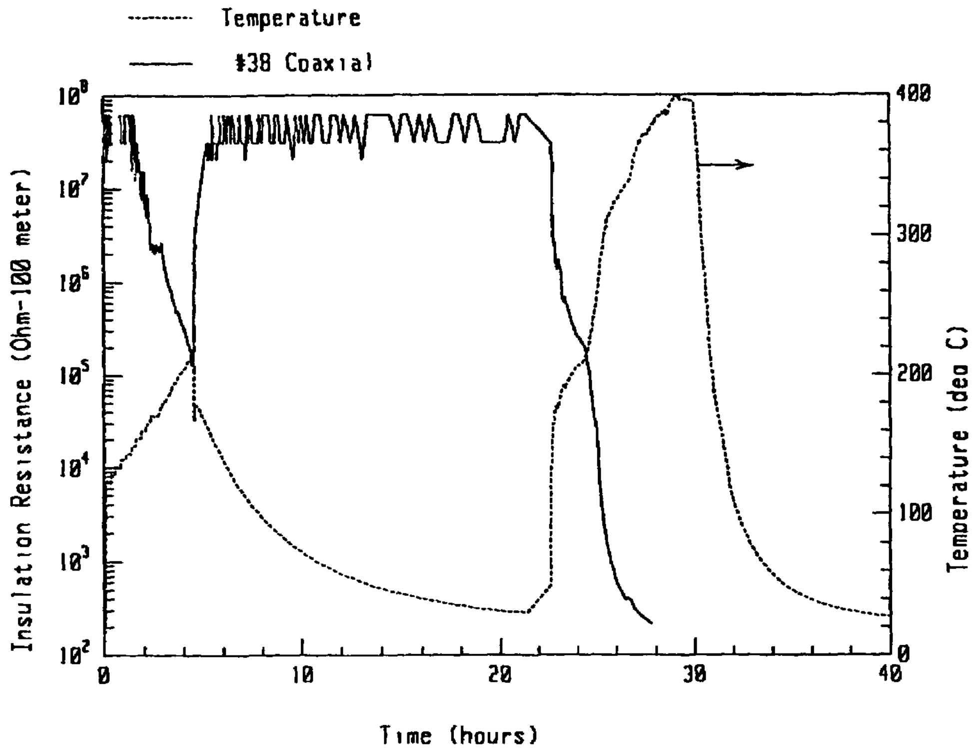

Figure A-33 IR of Rockbestos Coaxial Conductor 20-38 During HTS3

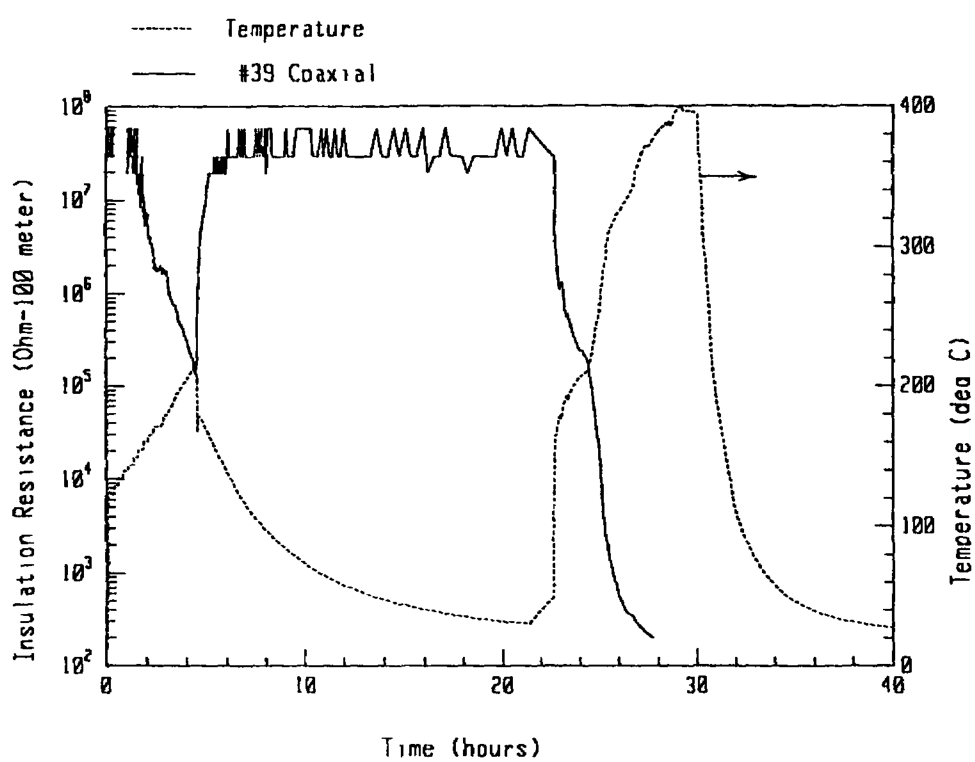

Figure A-34 IR of Rockbestos Coaxial Conductor 20-39 During HTS3

Appendix B Insulation Resistance of each Conductor During Submergence Testing

The plots in this appendix give the insulation resistance of each conductor during submergence. The temperature profile during the submergence exposure is given in Table 5. The data point on each plot at about 1400 hours was measured in a dry environment after the test. The baseline data point (prior to 0 time on the plots) was also measured in a dry environment. Where data is not shown on the plots, the insulation resistance was too low to be measured (see Table 7).

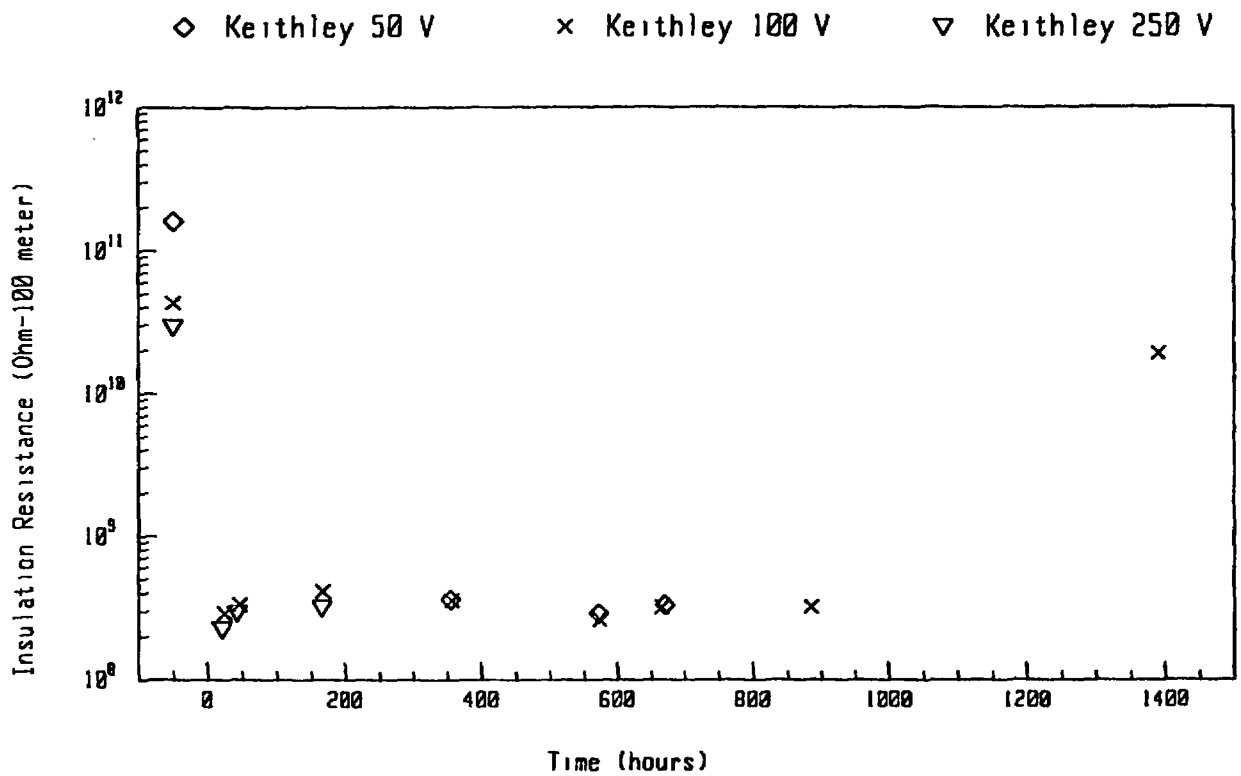

Figure B-1 IR of Brand Rex Conductor 40-1 During Submergence

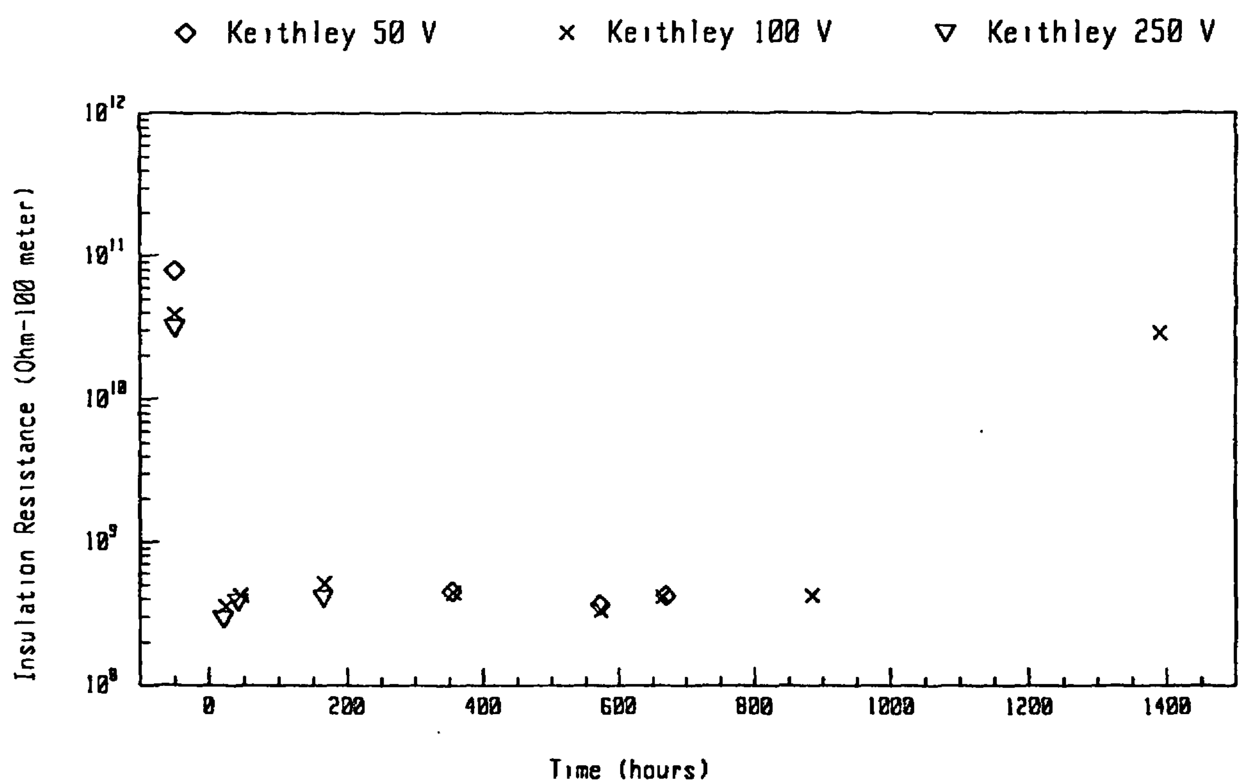

Figure B-2 IR of Brand Rex Conductor 40-2 During Submergence

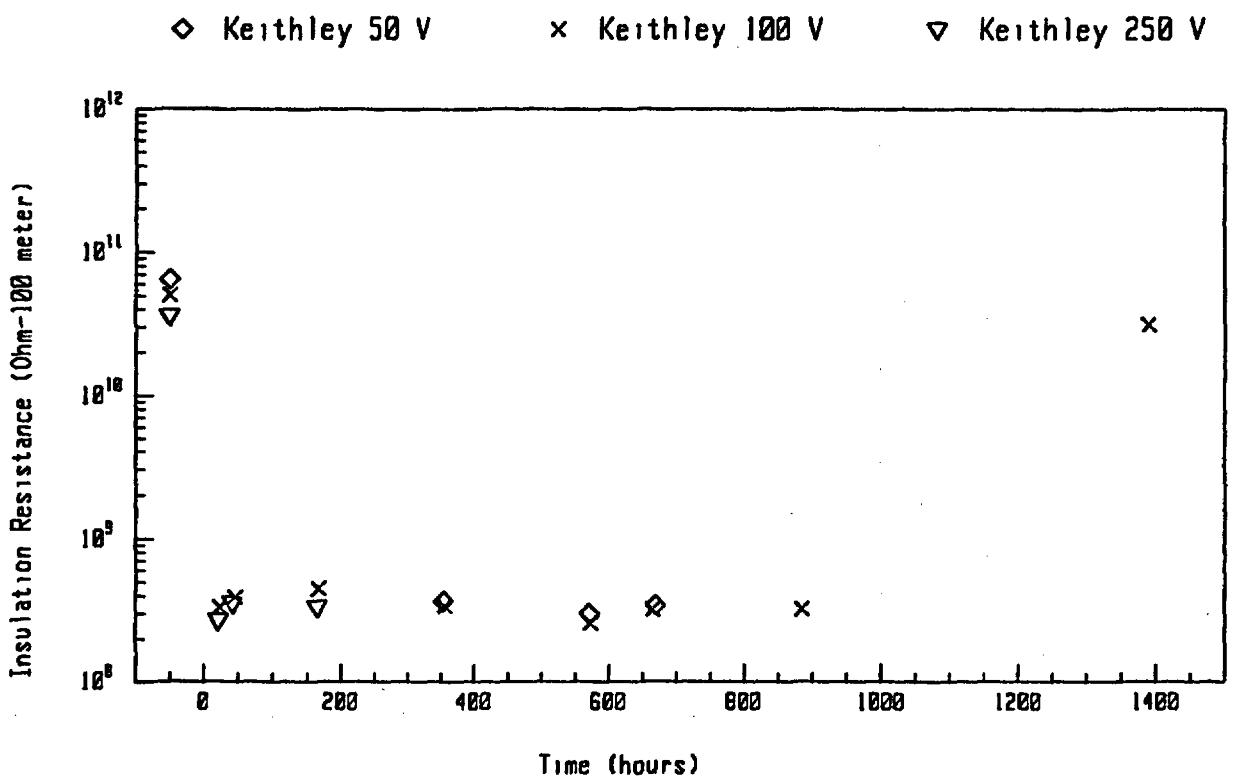

Figure B-3 IR of Brand Rex Conductor 40-3 During Submergence

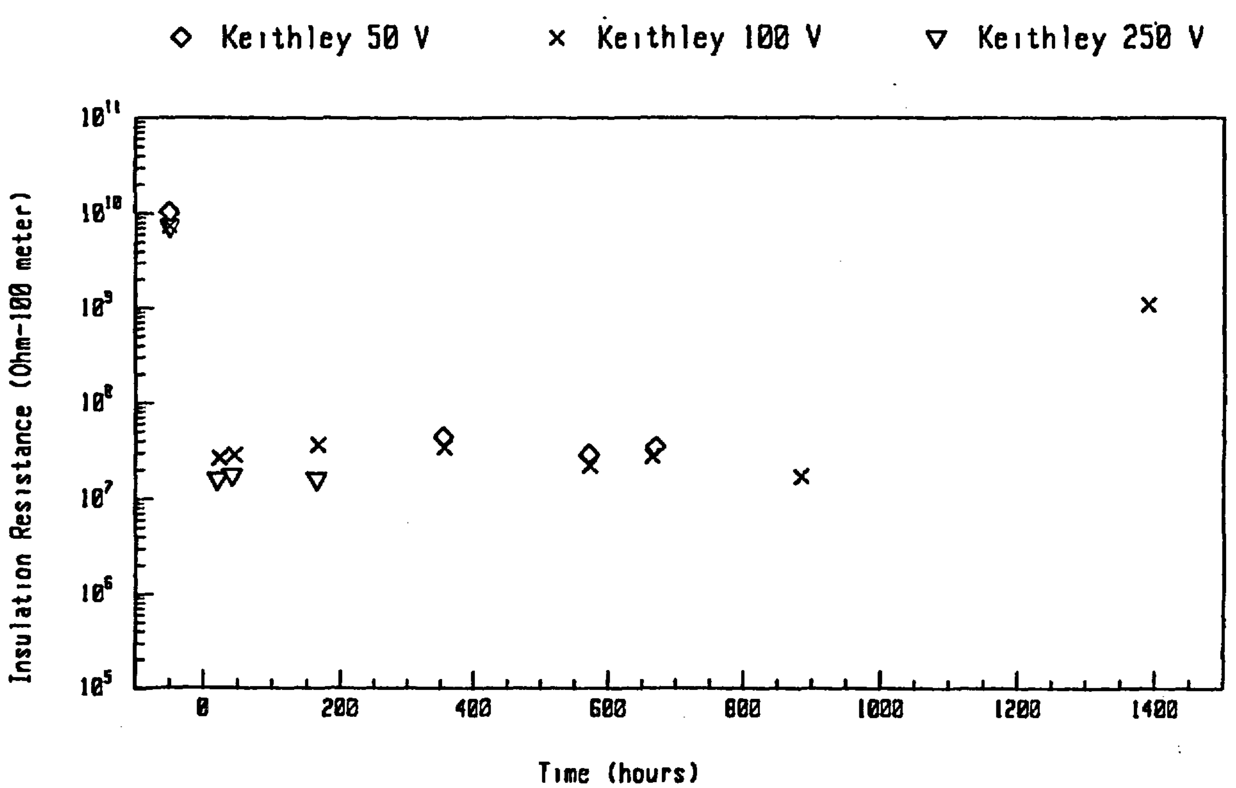

Figure B-4 IR of Anaconda Conductor 40-4 During Submergence

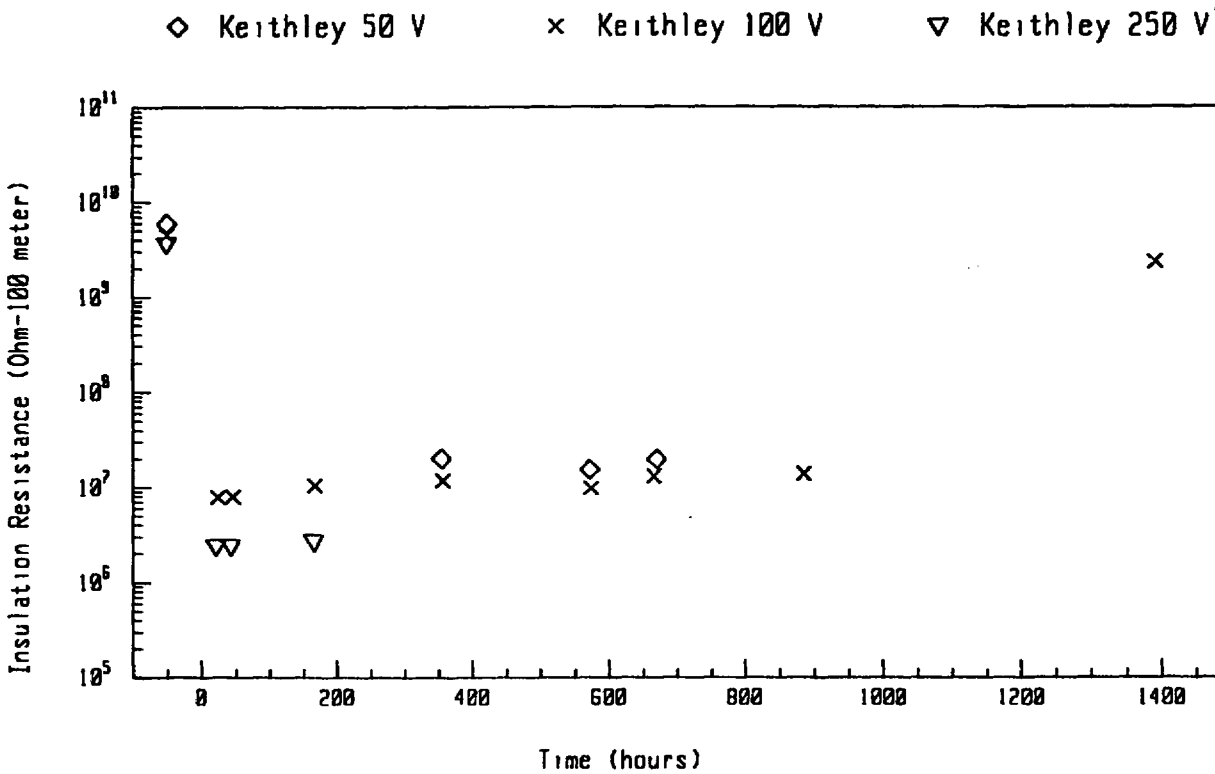

Figure B-5 IR of Anaconda Conductor 40-5 During Submergence

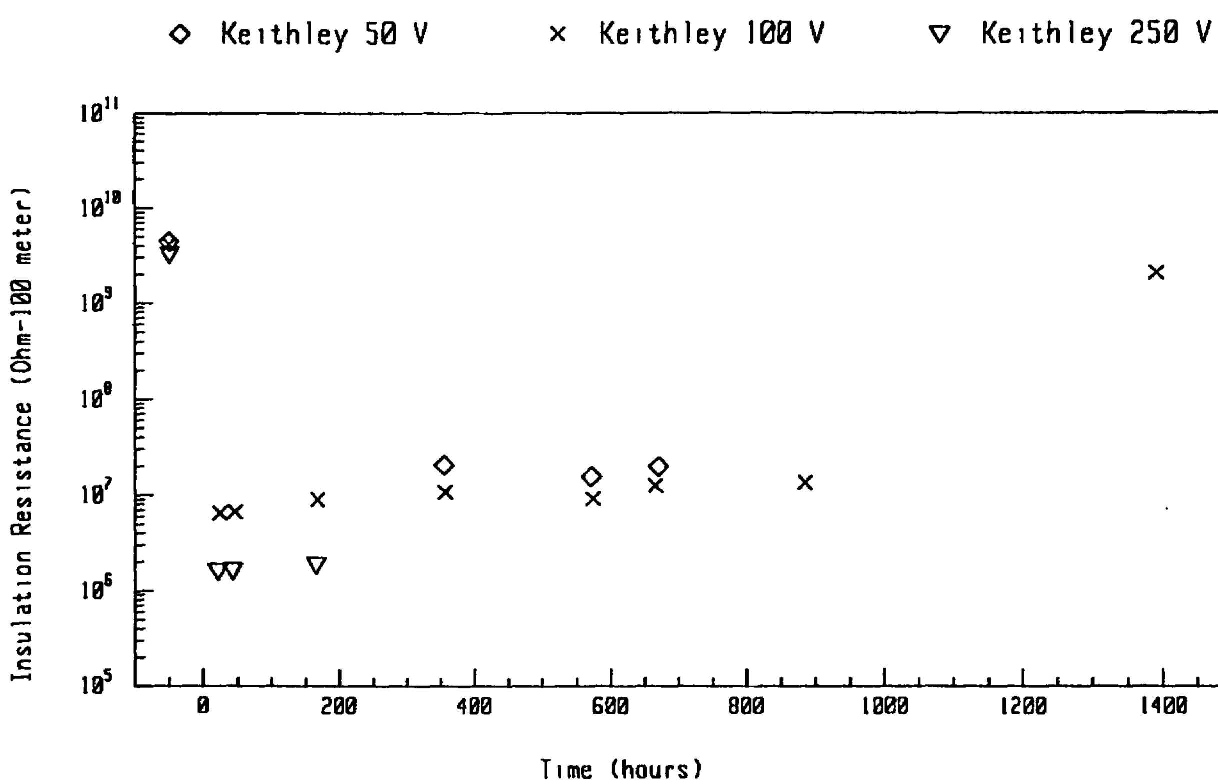

Figure B-6 IR of Anaconda Conductor 40-6 During Submergence

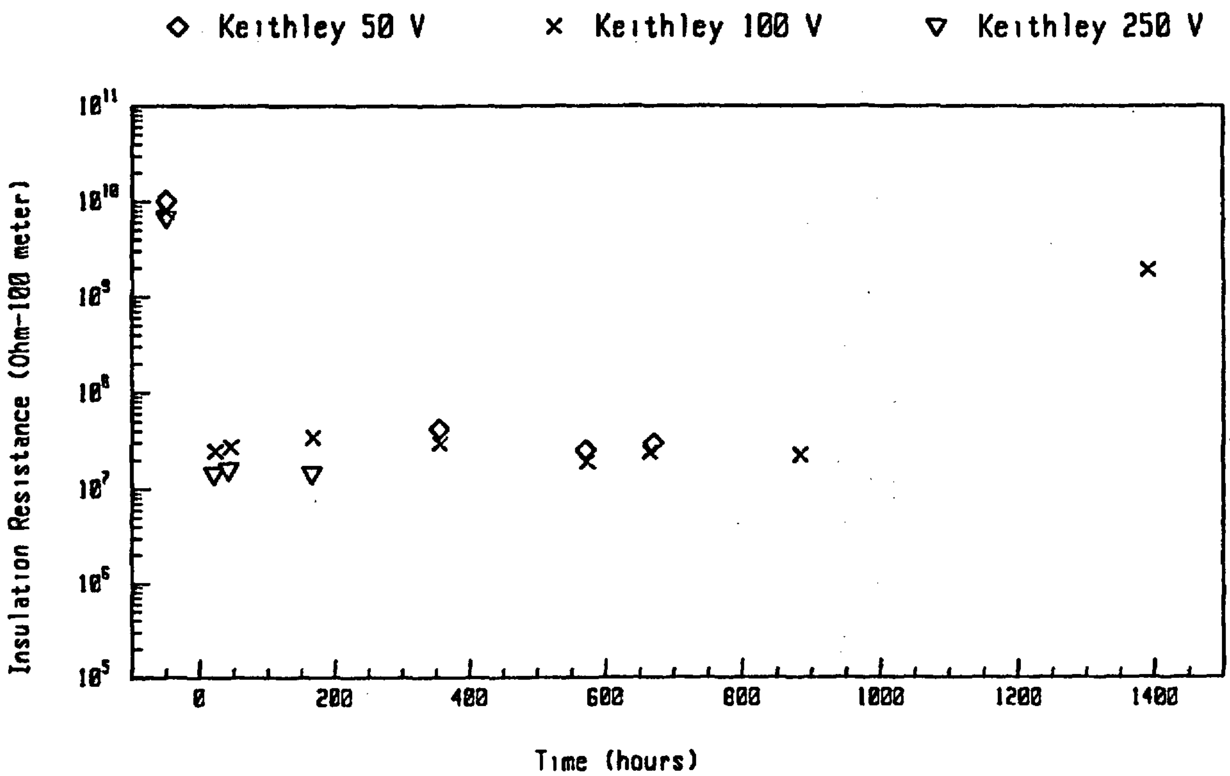

Figure B-7 IR of Anaconda Conductor 40-7 During Submergence

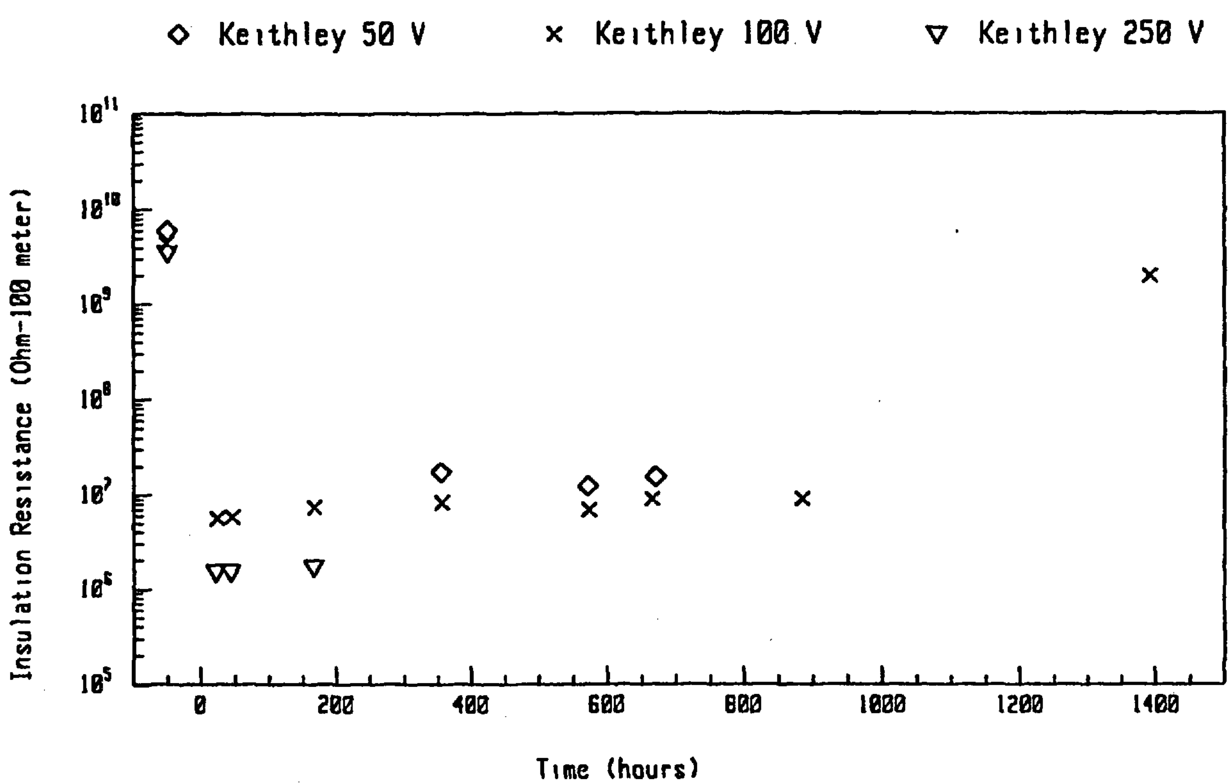

Figure B-8 IR of Anaconda Conductor 40-8 During Submergence

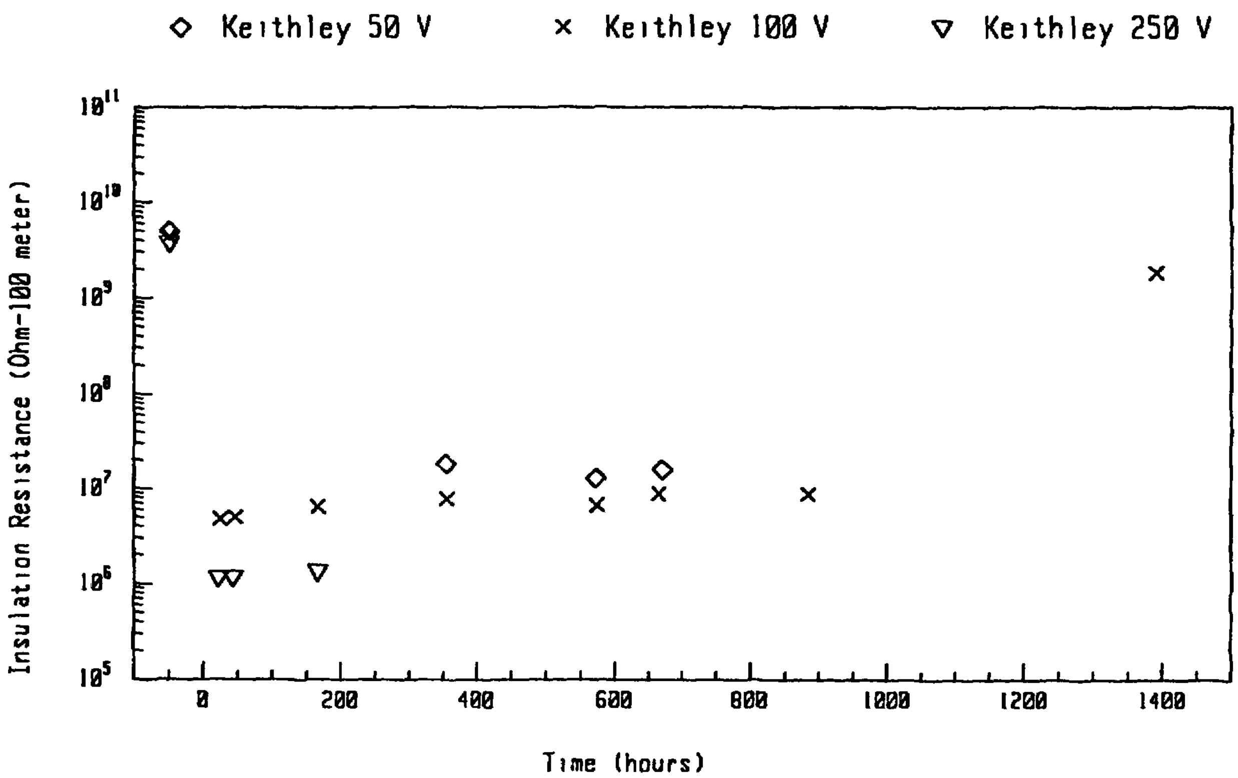

Figure B-9 IR of Anaconda Conductor 40-9 During Submergence

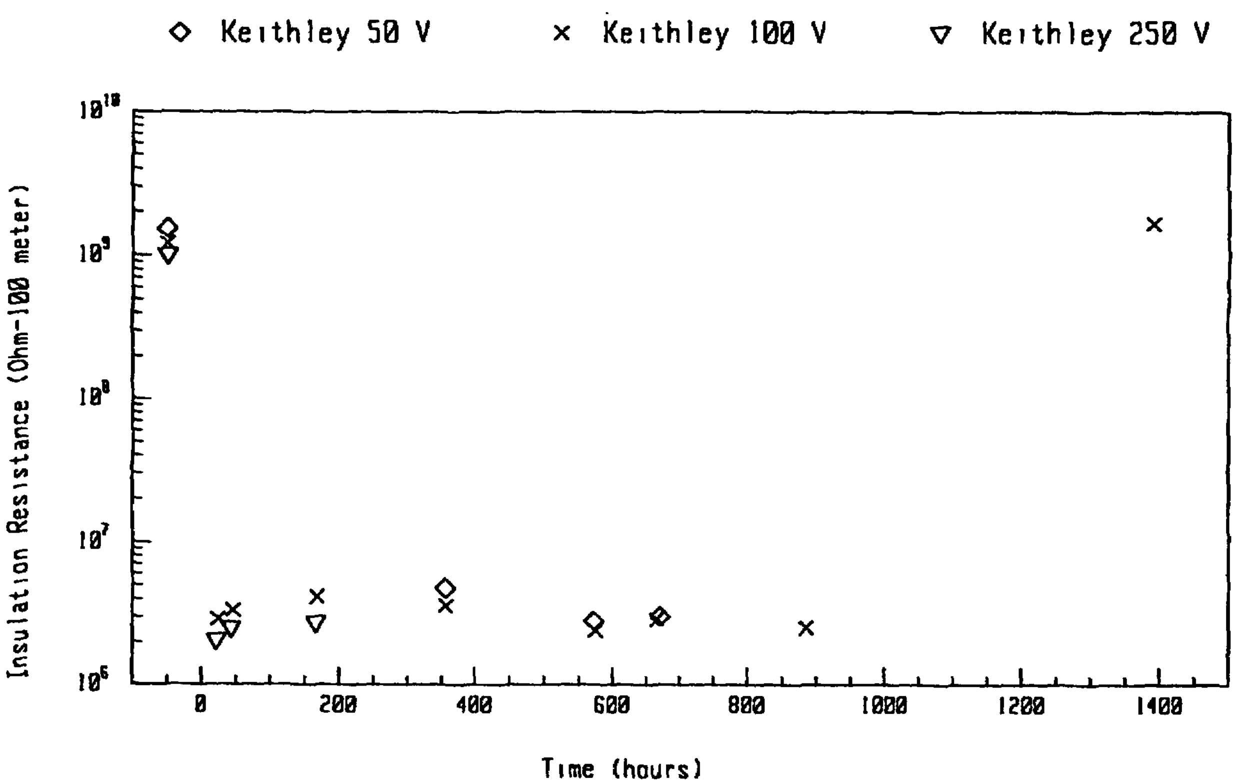

Figure B-10 IR of BIW Conductor 40-10 During Submergence

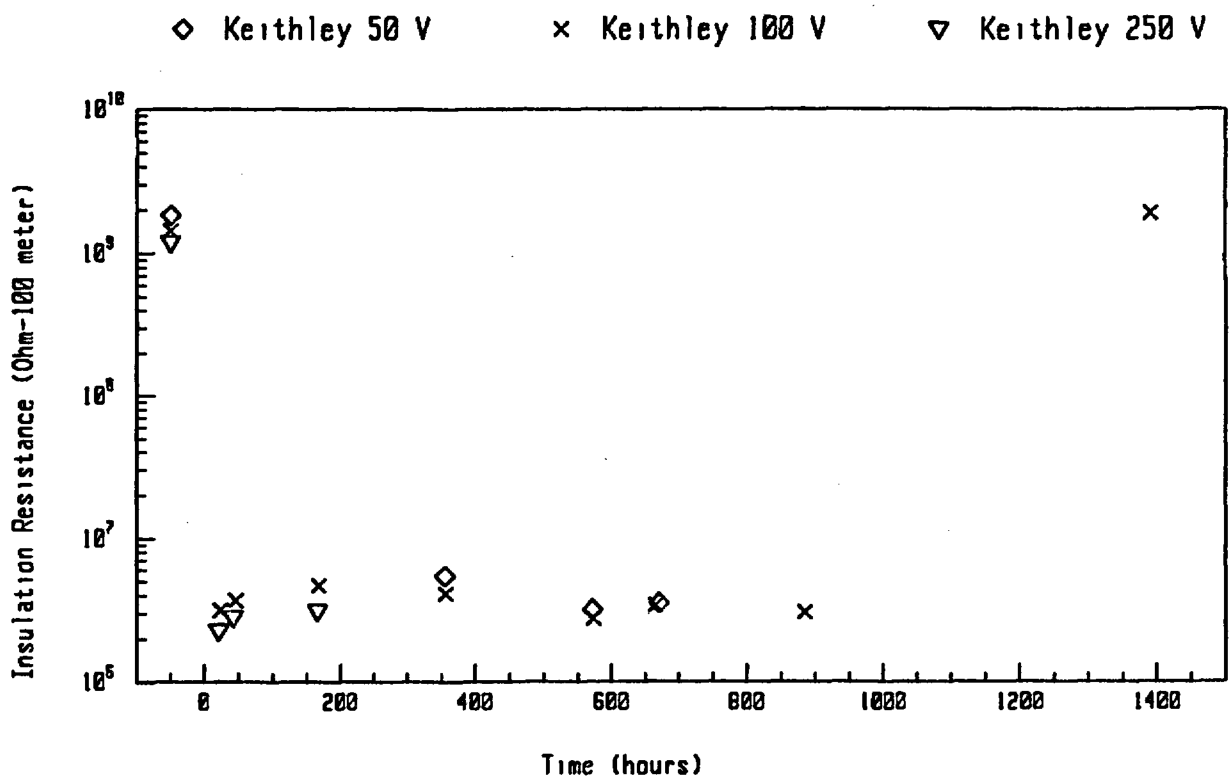

Figure B-11 IR of BIW Conductor 40-11 During Submergence

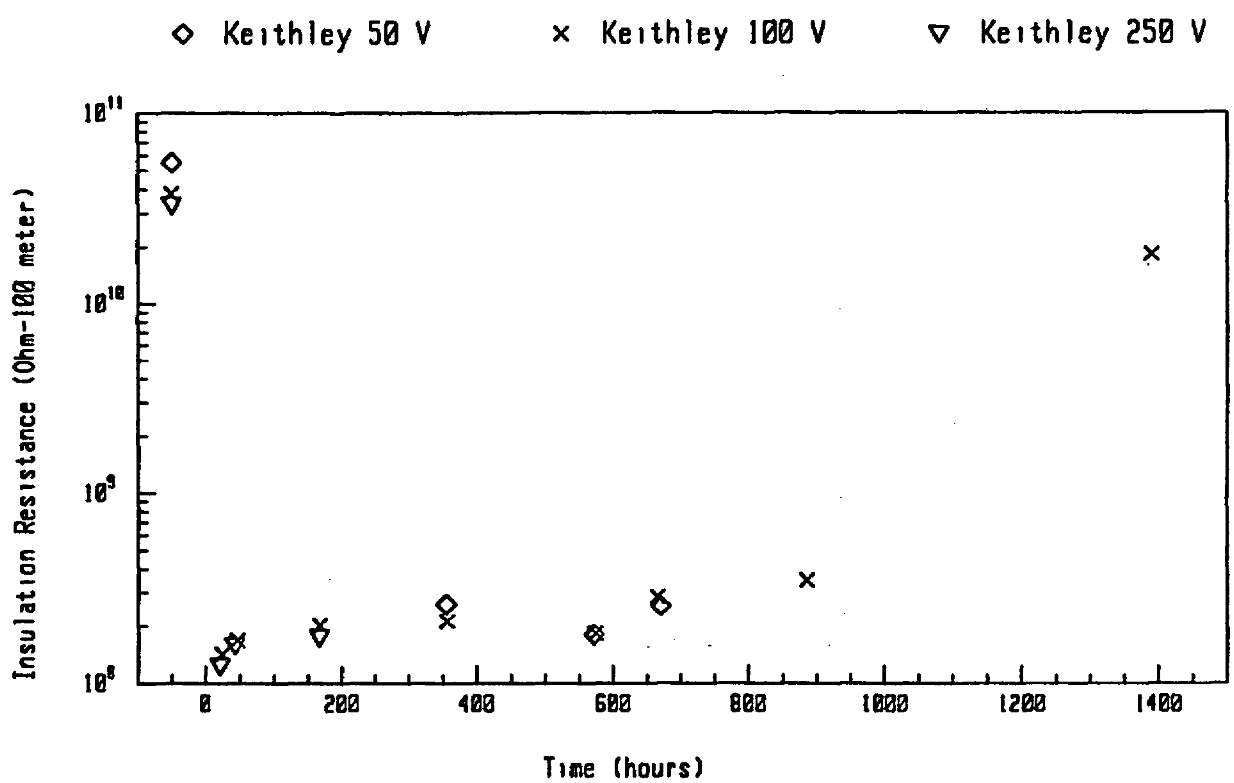

Figure B-12 IR of Rockbestos Conductor 40-12 During Submergence

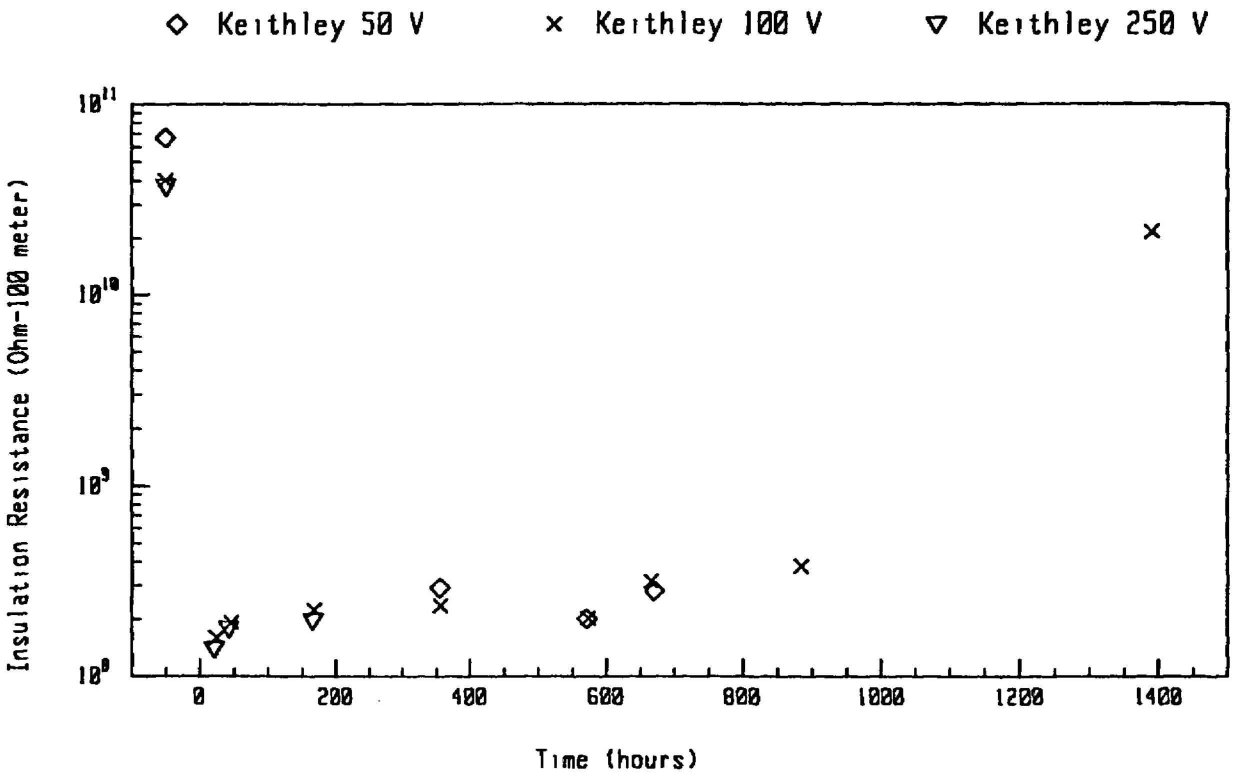

Figure B-13 IR of Rockbestos Conductor 40-13 During Submergence

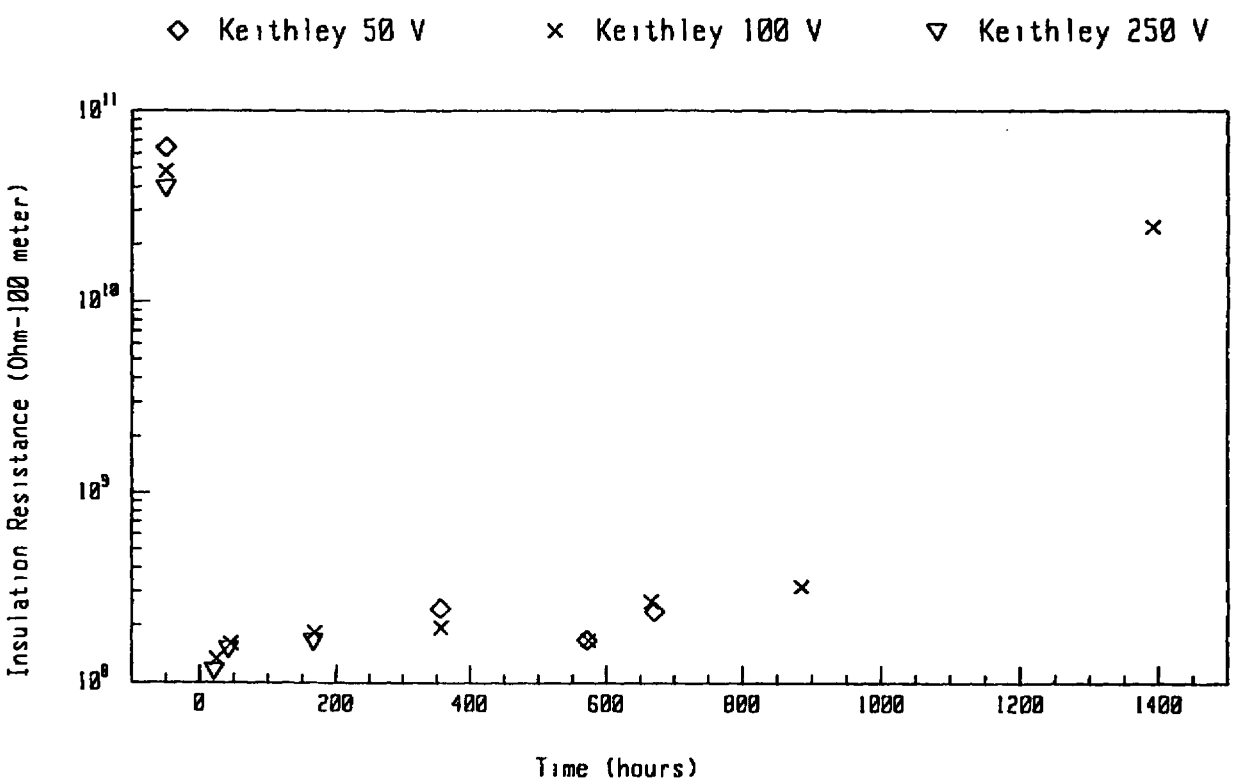

Figure B-14 IR of Rockbestos Conductor 40-14 During Submergence

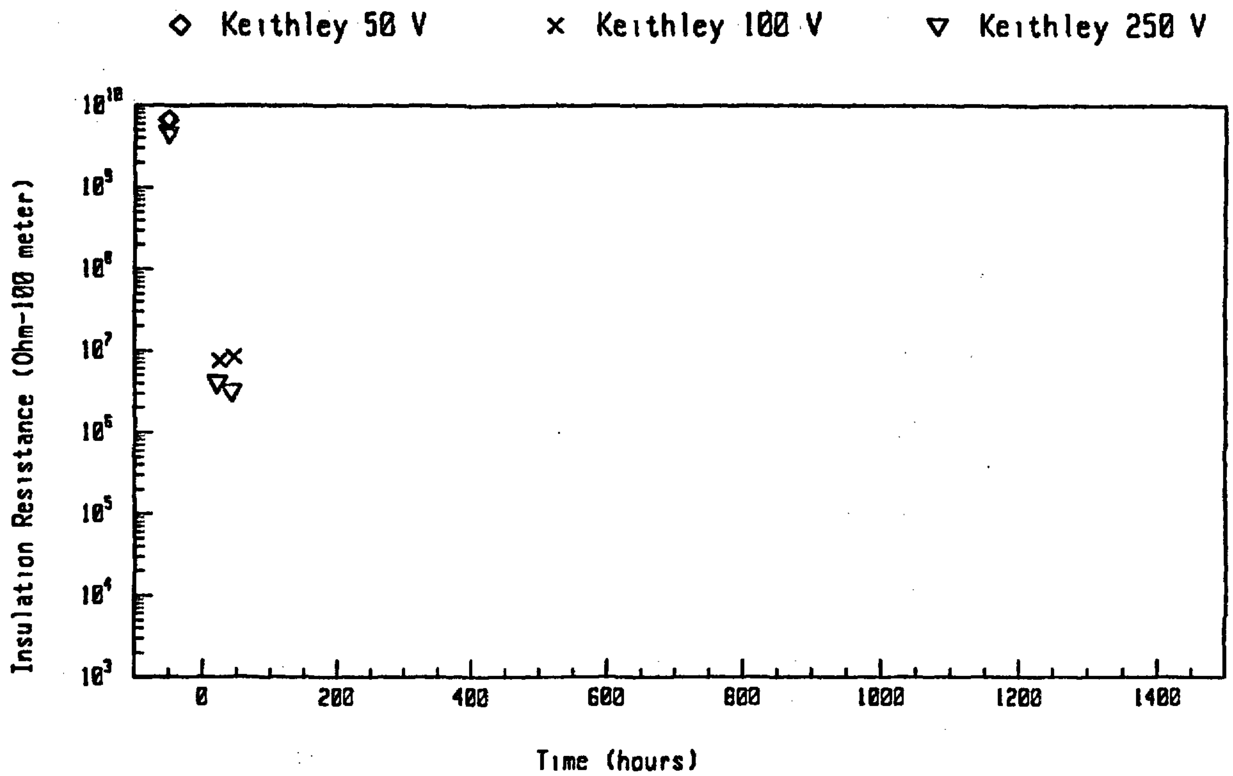

Figure B-15 IR of Dekorad Conductor 40-15 During Submergence

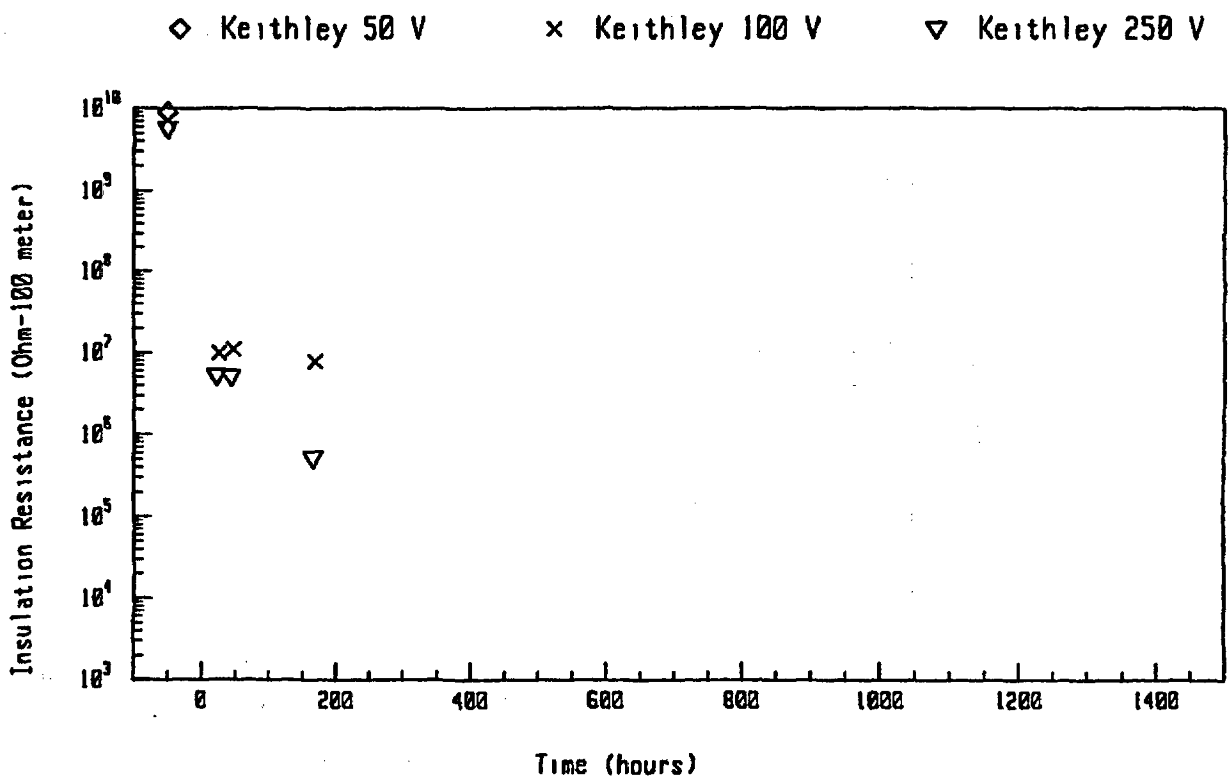

Figure B-16 IR of Dekorad Conductor 40-16 During Submergence

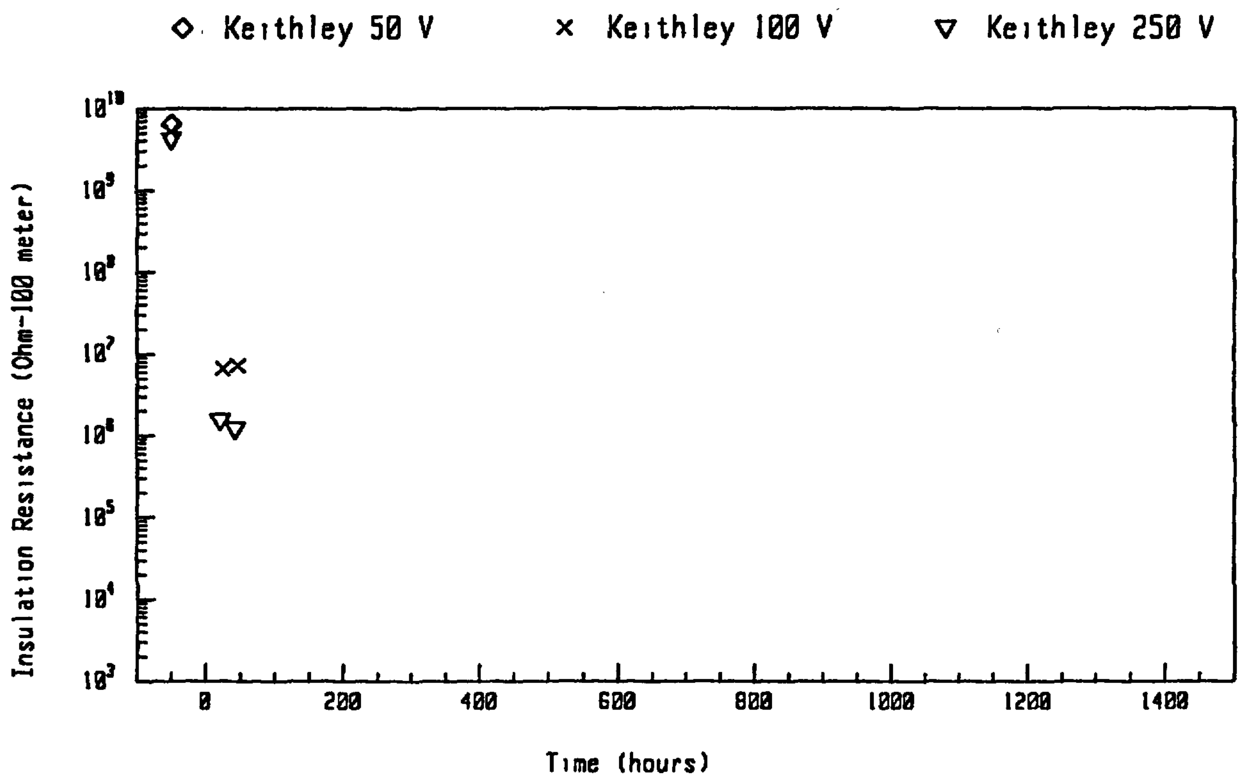

Figure B-17 IR of Dekorad Conductor 40-17 During Submergence

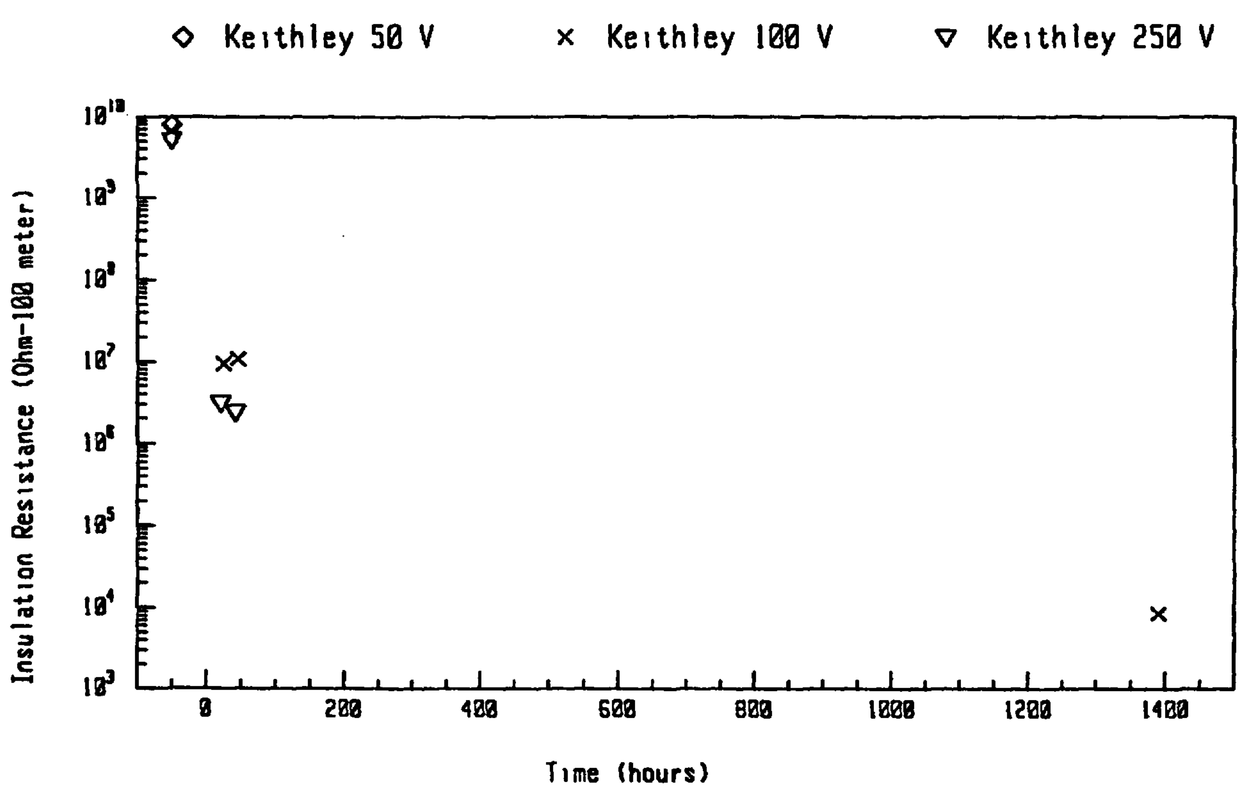

Figure B-18 IR of Dekorad Conductor 40-18 During Submergence

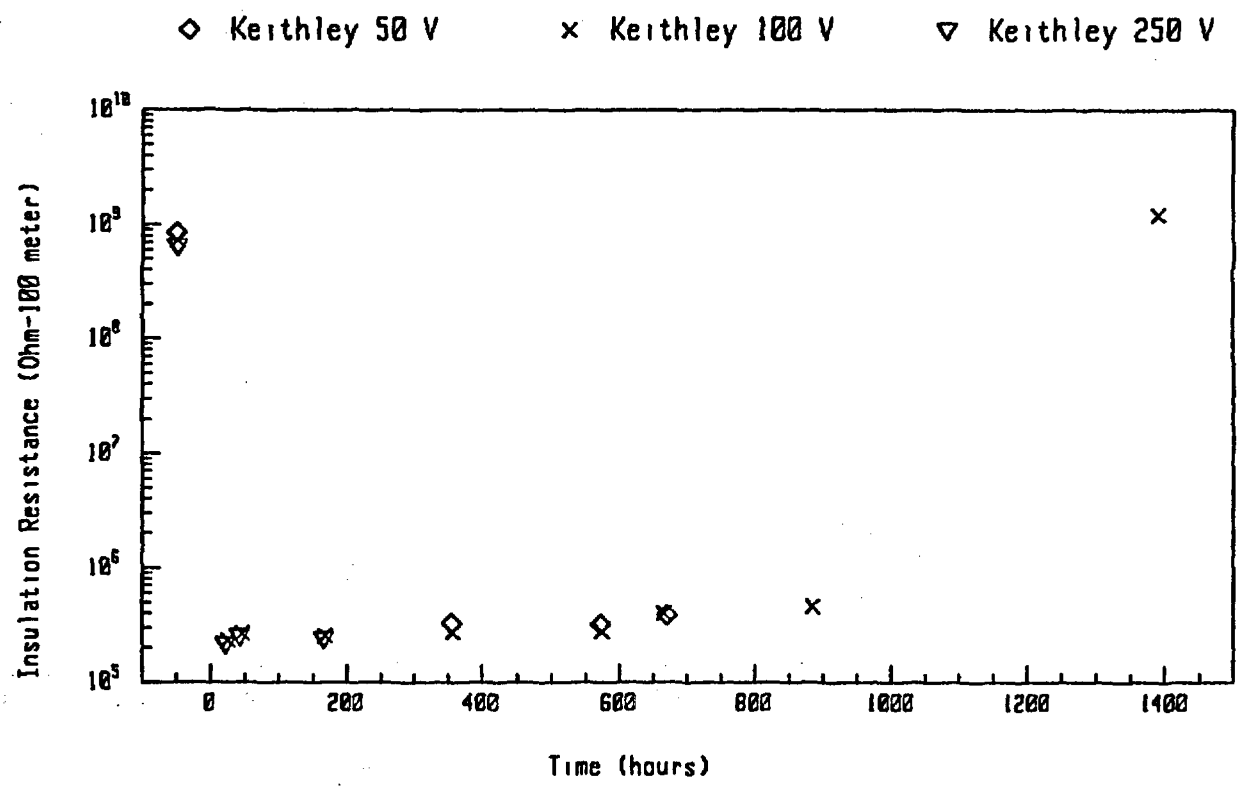

Figure B-19 IR of Polyset Conductor 40-19 During Submergence

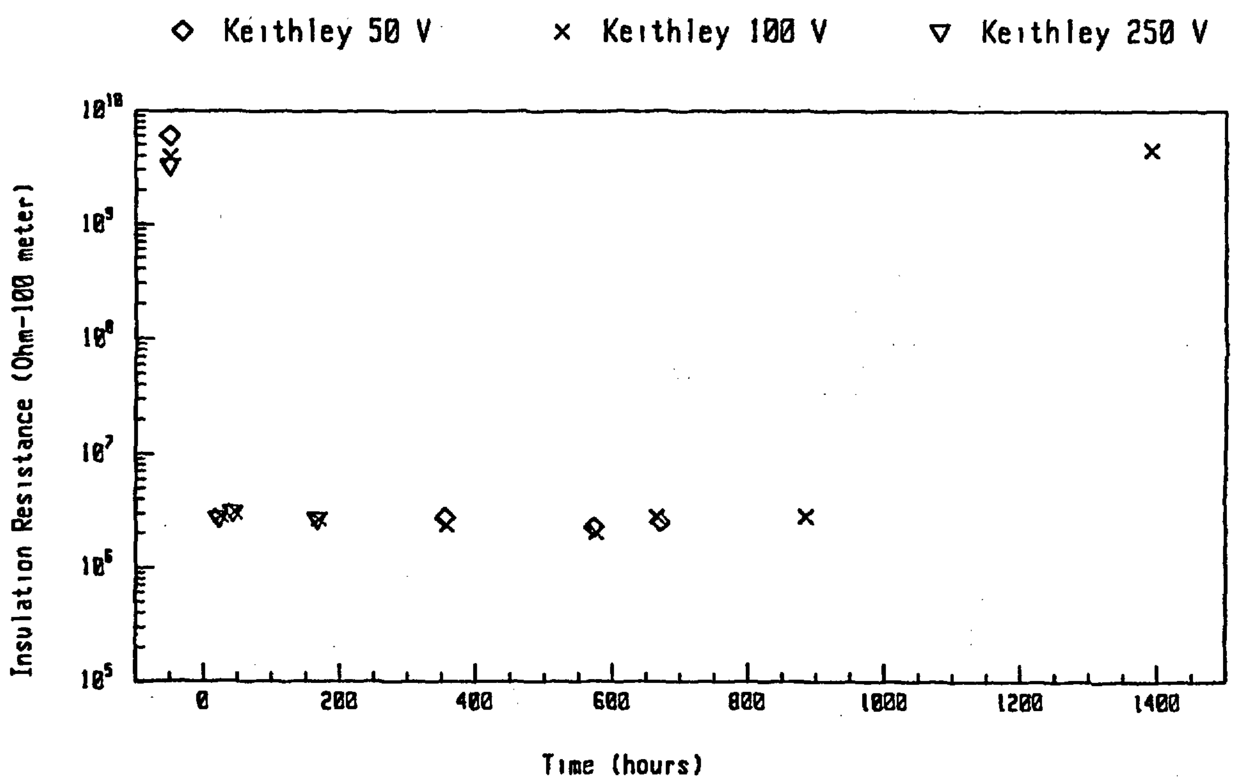

Figure B-20 IR of Polyset Conductor 40-20 During Submergence

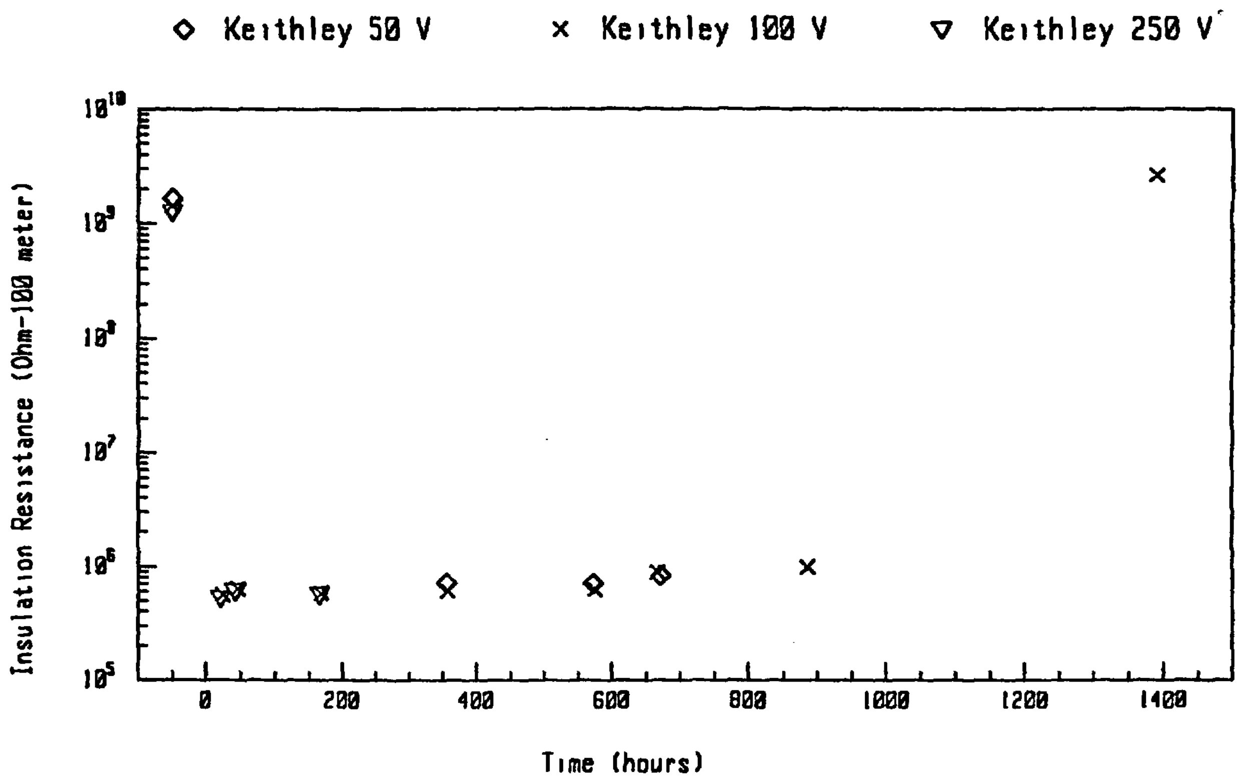

Figure B-21 IR of Polyset Conductor 40-21 During Submergence

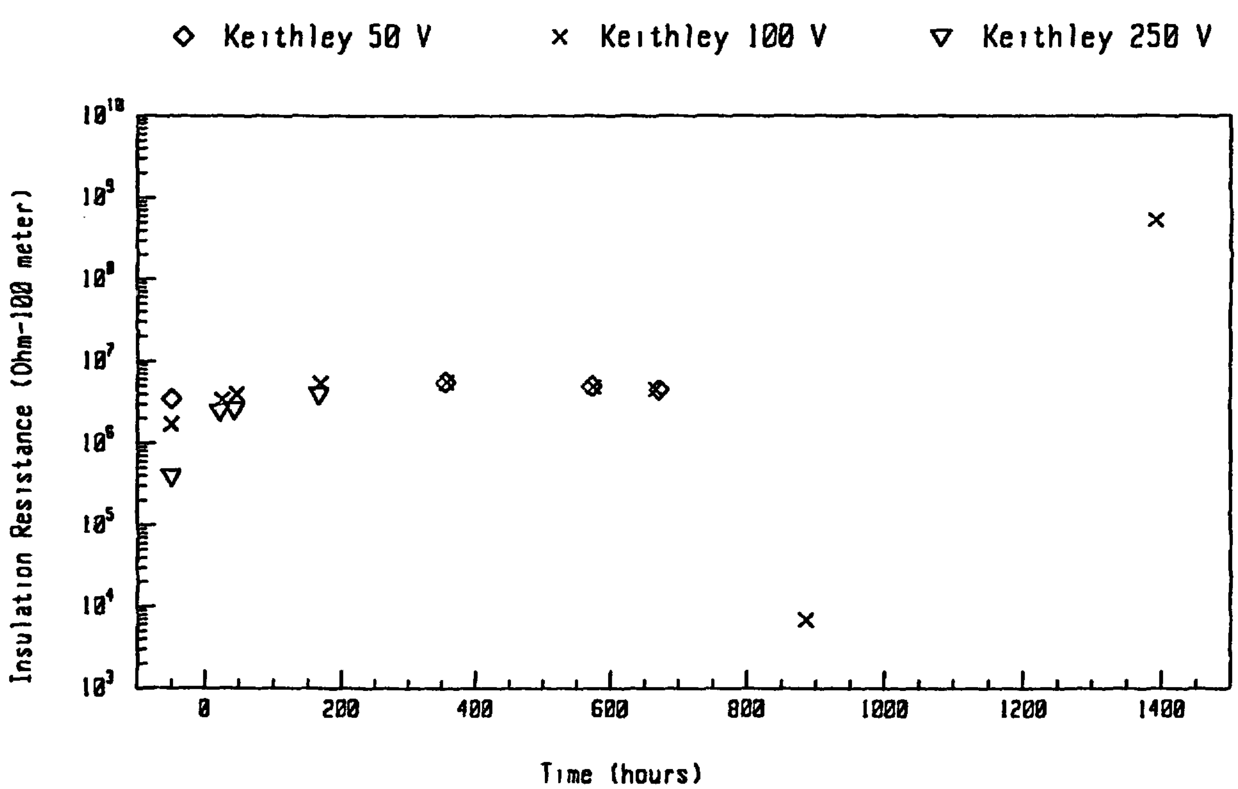

Figure B-22 IR of Silicone Conductor 40-22 During Submergence

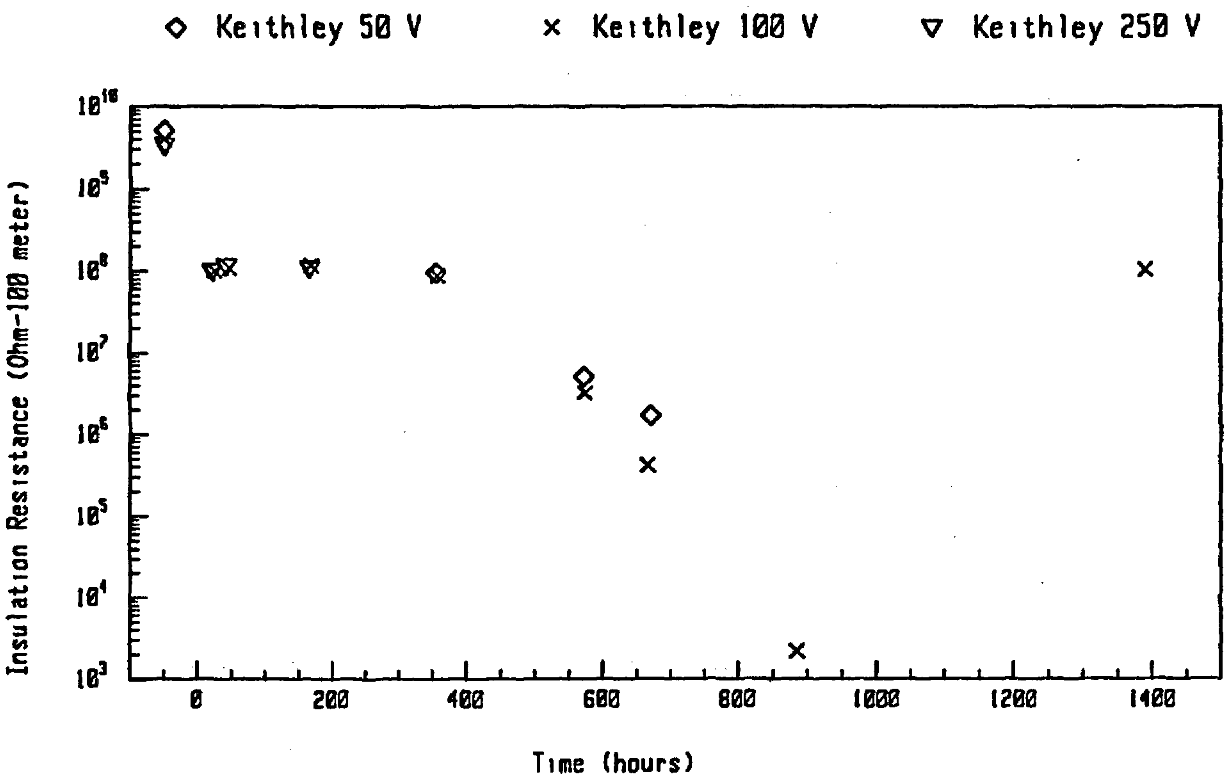

Figure B-23 IR of Silicone Conductor 40-23 During Submergence

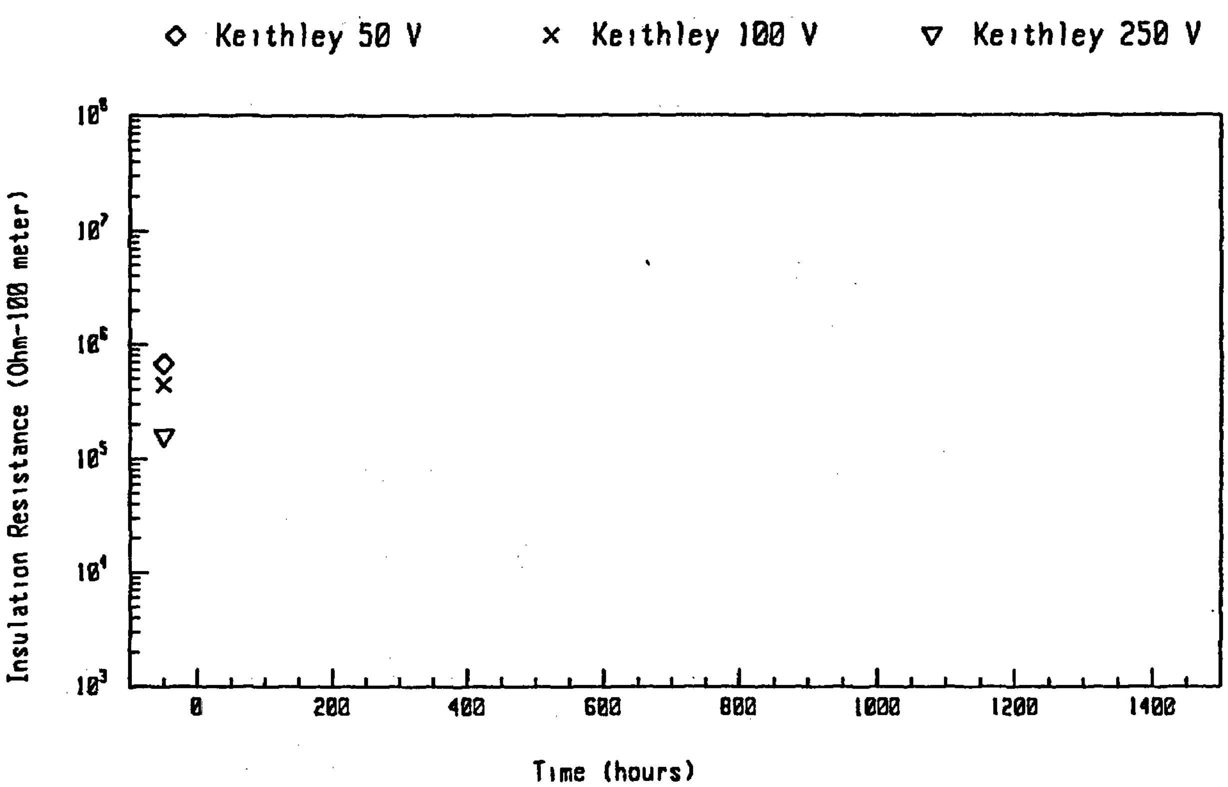

Figure B-24 IR of Kapton Conductor 40-24 During Submergence

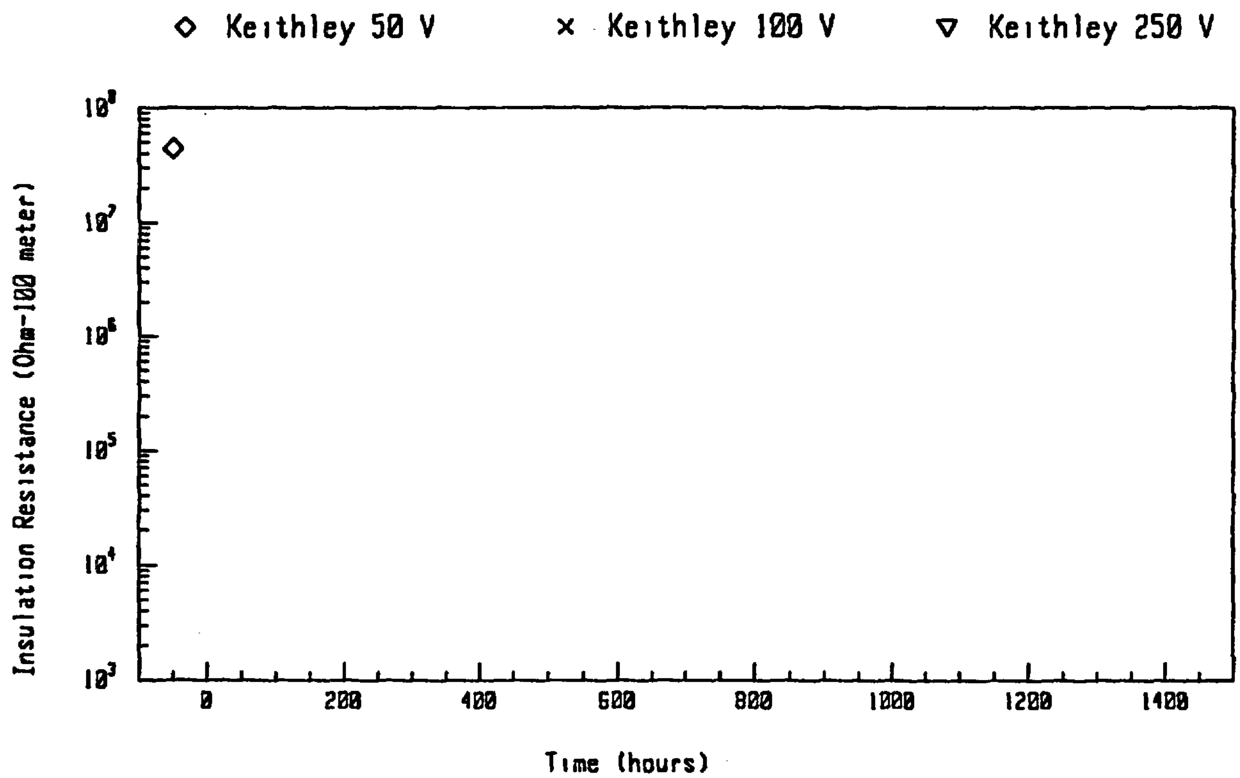

Figure B-25 IR of Kapton Conductor 40-25 During Submergence

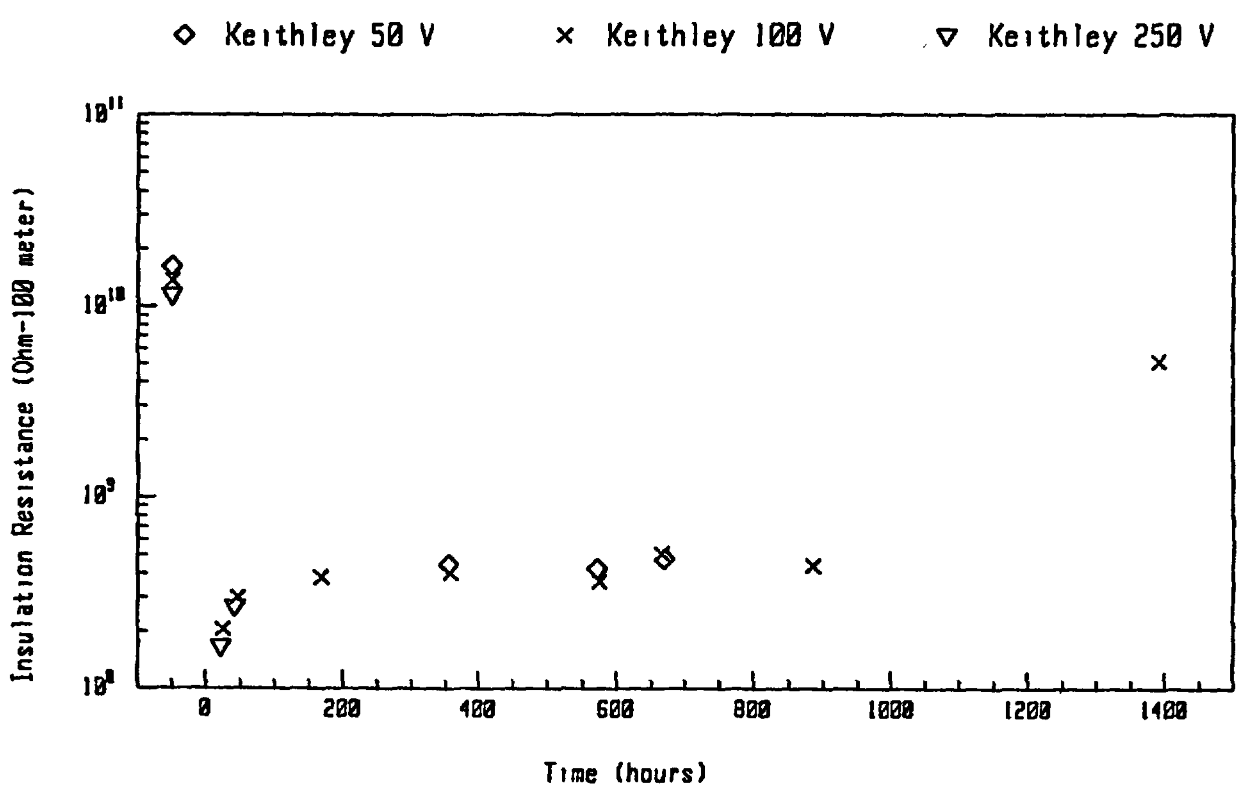

Figure B-26 IR of Anaconda Conductor 40-26 During Submergence

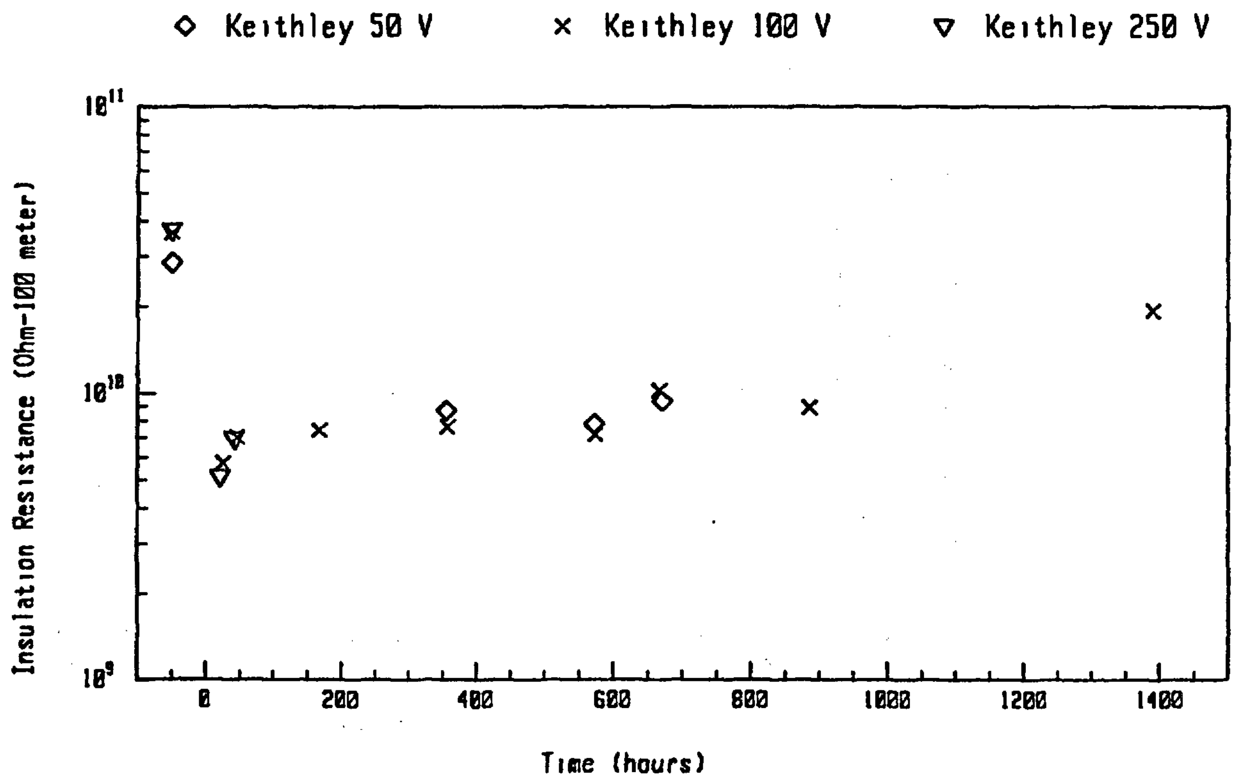

Figure B-27 IR of Raychem Conductor 40-27 During Submergence

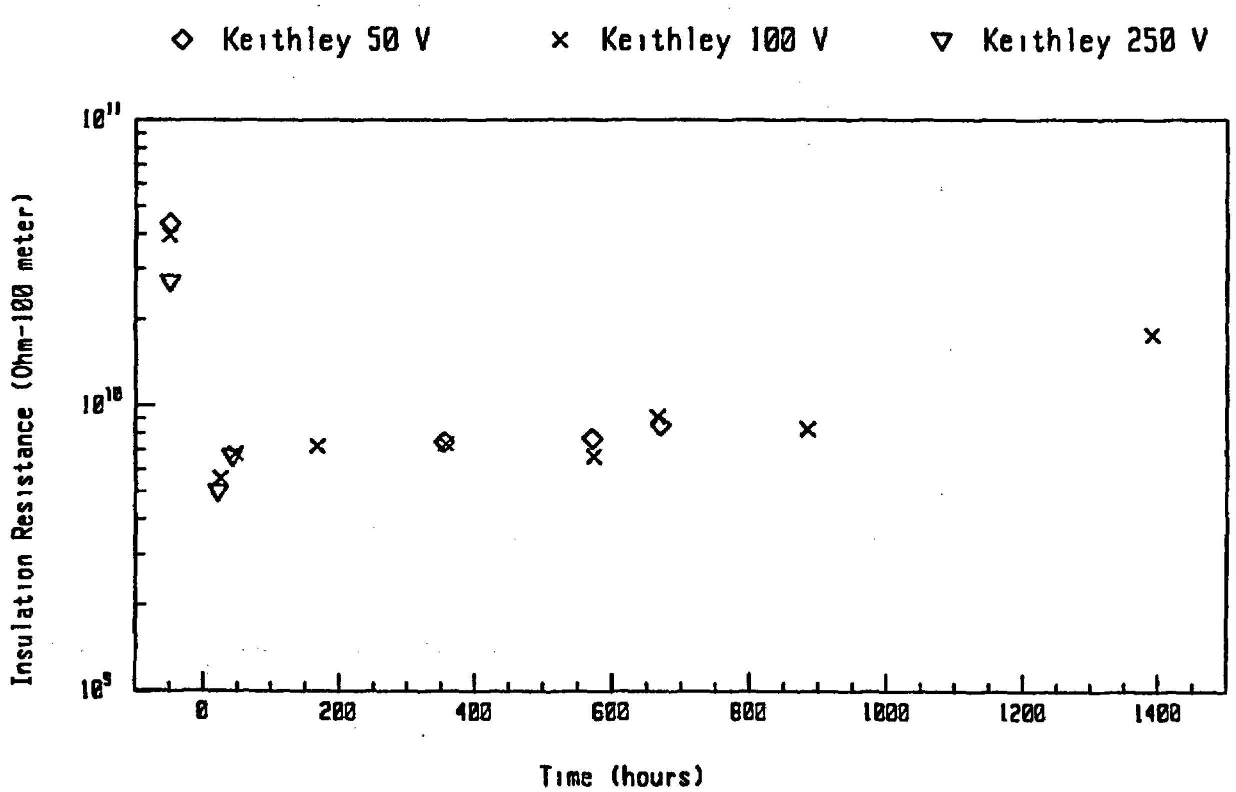

Figure B-28 IR of Raychem Conductor 40-28 During Submergence

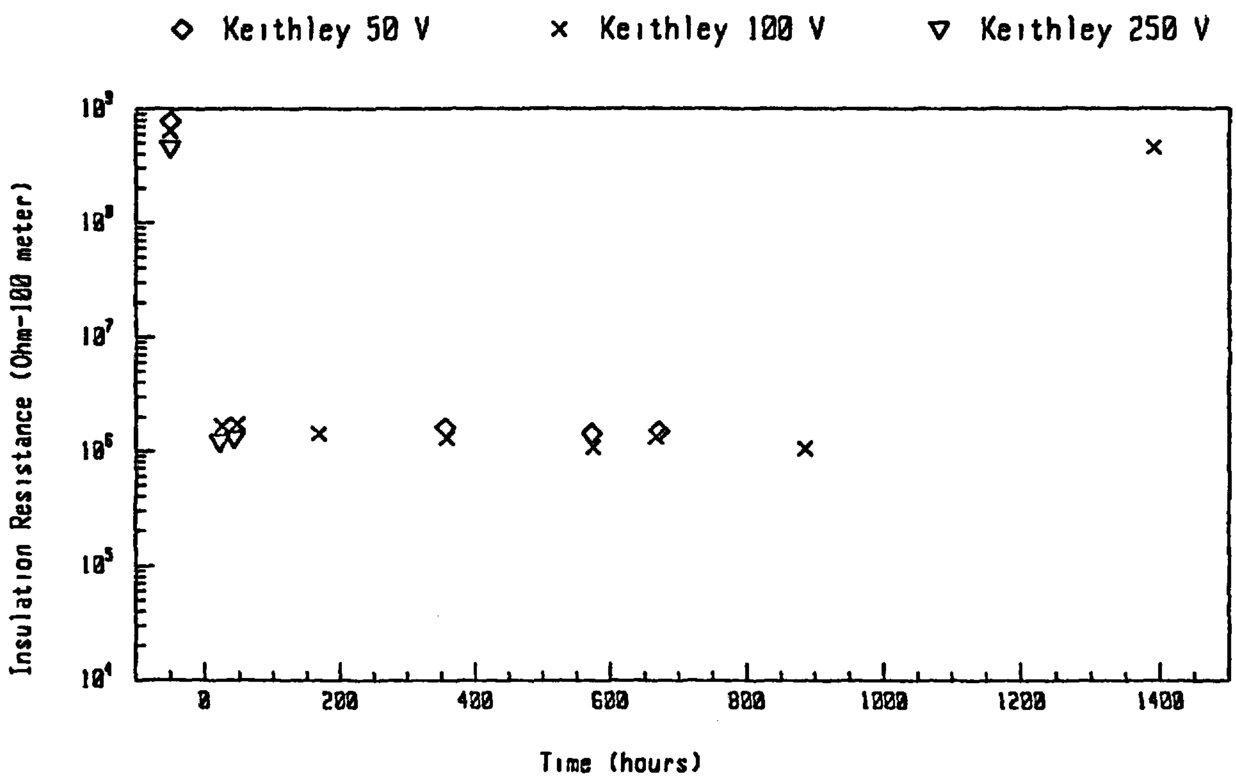

Figure B-29 IR of BIW Conductor 40-29 During Submergence

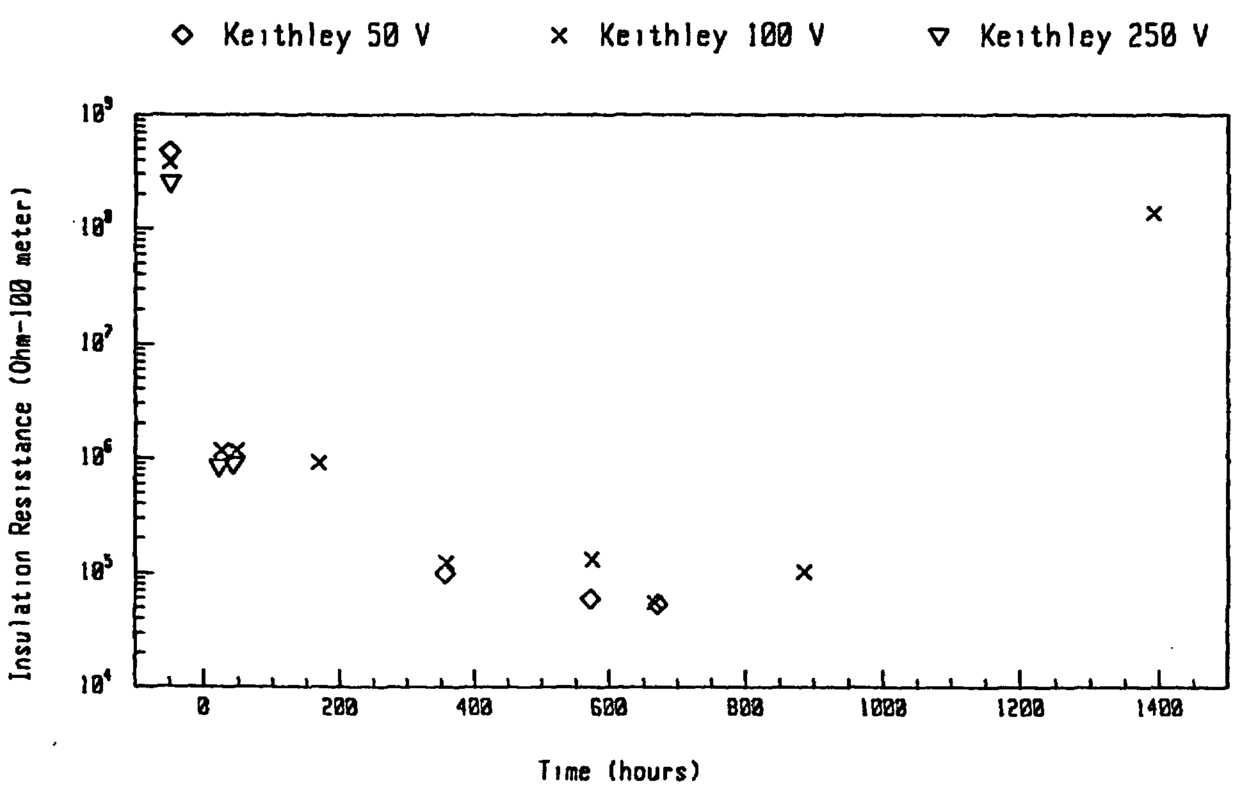

Figure B-30 IR of BIW Conductor 40-30 During Submergence

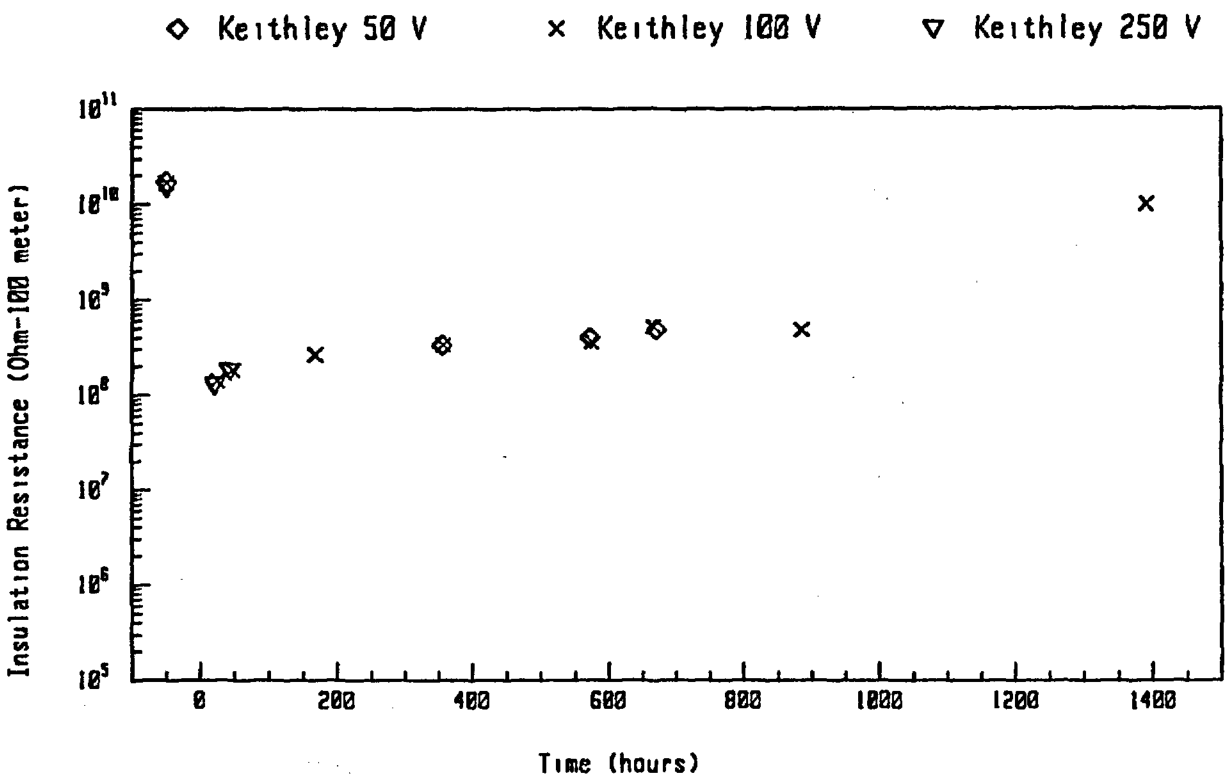

Figure B-31 IR of Okolon Conductor 40-31 During Submergence

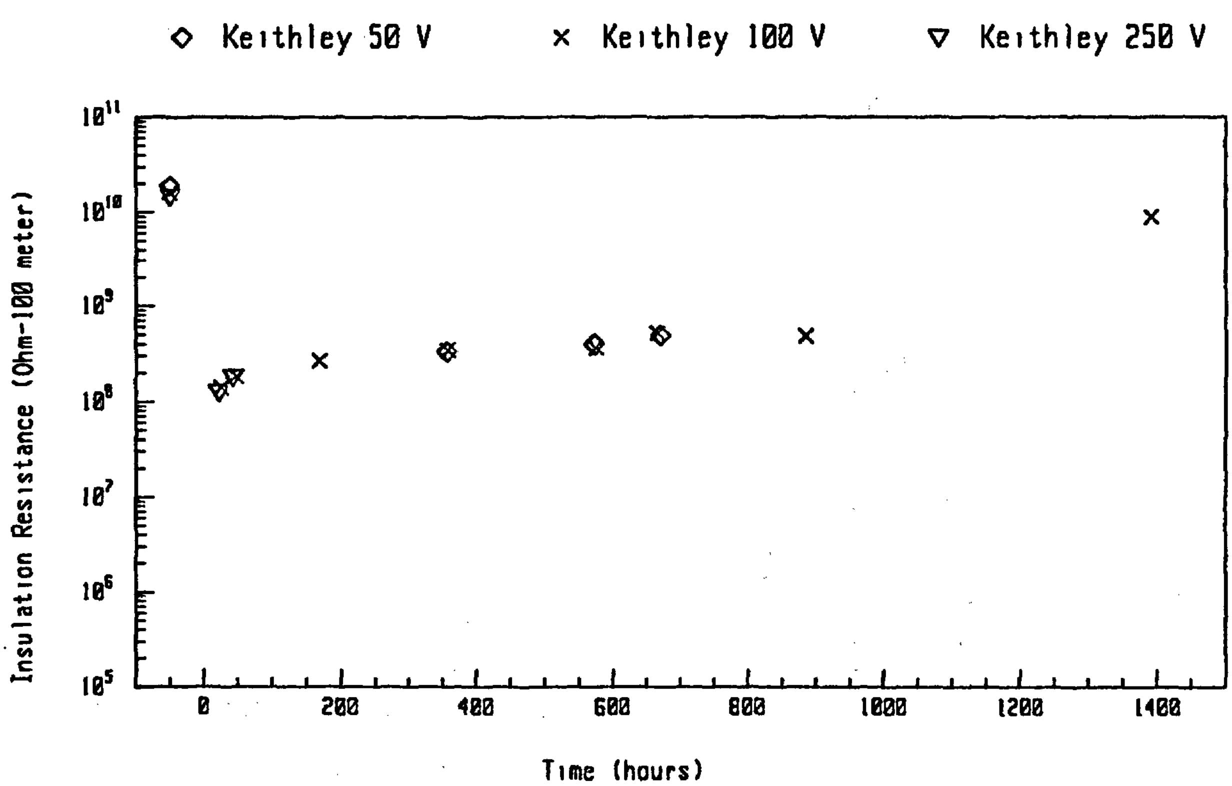

Figure B-32 IR of Okolon Conductor 40-32 During Submergence

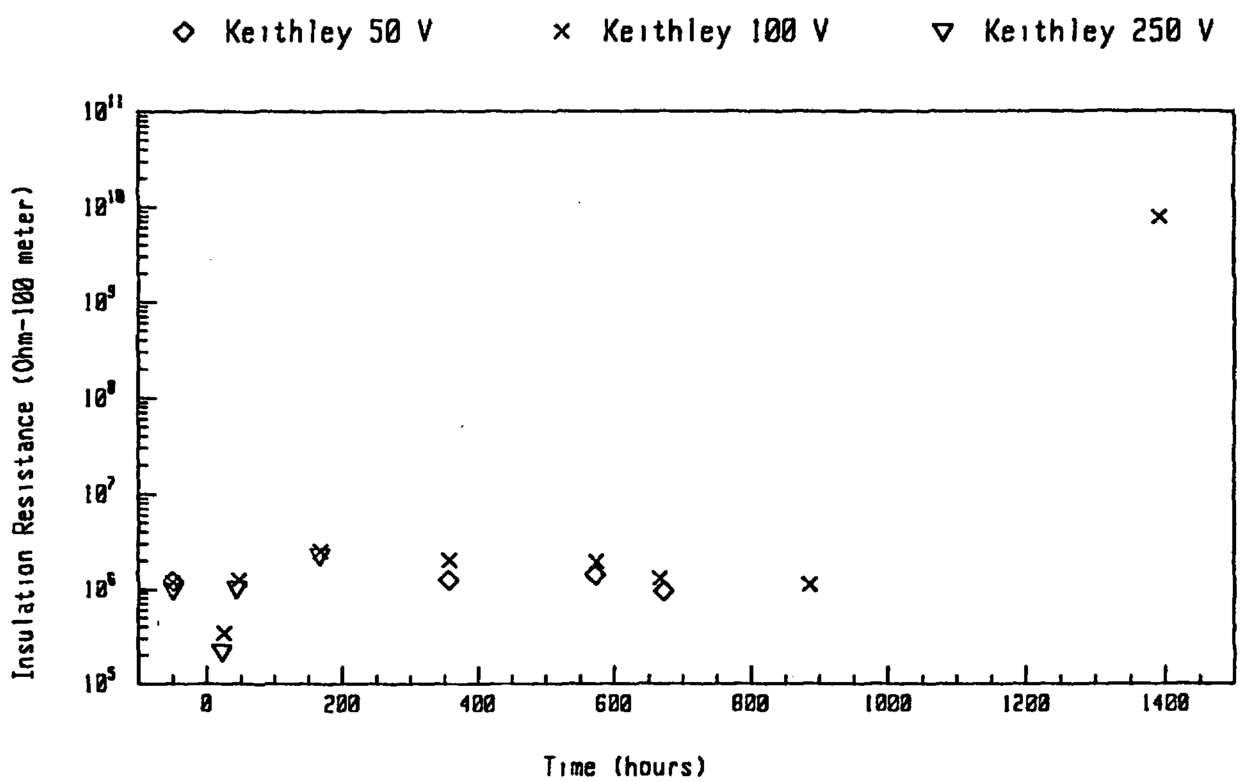

Figure B-33 IR of Okolon Conductor 40-33 During Submergence

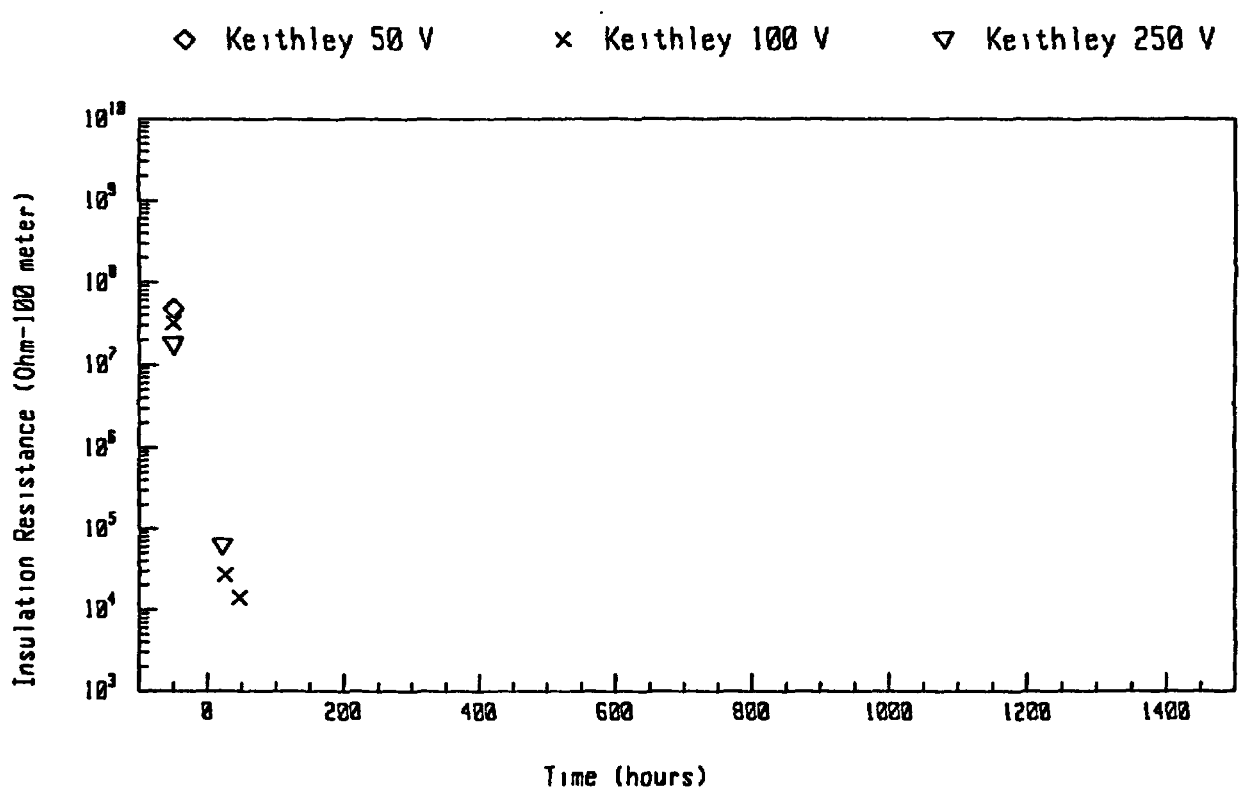

Figure B-34 IR of Dekorad Conductor 40-34 During Submergence

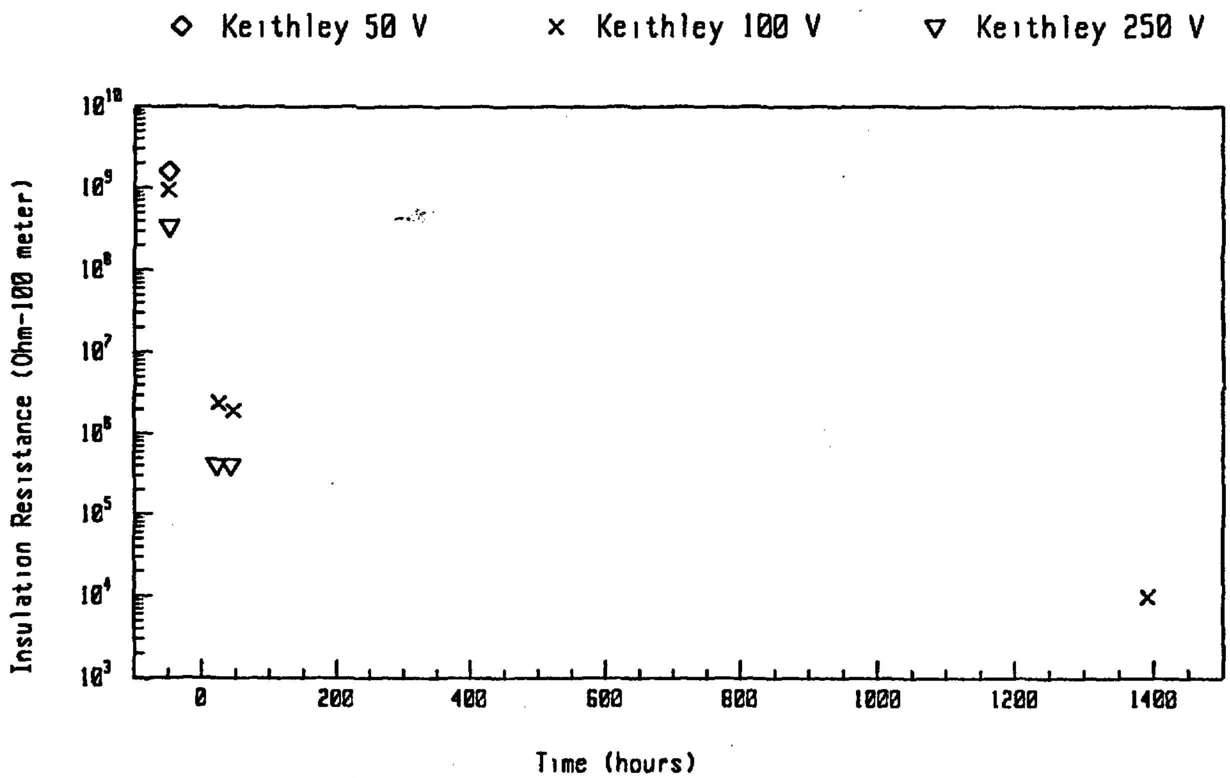

Figure B-35 IR of Dekorad Conductor 40-35 During Submergence

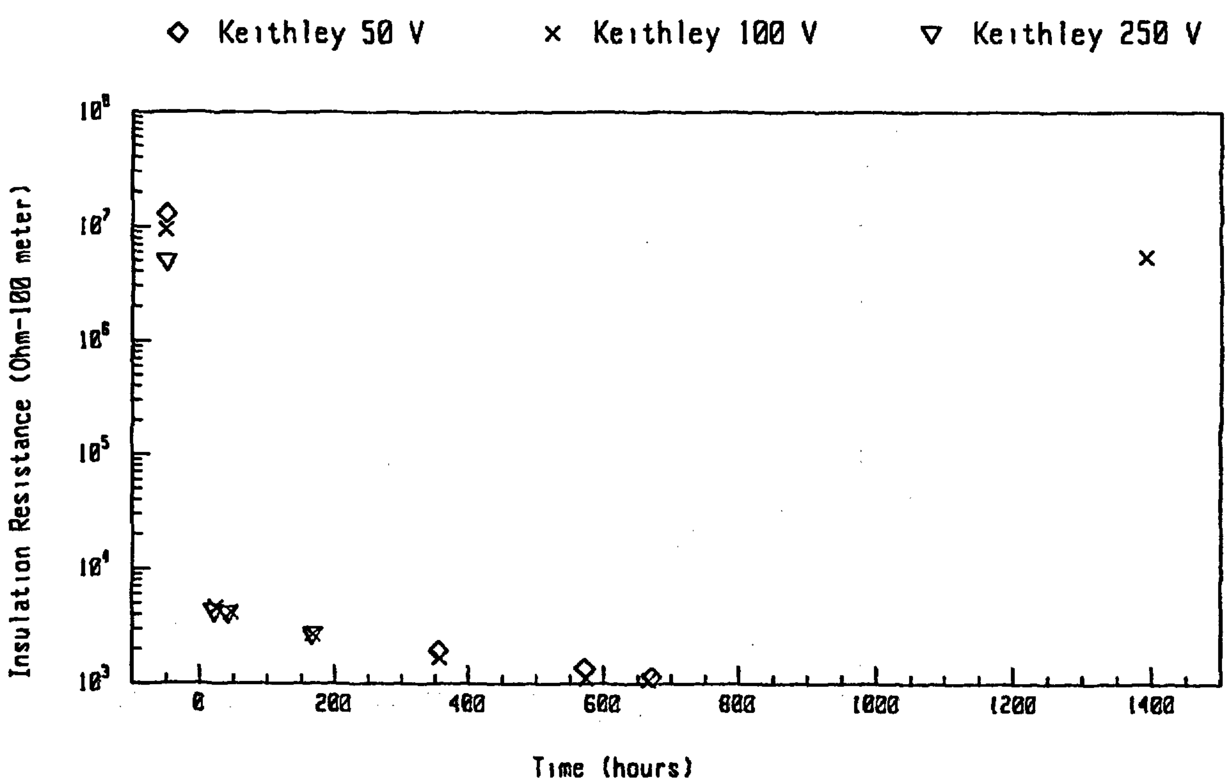

Figure B-36 IR of Kerite Conductor 40-36 During Submergence

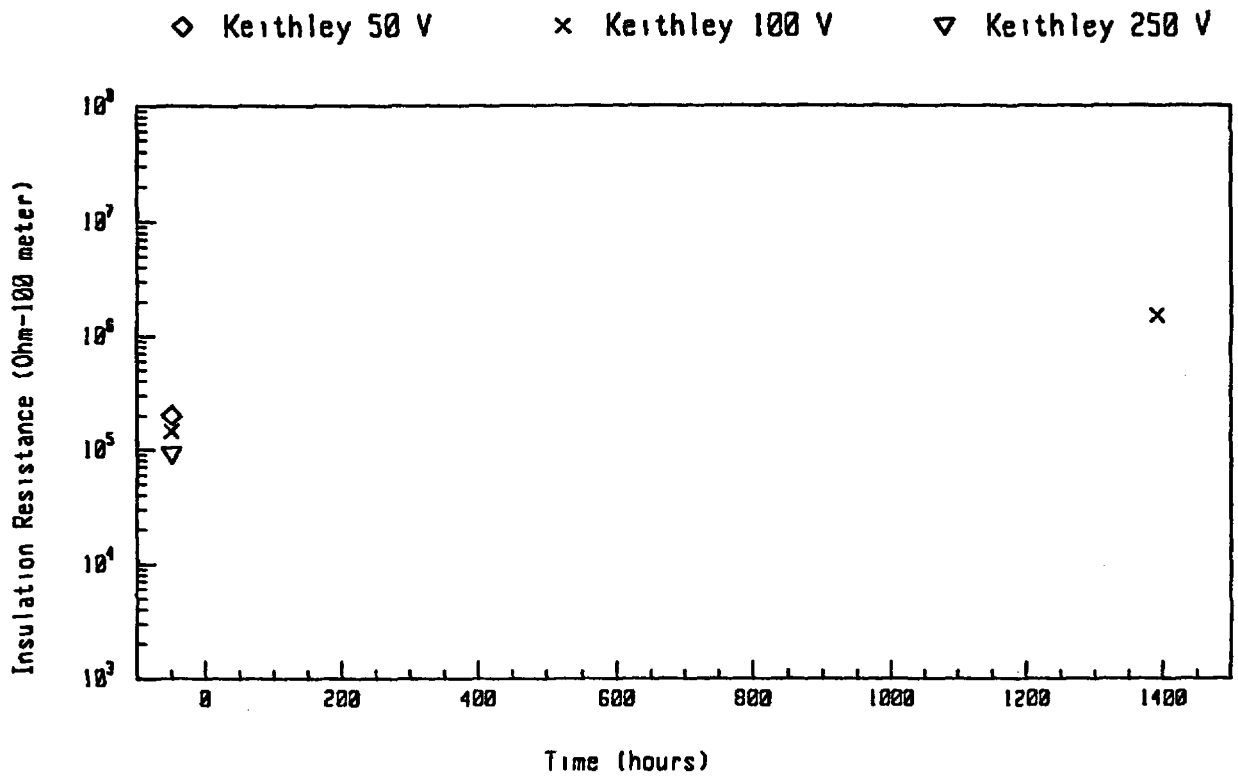

Figure B-37 IR of Kerite Conductor 40-37 During Submergence

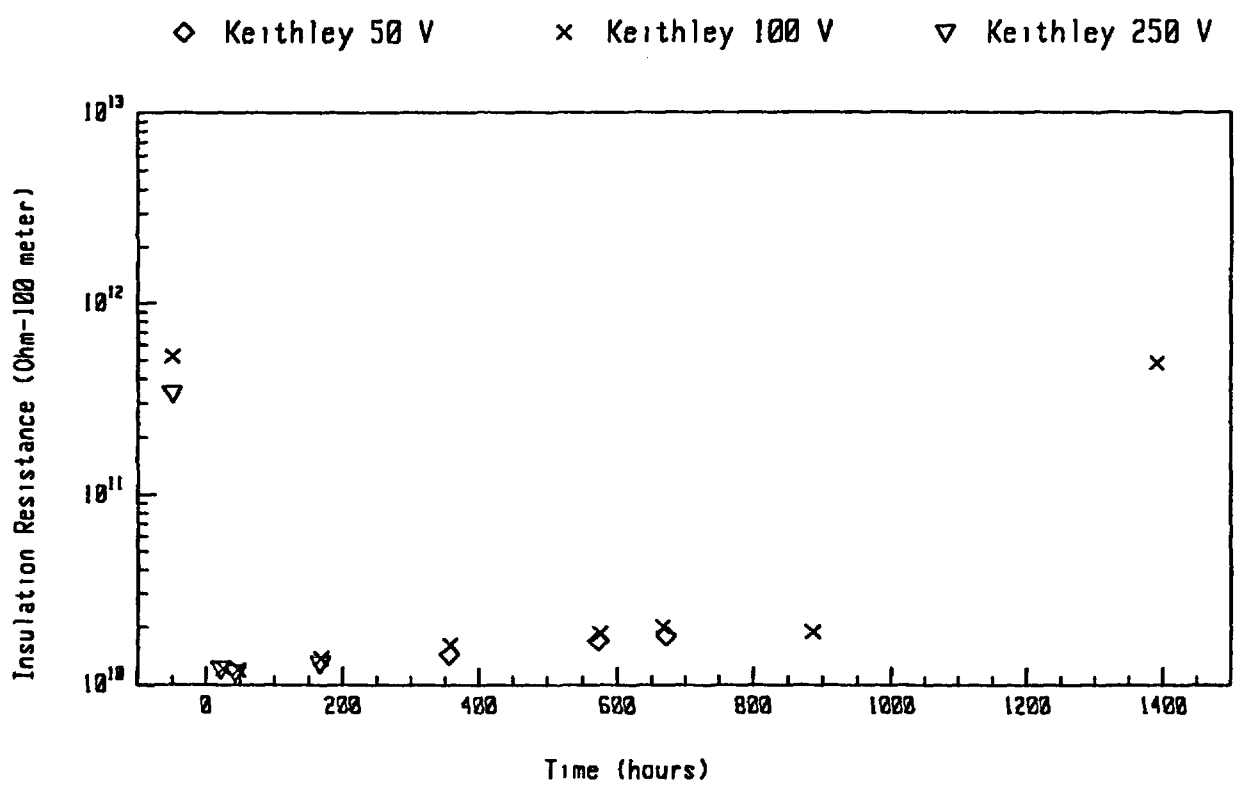

Figure B-38 IR of Coaxial Conductor 40-38 During Submergence

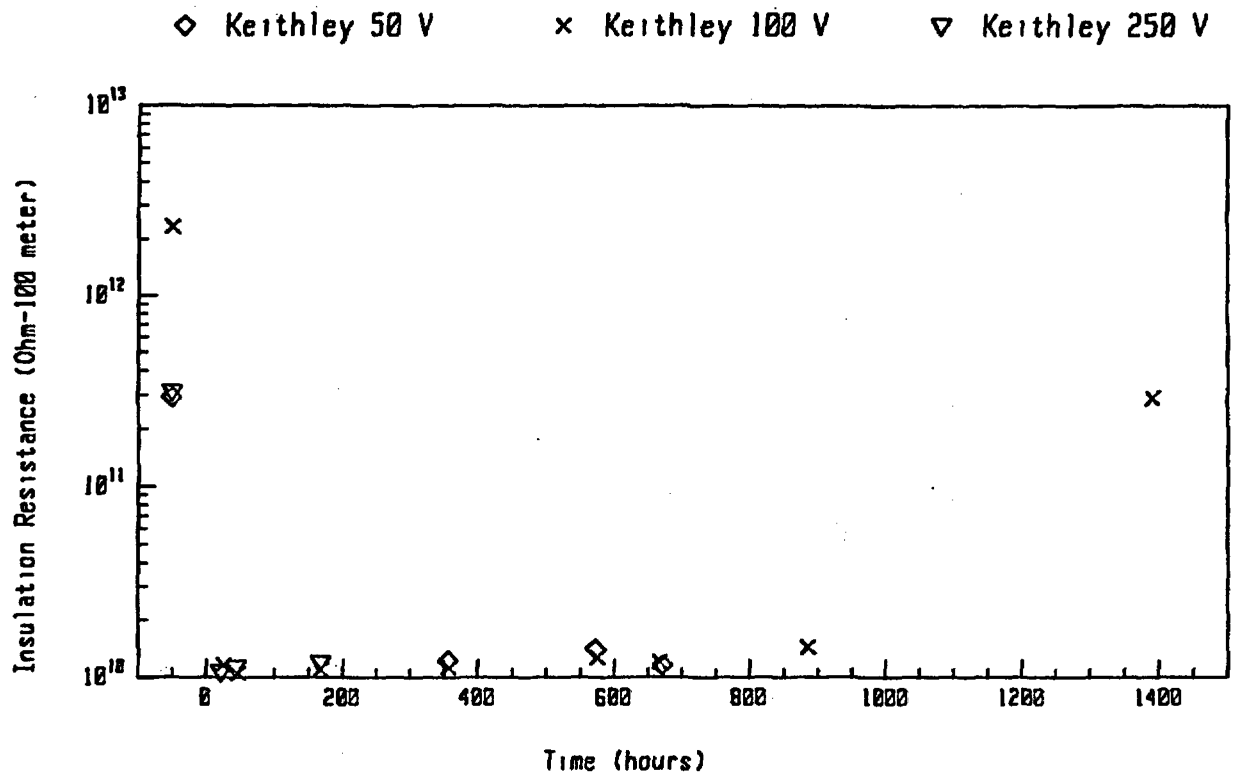

Figure B-39 IR of Coaxial Conductor 40-39 During Submergence

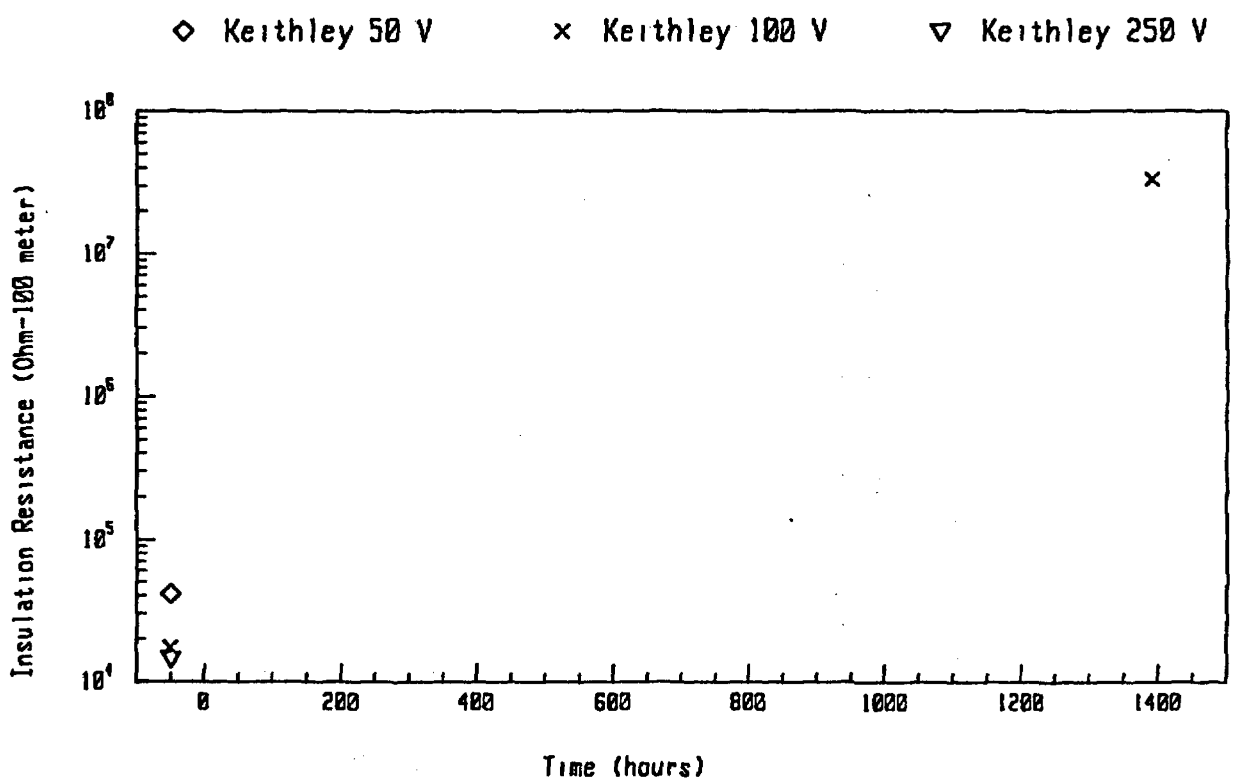

Figure B-40 IR of BIW Jacket 40-40 During Submergence

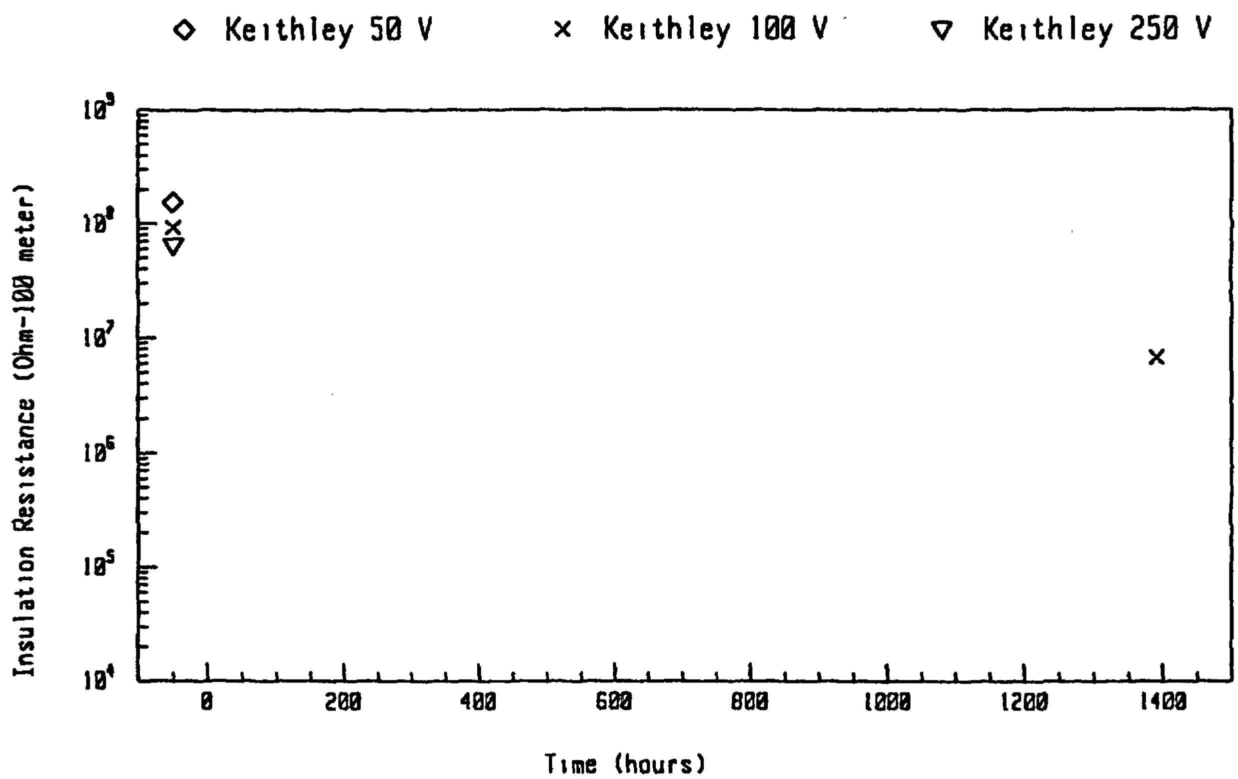

Figure B-41 IR of Polyset Jacket 40-41 During Submergence

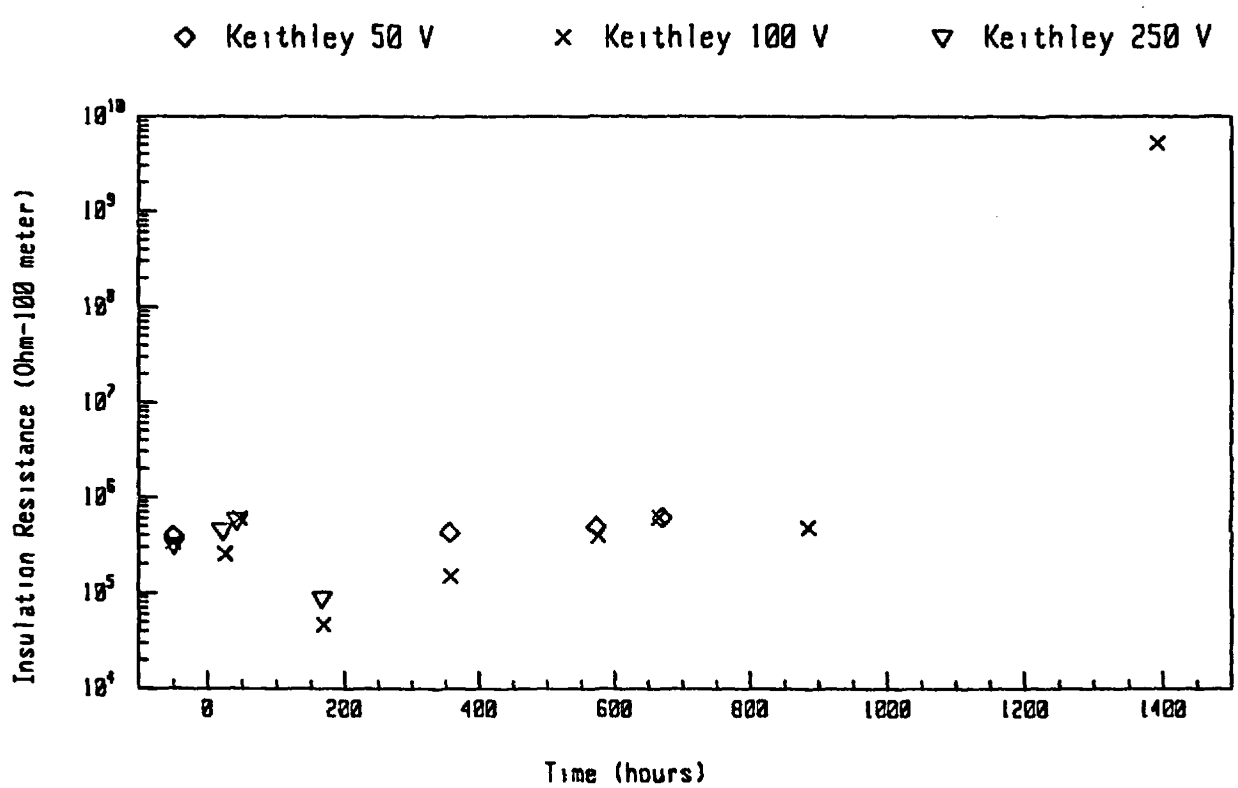

Figure B-42 IR of Coaxial Jacket 40-42 During Submergence

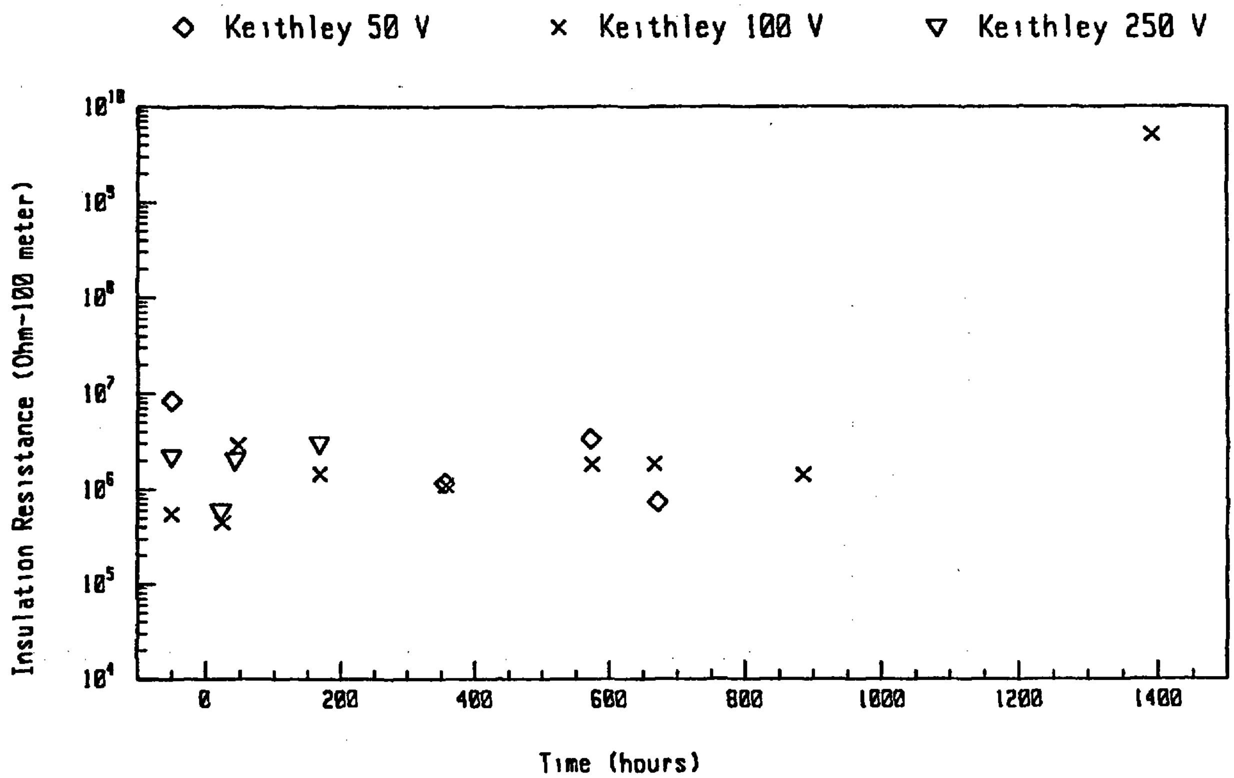

Figure B-43 IR of Coaxial Jacket 40-43 During Submergence

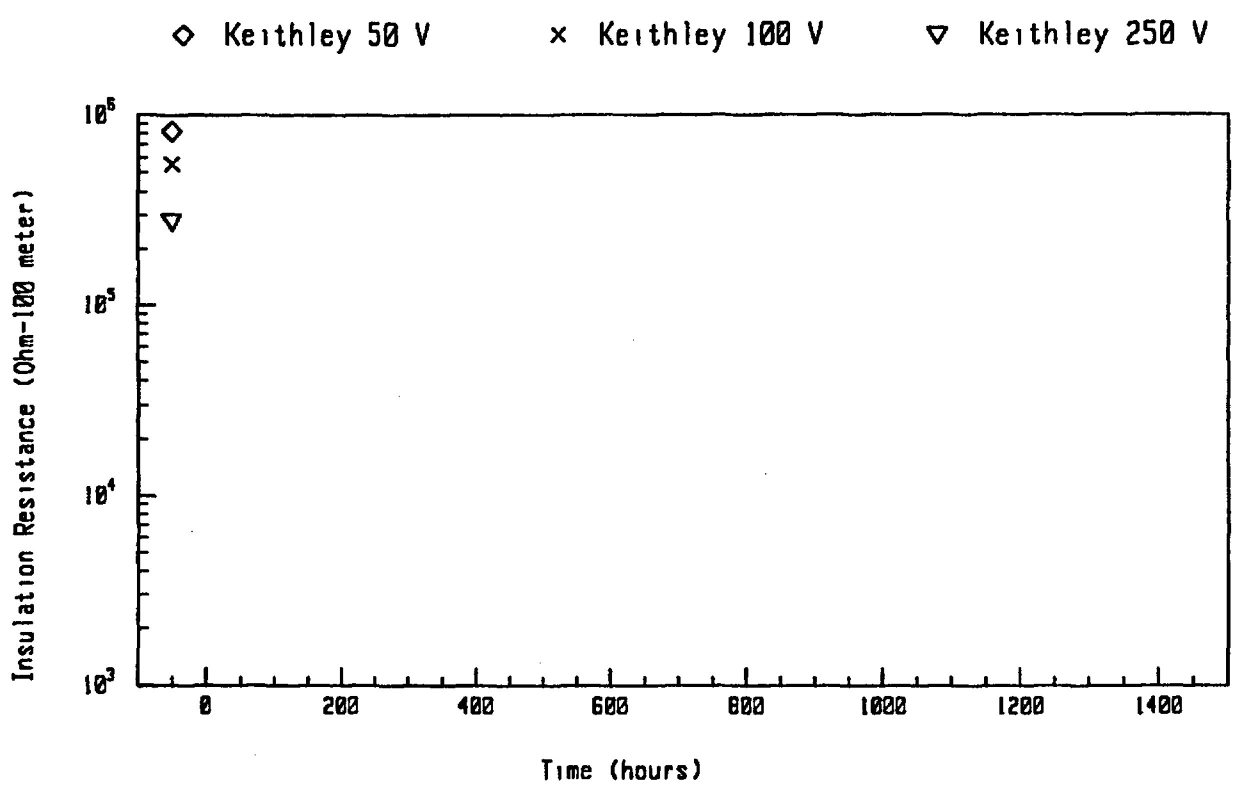

Figure B-44 IR of Dekorad Jacket 40-44 During Submergence

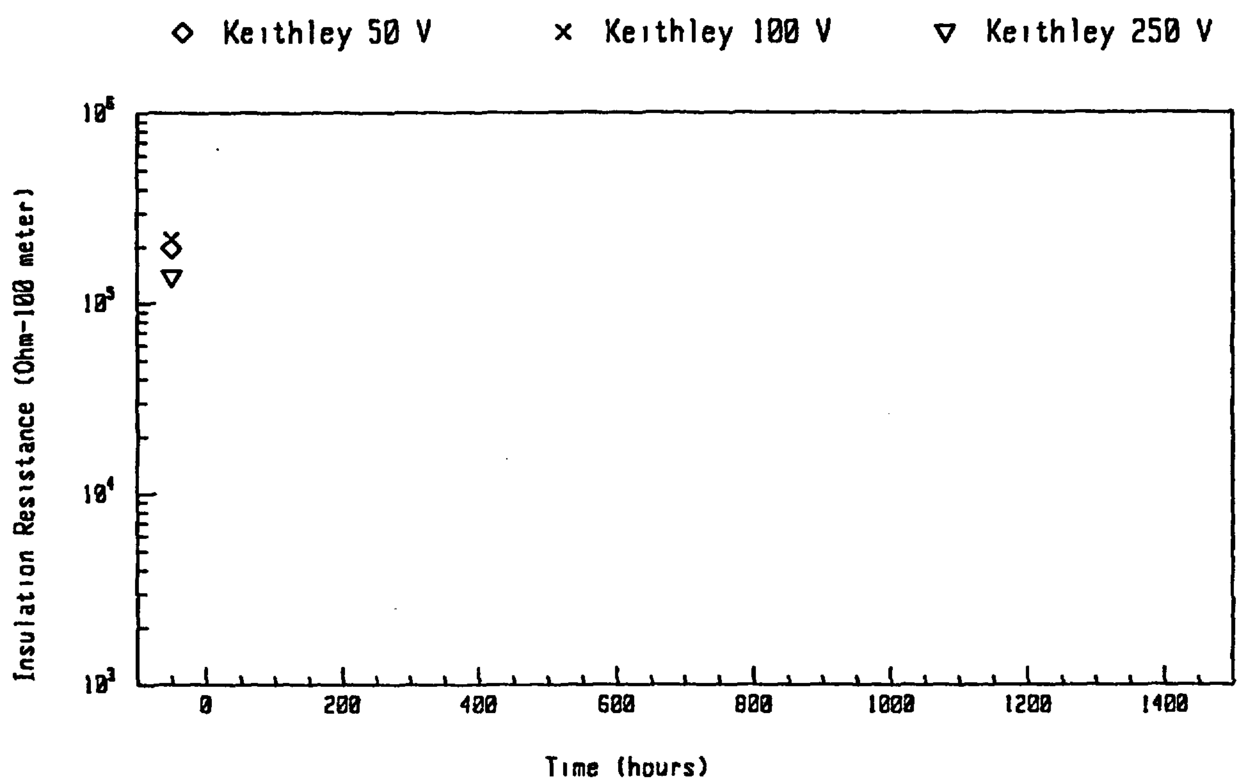

Figure B-45 IR of Dekorad Jacket 40-45 During Submergence

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This report describes the results of high temperature steam testing and submergence testing of 12 different cable products that are representative of typical cables used inside containments of U.S. light water reactors. Both tests were performed after the cables were exposed to simultaneous thermal and radiation aging, followed by exposure to loss-of-coolant accident simulations. The results of the high temperature steam test indicate the approximate thermal failure thresholds for each cable type. The results of the submergence test indicate that a number of cable types can withstand submergence at elevated temperature, even after exposure to a loss-of-coolant accident simulation.

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