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Loss-of-Coolant Accident (LOCA) Testing of Aged Cables for Nuclear Plant Life Extension

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ABSTRACT

Sandia National Laboratories is conducting long-term aging research on representative samples of nuclear power plant Class 1E cables. The objectives of this program are to determine the suitability of these cables for extended life (beyond 40-year design basis) and to assess various cable condition monitoring (CM) techniques for predicting remaining cable life. Twelve different cable products have been aged for long times at relatively mild exposure conditions in three test chambers to nominal equivalent lifetimes of 20, 40, and 60 years. Following the aging process, the cables in each chamber were exposed to a sequential accident profile consisting of 110 Mrad of high dose rate gamma irradiation followed by a simulated design basis loss-of-coolant accident (LOCA) steam exposure (except the 20-year chamber, which has not yet been LOCA tested). This paper discusses the results of the LOCA testing on the cables aged to 60 years. Although some of the cables experienced electrical failures, the results of these tests indicate a good life extension potential for a number of popular cable products.

1.0 INTRODUCTION AND OBJECTIVES

The primary purposes of this test program are to assess the effectiveness of various cable CM techniques for predicting how cables will perform in an accident environment and to gain an indication of whether cable life extension beyond 40 years is practical. To accomplish these objectives, we have conducted simultaneous radiation and thermal aging on three test chambers to equivalent nominal lifetimes of 20, 40, and 60 years. After aging, a sequential accident exposure consisting of high dose rate radiation followed by a steam exposure has been completed on the 40- and 60-year test chambers. Data obtained from CM techniques employed during aging will be correlated with observed performance of cables during the LOCA. This paper only discusses the results of the LOCA testing on the cables aged to 60 years.

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2.0 EXPERIMENTAL ARRANGEMENT

The testing is being performed in two phases: a long-term simultaneous thermal and radiation aging phase followed by a sequential accident exposure consisting of high dose rate radiation followed by steam exposure. Twelve cable products, representative of nuclear plant usage, are included in our study.[1] Cable insulation materials include cross-linked polyethylene (XLPE), ethylene propylene rubber (EPR), polyimide, and silicone rubber (SR). Cable jacket materials include neoprene, chlorosulfonated polyethylene, and fiber glass braid. Three different sets of cable specimens are being tested: one set aged to a nominal lifetime of 20 years, a second to 40 years, and a third to 60 years. Actual simulated lifetimes will vary because of the different activation energies of the specimens. We chose artificial aging times of 3, 6, and 9 months. The aging temperature selected was based on an assumed plant ambient temperature of 55°C with no conductor heat rise. Based on the Arrhenius equation and an assumed activation energy of 1.15, the resulting aging temperature is 95°C. A nominal aging temperature of 100°C was selected for the aging exposure. The planned radiation aging dose was 1 Mrad/year of simulated life. The resulting (accelerated) dose rate for our test is 9 krads/hr. The actual exposure rate is about 10 krads/hr, substantially less than typically employed in industry qualifiaction tests. Additional details of the test program and the CM measurements employed may be found in Reference 1.

The accident tests consisted of irradiation followed by a simulated design basis LOCA steam exposure. The accident dose was 110 Mrads at a dose rate of 600 krad/hr. The accident profile was similar to that in IEEE 323-1974,[2] Appendix A for "generic" qualification, except that the accident exposure was accelerated to 10 days and no chemical spray was included. The accident profile included superheated steam conditions during the first 11 hours of the test, followed by saturated steam for the rest of the test. The actual temperature and pressure profiles from the accident test are shown in Figure 1 for the first 24 hours. The temperature and pressure remained constant from 24 hours until 245 hours, when they were gradually reduced to ambient conditions.

During the LOCA test, most of the conductors were energized to a nominal voltage of 110 Vdc through a 1 A fuse. All shields, as well as the few conductors that were not energized to 110 V, were connected to ground. Insulation resistances (IRs) of the powered cables were monitored automatically throughout the LOCA test at varying scan intervals. These intervals ranged from 10 seconds during the transient portions of the tests to 5 minutes during long steady portions. Measurements on every cable were also performed periodically at 50, 100, and 250 Vdc with an IR test apparatus that uses a Keithley electrometer. The IR test apparatus was designed and used for CM during aging.[1] In the figures that follow, the periodic measurements are shown along with the "continuous" measurements. Prior to testing, both measurement methods were verified using resistors of known value. Because of the design of the "continuous" system, its absolute upper range was 10^9 Ω. However, its accuracy degrades rapidly above about 3×10^8 Ω. By contrast, the electrometer measurements are accurate in the 10^{12} Ω region.

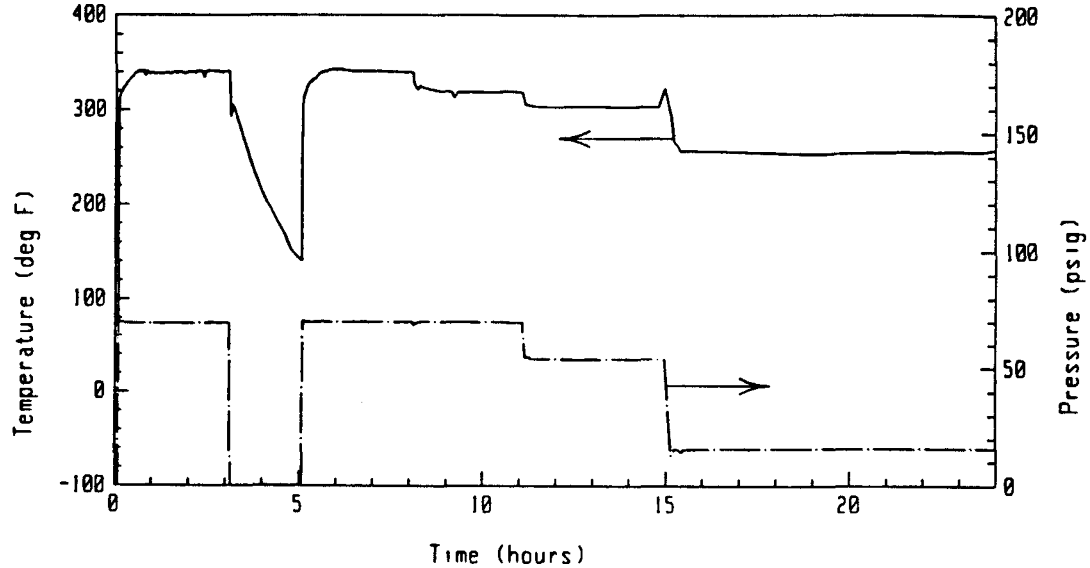

Figure 1 Accident Test Temperature and Pressure Profiles

3.0 EXPERIMENTAL DATA

This section presents some of the IR data from the LOCA tests on cables aged to 60 years. It should be remembered that the actual simulated lifetimes of the tested cables varies depending on the assumed plant ambient conditions and the actual activation energies of the materials of each cable product. All of the tested cables had an exposed cable length of about 15 feet in the test chamber.

3.1 Cross-Linked Polyethylene Insulated Cables

Figure 2 shows the results from Rockbestos 3-conductor irradiation XLPE cables. The figure shows the average of 3 samples (of 4 that were energized) whose fuses did not open throughout the 10 day test. Only the first 24 hours of the test are shown in Figure 2--the remainder of the plot would be above 10^7 Ω. Figure 3 shows the IR behavior of the remaining energized conductor. The fuse for this conductor opened at about 84 hours into the test. The IR degraded rapidly, going from greater than 10^7 ohms (consistent with the IRs for the other conductors) down to fuse opening within one hour. Based on the discrete IR measurements, the 2 Rockbestos conductors that were not energized continuously showed no evidence of failure. The reason for the one conductor failing has not yet been determined.

Figure 4 shows the average IR behavior of 2 conductors of a Brand Rex 3-conductor cable. The IR remained well above 10^6 Ω throughout the test and was above 10^8 Ω for the part of the test that is not shown. The only other XLPE cable included in the test program, Raychem Flamtrol single conductors, maintained IRs above 10^7 Ω throughout the test.

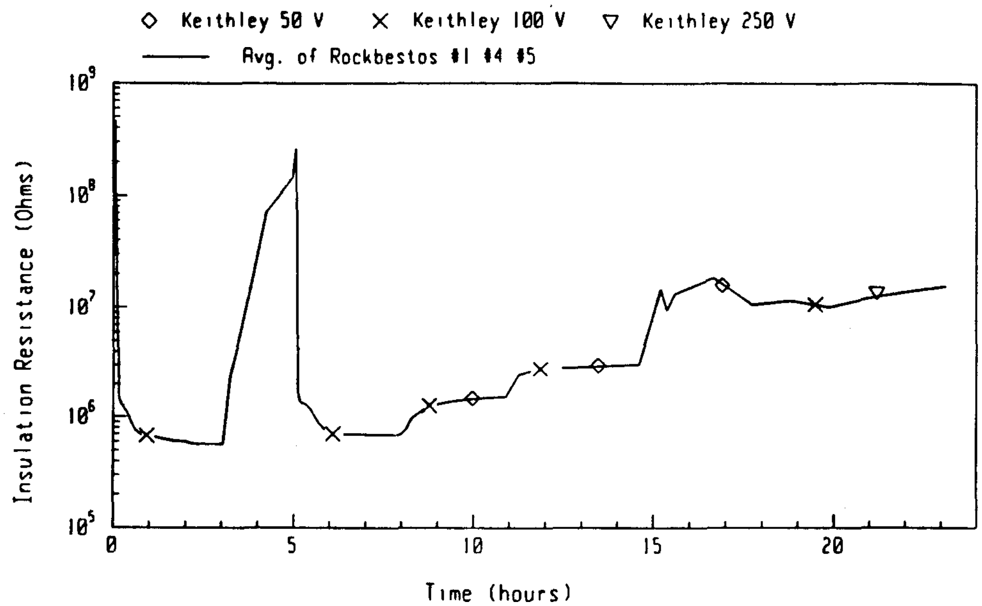

Figure 2 Performance of 3 Rockbestos XLPE Multiconductors

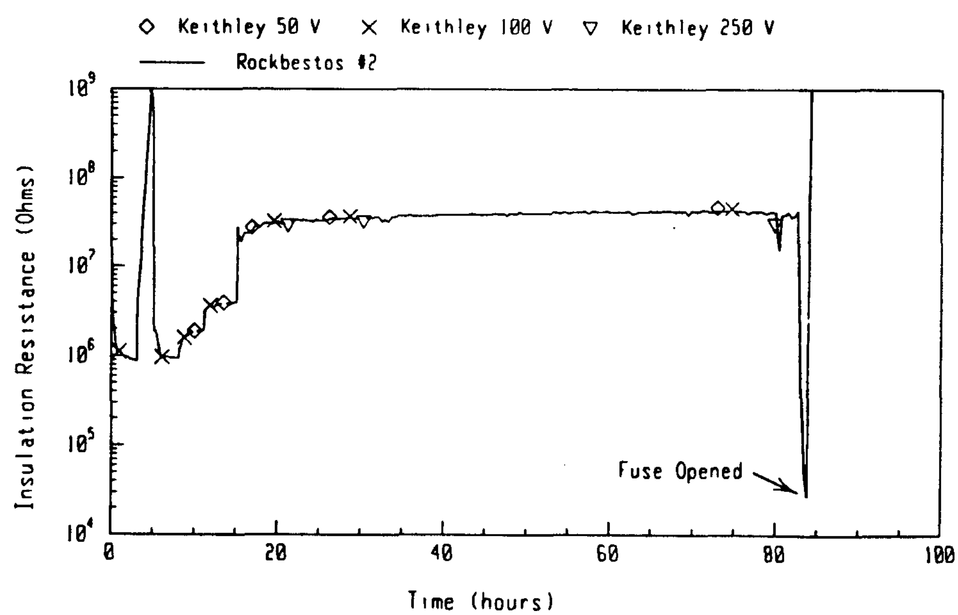

Figure 3 Performance of 1 Rockbestos XLPE Multiconductor That Failed

3.2 Ethylene Propylene Rubber Insulated Cables

Figure 5 shows the behavior of Anaconda FR-EP single (from disassembly of a multiconductor cable) and multiconductor cables during the first 24 hours of the accident test. The IRs were well above 10^5 Ω throughout the test. The single conductor had consistently higher IR than the multiconductors, typically by a factor of 4-10.

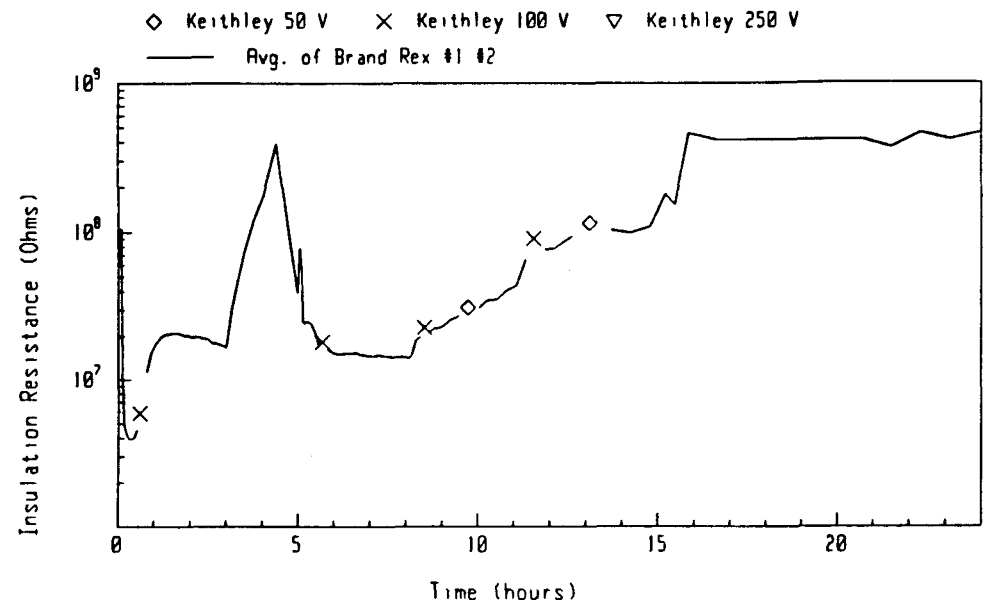

Figure 4 Performance of 2 Brand Rex XLPE Multiconductors

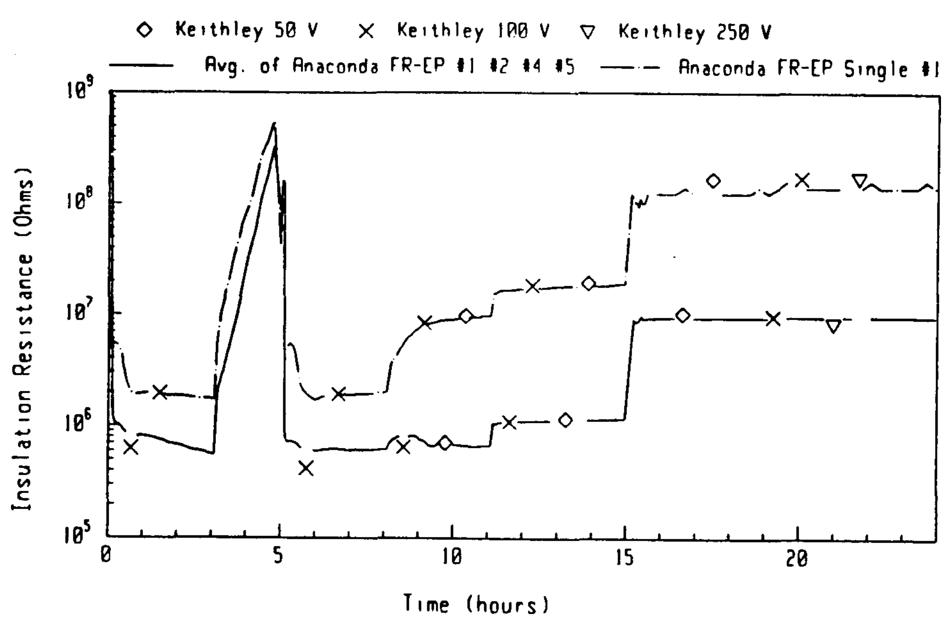

Figure 5 Performance of Anaconda FR-EP Single and Multiconductors

Figure 6 compares the behavior of BIW Bostrad 7E single conductors (removed from multiconductor cables) with multiconductor cables during the first 24 hours of the accident test. The IR of the multiconductors fell as low as 3.6×10^4 Ω during the most severe part of the accident exposure, while the single conductors remained above 10^5 Ω. The single conductors had IRs 2-6 times higher than the multiconductors. The minimum IRs of the multiconductors are in the range where the accuracy of certain sensitive instrumentation circuits could be affected.

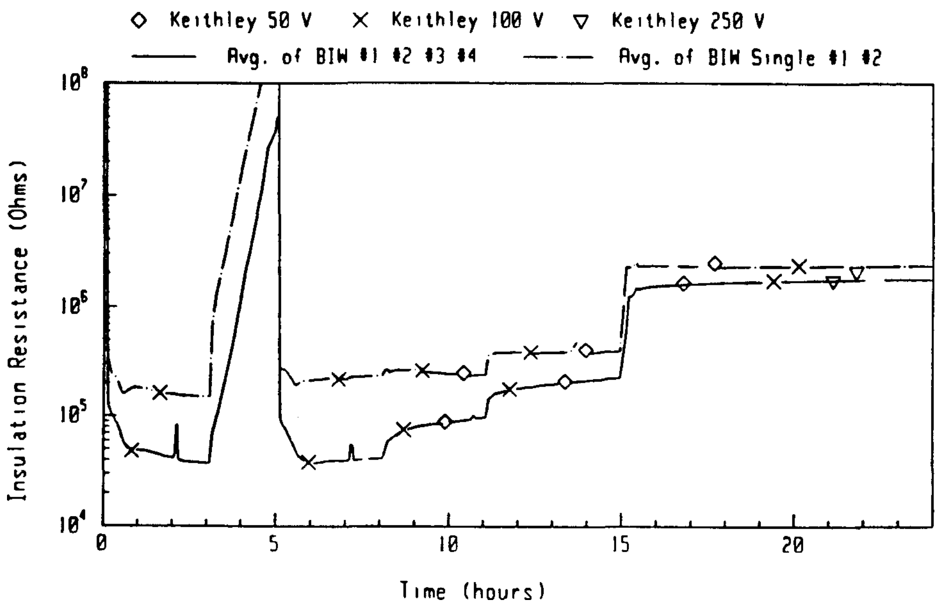

Figure 6 Performance of BIW Bostrad 7E Single and Multiconductors

Of 4 Okonite Okolon single conductors that were tested, 3 of them maintained IRs well above 10^6 Ω throughout the accident test. The behavior of the other conductor is shown in Figure 7. The fuse for this conductor opened at 172 hours. The cable experienced an initial rapid decrease in IR of several orders of magnitude at 133 hours, followed by a gradual decrease over the next 40 hours. The reason for this failure is still being investigated. Prior to the 133 hour point, there was no indication that this cable was behaving differently than the other Okolon conductors.

Figure 8 compares the IR of 2 Dekoron Dekorad ethylene propylene diene monomer (EPDM, a category of EPRs) single conductors (removed from a multiconductor cable) with the 2 conductors of a multiconductor cable. In all cases, the IRs remained above 10^6 Ω, but the difference between single conductors and multiconductors was only evident during the 340°F exposure and was only about a factor of 2. The fuses for two additional conductors from a second multiconductor cable both opened (Figure 9), one at 178 hours and one at 181 hours. For the first 140 hours of the test, the IRs for these cables were very close to the IRs of the cables that successfully completed the entire test. At 140 hours, conductor #1 began a gradual degradation that lasted 40 hours before its fuse opened. Conductor #2 began losing IR at 158 hours into the test, but its fuse did not open until 20 hours later. A significant decrease in IR occurred soon after a 250 V IR was completed at 173 hours. The higher voltage stress may have accelerated the IR degradation. At the time of the 250 V measurement, the IR of conductor #1 had already degraded much more than the IR of conductor #2. When the chamber was opened after the accident test, the failed multiconductor was found severely degraded. The jacket was split open with bare conductors visible along the cable.

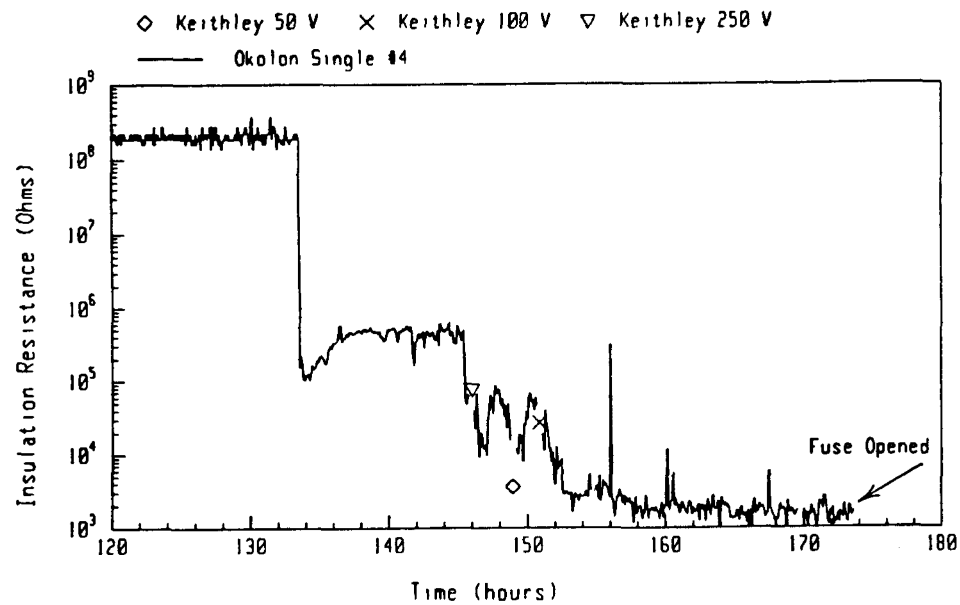

Figure 7 Performance of Okonite Okolon Single Conductor That Failed

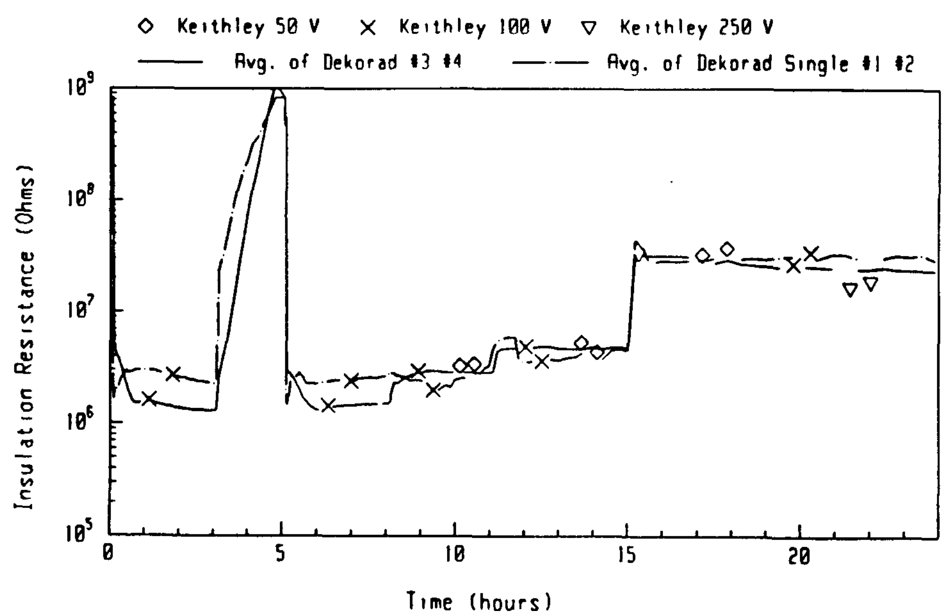

Figure 8 Performance of Dekoron Dekorad Single and Multiconductors

3.3 Other Cable Insulations

Figure 10 shows the behavior of Kerite FR/FR single conductors during the first 24 hours of the test. The IR dipped as low as 6000 Ω during the second transient to 340°F, but then it recovered by an order of magnitude. The superheated steam conditions may have contributed to the recovery by drying out the cable. As the temperature was lowered to 320°F and to 300°F, the IR did not recover as it typically did for most cables. Rather, the IR decreased to about 10000 Ω. When the temperature was lowered to 250°F, the IRs increased, but they never exceeded 10^5 Ω until the cooldown to ambient temperature began. The ambient temperature IRs after cooldown were about 10^6 Ω.

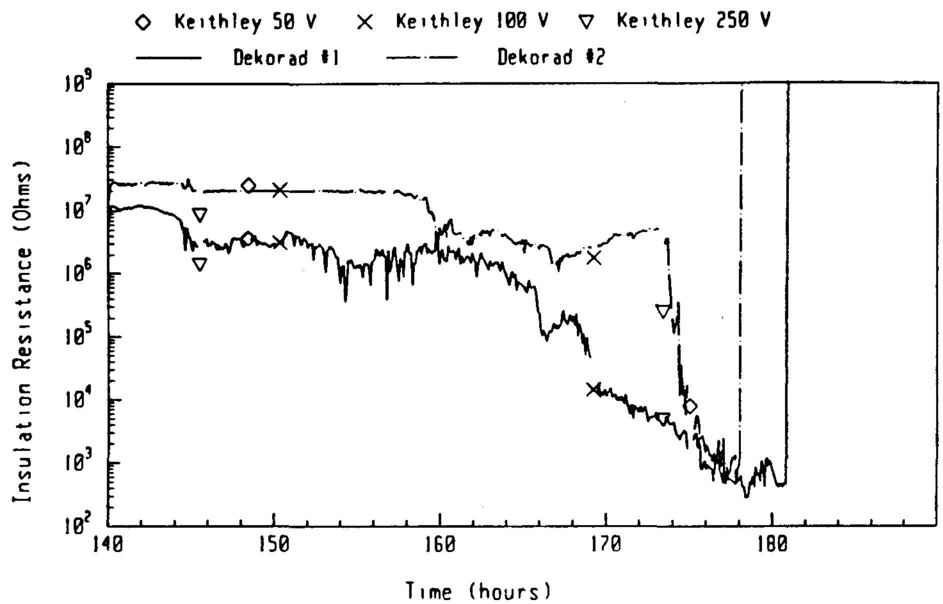

Figure 9 Performance of Dekoron Dekorad Multiconductors That Failed

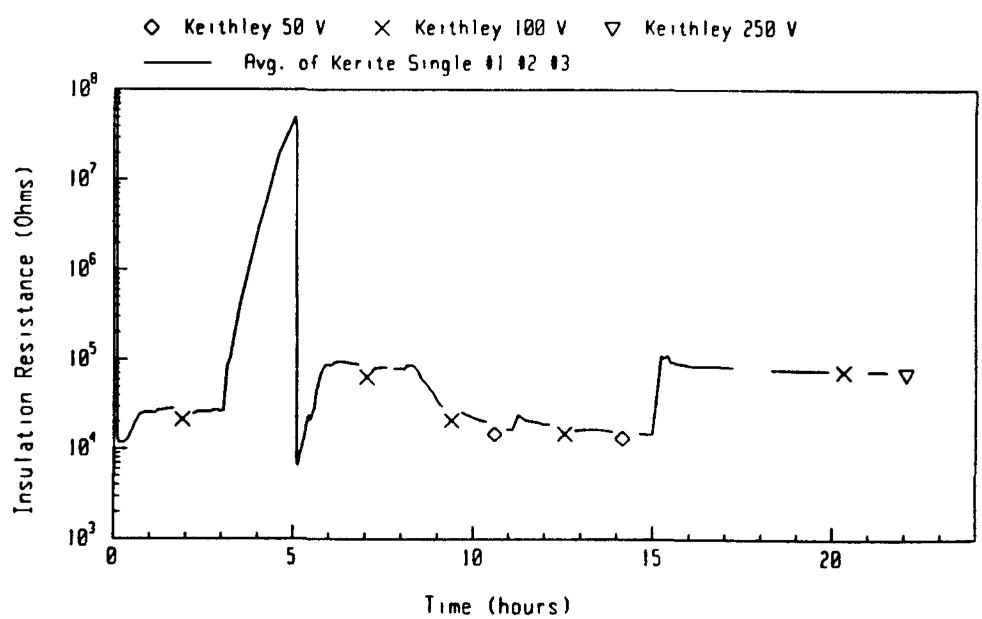

Figure 10 Performance of Kerite FR/FR Single Conductors

Two Rockbestos SR single conductor silicone cables were tested. Both of these cables had IRs that were well above 10^7 Ω throughout the test. Two cables with polyimide (Kapton) insualtion were also tested. One of them was damaged during test setup and its fuse opened very early into the test. The IR behavior of the second conductor is shown in Figure 11. Although the IR was normally above 10^7 Ω, a very substantial thermal transient behavior is indicated by the Figure, with the IR dipping down to about 10^5 Ω during the first transient, then recovering by more than 2 orders of magnitude.

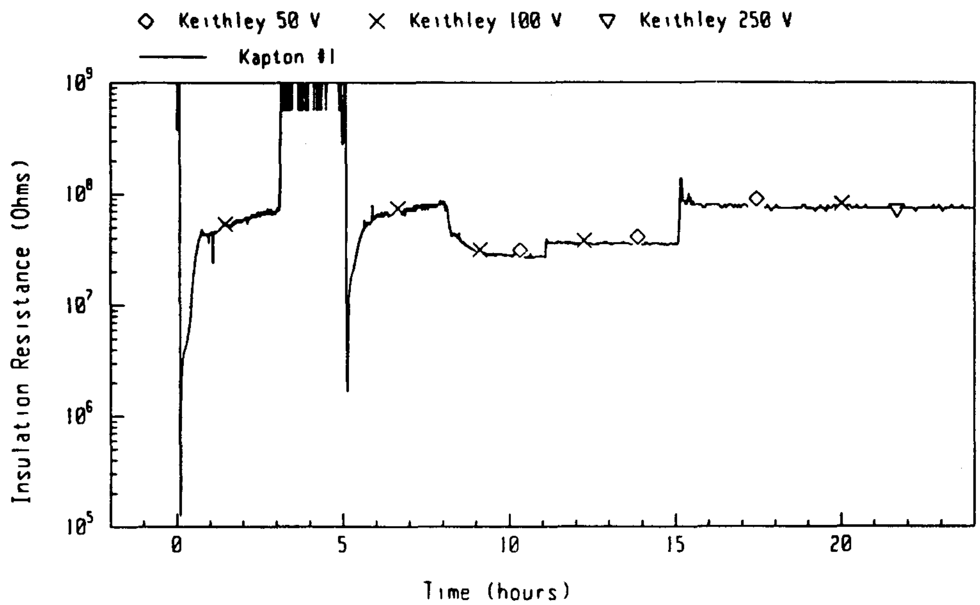

Figure 11 Performance of Polyimide (Kapton) Single Conductor

The final cable type tested was Rockbestos RSS-6-104/LE coaxial cable. The IR behavior of one of these cables is shown in Figure 12. The other one performed very similarly. The IRs remained above $5x10^7$ Ω throughout the test. Note that the on-line measurement setup was unable to accurately measure the high IR this cable had throughout much of the exposure.

3.4 Single Versus Multiconductor Performance

Three EPR cable products were represented in both single and multiconductor configurations. In all cases, the single conductors had higher IRs than the multiconductors during the 340°F peaks. As the temperature was reduced, the differences became more significant for Anaconda FR-EP cables, less significant for the BIW Bostrad cable, and disappeared altogether for the Dekoron Dekorad cables. A typical test strategy following IEEE 383-1973[3] might include only single conductors, which is non-conservative for some cable types. Whether this difference is significant would depend on the application of the cable as well as the absolute value of the cable IR during the test.

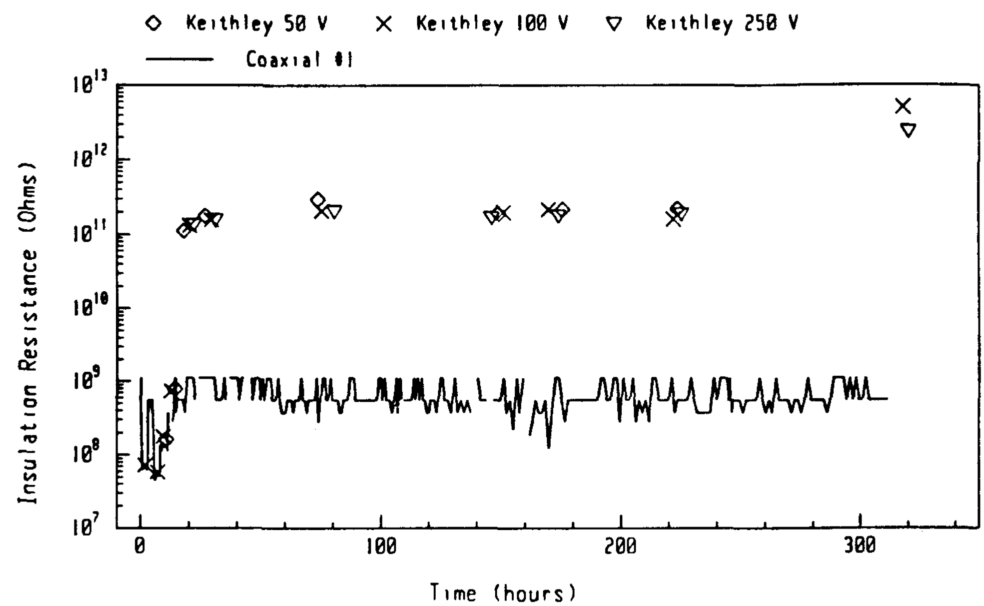

Figure 12 Performance of Rockbestos RSS-6-104/LE Coaxial Cable

3.5 Cable Performance During Transients

Although the previous figures are not scaled to examine the transient behavior of the cables, they do give some indications. Since data was acquired every 10 seconds during the transient, we have expanded plots to provide more detail during the first hour of the test. Although the plots will not be shown here, an indication of the cable behavior will be given. Most of the multiconductor cables exhibited a thermal lag characteristic similar to what would be expected. A steady value of IR for the multiconductors was attained in about 3 minutes. This lag time was fairly consistent for all of the multiconductors. The Brand Rex cable showed a significant recovery effect, with the IR increasing by a factor of 5 between several minutes and an hour into the transient.

As expected, single conductors had much less thermal lag. The time lag was typically 30 seconds to reach a steady IR. The polyimide cable had the most interesting transient behavior after the initial lag period--it recovered more than two orders of magnitude during the next 30 minutes.

During the second transient, the cable behavior was generally the same. However, the Brand Rex IR went directly to its steady state value with no overshoot/recovery; the Kerite had more overshoot, followed by more recovery (to a net higher steady state IR after the second transient); and the initial IR decrease for the polyimide was an order of magnitude less than in the first transient.

3.6 Cable Behavior Versus Applied Voltage

The discrete data that was acquired with the electrometer apparatus at 50 V, 100 V, and 250 V provides some insight into cable IR behavior at different voltages. Although IR should theoretically be constant with applied voltage, it has been argued that IR actually decreases as applied voltage is increased. The data in Figures 2-12 indicates that IR is largely independent of voltage over the range of 50-250 V for the cables tested.

3.7 Discrete Versus Continuous Insulation Resistance Measurements

In this test program, both discrete and (almost) continuous IR measurements were performed. The agreement between the two independent methods is excellent for IRs in the range of the on-line measurement system. The data indicates that discrete IR measurements are generally adequate for IR monitoring. However, a number of cables showed significant effects during the transient portions of the test that would not be seen with only the discrete measurements. For example, the polyimide IR measured after it reached steady state was well above 10^7 Ω at 340°F, while the minimum IR during the exposure was down near 10^5 Ω.

4.0 CONCLUSIONS

The conclusions that may be drawn from the data presented above are as follows:

a) Many cables successfully passed the accident exposure following artificial aging to a nominal lifetime of 60 years using an aging acceleration factor of about 80.

b) Several cable samples opened 1 A fuses during the accident exposure, with the earliest failure (other than the damaged polyimide cable) at 80 hours. Other samples had IRs early in the accident exposure that might be marginal for some applications.

c) Although one of the cables using polyimide insulation was inadvertently damaged when tightening a test chamber flange, the other one did well during the LOCA tests (it did exhibit a strange thermal shock effect).

d) Single conductor EPR cables had IRs ranging as much as a factor of 10 above comparable multiconductors. During the 340°F part of the test, the single conductors IRs were at least a factor of two higher than the multiconductors. Tests using only single conductors can therefore be non-conservative in estimating accident IRs.

e) Total thermal lag time was typically 3 minutes for multiconductor cables and 30 seconds for single conductors.

Some cables exhibited IR recovery following the initial thermal lag. This indicates that discrete time IR measurements may not capture worst case IR values. Otherwise, discrete measurements appear suitable for performance monitoring.

f) Over the range of 50-250 Vdc, cable insulation resistance was essentially independent of applied voltage.

5.0 REFERENCES

1. M. J. Jacobus, G. L. Zigler, and L. D. Bustard, "Cable Condition Monitoring Research Activities at Sandia National Laboratories," SAND88-0293C, *Proceedings: Workshop on Power Plant Cable Condition Monitoring*, Electric Power Research Institute EPRI EL/NP/CS-5914-SR, July 1988.

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3. "IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations," IEEE Std 383-1974, The Institute of Electrical and Electronic Engineers, 1974.