

# Light Water Reactor Sustainability Program

## Crystal River 3 Cable Materials for Thermal and Gamma Radiation Aging



September 2017

U.S. Department of Energy

Office of Nuclear Energy

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# **Crystal River 3 Cable Materials for Thermal and Gamma Radiation Aging**

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**Prepared for the  
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## SUMMARY

The Expanded Materials Degradation Assessment Volume 5: Aging of Cables and Cable Systems (EMDA) summarizes the state of knowledge of materials, constructions, operating environments, and aging behavior of low voltage and medium cables in nuclear power plants (NPPs) and identifies potential knowledge gaps with regard to cable operation beyond 60 years. The greatest area of uncertainty relates to how well the accelerated aging used in the original equipment qualification (EQ) processes predicts the performance of cable materials in extended operation. General opinion and utility experience have indicated that actual operating environments of in-plant cables are not as severe, however, as the operating and design basis environments used in the qualification process. Better understanding of the long term aging behavior of cable insulation materials in service conditions and the analysis of actual cable operating environments are the objectives of ongoing research to support subsequent license renewal activities in particular and long term cable aging management in general.

A key component of the effort to better understand cable material aging behavior is the availability of representative samples of cables that have been installed in operating light water reactors and have experienced long term service. Unique access to long term service cables, including relatively rich information on cable identity and history, occurred in 2016 through the assistance of the Electric Power Research Institute (EPRI). EPRI facilitated DOE receipt of harvested cables from the decommissioned Crystal River Unit 3 (CR3) pressurized water reactor representing six of the nine most common low voltage cable manufacturers (EPRI 103841R1): Rockbestos, Anaconda Wire and Cable Company (Anaconda), Boston Insulated Wire (BIW), Brand-Rex, Kerite and Okonite. Cable samples received had been installed in the operating plant for durations ranging from 10 years to 36 years. These cables provide the opportunity to assess actual in-plant material aging and compare it to the expectations for service aging implied in original equipment qualification. The received samples are from cables manufactured as early as 1971 and as late as 1998. Of the original manufacturers, BIW, Anaconda and Kerite no longer supply low-voltage cables to the nuclear industry. Okonite, Rockbestos, and Brand-Rex do still supply nuclear-grade low-voltage cables, but most cable insulation formulations have changed over the years. Thus the availability of the CR3 samples representative of cables installed in existing U.S. NPPs also presents the opportunity for additional aging studies on the most relevant insulation and jacketing materials.

This report describes the cables received from CR3 through EPRI assistance, specific knowledge gaps that this study can be used to address, and experimental plans for addressing those gaps using these materials.

Harvested cables from CR3 and other operating or decommissioned NPPs that have experienced long term service, new old stock cables (manufactured before 2000, but never put in service), and relevant modern nuclear cables and materials from cable manufacturers are enabling research to address identified knowledge gaps and better understand long term aging behavior for cable materials currently installed in NPPs. This research, combined with refined understanding of actual service environments and conditions, will both support subsequent licensing activities and more efficient plant cable aging management.

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## ACRONYMS

|         |  |
|---------|--|
| AC      | Alternating Current                                    |
| BIW     | Boston Insulation Wire                                 |
| CPE     | Chlorinated polyethylene                               |
| CR3     | Crystal River Unit#3                                   |
| CSPE    | Chlorosulfonated polyethylene                          |
| DC      | Direct Current   |
| EAB     | Elongation-at-break                                    |
| EMDA    | Expanded Materials Degradation Assessment              |
| EPRI    | Electric Power Research Institute                      |
| EQ      | Equipment Qualification                                |
| EPR     | Ethylene-propylene rubber                              |
| FMR-EPR | Flame and moisture resistant ethylene-propylene rubber |
| FR-EP   | Flame retardant ethylene-propylene rubber              |
| ITE     | Inverse temperature effect                             |
| Mwt     | Megawatt   |
| mADC    | Milliamp Direct Current                                |
| NPP     | Nuclear power plant                                    |
| NRC     | Nuclear Regulatory Commission                          |
| STP     | Shielded twisted pair                                  |
| STQ     | Shielded twisted quad                                  |
| VDC     | Volts - Direct Current                                 |
| XLPE    | Crosslinked polyethylene                               |



## EMDA RECOMMENDATIONS FOR CABLE USE BEYOND 60 YEARS

The concluding section of the EMDA (NUREG/CR-7153) document recommends the following research objectives:

1. Reassess the number of cable circuits and cable types present in high radiation zones (i.e. 70 Mrad over 80 years (up to 1Gy/h) between 45 and 55 °C).
2. Measure operating temperatures of installed cables.
3. Refine activation energies for thermal aging of specific cables in specific environments.
4. Better understand combined thermal/radiation aging effects, including the potential for inverse temperature effects of higher doses at lower temperatures.
5. Better understand the consequences of long-term wetting on low and medium voltage cables.
6. Reevaluated environmental oxygen concentration considerations in loss-of-coolant accident simulation experiments.

Harvested cables from CR3 particularly provide the opportunity to address these recommendations by pursuing 1) better understanding of material and condition-specific activation energies, and 2) better understanding of the combined effects of thermal and gamma radiation aging.

## HARVESTED CABLES FROM CRYSTAL RIVER UNIT 3

According the Nuclear Regulatory Commission (NRC) website (<https://www.nrc.gov/info-finder/decommissioning/power-reactor/cr3.html>), Page Last Reviewed/Updated Friday, March 04, 2016):

Crystal River Unit 3 Nuclear Generating Plant (CR-3) was a 2,609 Mwt, pressurized water reactor that was licensed to operate from December of 1976 to February 20, 2013. During a refueling outage that started on September 26, 2009, CR-3 replaced the steam generators (SG), requiring a large hole to be made in the containment structure. When attempting to restore the containment structure following the SG replacement, damage to the containment structure was observed. The licensee attempted to repair the damage, but later decided to decommission the reactor.

The facility is currently transitioning to a SAFSTOR condition. The licensee submitted the CR-3 post-shutdown decommissioning activities report, including the site-specific cost estimate, on December 2, 2013. The plant is planning for the transfer of spent fuel to dry storage most likely in 2017.

The following subsections describe the specific cable samples received to Pacific Northwest National Laboratory (PNNL) through EPRI from the decommissioned CR3 nuclear power plant, organized by manufacturer.

## ANACONDA WIRE AND CABLE COMPANY

Anaconda EPR is the second most common insulation in containment, found in one-third of plants (EPRI TR-103841). Anaconda EPR-based insulation formulation trade names include Uniblend EP and Unishield EP for medium voltage power cables, Unicon and Durasheath EP for low voltage power cables, and Flame-Guard or Anaconda EP for Instrumentation and Control Cable (Anaconda Catalog).

The Anaconda cable from CR3, jacket labeled “ANACONDA-Y 4/C #16 FLAME-GUARD FR-EP 600V”, was manufactured in 1985 and installed in the CR3 Reactor Coolant system in the same year. It is a 600 V instrument cable of shielded twisted quad (STQ) construction, with four #16 conductors and 1

#18 copper drain, as visible in Figure 1. The 26 mil thick, Flame-Guard (FR-EP) ethylene-propylene rubber (EPR) insulation variations are red, black, green and white. The 55 mil thick chlorinated polyethylene (CPE) jacket, seen in Figure 2, is green on the outside and black on the inside. There is a plastic liner layer between the foil wrapper shield layer and the jacket. Documents indicate that the cable operated at 5 VDC, at less than 5 mADC, with a 100% duty factor for 30 years. The specific temperature and dose rate of the environment during the cable operation between 1985 and 2009 are not known.



Figure 1. Anaconda Flame-Guard FR-EP/CPE Cable components



Figure 2. Anaconda Flame-Guard FR-EP/CPE Cable with Jacket Label

## **BOSTON INSULATED WIRE CABLE SYSTEMS INC.**

BIW EPR is the ninth most common insulation in containment, found in 19% of plants (EPRI TR-103841). BIW flame and radiation resistant EPR insulation has tradename BOSTRAD 7E and chlorosulfonated polyethylene (CSPE) jacket tradename BOSTRAD 7 (BOSTRAD report).

The BIW cable from CR3, jacket labeled “BIW CABLE SYSTEMS, INC. BOSTRAD 7E 16 AWG ITSP EPR-CSPE INS/CSPE JKT 600V INST”, was manufactured in 1983 and installed in the CR3 Reactor Coolant system in 1985. It is a 600 V instrument cable of shielded twisted pair (STP) construction, with two #16 conductors and 1 #18 copper drain, as seen in Figure 4. The 28 mil thick, BOSTRAD 7E EPR insulation variations are black with the words “Black” and “White” printed on them in white letters, respectively. The 59 mil thick CSPE jacket, seen in Figure 4, is green and with a black, fiber-reinforced liner. A clear plastic ribbon, printed with “BIW CABLE SYSTEMS” in black lettering lies between the foil wrapper shield and the jacket. Documents indicate that the cable operated at 24

VDC, and 4-20 mADC, with a 100% duty factor over its 30 years in service. The specific temperature and dose rate of the environment during the cable operation between 1985 and 2009 are not known.



Figure 3. BIW BOSTRAD 7/BOSTRAD 7E EPR/CSPE Cable Components



Figure 4. BIW BOSTRAD 7/BOSTRAD 7E EPR/CSPE Cable Components

## BRAND-REX

Brand-Rex crosslinked polyethylene (XLPE) is the third most common insulation in containment, found in 28% of plants (EPRI TR-103841).

The Brand-Rex cable from CR3, jacket labeled “BRAND-REX ULTROL INSTRUMENTATION CABLE 600V 1 SHIELDED PR #16 AWG”, was manufactured in 1986 and installed in the CR3 Main Feedwater system in 1994. It is a 600 V instrument cable of STP construction, with two #16 conductors



and a drain wire, as seen in Figure 5. The 25 mil thick, Ultrol XLPE insulation variations are black and white. The 45 mil thick CSPE jacket is black, as seen in Figure 6. There is a foil wrapper shield layer. Documents indicate that the cable operated at 24 VDC, at 4-20 mADC, with a 100% duty factor over its 21 years in service. The specific temperature and dose rate of the environment during the cable operation between 1994 and 2009 are not known.



Figure 5. Brand-Rex FR-XLPE/CSPE Cable Components



Figure 6. Brand-Rex FR-XLPE/CSPE Cable

## KERITE

Kerite HTK is the fifth most common insulation in containment, found in one-fifth of US plants (EPRI TR-103841). HTK is reported to be an EPR-like material.

The Kerite cable from CR3 had no label on its jacket, was manufactured in 1971 and installed in the CR3 Condenser Air Removal system in 1973. It is a 600 V control power cable composed of two #10 insulated conductors. The brown HTK insulation is printed with “Black” and “White” labels in white letters, respectively, as seen in Figure 7. The 63 mil thick black Kerite FR jacket, as seen in Figure 8, integral with an asbestos filler, was removed from the insulated conductors through a certified abatement procedure and disposed of accordingly. Documents indicate that the cable operated at 125 VDC, and 15A, with a 100% duty factor over its 42 years in service. The specific temperature and dose rate of the environment during the cable operation between 1985 and 2009 are not known.



Figure 7. Kerite (HTK/FR) Cable Components



Figure 8. Kerite (HTK/FR) Cable

## THE OKONITE COMPANY

Okonite EPR is the fourth most common insulation in containment, found in 25% of plants (EPRI TR-103841).

The Okonite cable from CR3, jacket labeled “OKONITE 4 3/C 14 AWG CU OKONITE FMR (EP)-CSPE 600V 18C 1998”, was manufactured in 1998 and installed in the CR3 Emergency Feedwater system in 1999. It is a 600 V, unshielded control cable with three #14 conductors and no drain wire, as seen in Figure 9. The 40 mil thick, Okonite flame and moisture resistant (FMR)-EPR insulation is black with “BLACK”, “RED” and “WHITE” labels in white letters, respectively. The 45 mil thick Okolon CSPE jacket is black, as seen in Figure 10. Documents indicate that the cable operated at 120 VAC, at 0.1 A, with a 100% duty factor over its 15 years in service. The specific temperature and dose rate of the environment during the cable operation between 1999 and 2009 are not known.



Figure 9. Okonite (EP-FMR/CSPE) Cable



Figure 10. Okonite (EP-FMR/CSPE) Cable

## ROCKBESTOS

Rockbestos XLPE is the most common insulation in containment, found in 58% of plants (EPRI TR-103841).

The Rockbestos cable from CR3, jacket labeled “2/C 16 AWG ROCKBESTOS® 600V B/M NO. NK-35A”, was manufactured in 1993 and installed in the CR3 Industrial Cooling system in 1994. It is a 600 V instrument cable of STP construction with two #16 conductors and one #18 drain wire, as seen in Figure 11. The 25 mil thick, Firewall III XLPE insulation variation are white and black. The 45 mil thick CSPE jacket is black, as seen in Figure 12. Documents indicate that the cable operated at 24 VAC, in the mA range, with a 100% duty factor over its 21 years in service. The specific temperature and dose rate of the environment during the cable operation between 1994 and 2009 are not known.



Figure 11. Okonite (EP-FMR/CSPE) Cable Components





Figure 12. Rockbestos Firewall III (XLPE/CSPE) Cable

## ACTIVATION ENERGIES AND LIFETIME PREDICTION

Most safety-related cables were qualified using type testing (IEEE 323-1974, 383-1974), in which a representative cable was exposed to simulated conditions expected to bound those experienced by the cable during the licensed operating life of the plant (initially 40 years). Thermal aging at a series of increasingly elevated temperatures and Arrhenius analysis of the results of aging, usually on degradation of mechanical properties, was used to predict the results of long term aging under operating conditions. For example, to predict the result of 40 years of exposure to 49 °C, samples of a representative cable construction were exposed to 121, 136, 150, and 180 °C. The exposure times at these temperatures at which the insulation elongation-at-break (EAB) reached 50% were determined, with the understanding that at this degradation level a cable is conservatively capable of performing its function in a design basis event (e.g. loss of coolant accident). The aging temperatures,  $T_i$ , and the durations at those temperatures to the selection reference point (e.g. 50% EAB),  $t_i$ , and the Boltzmann constant,  $k$ , are used to calculate the activation energy,  $E_a$ , of the degradation reaction:

$$E_a = \frac{T_1 T_2 k \ln(t_1/t_2)}{T_1 - T_2}.$$

Extrapolation to predict time to the reference performance point,  $t_{life}$ , at an anticipated temperature (e.g. 49°C),  $T_{life}$ , can be accomplished using the known time to reference point,  $t_{age}$  at an aging temperature,  $T_{age}$ , the Boltzmann constant,  $k$ , and the activation energy,  $E_a$ , using the following form of the Arrhenius equation:

$$t_{life} = t_{age} \exp\left(\frac{E_a}{k} \left[\frac{1}{T_{life}} - \frac{1}{T_{age}}\right]\right).$$

This approach to using shorter term testing at high temperatures to predict long term performance at lower temperatures is most useful when the degradation mechanism, and hence the activation energy, is constant over the temperatures of accelerated aging and the temperature at which performance is to be predicted.

The observation of “non-Arrhenius behavior” in certain polymer systems, where the activation energy at higher temperatures differs from that at lower temperatures, has raised the question as to how much of a concern this might be for common cable insulations.

The EMDA list several examples of cable jacket materials that exhibit lower activation energies at lower aging temperatures. The examples include Okonite and Rockbestos Firewall III neoprene (polychloroprene) jacket materials. Also included were Samuel Moore Dekoron and BIW BOSTRAD 7E jacket materials composed of CSPE. All of these examples are chlorinated polymers and are used for cable jackets. Degradation of bonded jacket material may directly affect the aging performance of insulation. Usually, however, cable jacketing is considered important mainly during installation and is

independent of cable insulation in terms of cable qualification and cable performance during a design basis event.

The EMDA also mentions that EPR materials can exhibit complex thermal aging behavior, depending on their degree of crystallinity, and represent a recommended target for further study to refine the understanding of activation energies with regard to qualification and lifetime prediction.

The four examples from different manufacturers of EPR-type insulations in the harvested CR3 cables—Anaconda, BIW, Kerite and Okonite—provide the chance to investigate activation energies of specific materials of major relevance to the nuclear industry.

Note: The NRC is pursuing a project to evaluate condition monitoring techniques on a variety of cables over an accelerated aging period corresponding to approximately 80 years of operation. The time for the experiments, based on the temperatures employed, is calculated using known activation energies. Determination of activation energies for the specific CR3 cables mentioned above will help inform the planning of the NRC project that is to include, among other cables, samples from the same source cables.

## **INVERSE TEMPERATURE EFFECTS**

It has been noted that many semi-crystalline polymers show an inverse temperature effect (ITE) when exposed to simultaneous thermal and radiation aging in which degradation is faster at temperatures below 60 °C than at the higher temperatures associated with accelerated aging, such as above 100 °C. Most XLPE polymers have melting phase transitions in the range of ~40 to 130°C. The Brand-Rex and Rockbestos cables with XLPE insulation therefore will be of interest to see if ITE are apparent in these materials. Anaconda Flame-Guard insulation does not exhibit significant melting peaks in this temperature region and has been reported as a material that does not reflect ITE (SAND10-7266). The Okonite, Kerite and BIW EPR insulations will be examined for potential ITE behavior.

## **NEAR-TERM EXPERIMENTS PLANNED FOR CR3 CABLE MATERIALS**

Insulation test specimens for aging and analysis have been prepared from each of the six CR3 cable types including 1) 100 mm lengths with conductor intact primarily for indenter modulus and electrical testing, and 2) 50 mm or 100 mm tubular straws of insulation with conductor removed primarily for tensile testing. The suite of complimentary characterization techniques including density, Fourier transform infrared spectroscopy, differential scanning calorimetry, oxidation induction time/temperature, gel fraction/uptake factor, etc. can be performed on small portions of one of the two specimen forms.

The main reference performance point for activation energy determination will be EAB, so straw-type specimens of cable insulation suitable for tensile testing are required. The length of cable needed for a series of aging experiments to determine  $E_a$  using a destructive test such as EAB can be calculated as #specimens in a test group (usually 5) x #data points at a given temperature x # temperatures + # samples to determine initial condition (usually 2x # in test group or 10). There is usually a yield factor involved in produced insulation straw samples from an intact cable as material is lost in the process in a manner that is dependent of the nature of the material itself. For example, with 10 specimens for initial condition determination, 4 test temperatures, 5 specimens per data point and 10 data points per temperatures the total number of specimens required is 232. For straw specimens of 50 mm length and an 80% specimen production yield, this corresponds to 11.6 m (38 ft) of cable, or approximately 10 ft of cable per test temperature. This cable length requirement can be reduced proportionally if more than one conductor in a multi-conductor cable is used for specimen production. For the above example, 19 ft of 2-conductor and 13 feet of 3-conductor cable would be required. Performance has been observed to differ with insulation



color and this should be considered when directly comparing data from different colors of insulation from the same cable.

At least three temperatures are required for  $E_a$  determination, but more are preferred. Targeted temperatures will be at least 10 K apart and selected with consideration of material phase transitions. Practical limitations in terms of the amount of cable and labor resources available limit the number of data points, temperatures and specimens characterized per data point that can be pursued. Similarly, how closely the aging tests replicate actual field aging in terms of temperature and duration is limited by project schedule constraints to experiments that can be performed in a few years or less.

The High Exposure Facility at PNNL represents a controlled temperature, gamma dose and dose rate opportunity to investigate inverse temperature effects in the CR3 materials. The current HEF configuration consists of a Co-60 source that produced a collimated gamma beam that extends in a 30 degree cone from the window in the steel column housing the source. A recent campaign exposed RSCC Firewall III XLPE to a series of dose rates from ~100 to 500 Gy/h for 0 to 25 days at 26, 60, 90, and 115 °C. In this configuration, one oven containing one rack of samples completely occupies the area of the gamma cone represented by these dose rates.

It was proposed in early FY2017 that a second collimator window be installed in the steel column of the HEF to permit a second gamma cone to be emitted and to effectively double the concurrent sample exposure capability. Mid-year LWRS funds were expected to become available for this capability upgrade, as the proposal had apparently reviewed favorably among competing proposals, but the mid-year funds did not end up becoming available. A second capability upgrade possibility, purchase of a new Co-60 source to replace the current source and bring a 3 to 5 fold increase in dosing power, was considered as preferable to adding a second column window. Funds to secure a new source were expected to be invested by PNNL with the new source coming online in the first half of FY18. Aging of CR3 at a series of dose rates similar to the completed RSCC cable series, but to higher total dose, is to be used to target evidence of ITE. Expectation of one of the imminent source upgrades mentioned above contributed to delay in initiation of the CR3 gamma exposure campaign and subsequent data collection. Due to the uncertainty in timing of resources for the source upgrade, the current plan is to begin an exposure campaign using the existing source. This will necessarily require the maximum dose rate to be reduced from ~500 Gy/h to ~300 Gy/hr in order to be able to practically achieve a constant dose rate over the course of the experiment as the source continues to decay at a rate of 1.1% per month. A total dose of 60 Mrad will require 2000 h of exposure at 300 Gy/h.

## **INITIAL TESTING OF THE ANACONDA CABLE**

As mentioned above, the Anaconda cable was manufactured and installed in CR3 in 1985 and saw 30 years of service. Anaconda cable insulation was selected as a priority for study as it is the most common EPR cable material in U.S. NPPs (EPRI TR-103841). It can be assumed that the EAB of the initial Flame-Guard EPR insulation in this cable as produced was similar to the ~340% initial elongation recorded by Sandia for black Flame-Guard insulation purchased in the late 1970s. Initial measurement of black and red insulation samples from the CR3 cable measured 212% +/- 9% and 209% +/- 41%, respectively. The before and after pulling photographs for a red insulation specimen and a black insulation specimen are seen in Figures 13 and 14, respectively. If these EAB values are accurate and the insulation materials are comparable, then this may indicate that the harvested Anaconda cable following 30 years of installation is well into the knee of its degradation curve as seen in Figure 15. Additional aging will confirm if this material is as close to end of life as this might imply.

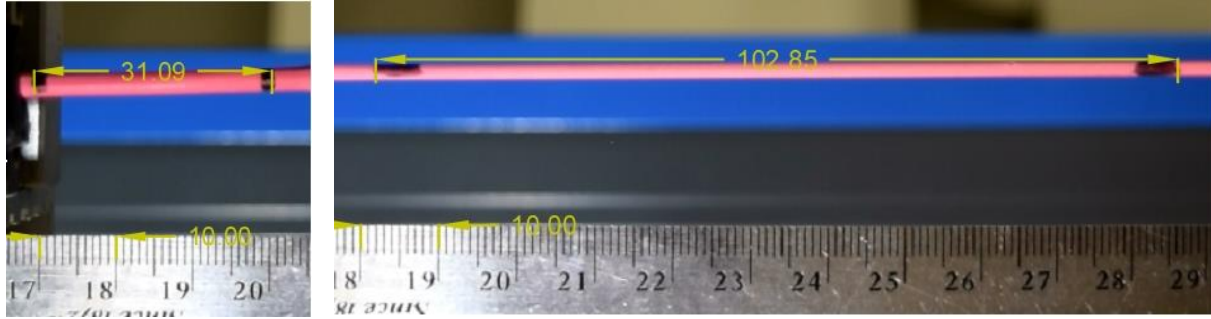


Figure 13. Before pull and just prior to break for red Anaconda EPR insulation

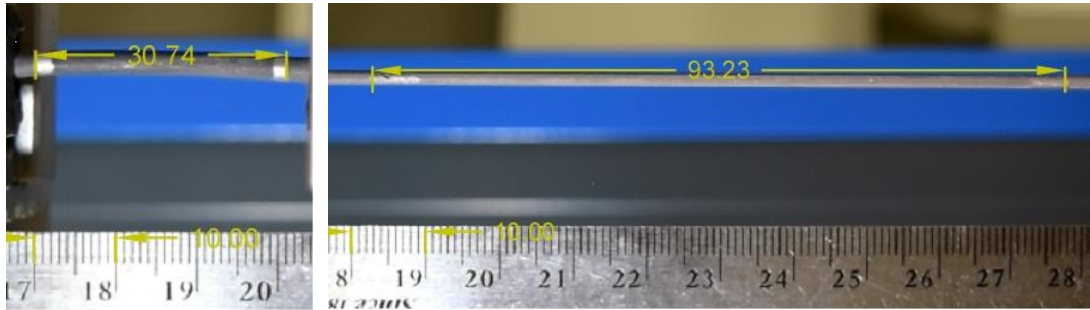


Figure 14. Before pull and just prior to break for black Anaconda EPR insulation

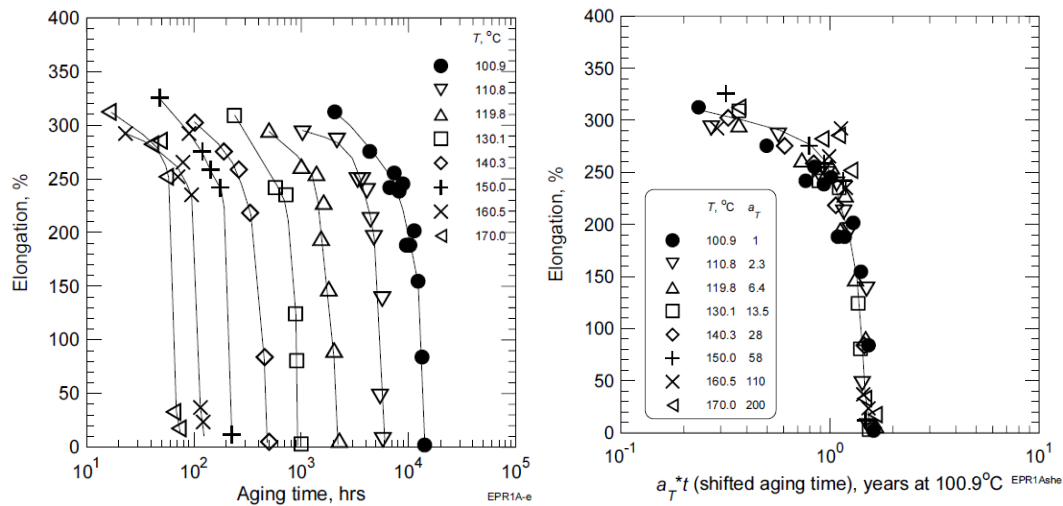


Figure 15. Anaconda Flame-guard EPR aging time versus Elongation % (Left) and Elongation data shifted to 109° C (Right) (Plots from SAND05-7331).

The black Anaconda Flame-Guard insulation previously measured (SAND2010-7331) had an (unaged) density of  $1.325 \text{ g.cm}^{-1}$ . The density of the red insulation from the CR3 Anaconda cable was measured to be  $1.340 \pm 0.0356 \text{ g.cm}^{-1}$ , and the density of the black insulation was measured to be  $1.421 \pm 0.0264 \text{ g.cm}^{-1}$ . This density increase is also consistent with significant aging in this harvested material.

The indenter modulus of the green Anaconda CPE jacket and the black, white, green and red Flame-Guard FR-EP insulations are listed in Table 1.

Table 1. Indenter Modulus of Anaconda Cable

| <u>Specimen</u>      | <u>Modulus (N/mm)</u> |
|----------------------|-----------------------|
| Green CPE Jacket     | 16.98 +/- 0.76        |
| Black EPR Insulation | 31.30 +/- 0.83        |
| White EPR Insulation | 31.92 +/- 0.93        |
| Green EPR Insulation | 29.46 +/- 0.74        |
| Red EPR Insulation   | 32.68 +/- 1.0         |

## CONCLUSION

Harvested cables from CR3 and other NPPs that have experienced long term service, new old stock cables (manufactured before 2000, but never put in service), and relevant modern nuclear cables and materials from cable manufacturers are enabling research to address identified knowledge gaps and better understand long term aging behavior for cable materials currently installed in NPPs. This research, combined with refined understanding of actual service environments and conditions, will both support subsequent licensing activities and more efficient plant cable aging management.

The greatest area of uncertainty identified in the EMDA in regard to operation beyond 60 years relates to how well the accelerated aging used in the original equipment EQ processes predicts the performance of cable materials in extended operation. A key component of the effort to better understand cable material aging behavior is the availability of representative samples of cables that have been installed in operating light water reactors and have experienced long term service such as the CR3 cables described herein. This report describes the cables received from CR3 through EPRI assistance, some of the specific knowledge gaps that study of these cable materials can be used to address, and experimental plans for addressing those gaps using these materials.

Expectation of one of the imminent Co-60 source upgrades for the PNNL High Exposure Facility mentioned above contributed to delay in initiation of the CR3 gamma exposure campaign and subsequent data collection. Due to the uncertainty in timing and availability of resources for the source upgrade, the current plan is to begin an exposure campaign of CR3 cable materials using the existing source.

## REFERENCES

Anaconda Wire and Cable Company Catalog for Power and Control Cables for Generating Stations

BOSTRAD7E CABLES FLAME AND RADIATION RESISTANT CABLES FOR NUCLEAR POWER PLANTS, REPORT NO. B 915, REV. 1, DECEMBER 1984, BIW CABLE SYSTEMS, INC., 65 Bay Street, Boston, Massachusetts 02125

EPRI TR-103841.Revision 1. *Low Voltage Environmentally-Qualified Cable License Renewal Industry Report*. Electric Power Research Institute. 1994.

IEEE Std 323-1974 "IEEE Standard for Qualifying Class IE Equipment for Nuclear Power Generating Stations." Institute of Electrical and Electronics Engineers.

IEEE Std 383-1974 "Type Test of Class IE Electric Cables, Field Splices, and Connections for Nuclear Generating Stations." Institute of Electrical and Electronics Engineers.

NUREG/CR-7153, Vol. 5 "Expanded Materials Degradation Assessment (EMDA) Volume 5: Aging of Cables and Cable Systems," ORNL/TM-2013/532, October 2014.

SAND2005-7331 Gillen, K.T.; Assink, R.A.; Bernstein, R.; "Nuclear Energy Plant Optimization (NEPO) Final Report on Aging and Condition Monitoring of Low-Voltage Cable Materials," November 2005.

SAND2010-7226 Gillen, K.T.; Bernstein, R.; "Review of Nuclear Power Plant Cable Aging Studies with Recommendations for Improved Approaches and for Future Work," November 2010.