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Pacific Northwest
NATIONAL LABORATORY

Light Water Reactor Sustainability Program

Progress in Characterizing Naturally-Aged Nuclear Power Plant Cables

May 2016

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Nuclear Science Project Management Office

Date

SUMMARY

The Cable Aging research task of the Light Water Reactor Sustainability Materials Aging and Degradation pathway seeks to increase understanding of the degradation that occurs in cable system materials during their operational lifetime. Many changes have occurred in cable manufacturing and in the formulation of cable insulation and jacketing materials since the oldest currently operating commercial nuclear power plants in the United States were constructed in the late 1960's/early 1970's. Developing a predictive understanding of the aging and degradation of cable system materials installed in existing nuclear plants is challenging since many of the materials are no longer manufactured and little information may be available about their formulations. Investigation of the aging behavior of these materials must rely on historical data, procurement of vintage materials from storage that may be fortuitously available, and harvesting of cables either following plant closure or during cable replacement activities. Harvesting of installed cables can also provide the opportunity for information about the aging of materials in actual plant environments.

The Electric Power Research Institute has been instrumental in providing new old stock cables and harvested cables in support of collaborative aging research. Cables provided to this program represent the most common insulation and jacket materials found in nuclear power plants, as well as those from the most common cable manufacturers.

Detailed in this report are initial characterization data for an instrumentation cable that was installed within containment at a four loop (four steam generator) Westinghouse, pressurized water reactor nuclear power plant for 30 years. Baseline characterization of the as-received cable is included as well as initial characterization of thermally aged jacket from a comparable cable sample provided by Oak Ridge National Laboratory.

The characterization of naturally-aged and subsequent laboratory-aged cable materials is informing our understanding of insulation and jacket degradation mechanisms. This knowledge will support our ability to monitor cable degradation state, develop methods to mitigate cable aging, and predict cable remaining useful life.

ACKNOWLEDGEMENTS

Naturally-aged cables have been graciously made available for this work through Andrew Mantey of the Electric Power Research Institute. Cable samples, including portions of thermally aged cable specimens were provided by Dr. Robert Duckworth of the Oak Ridge National Laboratory.

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FIGURES

TABLES

ACRONYMS

AMP	aging management program
AWG	American wire gauge
BIW	Boston Insulated Wire & Cable Company
CSPE	chlorosulphonated polyethylene
DSC	differential scanning calorimetry
EAB	elongation at break
EMDA	Expanded Materials Degradation Assessment (NUREG/CR-7153)
EPR	ethylene-propylene rubber
EPDM	ethylene-propylene-diene M-type (ASTM D1418, 2010)
EPRI	Electric Power Research Institute
FR	fire resistant
FMR	fire and moisture resistant
FWIII	Firewall® III
HTK	or HT-Kerite, product name of Kerite Corporation (NUREG/CR-7102, 2011)
ID	identifier
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IM	indenter modulus
LWRS	Light Water Reactor Sustainability [program]
MAaD	Material Aging and Degradation [pathway]
NOS	new old stock
NPP	nuclear power plant
OA	overall [jacket]
OIT	oxidation induction time
OITP	oxidation induction temperature
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
SiR	silicone rubber
XLPE	cross-linked polyethylene
XLPO	cross-linked polyolefin

INTRODUCTION

The Cable Aging research task of the Light Water Reactor Sustainability (LWRS) Materials Aging and Degradation (MAaD) pathway seeks to increase understanding of the degradation that occurs in cable system materials during their operational lifetime in active nuclear power plants (NPPs). Knowledge of these changes helps to support plant cable aging management program (AMP) cable assessment and replacement planning as well as development of condition monitoring technologies.

Specification of cables for use in NPPs is based on performance, not on materials of construction. Many changes have occurred in cable manufacturing and in the formulation of cable insulation and jacketing materials since the oldest currently operating commercial nuclear power plants in the United States were constructed in the late 1960's/early 1970's. Developing a predictive understanding of the aging and degradation of cable system materials installed in existing nuclear plants is challenging since many of the materials are no longer manufactured and little information may be available about their formulations. Investigation of the aging behavior of these materials must rely on historical data, procurement of vintage materials from storage that may be fortuitously available, and harvesting of cables either following plant closure or during cable replacement activities. Harvesting of installed cables can also provide the opportunity for information about the aging of materials in actual plant environments.

The most common insulation materials found in NPPs are cross-linked polyolefins (XLPOs) (including cross-linked polyethylene (XLPE)), ethylene-propylene rubbers (EPRs) (including ethylene-propylene diene type "M" (EPDM) and Kerite HTK polymers), and silicon rubbers (SiRs) (EPRI TR-103841.R1, 1994). The most commonly found XLPE insulation materials in NPPs prior to 1994 are Rockbestos Firewall III, Brand-Rex XLPE, and Raychem Flametrol. The most commonly found EPR-type insulation materials in NPPs prior to 1994 are Anaconda Y Flame-Guard FR, Okonite FMR, Samuel Moore Dekoron Dekorad, BIW Bostrad 7E, and Kerite HTK (or KT-Kerite) (NUREG/CR-7102, 2011). The most commonly found SiR insulations in NPPs prior to 1994 were Rockbestos and Kerite FR. (from EPRI TR-103841.R1, 1994 as summarized in Anandakumaran, 2007).

The Electric Power Research Institute (EPRI) has been instrumental in providing new old stock (NOS) cables and harvested cables to MAaD researchers and for research activities of the Nuclear Regulatory Commission (NRC) in support of collaborative cable research. Cables provided include those of many of the types and from many of the manufacturers listed above. Focus of these research efforts on the most common cables and materials supports the widest relevance of knowledge gained.

The following section describes many of the naturally aged cable systems available for ongoing studies in cable aging by the Pacific Northwest National Laboratory (PNNL) and Oak Ridge National Laboratory (ORNL). Selected characterization results are described for one example EPR instrumentation cable, manufactured by Boston Insulated Wire (BIW), that has been harvested from a location within containment at a four loop (four steam generator) Westinghouse pressurized water reactor (PWR) NPP where it had been installed for approximately 30 years. Baseline characterization of this as-received cable is included as well as initial characterization of thermally aged jacket from a comparable cable sample provided by ORNL.

The characterization of naturally aged and subsequently laboratory-aged cable materials broadens the understanding of insulation and jacket degradation mechanisms. This knowledge supports the ability to monitor cable degradation state, to develop methods to mitigate cable aging, and to predict cable remaining useful life.

NATURALLY AGED NUCLEAR POWER PLANT CABLES

The term "naturally aged" is used to refer to cables that have not undergone accelerated "laboratory aging." Of special interest to this program are naturally aged cables that were manufactured for use in nuclear power plants at the time of initial plant operation. Cables manufactured prior to 1990 are of interest due to their historic material formulations that differ from modern cable formulations and because of interest in cable material changes while in storage or use over significant periods of time. NOS (new old stock cable) is naturally aged cable of historic material formulation and construction that has been stored in nominally environmentally controlled conditions since its manufacture. NOS cable has not been exposed to elevated temperatures, radiation, sunlight, moisture, or other environmental stresses of significance. Examples of NOS cables available for LWRS cable research are described in Table 1. The term "harvested cable" is used here to refer to naturally aged cable that has been installed in an operating NPP. Harvested cable may or may not have been energized or exposed to stresses other than time and those associated with the installation process. Cables may have been harvested due to failure or noted degradation from in-use stress, or they may have been harvested for reasons unassociated with their performance such as replacement of a component to which they were connected or closure of the NPP in which they were installed. Examples of harvested cables available for LWRS cable research are described in Table 2.

Table 1. New Stock Old Cables at PNNL

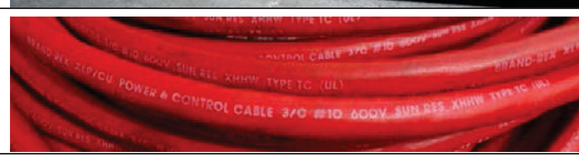
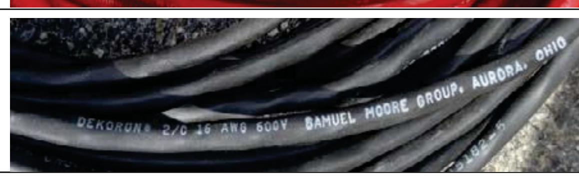
Labeling on Cable Jacket	**Cable Image**
BRAND-REX XLP/CU POWER & CONTROL CABLE 3/C #12 600V SUN RES XHHW TYPE TC (UL)	
BOSTON INSULATED WIRE & CABLE CO. 2/C	
THE OKONITE CO EPR CSPE 2/C 12 AWG	
BRAND-REX XLP/CU POWER & CONTROL CABLE 3/C #10 600V SUN RES XHHW TYPE TC (UL)	
DEKORON® 2/C 16 AWG 600V SAMUEL MOORE GROUP, AURORA, OHIO	

Table 2. Harvested Cables at PNNL

Labeling on Cable Jacket	Cable Image
ROCKBESTOS® 2/C 16AWG 600V	
OKONITE FMR (EP)-CSPE 600V 3/C 14 AWG 1998	
BRAND-REX ULTROL INSTRUMENTAION CABLE 600V 1 SHIELDED PR #16 AWG	
BIW CABLE SYSTEMS, INC. BOSTRAD 7E 16 AWG ITSP EPR-CSPE INS/CSPE JKT 600V INST 1982	
ANACONDA-Y 4/C #16 Flame-Guard FR-EP 600V	
Boston Insulated Wire & Cable Co. (1979) 600V 2/C #12 AWG 22/C #20 AWG O/A Shield	

HARVESTED BIW CABLE

One of the major manufacturers of EPR-insulated cable in the 1970s was Boston Insulated Wire & Cable Co. (BIW). BIW cable can be found inside containment in approximately 20% of NPPs (EPRI TR-103841.R1). A length of BIW instrumentation cable, labeled "Boston Insulated Wire & Cable Co. (1979) 600V 2/C #12 AWG 22/C #20 AWG O/A Shield" has been harvested from within containment at a four loop (four steam generator) Westinghouse, pressurized water reactor (PWR) nuclear power plant, where it had been installed for 30 years. The cable conductor construction features EPR insulation bonded to Hypalon® chlorosulphonated polyethylene (CSPE) jacket. This is a particularly interesting cable construction to study as the degradation of the CSPE jacket and the EPR insulation are therefore coupled. The cable in question is comprised of 22 smaller, 20 gauge (#20), insulated conductors, 2 larger, 12 gauge (#12), insulated conductors, a bare ground wire, and an overall foil wrapped shield. The CSPE jacket of each conductor is color-coded. As seen in Figure 1, the conductors are arranged with an outer ring of 15 elements: the 12 #20 conductors plus the 2 #12 conductors and a ground wire. There is a middle ring of 8 #20 conductors, and a center region with the 2 remaining #20 conductors. On the outside of the cable, around the overall foil shield is a CSPE jacket. The components of this cable are being characterized to assess their current state of degradation, following 30 years of operation, and to establish a baseline for future accelerated aging. Initial laboratory thermal aging has been performed on specimens of the CSPE jacket, and oxidative induction temperature (OITP) characterization data of a 100°C series of aging experiments is displayed below.

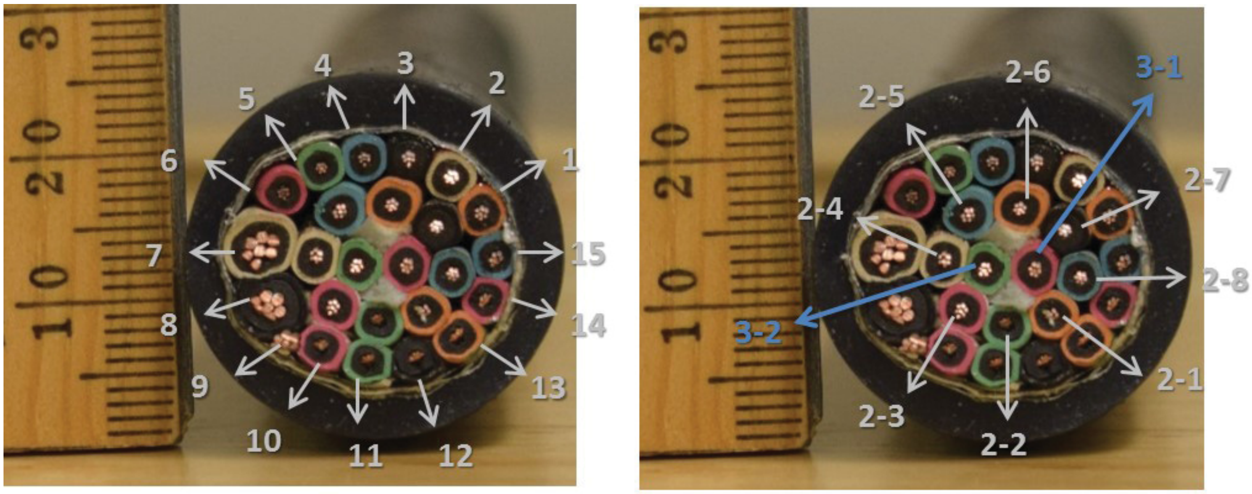


Figure 1. BIW cable cross-section illustrating construction, with component IDs labeled.

Before dissembling the BIW cable, indenter modulus (IM) measurements were performed using an instrument on loan from EPRI and according to international standard practice (IEC/IEEE 62582-2, 2011). Figures 2 and 4 show photos of BIW cable pieces 1 and 2, respectively, and the locations selected on the cables for IM measurements. Figures 3 and 5 plot the IM values measured at those locations. Figure 6 is a schematic and photo illustrating the radial measurement points accessed at each location.

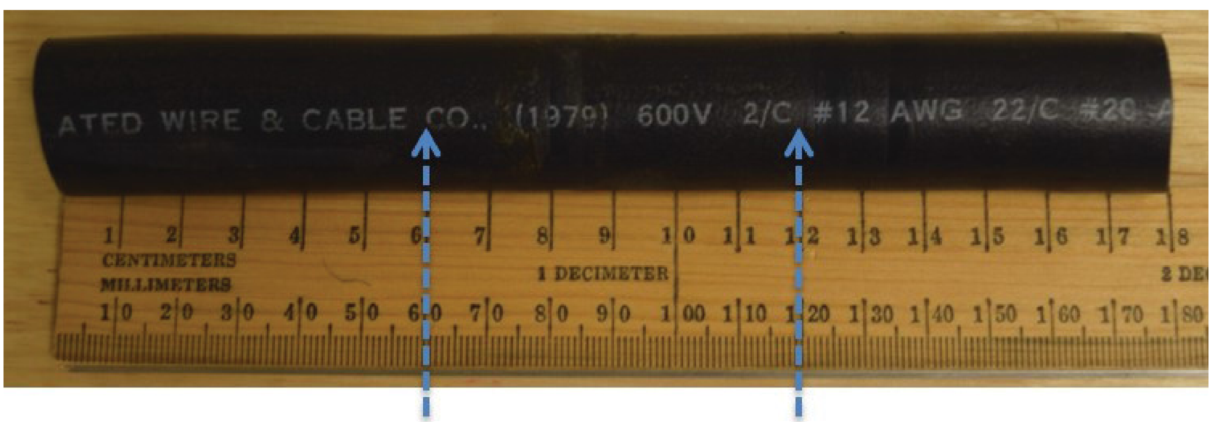


Figure 2. BIW intact cable piece 1 showing 2 locations of indenter measurements

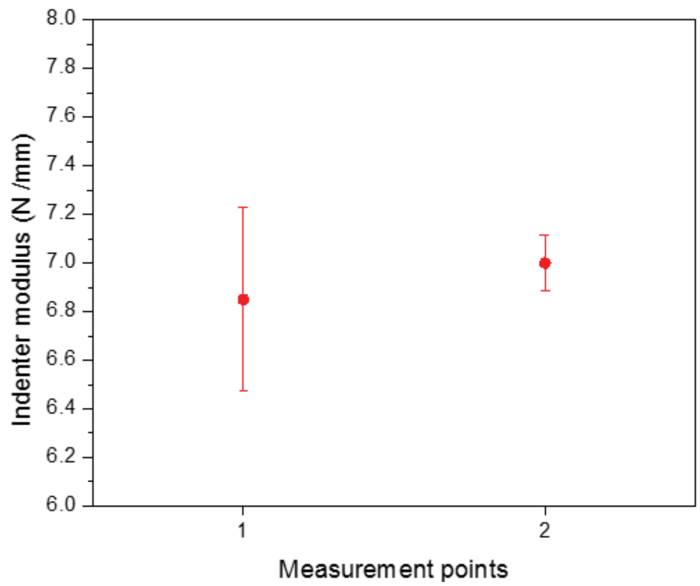


Figure 3. BIW intact cable piece 1 indenter measurement results

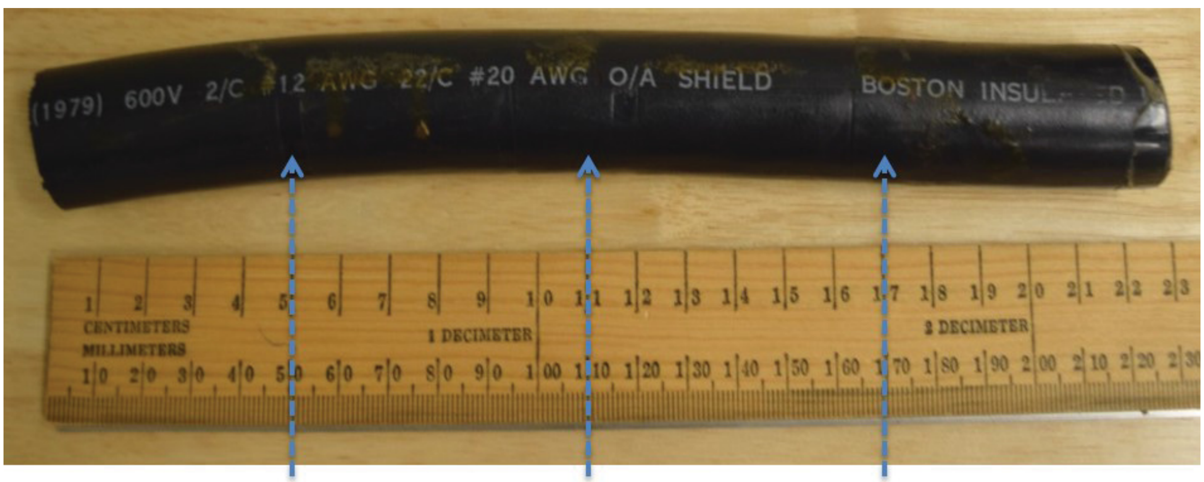


Figure 4. BIW intact cable piece 2 showing 3 locations of indenter measurements

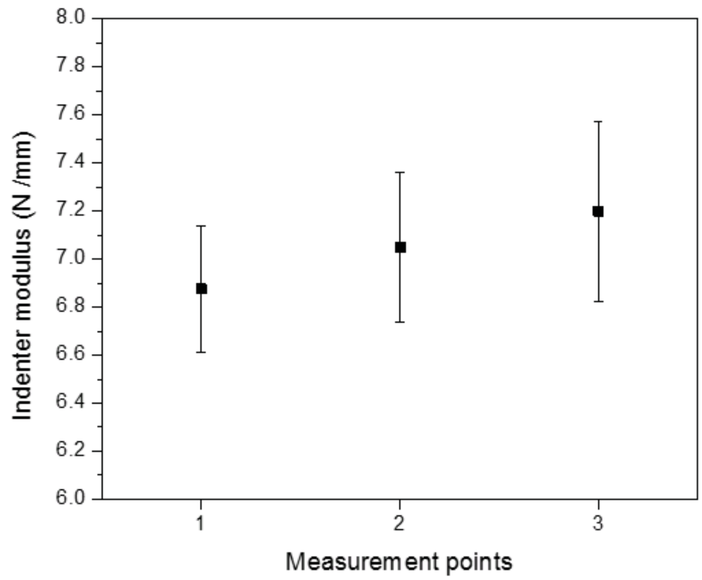


Figure 5. BIW intact cable piece 2 indenter measurement results

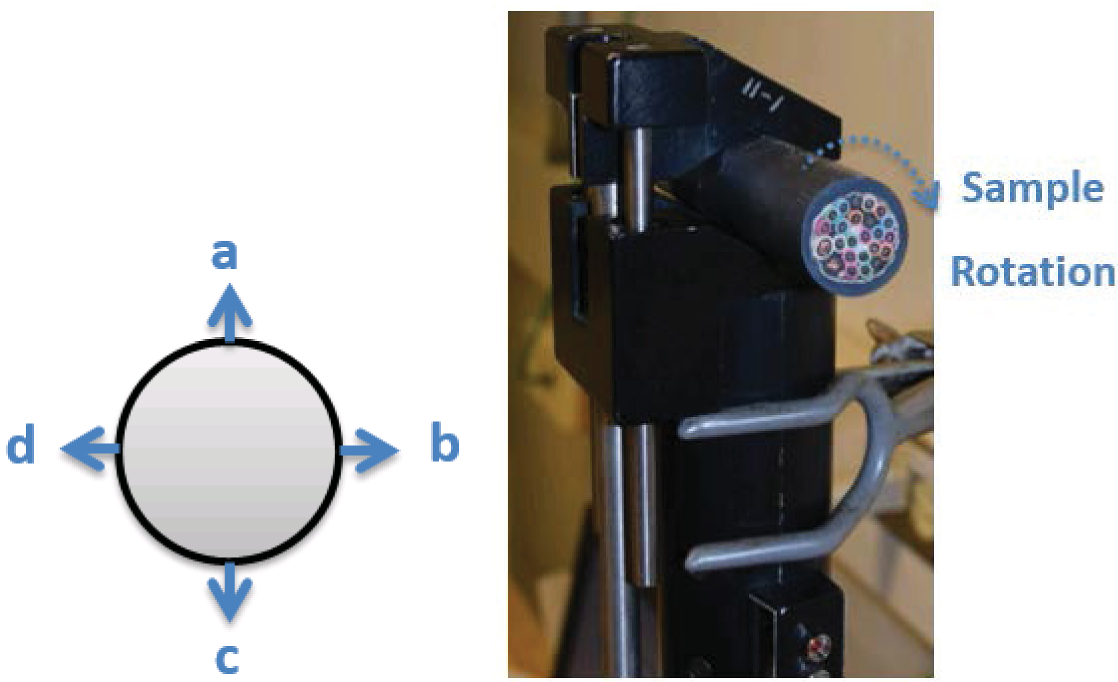


Figure 6. Schematic illustrating 4 radial positions of each indenter measurement

Following indenter measurements of the intact cable, the cable was dissembled by slitting the outer jacket, as seen in Figures 10 and 11 below.

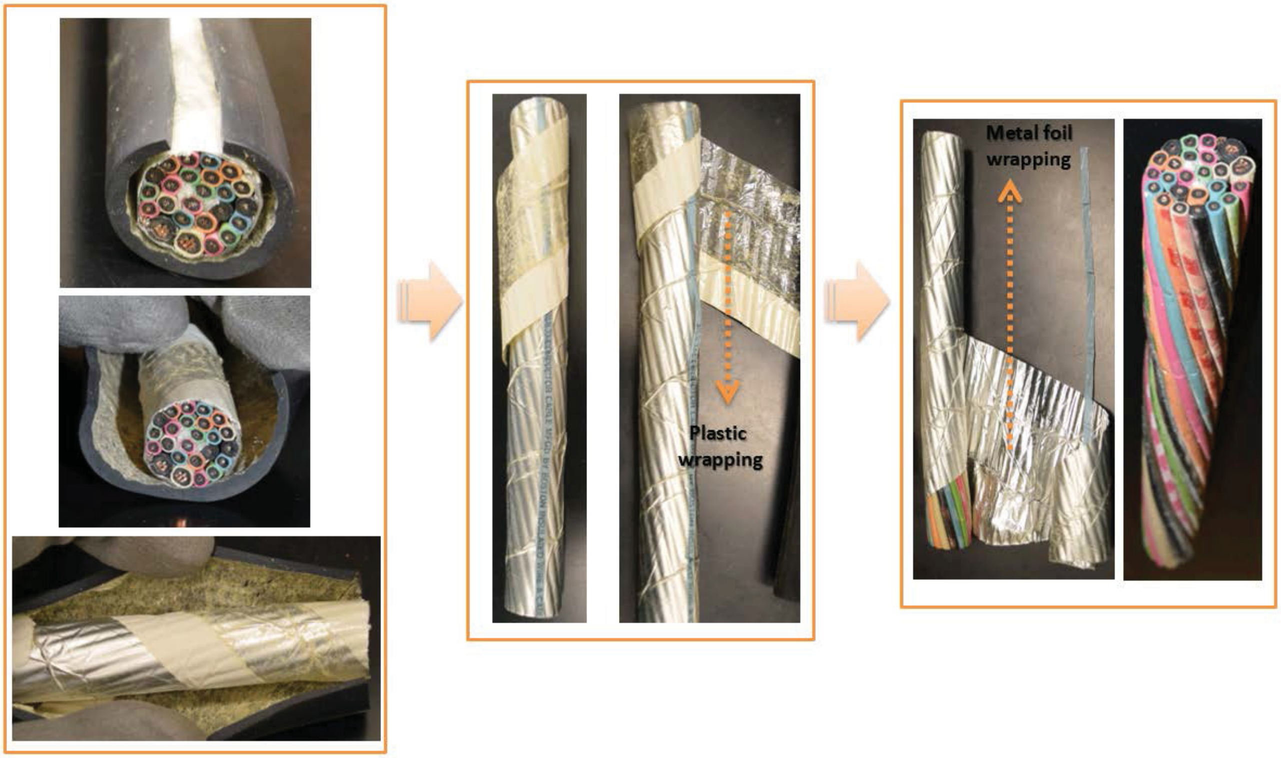


Figure 7. BIW cable disassembly to reveal individual conductor layers

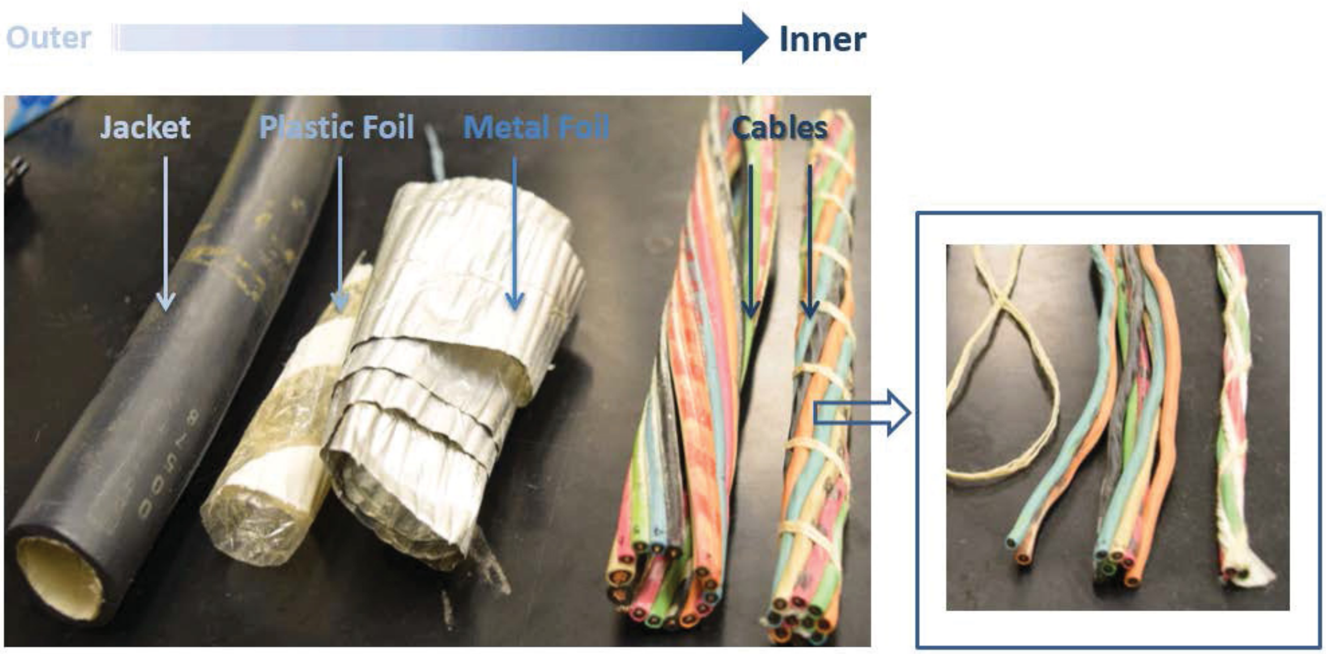
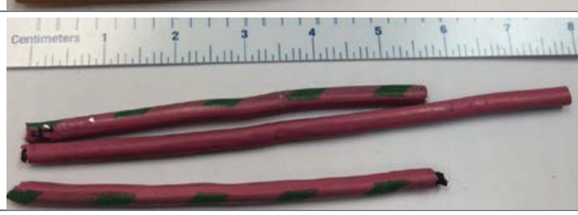
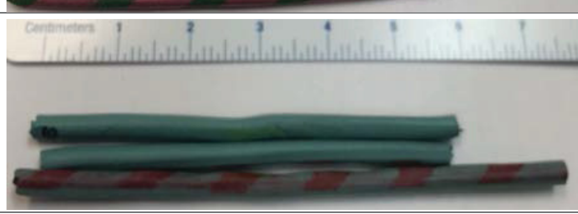


Figure 8. BIW cable components

The metal conductor strands were removed from each of the 24 insulated conductors to prepare insulation straws for EAB (elongation at break) measurements. Images of the straws produced along with the individual component ID, the apparent color scheme of the individual jacket, the conductor size and the location within the cable of the individual conductor are listed in Table 3.

Table 3. BIW Conductors in outer ring

ID	Image	Color Code	AWG	Location
1		Orange with Red Stripe	20	Outer Ring
2		White with Red Stripe	20	Outer Ring
3		Black with Red Stripe	20	Outer Ring
4		Blue with White Stripe	20	Outer Ring
5		Green with White Stripe	20	Outer Ring
6		Red with White Stripe	20	Outer Ring
7		White	12	Outer Ring

8		Black	12	Outer Ring
9		Ground Wire		Outer Ring
10		Red with Black and White Stripe	20	Outer Ring
11		Green with Black and White Stripes	20	Outer Ring
12		Black with Red and White Stripes	20	Outer Ring
13		Orange with Green Stripes	20	Outer Ring
14		Red with Green Stripes	20	Outer Ring
15		Blue with Red Stripes	20	Outer Ring

2-1		Orange with Black Stripes	20	Middle Ring
2-2		Green with Black Stripes	20	Middle Ring
2-3		Red with Black Stripes	20	Middle Ring
2-4		White with Black Stripes	20	Middle Ring
2-5		Blue	20	Middle Ring
2-6		Orange	20	Middle Ring
2-7		Black with White Stripes	20	Middle Ring
2-8		Blue with Black Stripes	20	Middle Ring

3-1		Red	20	Core
3-2		Green	20	Core
OA		Black	NA	Overall Jacket

The indenter modulus of each of the individual jacketed insulated conductors was measured prior to removal of the metal conductor strands. Figure 12 shows IM values along individual conductors and Figure 13 show average IM values for several color-coded conductors.

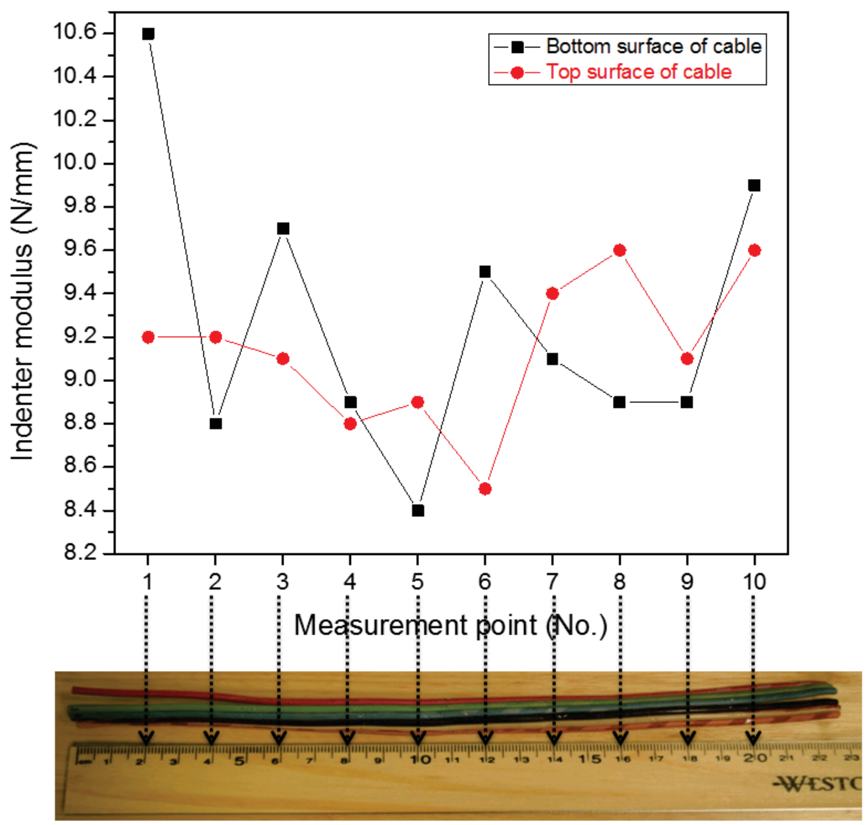


Figure 9. IM results as a function of location along individual conductors

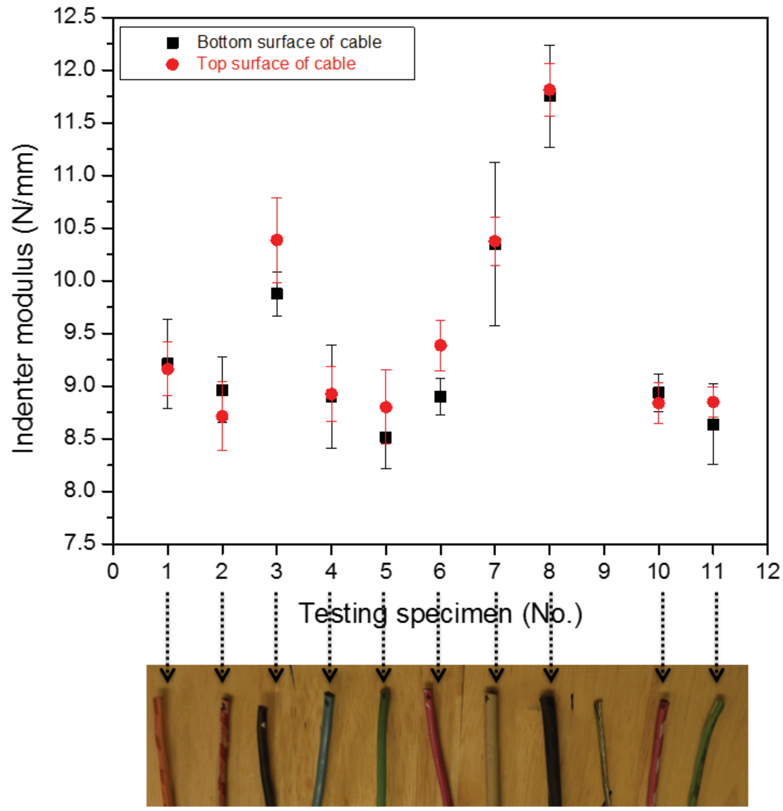


Figure 10. Average IM results of some of outer ring conductors

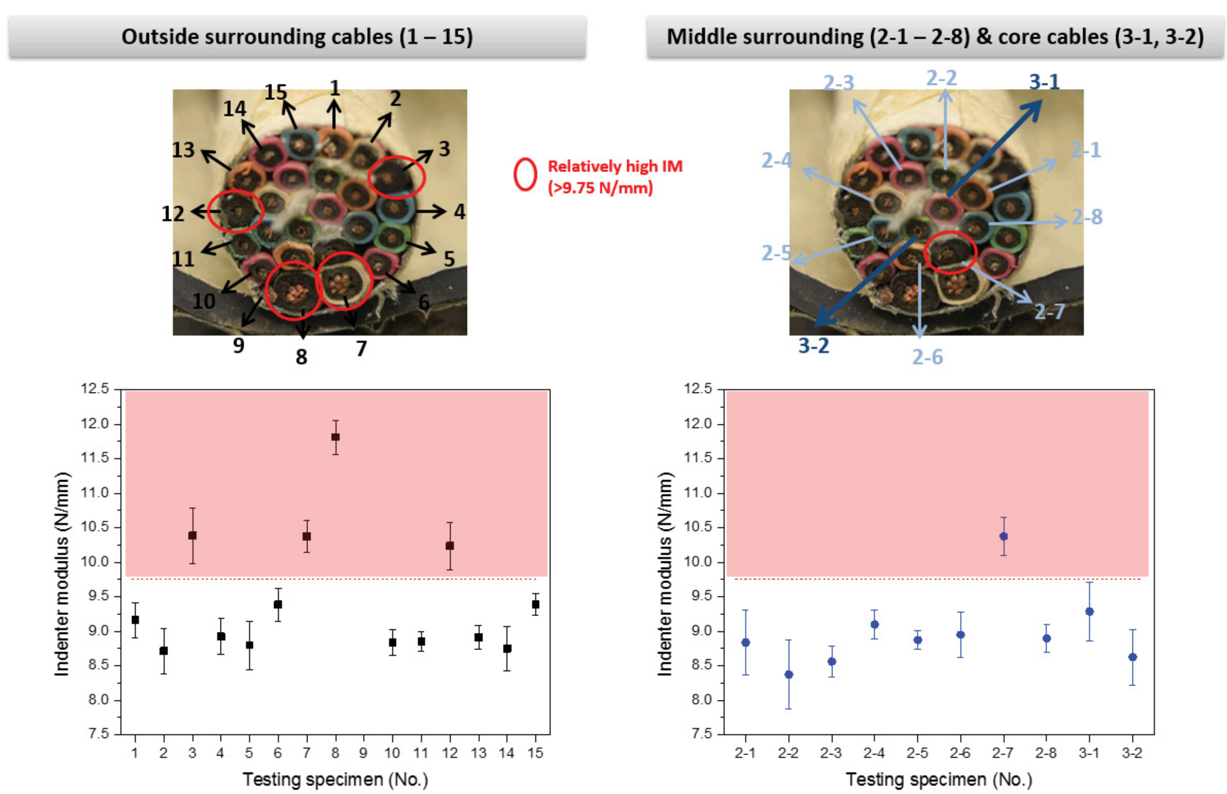


Figure 11. Average IM values for conductors with high IM values indicated

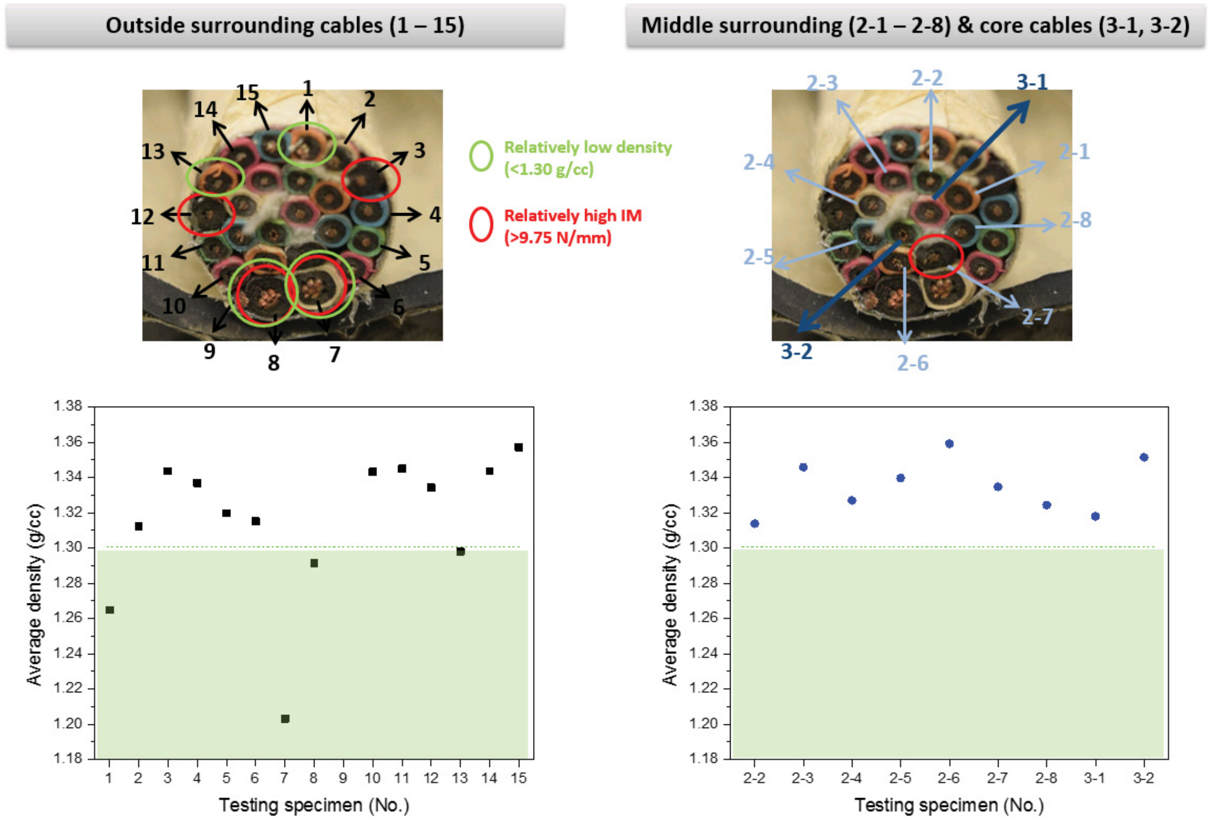


Figure 12. Individually jacketed insulation densities with low density values indicated

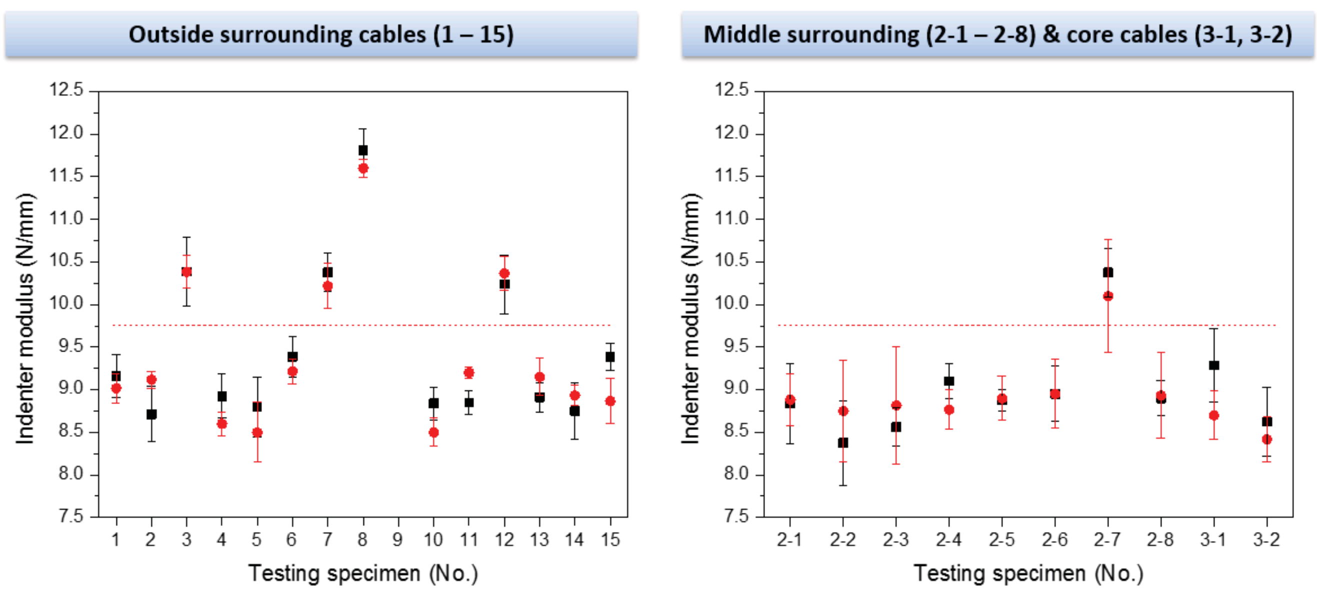


Figure 13. IM values were very reproducible for conductors from different BIW samples

It is noted in Figures 14 and 15 that certain of the individual conductors exhibit reproducible differences in IM and density. The two larger, 12 gauge conductors, for instance, express higher IM and lower density values compared to the other conductors. These differences may be due to formulation or construction differences. The conductors with black colored individual jackets, 3 and 12, feel stiffer and consistently measure as higher IM. The conductors with orange colored individual jackets registered lower density, but only for those in the outer ring, 1 and 13, not for those in the middle ring, 2-1 and 2-6.

Oxidation induction time (OIT) and oxidation induction temperature (OITP) methods, informed by industry standards (IEC/IEEE 62582-4, 2011 and ASTM D3895-14, 2014) and literature experience (EPRI TR-106370, 1996), are being used by PNNL to assess changes in materials with construction and aging. In characterization of the BIW cable with bonded individual CSPE jacket onto EPR insulation, the black insulation was separated from the colored individual jackets for each of the conductor components for OITP measurements. For each measurement, the ~10mg sample was equilibrated at 50°C in nitrogen in a Thermal Analysis Differential Scanning Calorimeter (DSC) (TA DSC 2000) before heating in air to 350°C at 10 degrees per minute. The heat flow scans are shown in the figures below, organized by similar conductor groups. Figure 17 displays curves of outer ring conductors with similar IM and density values. Figure 18 shows curves of middle ring and core conductors with similar IM and density values. Figure 19 plots curves for the conductors in the outer ring and middle ring that exhibited relatively high IM values and/or relatively low density values. Phase transition analysis of the EPR insulation specimens taken from the BIW cable as determined by OITP are summarized in Table 4.

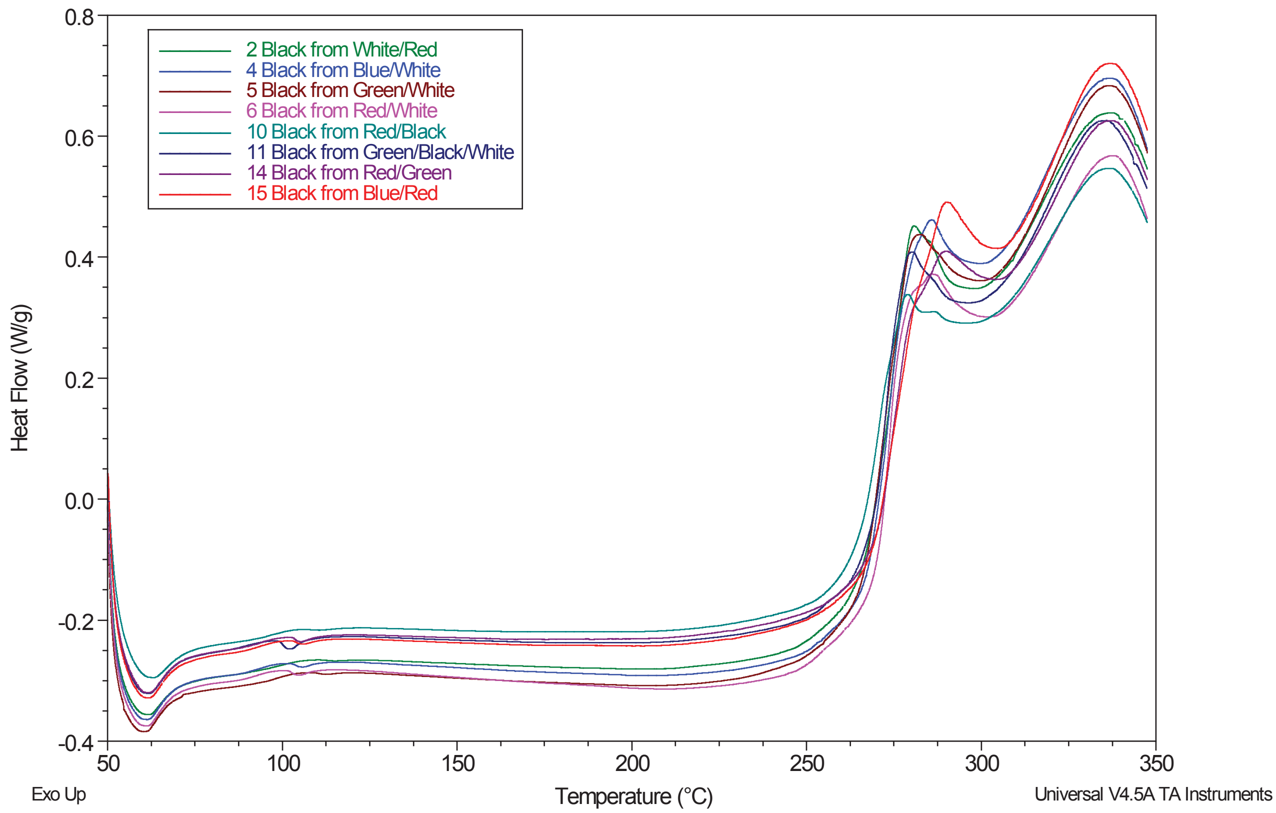


Figure 14. OITP curves of insulation from similar outer ring conductors

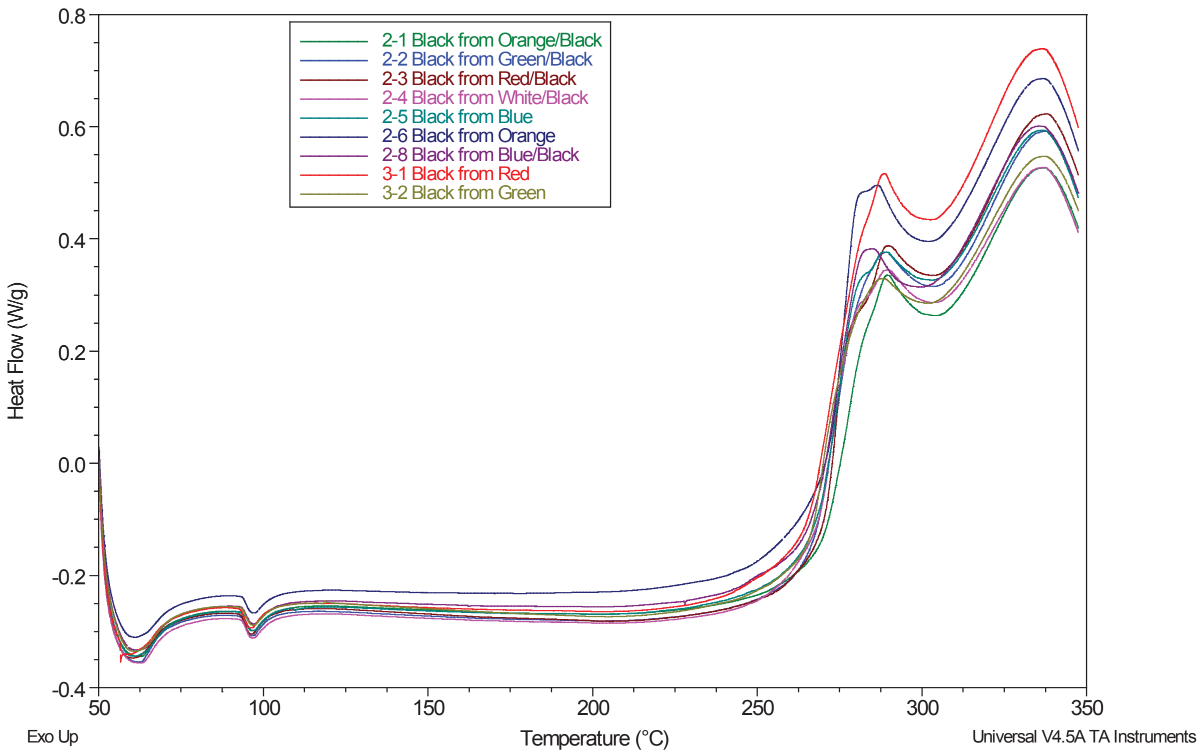


Figure 15. OITP curves of insulation from similar middle ring and core conductors

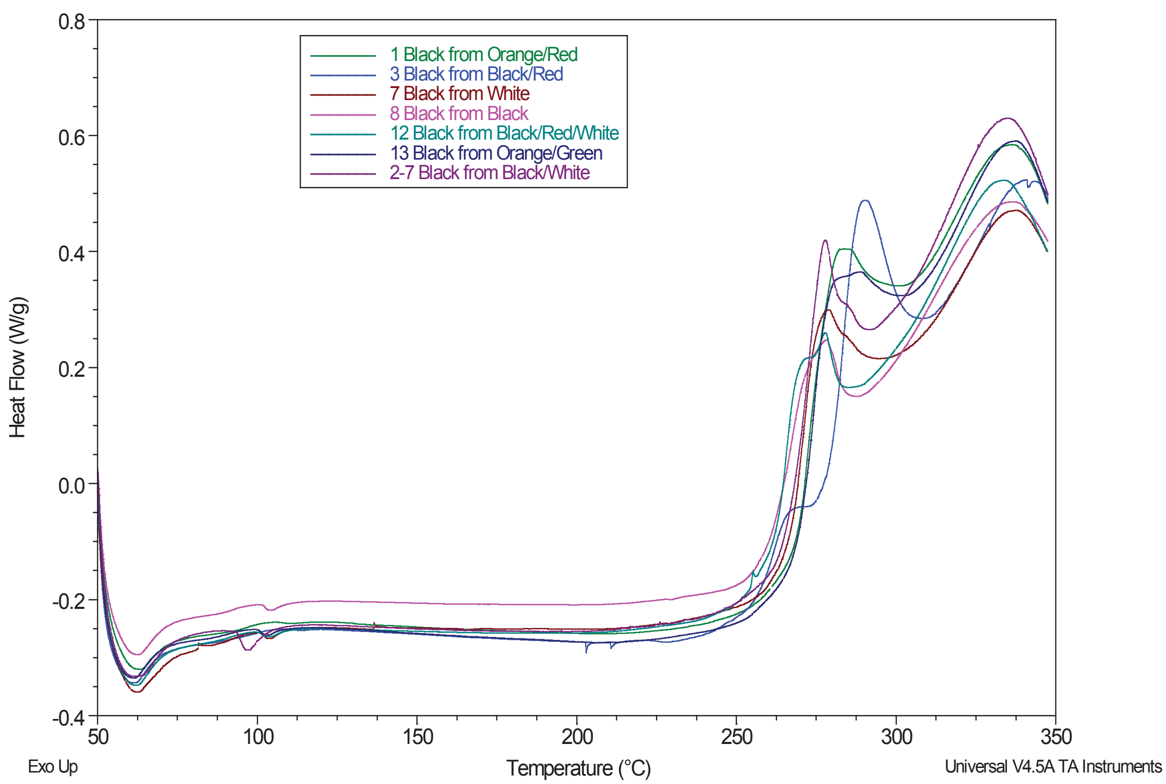


Figure 16. OITP curves of insulation from conductors with dissimilar IM or density

Table 4. Peak analysis results from BIW conductor insulation OITP curves (values in °C)

ID	Endotherm 1	Endotherm 2	OITP 1 Δ	OITP 1 Tangent	OITP 2 Δ	OITP 2 Tangent
	61.56		251.76	268.04	308.42	307.41
1	62.00		251.92	266.97	311.11	308.57
2	61.24		249.94	261.81	309.93	307.31
3	60.35		252.03	254.00	277.18	277.93
4	61.02		250.14	264.48	308.20	307.22
5	59.95		248.79	263.60	308.89	307.84
6	61.62		250.65	266.28	311.41	309.35
7	62.51		253.48	262.83	309.65	307.50
8	61.74		254.36	257.58	299.99	299.99
10	62.68		249.38	261.31	309.70	307.67
11	61.13		252.45	263.60	307.33	306.93
12	61.28		249.38	260.04	296.40	297.33
13	59.81		254.18	254.18	310.44	309.08
14	61.29		253.29	267.57	312.77	310.95
15	60.73		253.13	266.13	313.28	312.01
2-1	61.60	96.65	255.24	266.88	313.61	311.58
2-2	62.24	96.65	251.93	264.55	312.81	310.92
2-3	59.40	96.2	254.68	267.45	313.61	311.65
2-4	62.38	96.57	251.85	264.04	312.81	310.81
2-5	59.66	96.35	248.32	265.28	312.80	310.51
2-6	60.04	96.82	248.56	267.00	310.74	308.92
2-7	60.85	97.19	248.94	261.92	305.77	304.62
2-8	60.38	97.5	247.78	264.17	310.30	308.55
3-1	56.66	96.12	245.29	262.59	311.99	310.27
3-2	61.39	97.02	247.09	263.82	312.42	310.14

It is observed that OITP curves for EPR insulation samples from the middle ring and core individual conductors exhibit endothermic transitions at ~97°C, while those of insulation from the outer ring conductors do not. This may be a sign of more accelerated aging of the outer portions of the cable relative to the more protected center.

Portions of the CSPE jacket were exposed to additional laboratory thermal aging by the laboratory of Dr. Robert Duckworth at ORNL. OITP analysis of these samples show changes with aging, as seen in Figure 20. Note OITP curve feature locations are summarized in Table 5.

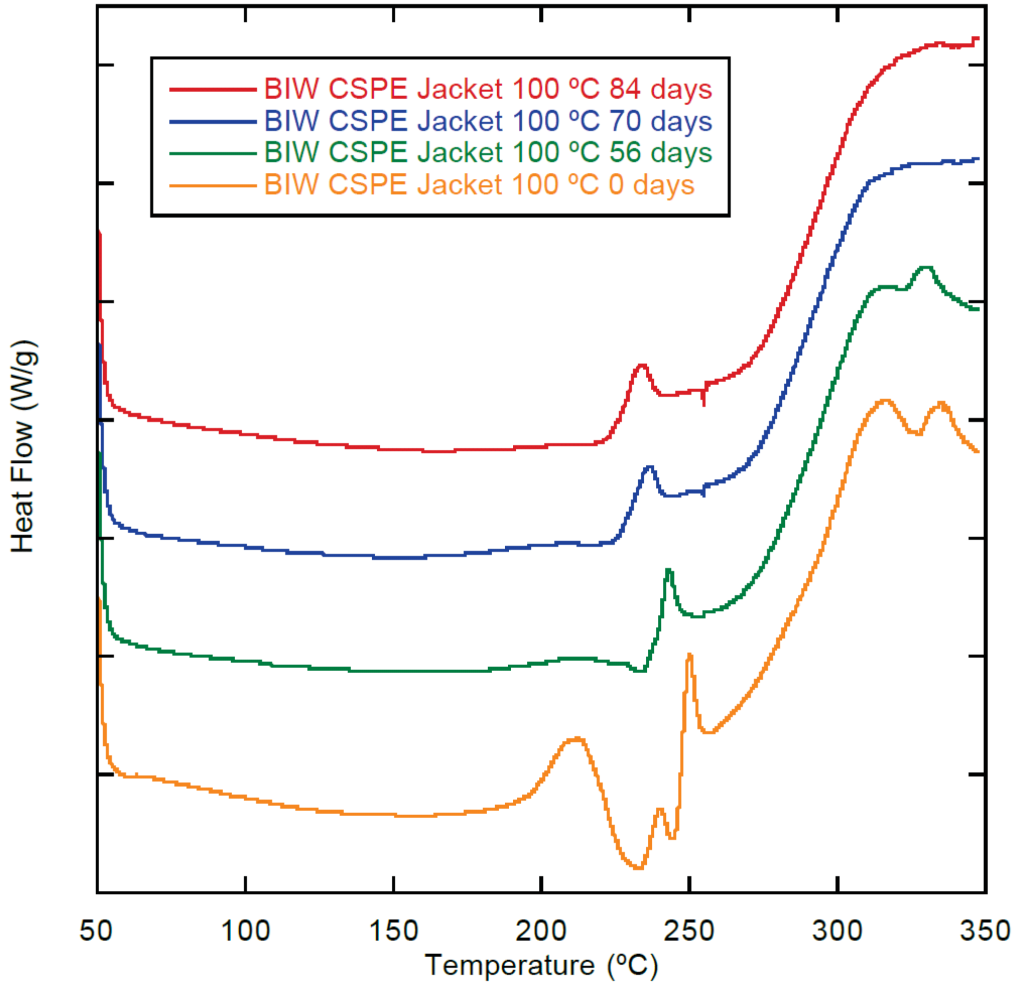


Figure 17. OITP curves for a series of samples exposed at 100°C for 0, 56, 70, and 84 days

Table 5. Peak analysis results from thermally aged BIW jacket OITP curves (values in °C)

100°C Exposure (d)	Feature 1	Feature 2	OITP 1 Δ	OITP 1 Tangent	OITP 2 Δ	OITP 2 Tangent
0	233.76	244.15	200.75	193.48	278.86	269.31
56	233.95		189.13	na	276.39	271.14
70			174.66	na	226.27	230.54
84	254.82		227.79	223.38	277.62	273.53

CROSS-LINKED POLYETHYLENE

XLPE and EPR are the most common cable insulations in NPP. Nearly two-thirds of NPPs have Rockbestos Firewall® III XLPE (FWIII) insulated cables inside containment (EPRI TR-103841.R1). Towards increasing understanding of the aging behavior of this material, NOS FWIII cable manufactured in 1989 is being characterized. The cable sample is labeled as 12 AWG 3/C ROCKBESTOS® 600V FIREWALL® III XLPE COPPER 90 C CSPE. IM of the outer CSPE jacket and construction of this material are discussed in the figures below. The photos in Figure 21 reveal the cable outer appearance and cross-section. Figures 22 show the locations of IM measurements along the FWIII sample and the radial points of measurement at each position. Figure 24 displays the IM results by position.

Figure 18. ROCKBESTOS® 600V FIREWALL® III XLPE cables and cross-section

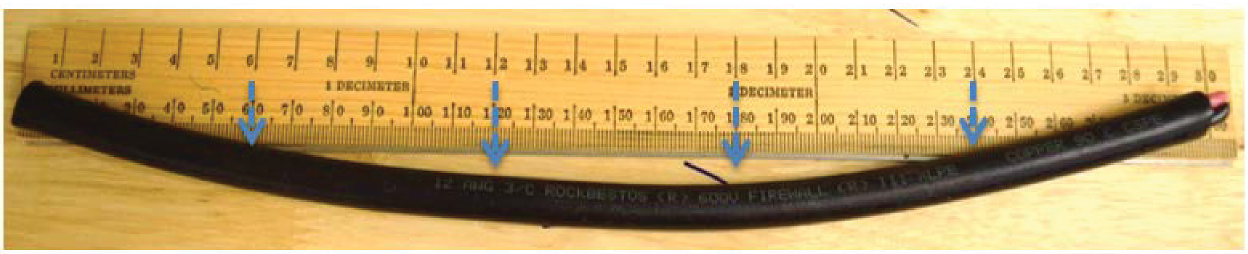


Figure 19. Locations of IM measurements for the FWIII cable are indicated

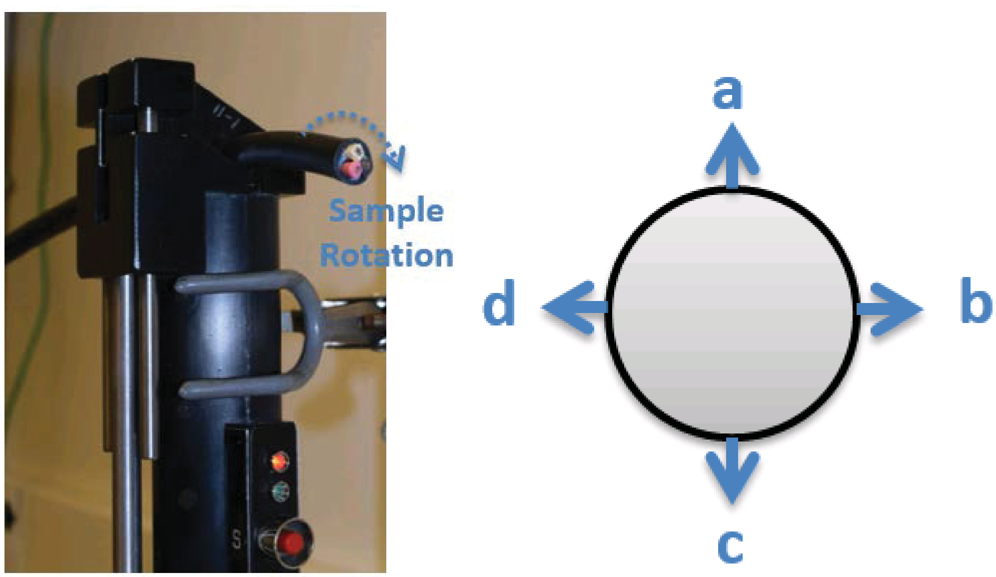


Figure 20. Radial points of IM measurements at each location are described

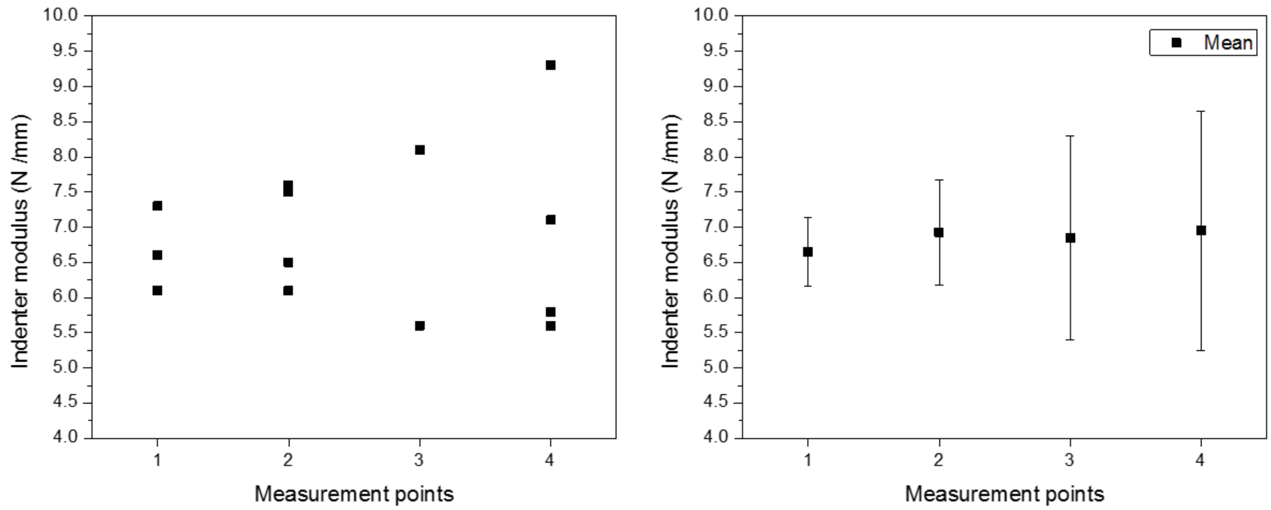


Figure 21. IM values for the FWIII cable by location point

Construction of the unshielded, three conductor FWIII cable is observed in Figures 25 and 26.

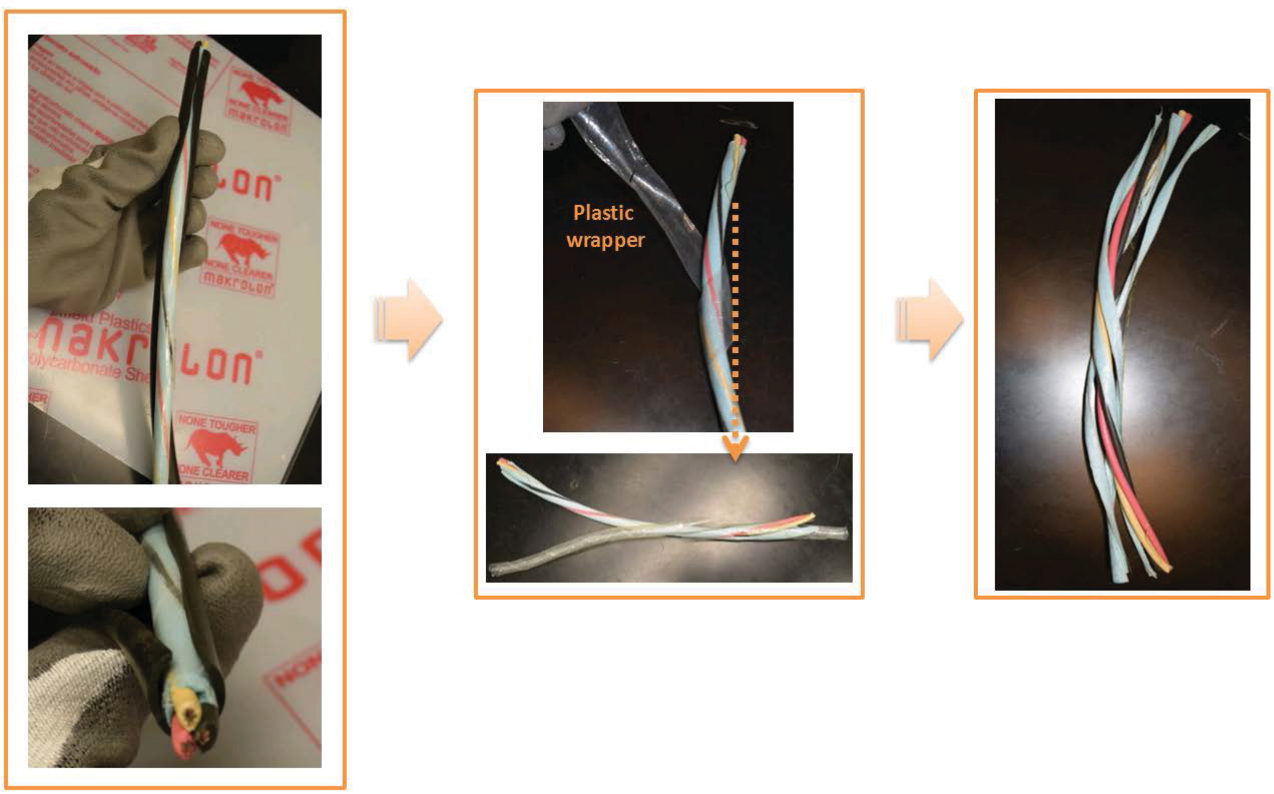


Figure 22. The FWIII cable consists of a CSPE jacket, 3 conductors, and no shield

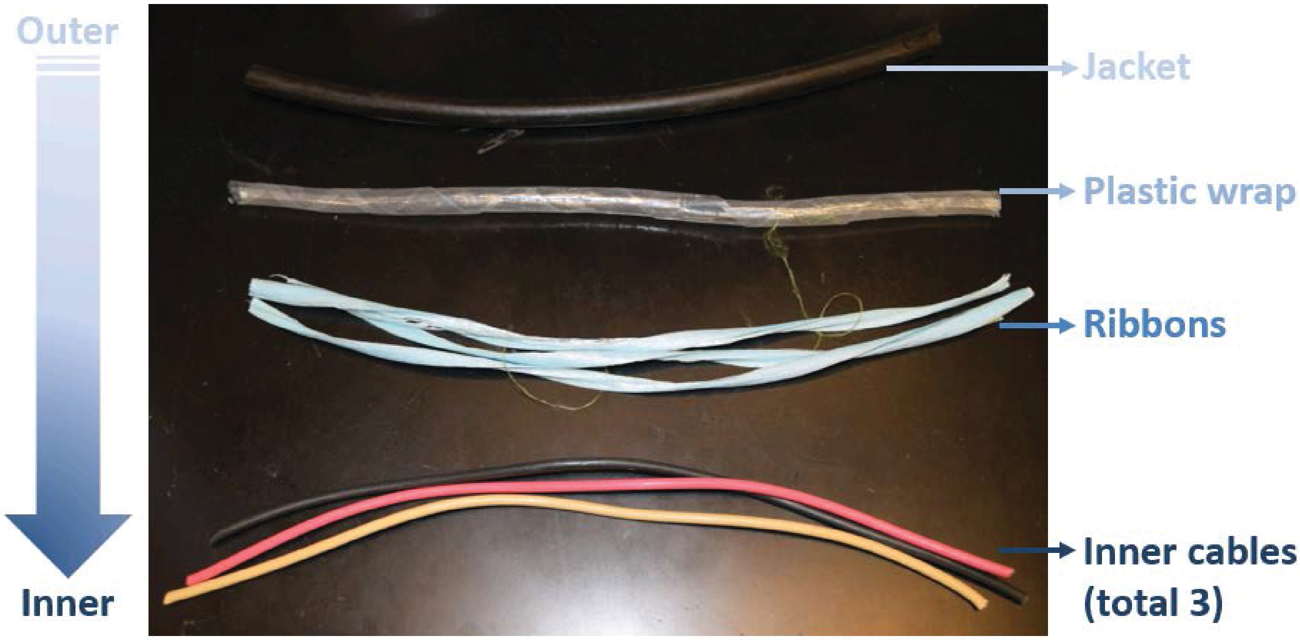


Figure 23. The FWIII cable components are illustrated

AGING AND CHARACTERIZATION PLAN

The BIW EPR/CSPE and FWIII XLPE/CSPE cable data illustrated above are examples of characterization in progress to baseline naturally aged cable. Subsequent laboratory accelerated aging including thermal only and combined thermal/gamma exposure will be performed to simulate in plant aging for these cables and other representative naturally aged cable materials and constructions. Analysis of cable samples aged under controlled conditions and of harvested materials supports validation and evolution of aging prediction models and assumptions used in age prediction.

TIE TO EMDA KNOWLEDGE GAPS

The fifth volume of the Expanded Materials Degradation Assessment (EMDA), "Aging of Cable and Cable Systems", identifies areas of potential concern for continued use of electrical cables in NPPs beyond sixty-years of operation and knowledge gaps in cable aging (NUREG/CR-7153, 2014). These gaps include:

- Reduced uncertainty of activation energies
- Importance of diffusion limited oxidation
- Dependence of aging on dose rate
- Relationship between thermal and radiation aging
- Effects of moisture on aging
- Better understanding of NPP environments.

These gaps relate the relationships between exposure conditions that cables face in NPPs and the degradation of the materials used in those cables. Addressing these gaps through additional research in a meaningful way requires focus of efforts on the actual materials used and/or an understanding of the differences between aging of the actual materials in plants and the materials studied. Similarly, understanding of the differences in effect of laboratory aging conditions and plant aging conditions is requirement for drawing meaningful conclusions regarding aging of installed materials from laboratory data. The availability of naturally-aged cables for investigation of activation energies, diffusion limited oxidation propensity, aging dependence on dose rate and the interaction of thermal and gamma exposures in aging is key to maximizing the value of knowledge gained.

CONCLUSION

The goal of this work is to develop a predictive understanding of the aging and degradation of cable system materials installed in existing nuclear plants involves. Investigation of the aging behavior of these materials relies on historical data, procurement of vintage materials from storage, and harvesting of cables either following plant closure or during cable replacement activities. Harvesting of installed cables provides the opportunity for information about the aging of inherently relevant materials in actual plant environments.

Examples of NOS and harvested cables available to the Cable Aging research task of the LWRS MAaD pathway are outlined above. They represent the most common insulation and jacketing materials and the most common manufacturers for cables for which long term aging information is sought. Laboratory aging can be used to simulate long term operations and to understand the differences between laboratory and field aging. Analysis of material changes before and aging will address gaps in knowledge of material aging and degradation behavior. This knowledge will support the ability to monitor cable degradation state, develop methods to mitigate cable aging, and predict cable remaining useful life.

REFERENCES

ASTEM D1418-10a. *Standard Practice for Rubber and Rubber Latices—Nomenclature.* ASTM International. 2010.

ASTM D3895-14. *Standard Test Methods for Oxidative-Induction Time of Polyolefins by Differential Scanning Calorimetry*. ASTM International. 2014

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

EPRI TR-106370. *Reduction of Oxidation Induction Time Testing to Practice as a Life Assessment Technique for Cable Insulation*. Electric Power Research Institute. 1996.

Anandakumaran, K.A. *Condition Monitoring of Low Voltage Cables*. Proceedings of the IEE Power Engineering Society Insulated Conductors Committee, November 4-7, 2007. Scottsdale, AZ.

IEC/IEEE 62582-2. *Nuclear power plants – Instrumentation and control important to safety –Electrical equipment condition monitoring methods –Part 2: Indenter modulus*. International Electrotechnical Commission/Institute of Electrical and Electronics Engineers. Edition 1.0. 2011.

IEC/IEEE 62582-4. *Nuclear power plants – Instrumentation and control important to safety –Electrical equipment condition monitoring methods –Part 4: Oxidation induction techniques*. International Electrotechnical Commission/Institute of Electrical and Electronics Engineers. Edition 1.0. 2011.

NUREG/CR-7102. *Kerite Analysis in Thermal Environment of FIRE (KATE-Fire): Test Results*. Final Report. SAND2011-6548P. United States Nuclear Regulatory Commission. 2011.

NUREG/CR-7153, Vol. 5. *Expanded Materials Degradation Assessment (EMDA) Volume 5: Aging of Cables and Cable Systems*. United States Nuclear Regulatory Commission. 2014.