PNNL-SA-120274

LWRS Cable Aging and Cable NDE

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Light Water Reactor Sustainability R&D Program

DOE-NE Materials Crosscut Coordination Meeting
August 16, 2016, Webinar

Cables in Nuclear Power Plants (NPPs)

Cable Functions

•Control	61%
•Instrumentation	20%
•AC power	13%
•Communication	5%
•DC power	1%

•Low Voltage, Medium Voltage

SAND96-0344

Amount of Cable

Boiling Water Reactor (BWR)

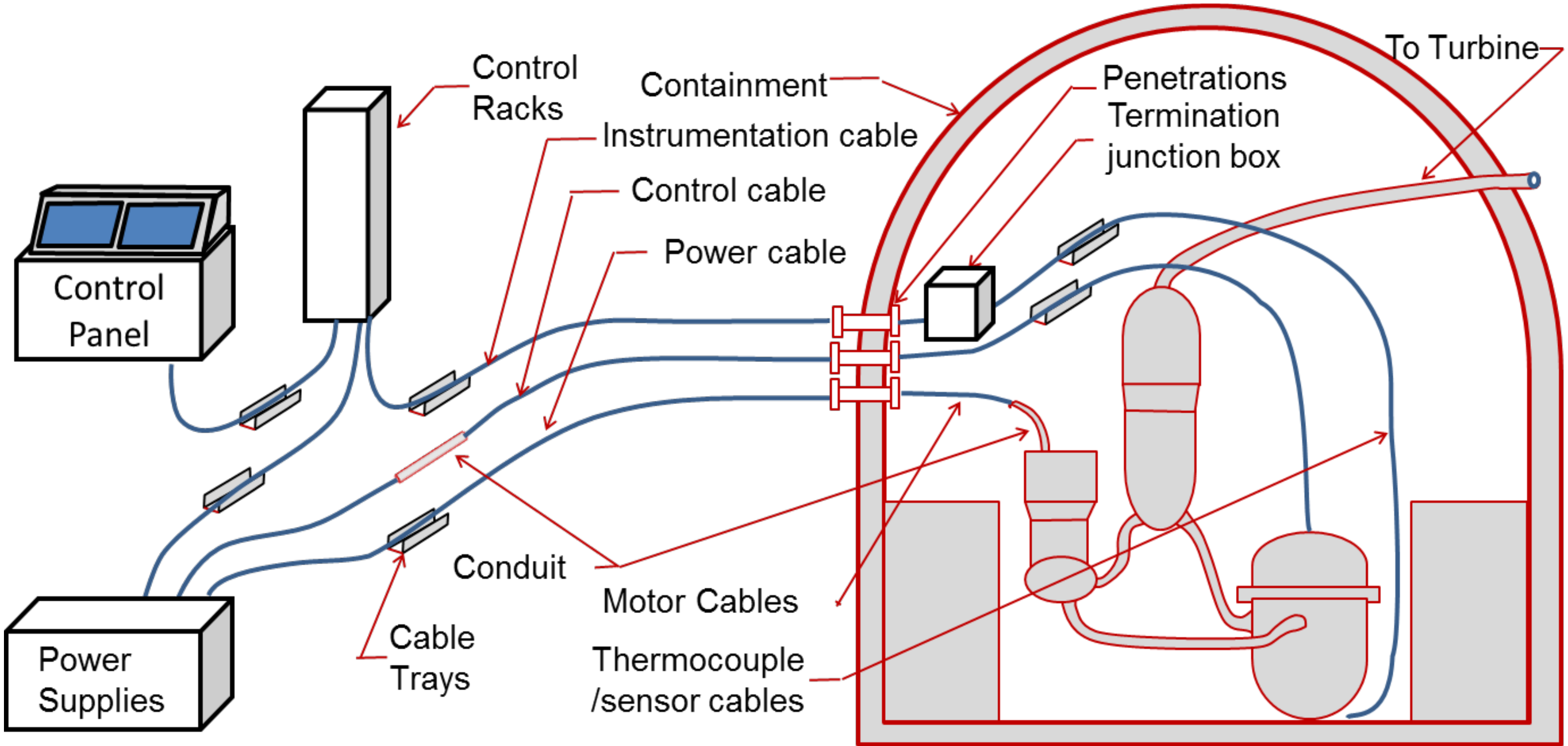
- 360 miles of cable in in primary/secondary containment

Pressurized Water Reactor (PWR)

- 1000 miles of cable in containment building

NUREG/CR-4257

Nuclear Power Plants (NPPs)

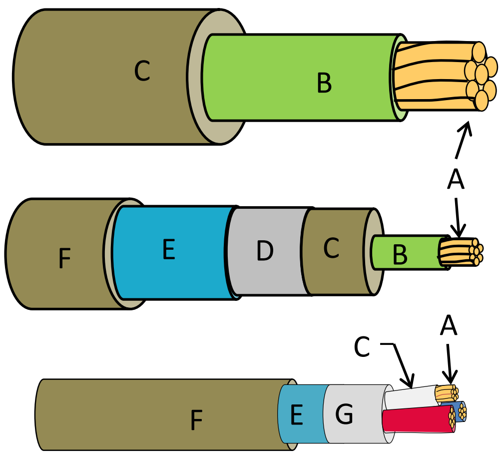


PNNL-25432

- Ramifications of *cable failure* can be significant, especially for cables connecting to: off-site power, emergency service water and emergency diesel generators

Cable Construction

- Insulated metal conductor
- Ground/drain wire
- Semiconducting screen
- Filler
- Metallic shield
- Individual and/or overall jacket
- Single or multi-conductor



A Uncoated copper conductor
B Semiconducting Screen
C Insulation
D Insulation screen extruded semiconductor
E Shielding copper tape with/without drain wire
F Jacket
G Helically applied binder tape

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MV power cable

LV I&C cable

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Cable Polymeric Materials

Insulation

- XLPE - cross-linked polyethylene (36% of cables)
- EPR - ethylene-propylene rubber (36% of cables)
- Kerite®-HT EPR-like material (5% of cables)
- SiR - silicone rubber (5% of cables)

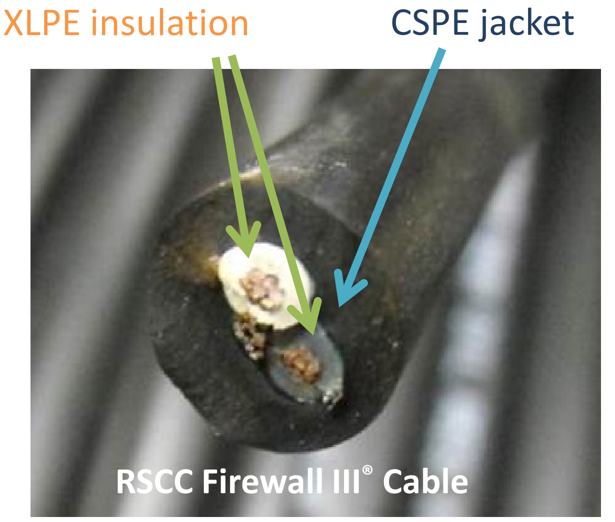
Jacketing

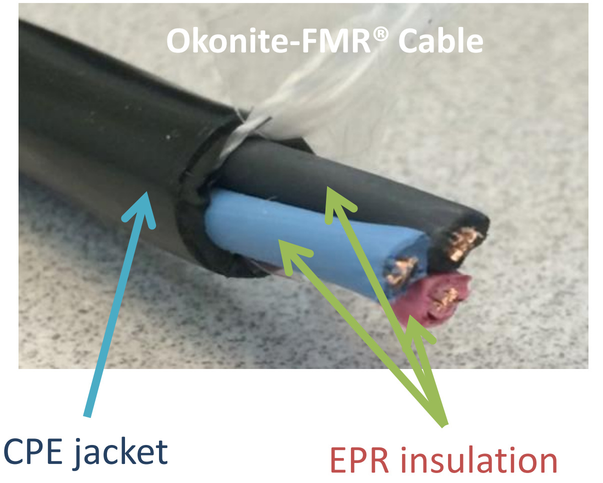
- Hypalon® - chlorosulfonated polyethylene (CSPE)
- Neoprene – polychloroprene
- CPE – chlorinated polyethylene
- PVC – poly(vinyl chloride)

NUREG/CR-7153

90% of NPPs have XLPE in containment

EPRI TR-103841 Rev.1





In Plant Conditions for Cables

Example Area Classification

	Applicable environmental conditions		
	Maximum values in normal service		Accident conditions
	Temp.	Total 40-yr dose	
A	≤ 40 °C	≤10^2 Gy (0.01 Mrad)	N/A
B	≤ 50 °C	≤5×10^4 Gy (5 Mrad)	N/A
C	≤ 50 °C	≤5×10^4 Gy (5 Mrad)	Applicable
D	Local conditions higher than for C (e.g. hot spots)		

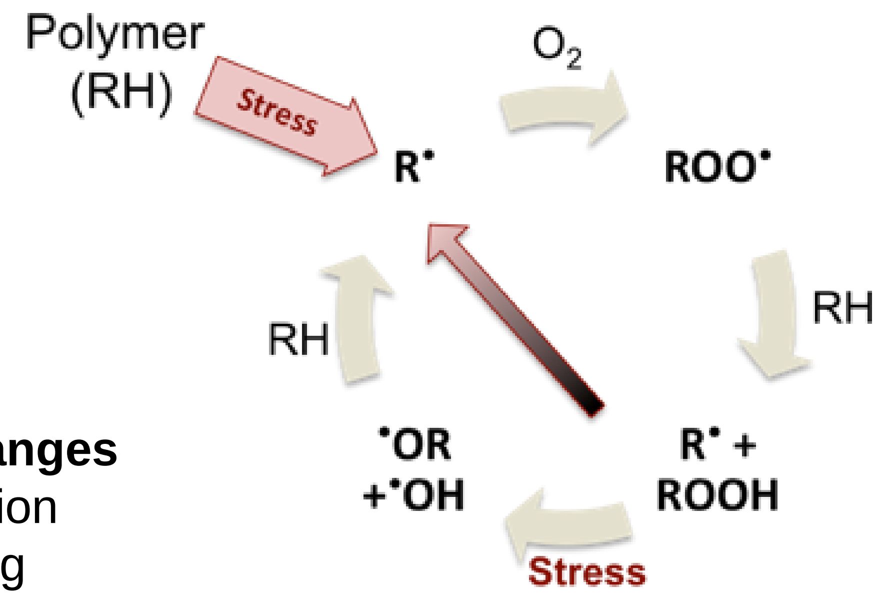
IAEA NP-T-3.6

Example Generic Hot Spots

Reactor type	Hot spot location region	Temperature	Rad. dose rate	Dose (40 yr)
PWR	Steam generator box	47-48 °C (max 100 °C)	0.1 Gy/h	4 Mrad
	Primary loop	50 °C	0.7 Gy/h	25 Mrad
BWR	Drywell neck	100 ± 5 °C	0.5 Gy/h	18 Mrad
	Primary steam relief valve	70 ± 5 °C	0.01 Gy/h	0.4 Mrad
	Power range monitor	80 ± 5 °C	0.24 Gy/h	8 Mrad

IAEA-TECDOC-1188 vol1

Confounding Environmental Stresses



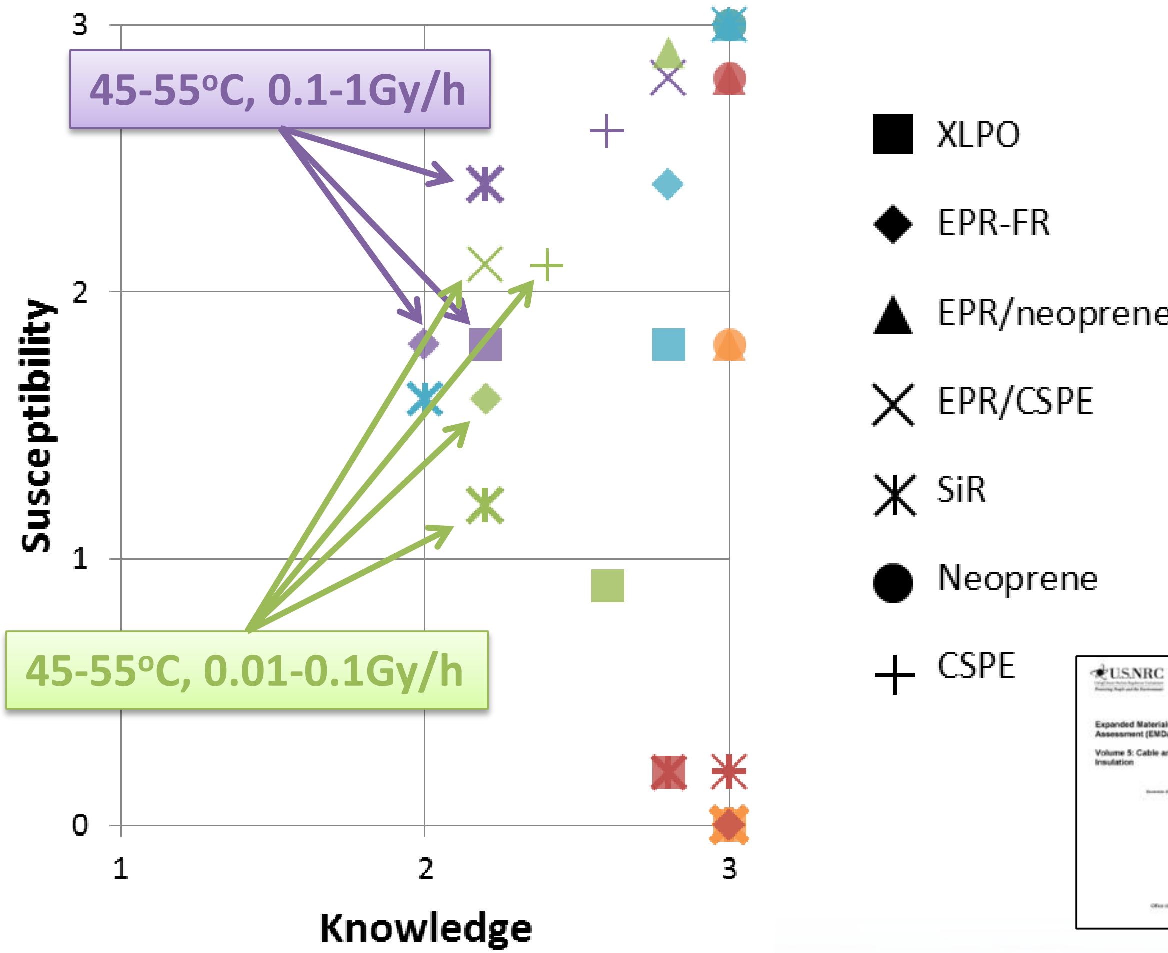
Environmental Stressors
- Radiation (UV, gamma)
- Thermal
- Mechanical (tensile, vibration)
- Moisture

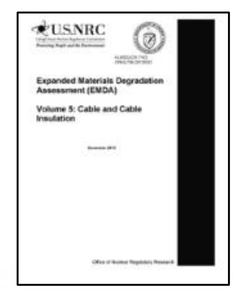
Chemical Changes
- Chain scission
- Cross-linking
- Loss of plasticizer
- Loss of anti-oxidant

Property Changes
- Mechanical
- Electrical
- Physical

EMDA Cable PIRT Analysis Provides Insights for Prioritized Needs

- Up to 35°C, 0 dose rate
- Up to 35-50°C, up to 0.01 Gy/h (1 rad/h)
- Up to 45-55°C, 0.01-0.1 Gy/h (1-10 rad/h)
- Up to 45-55°C, 0.1-1 Gy/h (10-100 rad/h)
- Up to 60-90°C, 0 dose rate





EMDA=Expanded Materials Degradation Assessment, NUREG/CR-7153, Vol. 5
PIRT=Phenomena Identification and Ranking Technique

Cable Degradation Knowledge Gaps:

- Diffusion limited oxidation (DLO)
  - How to improve correlation between field and accelerated aging?
- Inverse temperature effects (ITE)
  - What dose/temp. combinations avoid ITE in accelerated aging?
- Thermal/radiation exposure
  - At what dose does thermal damage dominate radiation damage?
- Synergistic effects
  - What is the effect of rad/heat exposure sequence on aging?
- Acceptance criteria for characterization techniques
  - What should measured values be for acceptable qualified condition?

*NUREG/CR-7153, Vol.5 2013

Cable Aging/NDE Task Activities Map to MAaD Targets

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<u>Activities</u>

Cable Aging
- Accelerated Aging Methods
- Materials Characterization
- Degradation Pathways
- Models of Aging (Accelerated vs. Long Term)
- Cable Rejuvenation

Cable NDE
- Key Indicators
- Current Methods
- New Methods
- Predictive Models

<u>LWRS Targets for Materials Aging and Degradation</u>

- Measurements of degradation
- Mechanisms of degradation
- Modeling and simulation
- Monitoring
- Mitigation strategies

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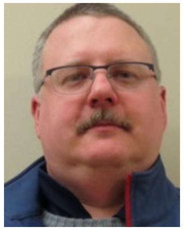
LWRS Materials Aging and Degradation MAaD Pathway

Pathway Lead – Keith Leonard (ORNL)

Deputy Pathway Lead – Tom Rosseel (ORNL)

Cable Aging – Leo Fifield (PNNL), Robert Duckworth (ORNL)



Cable NDE – Bill Glass (PNNL)

Light Water Reactor Sustainability

LWRS Cable Research Program

Iowa State University

University of Nebraska Lincoln

Washington State University

The University of Tennessee Knoxville

South Dakota State University

Pacific Northwest National Laboratory

Oak Ridge National Laboratory

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

EPRI Electric Power Research Institute

Marmon

RSCC World Class Engineered Cable

The Okonite Company

Fauske & Associates, LLC

AMS

TL

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Cable Research Coordination & Collaboration Team (CRCCT)

- Meets face-to-face 1-2 times per year
- Often co-located with EPRI Cable Users Group
- Cable Research Working Group Collaboration Portal (SharePoint)
- Coordinated Roadmap of activities
- Avoid duplication toward common goals

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Pacific Northwest NATIONAL LABORATORY

OAK RIDGE National Laboratory

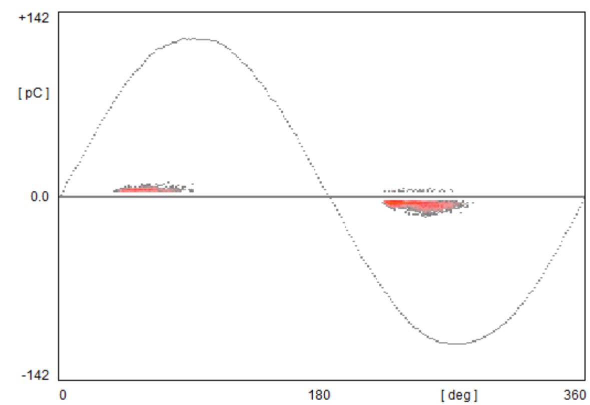
U.S.NRC United States Nuclear Regulatory Commission *Protecting People and the Environment*

LWRS Light Water Reactor Sustainability

Working with Industrial Partners

- ***AMS FDR Measurements***
  - Frequency Domain Reflectometry (FDR) based condition monitoring system has been developed by Analysis & Measurement Systems (AMS) Corporation through DOE LWRS Phase II SBIR
  - Measurable differences observed over course of irradiation
- ***San Onofre MV Splice Measurements***
  - Splices harvested from San Onofre switchyard by AMS
  - PD and AC Withstand measured
  - Two out of three failed to meet standard for AC withstand.
  - CHAR measurement planned to see if changes happened during handling

Two 50-foot long cables with 1 foot exposures prior to insertion into Co-60 irradiator (left) and FDR measurement by AMS (above)



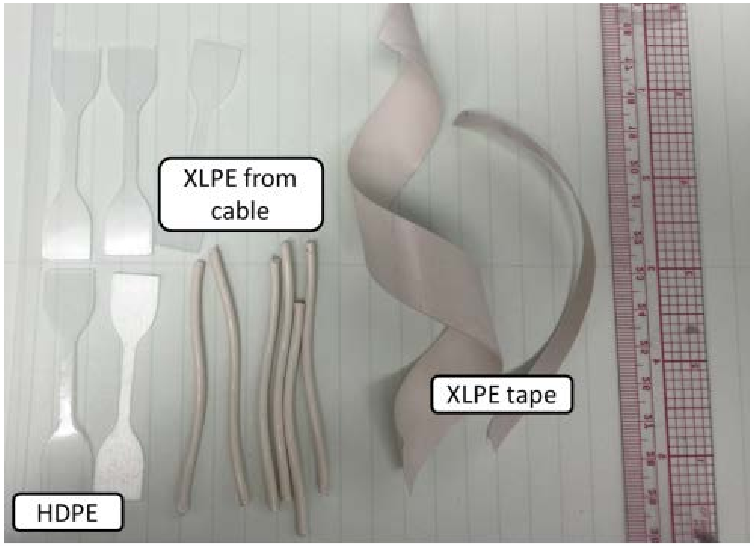
Setup of AC Withstand/PD Meas. (left) and resultant PD waveform at 7 kV (right)

University Partnership Example

Iowa State University NEUP on Cable NDE

Professor Nicola Bowler group

- Developing new characterization methods
- Fundamental modeling of degradation
- Access to ISU resources in
  - Nuclear engineering
  - Complex data analysis
  - Spectroscopy



www.mse.iastate.edu/nbowler/

Gamma Exposure Capabilities

PNNL

High Exposure Facility (HEF)

- Temperature control through mechanical convection ovens
- Dose rates from 1 to 1000 Gy/h

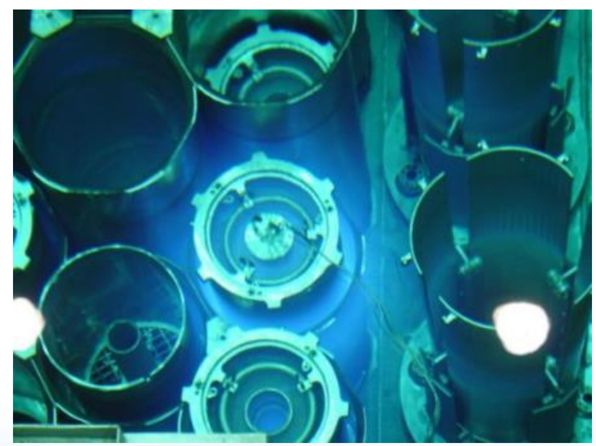
ORNL

High Flux Isotope Reactor (HFIR) Spent Fuel Gamma Irradiation Facility (GIF)

- Dose rates from 200 to 1000 Gy/h

Co-60 Irradiator

- Uniform dose rate of 140 Gy/h



Firewall® III XLPE Specimen Matrix

Dose Rate (Gy/h)	60C	90C	115C
552	10d, 15d, 25d	10d, 15d, 25d	10d, 15d, 25d
501	5d, 20d, 25d	5d, 20d, 25d	5d, 20d, 25d
458	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d
419	5d, 20d, 25d	5d, 20d, 25d	5d, 20d, 25d
385	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d
355	5d, 20d, 25d	5d, 20d, 25d	5d, 20d, 25d
328	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d
304	5d, 20d, 25d	5d, 20d, 25d	5d, 20d, 25d
283	5d, 20d, 25d	5d, 20d, 25d	5d, 20d, 25d
263	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d
246	5d, 20d, 25d	5d, 20d, 25d	5d, 20d, 25d
230	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d
215	10d, 15d, 25d	10d, 15d, 25d	10d, 15d, 25d
202	5d, 20d, 25d	5d, 20d, 25d	5d, 20d, 25d
190	10d, 15d, 25d	10d, 15d, 25d	10d, 15d, 25d
179	5d, 20d, 25d	5d, 20d, 25d	5d, 20d, 25d
169	5d, 20d, 25d	5d, 20d, 25d	5d, 20d, 25d
160	5d, 20d, 25d	5d, 20d, 25d	5d, 20d, 25d
151	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d
143	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d
136	5d, 20d, 25d	5d, 20d, 25d	5d, 20d, 25d
129	10d, 15d, 25d	10d, 15d, 25d	10d, 15d, 25d
123	5d, 20d, 25d	5d, 20d, 25d	5d, 20d, 25d
117	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d	5d, 10d, 15d, 20d

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Polymer Aging Characterization and Testing Laboratory at PNNL

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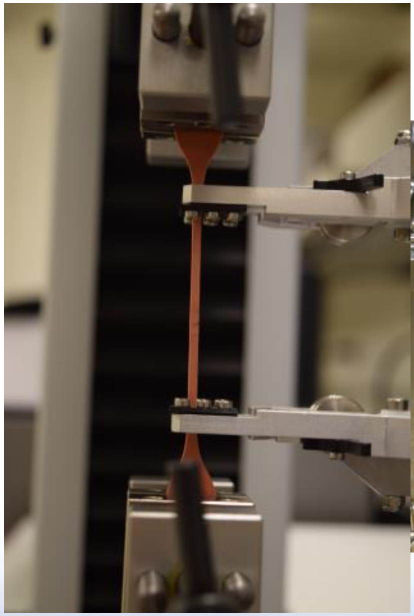
Aging

- Advanced protocol ovens with temperature logging
- Dedicated dynamic mechanical analyzer (DMA) for in-situ aging

Test and Characterization

- Test stand with contact extensometer
- Modulated differential scanning calorimeter (M-DSC)
- Digital microscope
- Photographic documention booth



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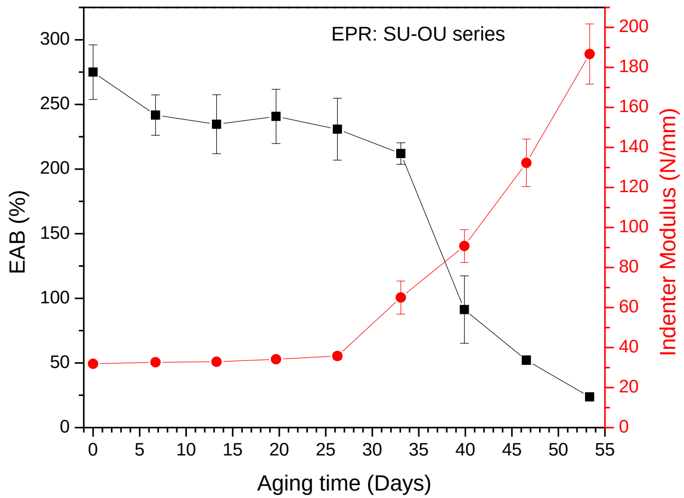
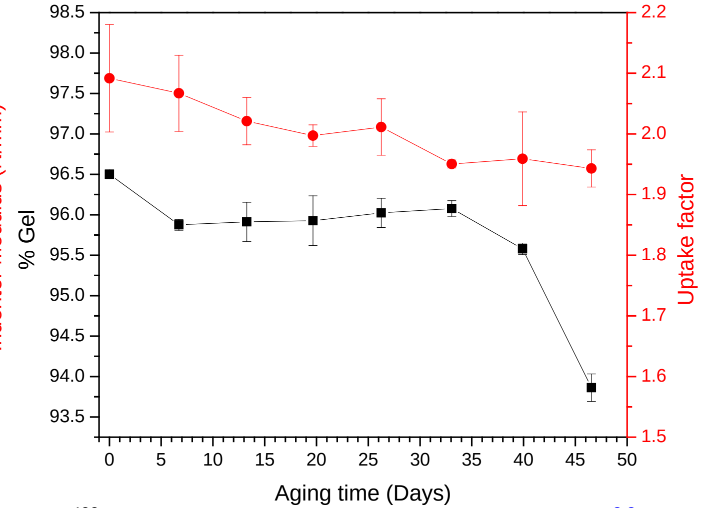
Characterization of Aged and Received Cable Materials

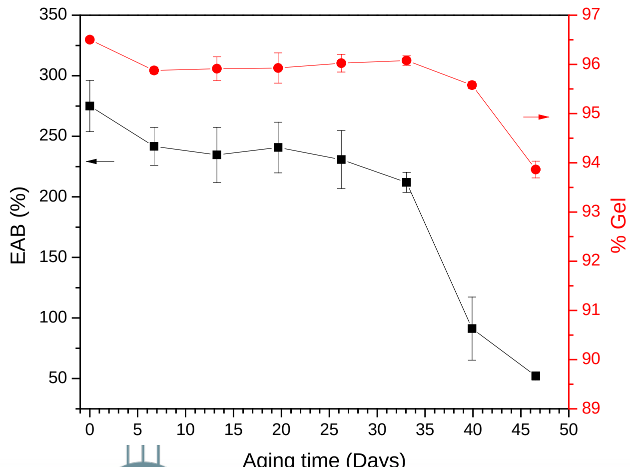
- Visual
- Density
- Mass
- DSC (differential scanning calorimetry) (incl. OITP, OIT)
- DMA (dynamic mechanical analysis)
- TGA (thermal gravimetric analysis)
- FTIR (Fourier transform infrared spectroscopy)
- XRD (x-ray diffraction)
- EAB (elongation at break)
- IM (indenter modulus)
- Gel/swell
- Permittivity
- Breakdown voltage
- SEM (scanning electron microscopy

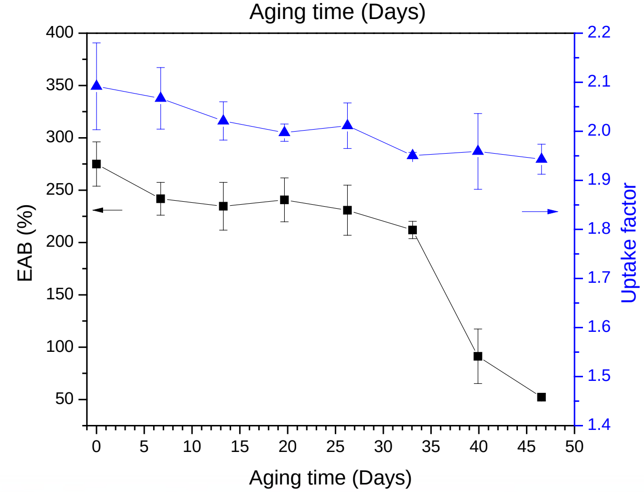
→ **Aging curves toward activation energies and end of life behavior determination**

Gel Content and Uptake Factor









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Inhomogeneous Aging Study
Understanding of Mechanisms

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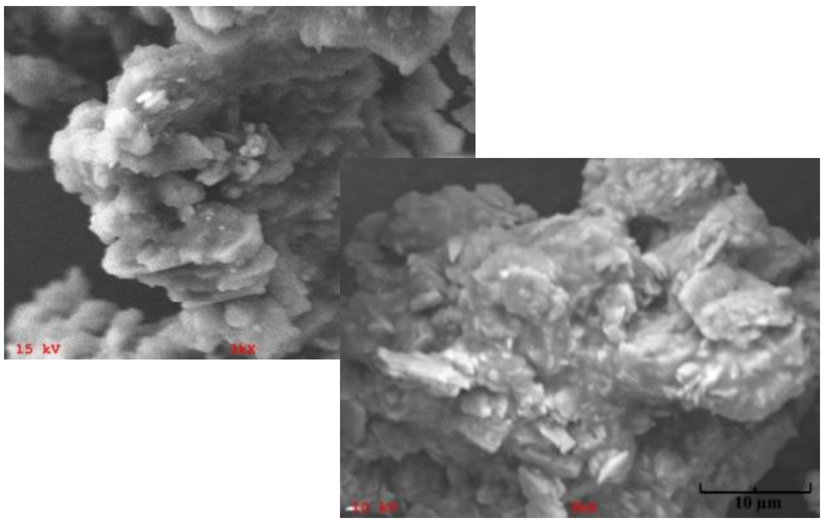
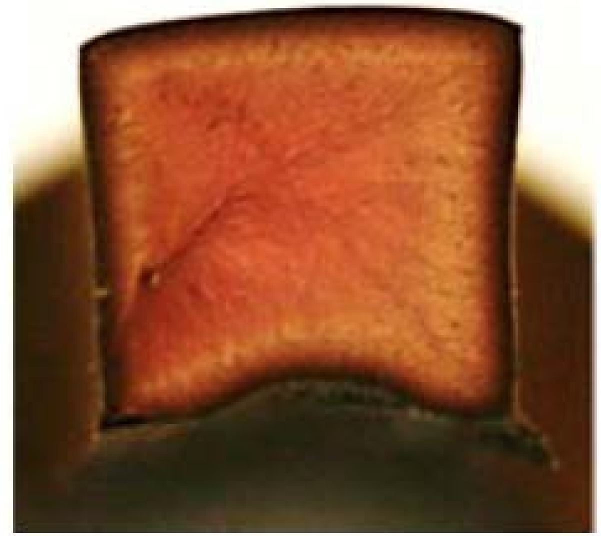
- Diffusion Limited Oxidation
- Nucleation of Degradation
- Effect of Sample Geometry





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Microstructure Analysis
Imaging and Quantifying Degradation

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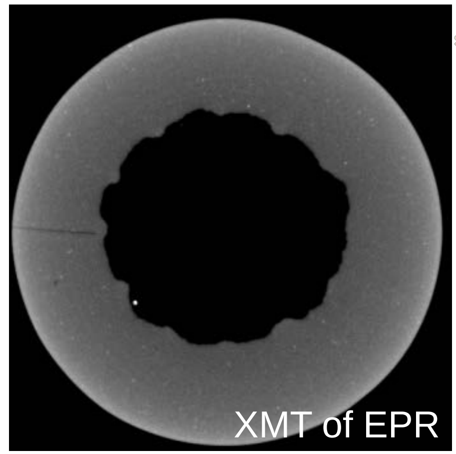
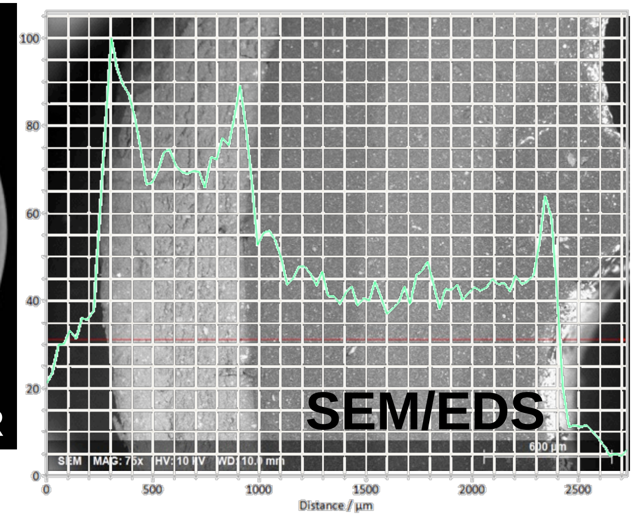
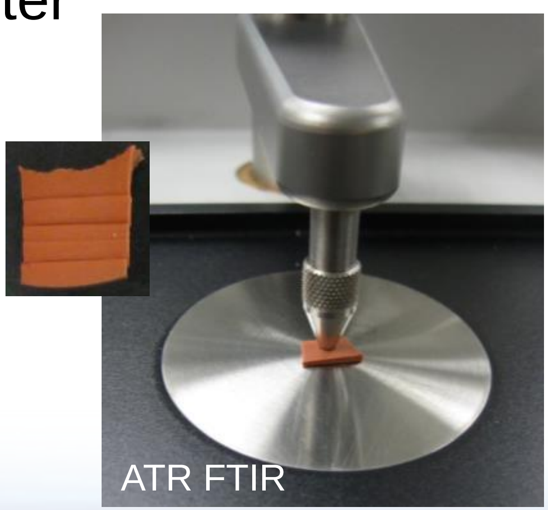
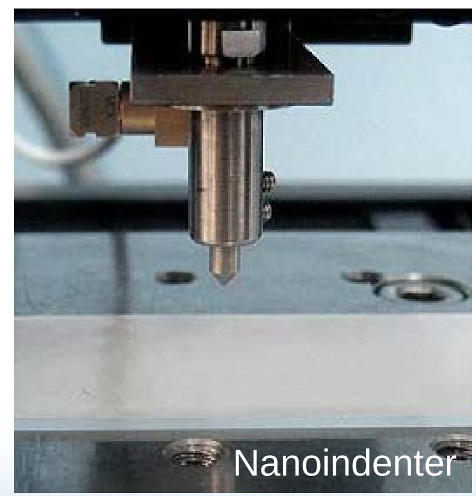
- Defect mapping
  - X-ray microtomography
- Chemical mapping
  - TOF-SIMS/XPS
  - SEM/EDS
  - FTIR/Raman
- Mechanical mapping
  - Nanoindenter









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Focus Cable Materials

- Legacy material formulations
  - XLPE, EPR insulation
  - Hypalon, Neoprene, CPE jackets
- Modern materials
  - That closely approximate legacy materials (Firewall III XLPE)
- New Old Stock
  - Stored since manufacture
- Harvested
  - Installed in nuclear power plant

Rank	Manufacturer	Insulation	# Plants
1	Rockbestos Firewall III	XLPE	61
3	Brand-Rex	XLPE	30
7	Raychem Flametrol	XLPE	23
2	Anaconda Y Flame-Guard FR	EPR	35
4	Okonite FMR	EPR	26
8	Samuel Moore Dekoron	EPDM	19
9	BIW Bostrad 7E	EPR	19
5	Kerite HTK	~EPR	25

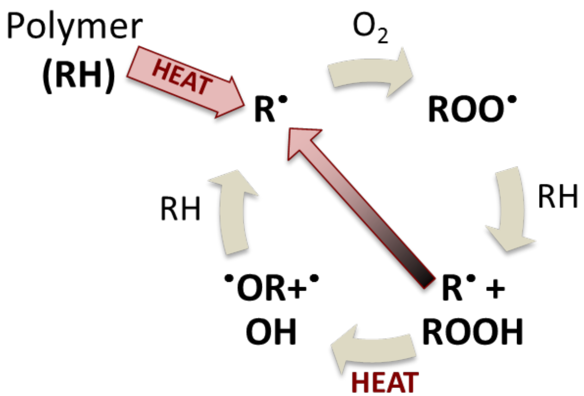
EPRI 103841R1

Cable Aging Mitigation: Cable Rejuvenation

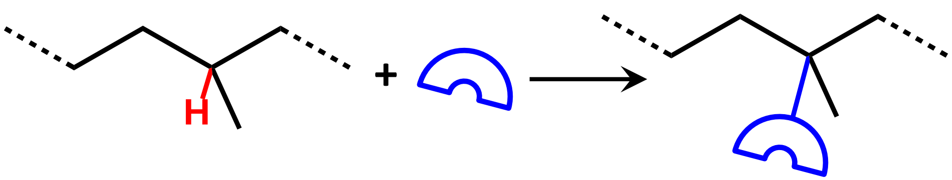
Goal: Recover performance and inhibit further degradation.

Sources of performance loss:
- Loss of plasticizer
- Molecular chain scission
- Degradative crosslinking

Strategies for Rejuvenation:
- Plasticizer replacement
- Constructive crosslinking
- New polymer network creation



Thermally-initiated radical reactions cause chain scission and crosslinking



Chemical anchors added to polymer: a platform for crosslinking and functionality

Challenges

- Availability of Materials
  - NOS relevant materials
  - Harvest materials with known conditions
- Knowledge of Actual Plant Conditions
  - Actual temps and totals doses over 40 years
- High Total Dose at Low Dose Rate
  - Time and $$ are limiting for low dose rate (<100Gy/h), high total dose (>50 Mrad) experiments

Cable Aging Path Forward

- Characterization of NOS/Harvested Legacy Cables
- Mid dose rate Combined Thermal/Gamma studies
- Inhomogeneous Aging studies
- Lower dose rate Combined Thermal/Gamma
- Revised Aging Models
- Cable Rejuvenation

Nuclear Power Plant Cable Aging Management Strategy

- **Evaluate for susceptibility –** focus on rooms/areas with highest temp and highest radiation. Also give special attention to most safety critical components. Select samples for test.
- **Visual walk-down** looking for visible indications on jackets.
- **FDR, Tan-Delta and other bulk tests** looking for worst case areas of degradation on sample of cables.
- **Local specific NDE** (indenter, capacitance, FTIR, …) at local area identified with bulk tests.
- **Repair/replace** where indicated. Consider also replacement in similar environments even if no degradation is observed.

PNNL-SA-120274

Condition-Monitoring Techniques for Electric Cables Used in NPPs

(NRC Reg Guide 1.218)

Test	Applicability	Ends	Damage	Comment
DC High Pot/ Step Voltage	Cable – 2/C	Both	Maybe	Not trendable
Very Low Freq. Tan-Delta	Cable – 2/C	Both	Yes	Not trendable
Visual / Illum. Borescope	Visible exterior	No	No	Not quantitative
Indenter	Local Jacket	No	No	Trendable
Dielectric Loss Dissipation	Cable – 2/C	Yes	No	Not for long/lrge cble
Insulation Resistance	Cable – 2/C	Both	No	Not trendble/uncrtain
Partial Discharge	Cable – 2/C	Both	Yes	Locates weak point
Time Domain Reflectometry	Cable – 2/C	Both	No	Limited val for insul.
Frequency Domain Reflectometry	Cable – 2/C	Maybe	No	Can ID local flaws
IR Thermography	Under load	No	No	Weak signal for insul.

Cable Health Evaluation

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- Destructive test vs. Nondestructive
- Full length cable vs. locally accessible point
- In-situ vs ex-situ (in place or sample to lab)
- Disconnected vs connected/energized
- Shielded vs non-shielded
- Multi vs single conductor

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Cable NDE and Condition Monitoring Objectives

Develop/Demonstrate NDE techniques that provide sensitive, in-situ assessment of cable performance with the ability to:

- Reduce uncertainty in safety margins
- Enable informed replacement planning
- Provide confidence in continued use

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Non-Destructive Evaluation (NDE) of Cable Remaining Useful Life

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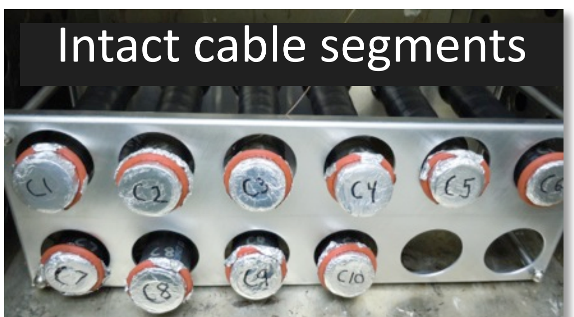
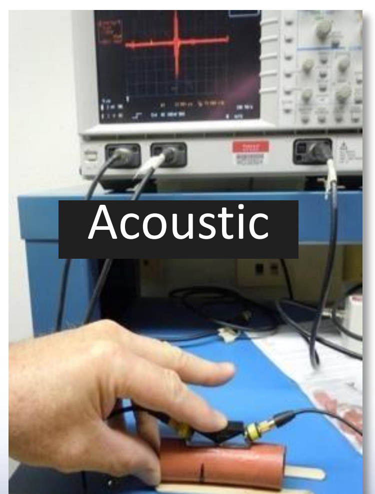
- Coordination Aging and NDE
- Sensitivity analysis of key indicators
- Correlation of destructive and non-destructive data
- Assessment of NDE methods

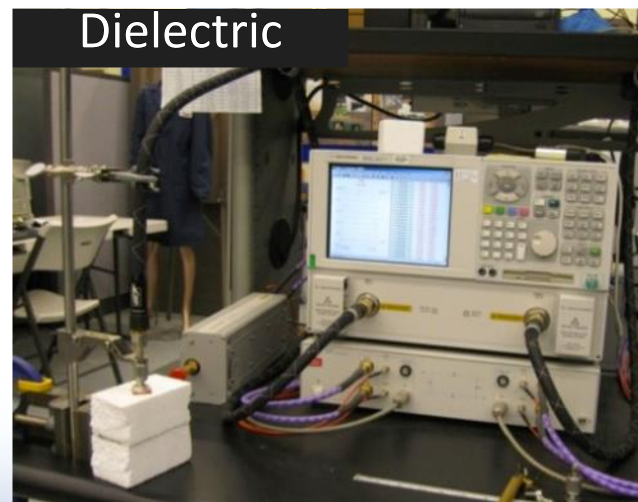
Monitoring during exposure



Intact cable segments



Acoustic



Dielectric

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Cable NDE and Condition Monitoring Scope:

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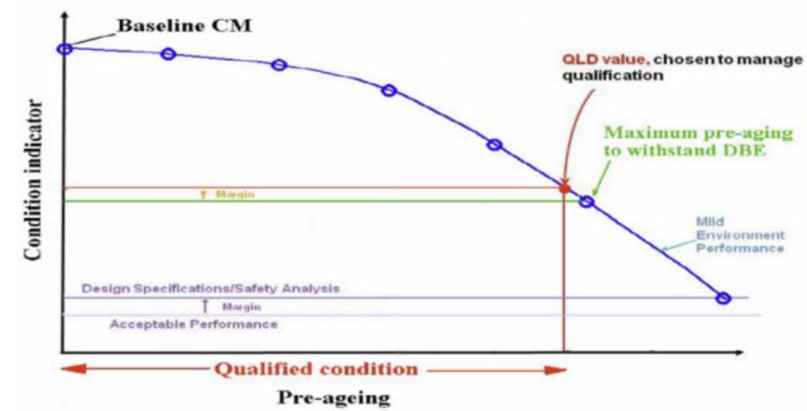
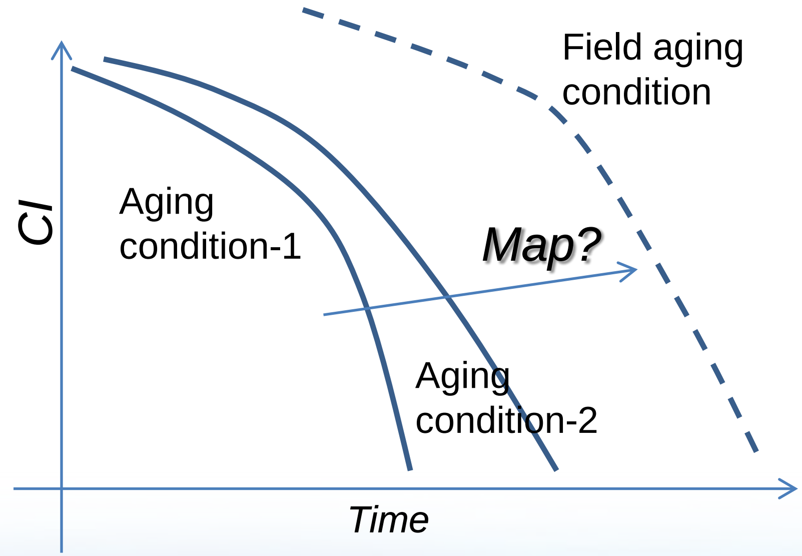
- Identify key indicators of aging
  - Determine measurements capable of "early warning" of condition degradation
  - Correlate aging with macroscopic material properties
- Advance state-of-the-art and develop new/transformational NDE methods
  - Enable in-situ cable condition measurements
  - Demonstrate on laboratory-aged and fielded cables
- Develop models for predicting condition-based remaining life
  - Enable condition-based qualification methodology
  - Use cable condition index data, condition-based aging models





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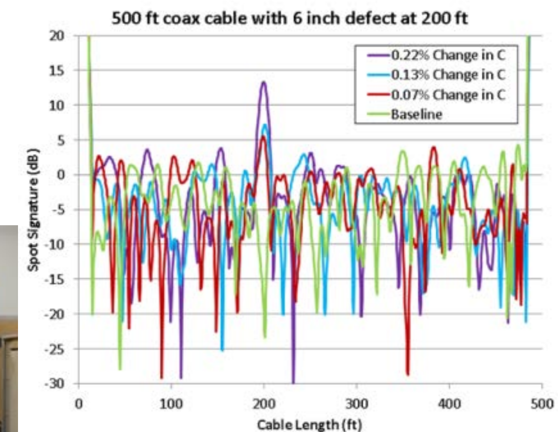
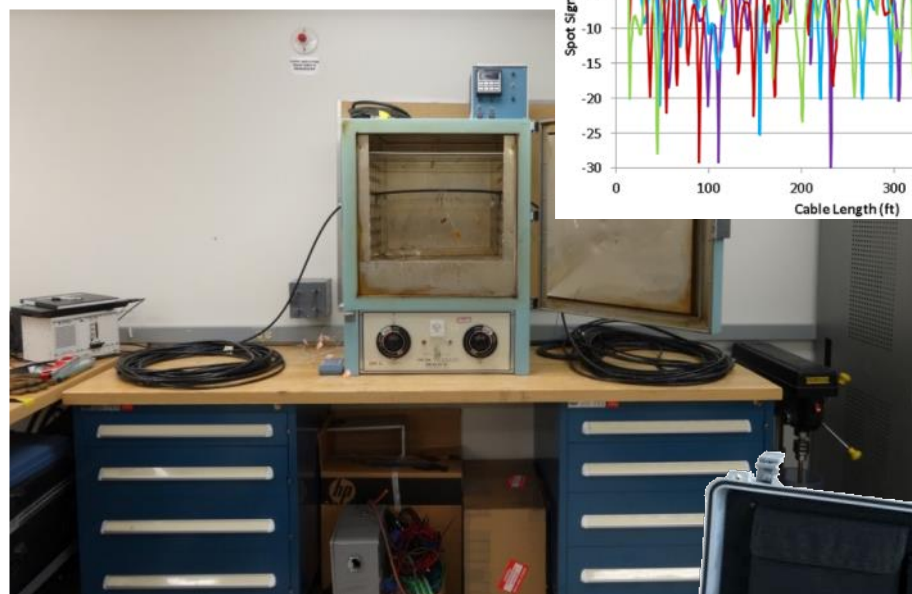
Full Cable Measurements

- Frequency Domain Reflectometry
- Dissipation Factor (tan δ)
- High Pot
- Partial Discharge





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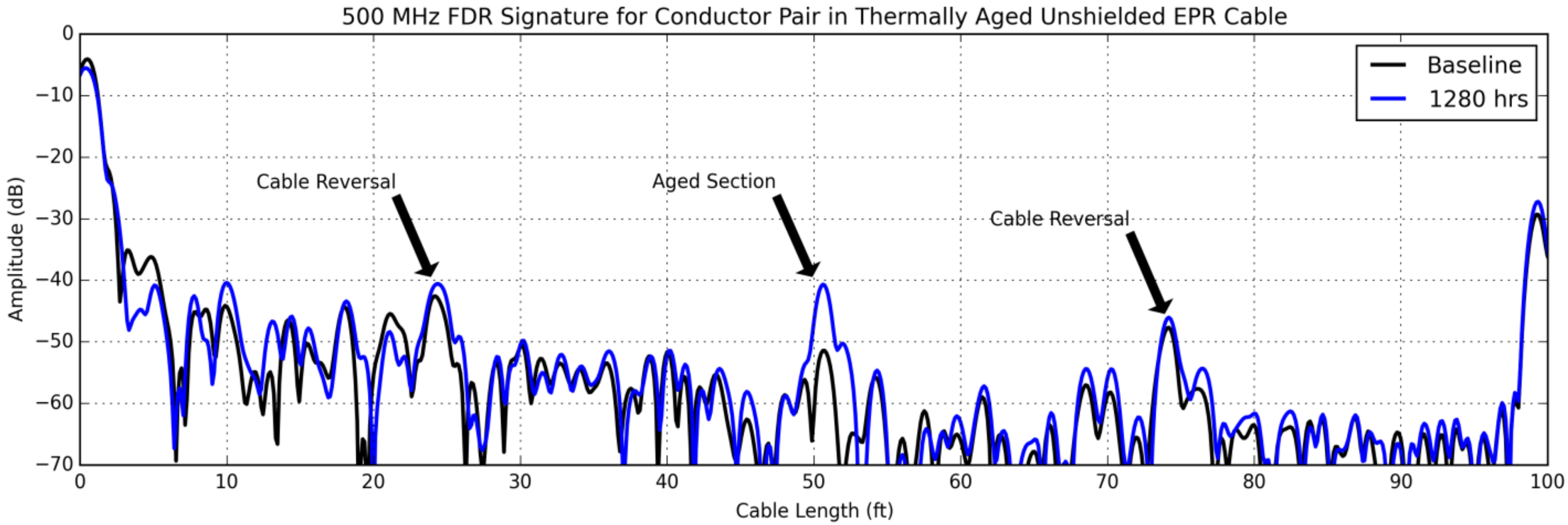
Thermally Aged Unshielded EPR Cable



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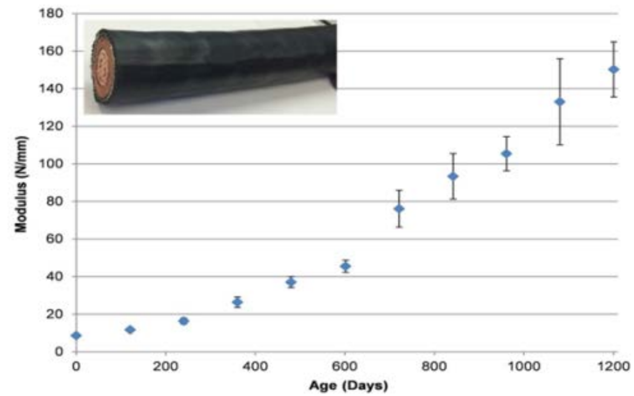
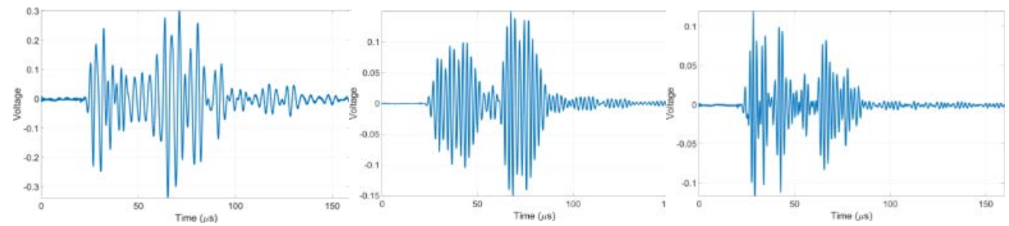
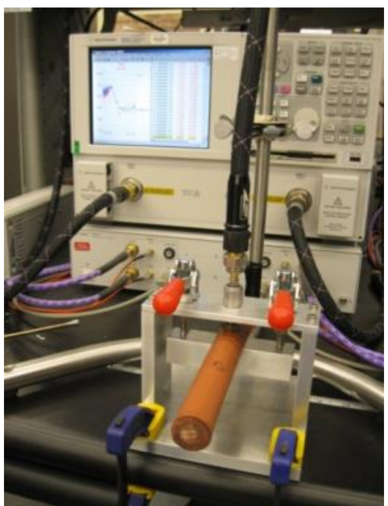
Local Spot Measurements

- Indenter
- Capacitance
- Acoustic
- Dielectric Constant



250 kHz 500 kHz 750 kHz





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Qualitative Assessment of Local Cable NDE Methods (from PNNL-25432)

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Technique	Ease/ Cost	Commercially Available	Correlates to EAB/Aging	Quantitative	R&D Needed
Visual Walk-downs	+	+	N	-(1)	+
IR Camera	N(2)	+	-	N(1,2)	+
Indenter	+	+	+	+	+
Recovery Time Indenter	+	N(4)	+	+	N(4)
DMA	-	-	N	+	-
FTIR	N	+	N	N	-
FT-NIR	N	+	N	N	-
Inter-Digital Capacitance	+	N	+	+	-
Ultrasound Velocity	-	-	-	-	-
Fiber-Optic Temp Sense	-(10)	+	N	N	-

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Cable NDE Path Forward

- **Numerical modeling** of FDR signal response due to insulation-related degradation
- **Linking numerical models with circuit models** to complete the physics-based understanding and representation of FDR response.
- **Further evaluating inter digital capacitance (IDC) as** alternate quantitative local test
- **Extending IDC** to assess insulation through jacket material

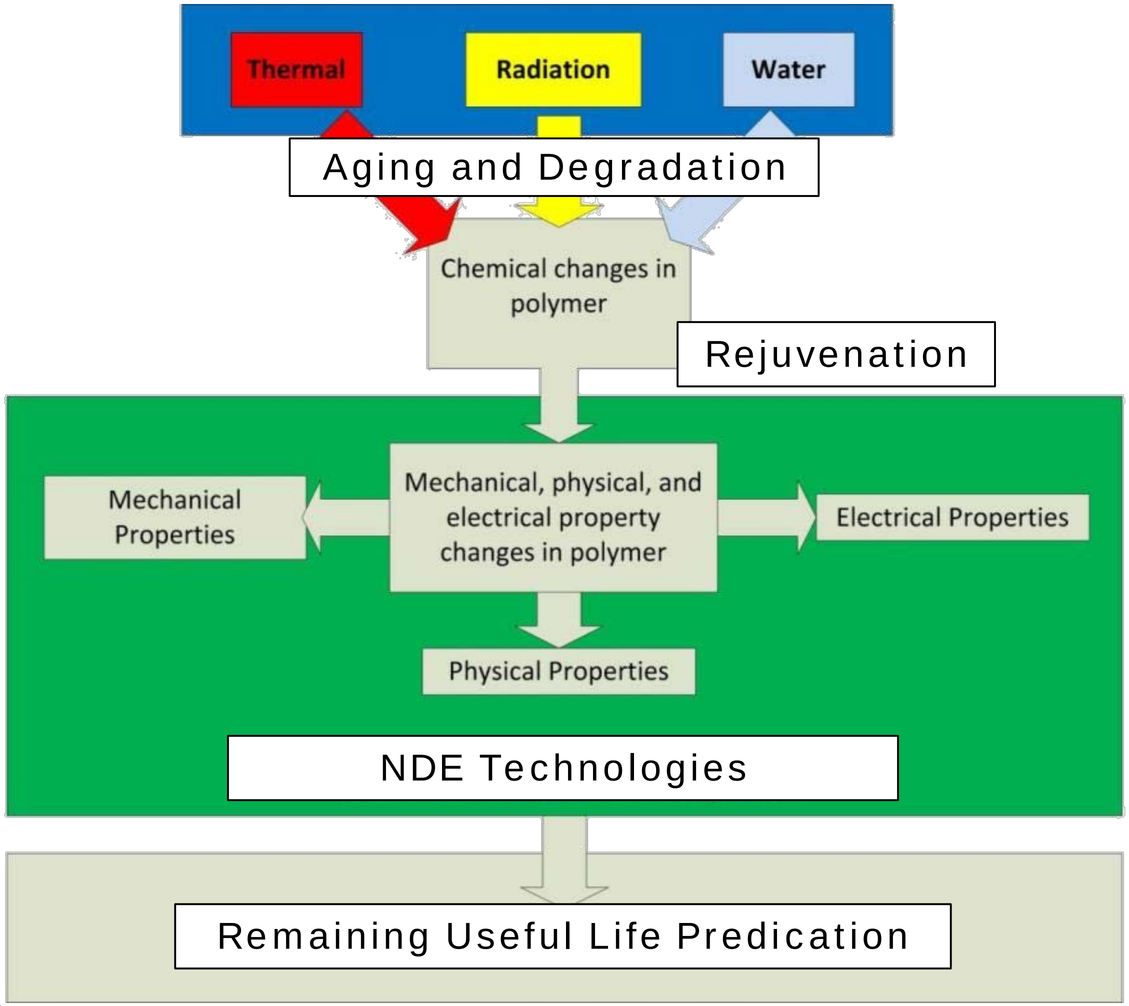
Cable Program Summary

Cable Stressors

Chemical Changes

Changes in Properties

Changes in Performance over Time



*LWRS NDE R&D Roadmap PNNL-21731 2012

GAPS

Detailed Understanding

Effective Treatments

Key indicators of cable aging

Transformational NDE

Methods for Life Prediction

Questions?

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