PNNL-SA-112992

LWRS Cable Aging and Cable NDE

Leonard S. Fifield, PhD
Pacific Northwest National Laboratory

DOE-NE Materials Crosscut Coordination Meeting
September 16, 2015, Webinar

Light Water Reactor Sustainability R&D Program

Cable Research Collaboration

LWRS

- Keith Leonard (ORNL)
- Thomas Rosseel (ORNL)

Cable Aging

- Robert Duckworth (ORNL)

Cable NDE

- S.W. (Bill) Glass (PNNL)
- Pradeep Ramuhalli (PNNL)

Goal: maximize impact

Non-LWRS

- Andrew Mantey (EPRI)

- Sheila Ray (NRC)
- Darrell Murdock (NRC)
- Robert Bernstein (SNL)
- Stephanie Watson (NIST)

- Nicola Bowler (ISU) (NEUP)

- Gary Harmon (AMS Corp)

Nuclear Power Plants (NPPs)

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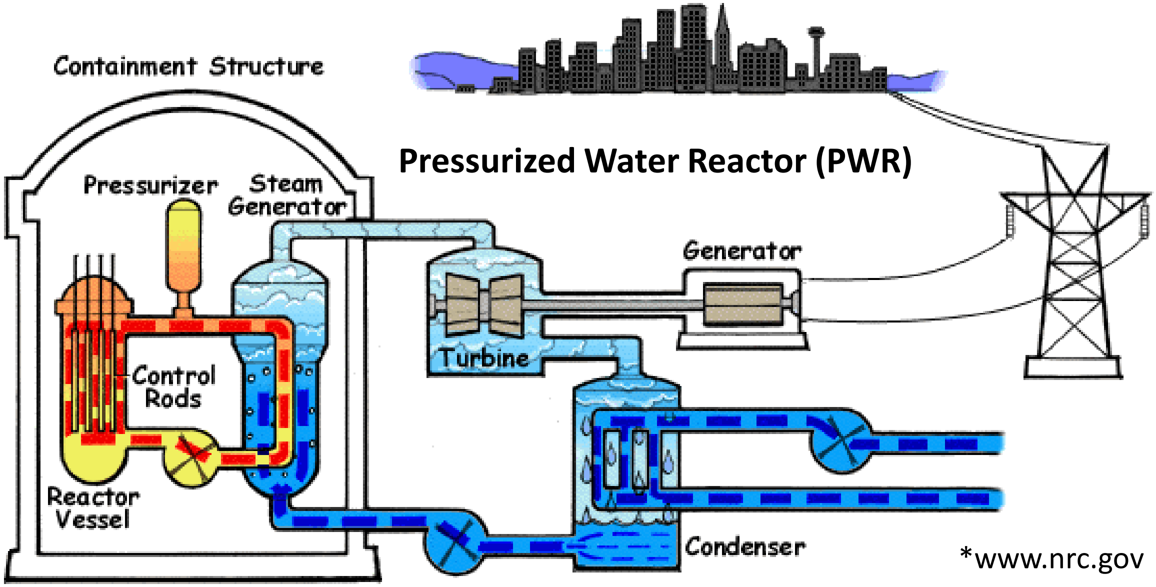

*www.nrc.gov

- U.S. NPPs contain *thousands of miles* of electrical cable in hundreds of types and sizes
- Ramifications of *cable failure* can be significant, especially for cables connecting to: off-site power, emergency service water and emergency diesel generators

Cables in Nuclear Power Plants

Application
- Instrument & Control (81%)
- Power cables (14%)
- Communication (5%)

Design voltage
- Low (≤2kV), Med, High (>46kV)

Construction
- Cables - Conductor, Insulation, Jacket
- Terminations
- Splices

Single Conductor

Multi Conductor

**SAND 96-0344*

Polymer Cable Materials

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Insulation

XLPE - Cross-linked polyethylene

EPR - Ethylene-propylene (diene) rubber

SiR - Silicone rubber

Jacketing

Hypalon® - Chlorosulfonated polyethylene (CSPE)

Neoprene - Polychloroprene (CR)

CPE - Chlorinated Polyethylene Elastomer

Vinyl - Poly(vinyl chloride) (PVC)

Cables in US Plants[1]

36% of cables are XLPE

36% of cables are EPR

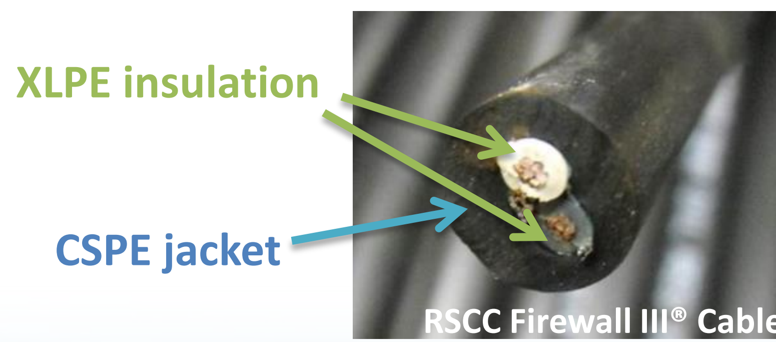
5% of cables are SiR

Cables in Containment[2]

90% of units have XLPE

70% of units have EPR

30% of units have SiR



LWRS Light Water Reactor Sustainability

[1]NUREG/CR-7153, Vol.5 2013

[2]EPRI TR-103841, Rev.1 1994

Polymer Degradation (Aging)

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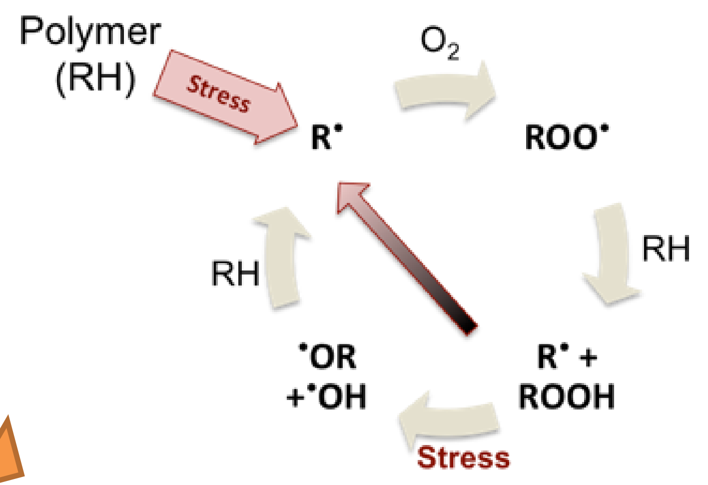

Environmental Stress

- Gamma Radiation
- Heat
- Light
- Moisture
- Vibration

Chemical Changes

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

Material Changes

- Mechanical (i.e. brittleness)
- Electrical (i.e. resistance)
- Physical (i.e. density)

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Light Water Reactor Sustainability

Cable Aging/NDE Task Activities Map to MAaD Targets

Activities

Cable Aging

- 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

LWRS Targets for Materials Aging and Degradation

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

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

EMDA Cable PIRT Analysis provides insights for prioritized needs

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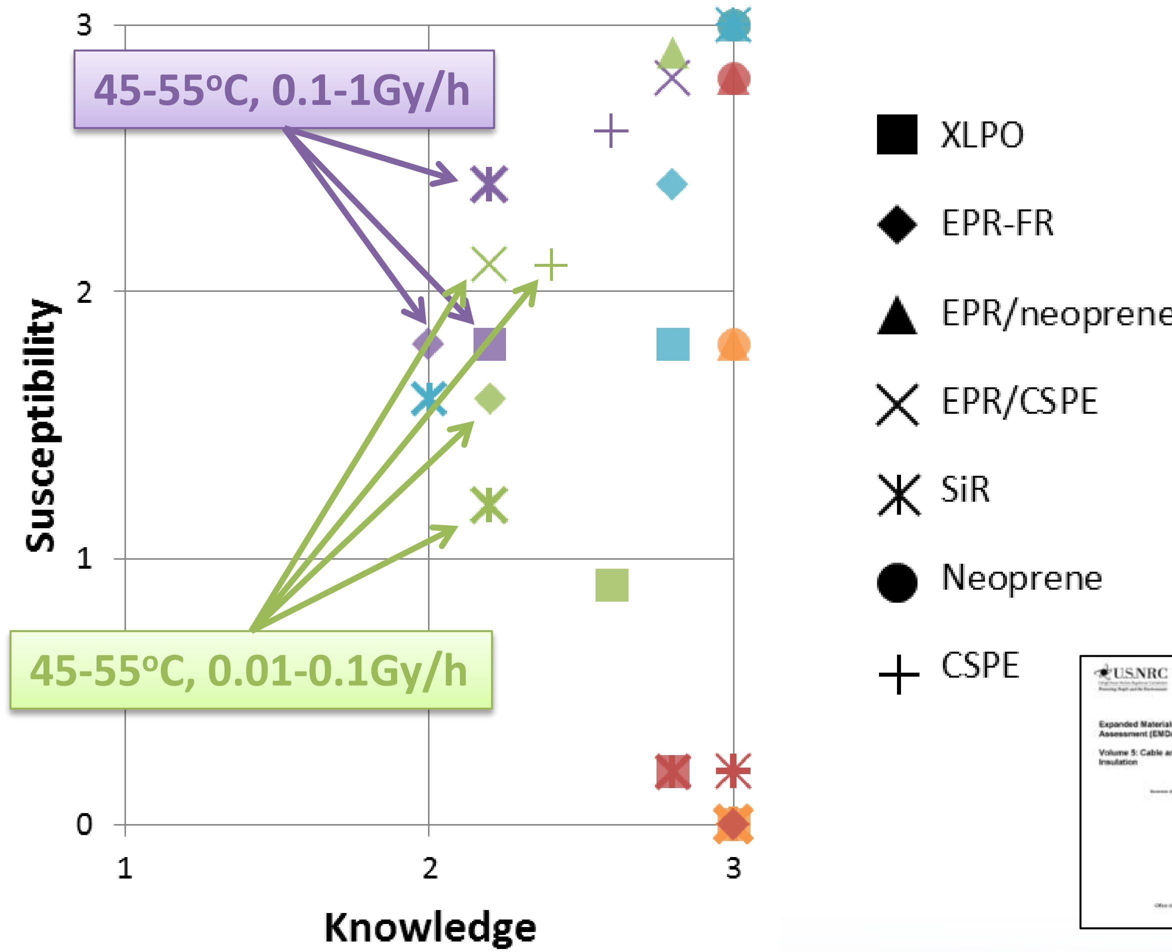
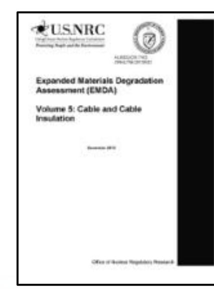
Up to 35°C, 0 dose rate
Up to 35-50°C, up to 0.01 Gy/h (1 rad/h)
Up to 45-55°C, 0.01-0.1 Gy/h (1-10 rad/h)
Up to 45-55°C, 0.1-1 Gy/h (10-100 rad/h)
Up to 60-90°C, 0 dose rate





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

Gamma Exposure Capabilities

PNNL

High Exposure Facility (HEF)

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

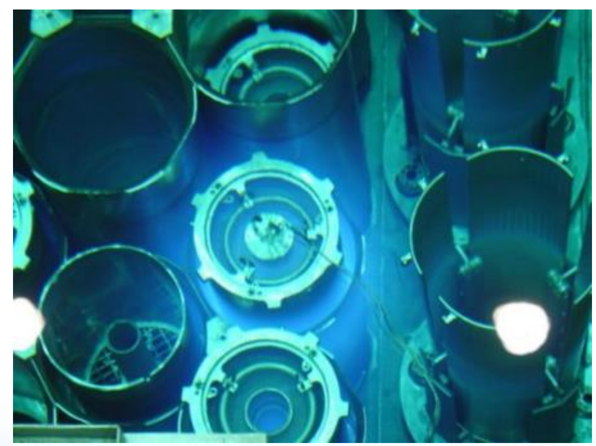
ORNL

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

- Dose rates from 10Gy/h to 100kGy/h

Co-60 Irradiator

- Uniform dose rate of 140 Gy/h



Polymer Aging Characterization and Testing Laboratory at PNNL

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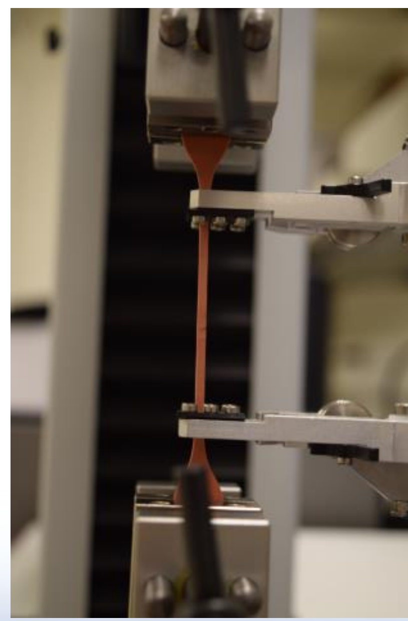
Aging

- 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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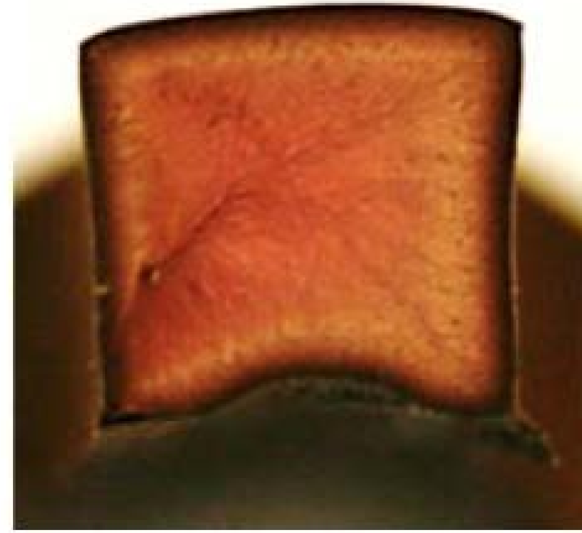
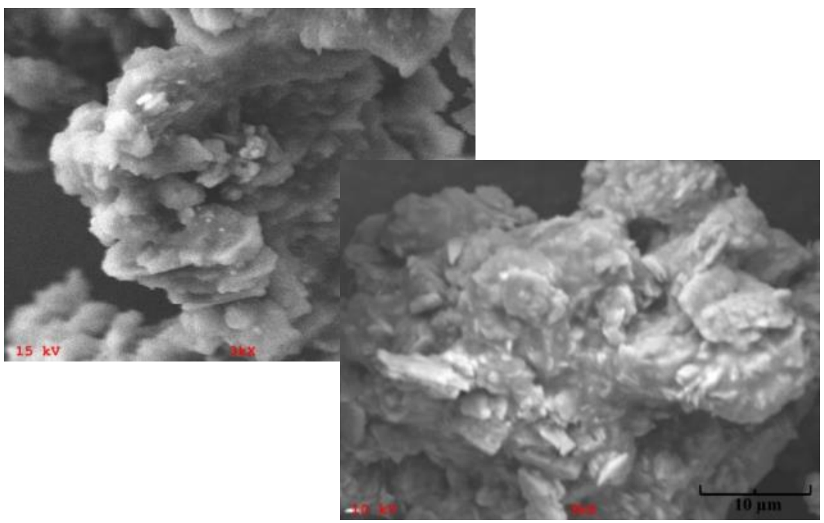
Inhomogeneous Aging Study
Understanding of Mechanisms

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

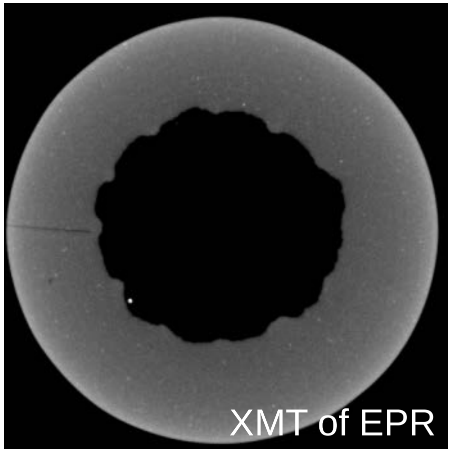


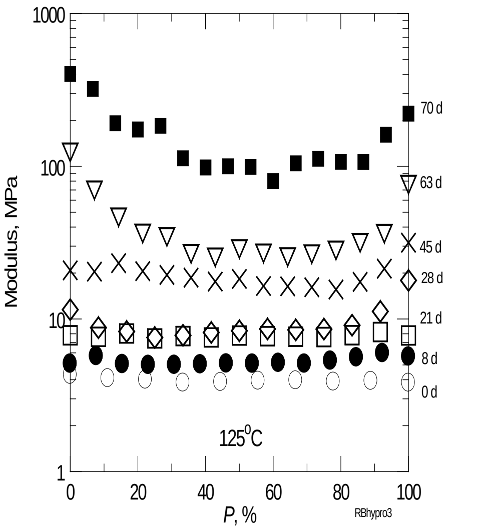


Light Water Reactor Sustainability

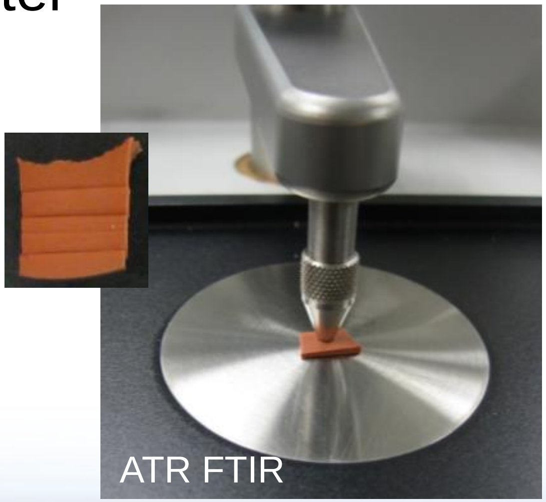
Microstructure Analysis
Imaging and Quantifying Degradation

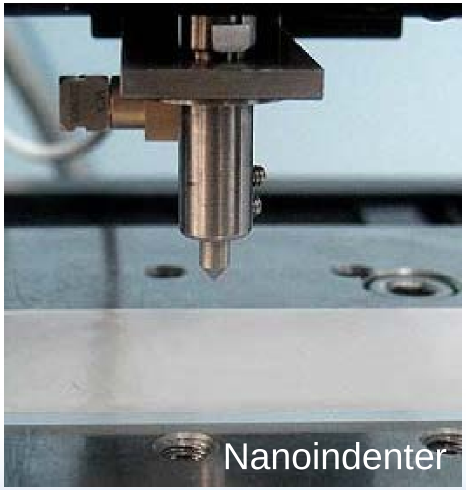
- Defect mapping
  - X-ray microtomography
- Chemical mapping
  - TOF-SIMS/XPS
  - X-ray diffraction
  - FTIR/Raman
- Mechanical mapping
  - Nanoindenter





*NUREG/CR-7153, Vol. 5





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

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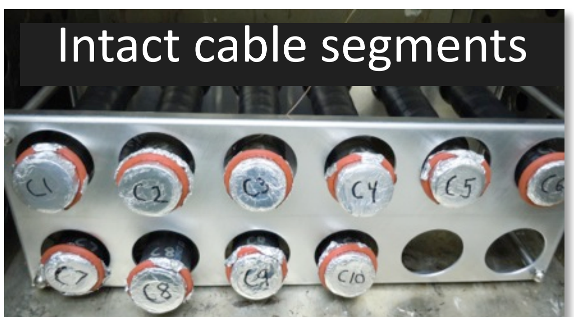
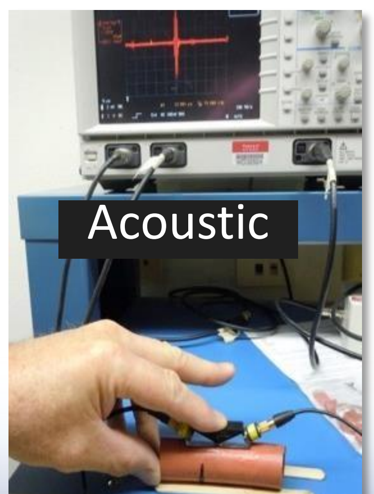
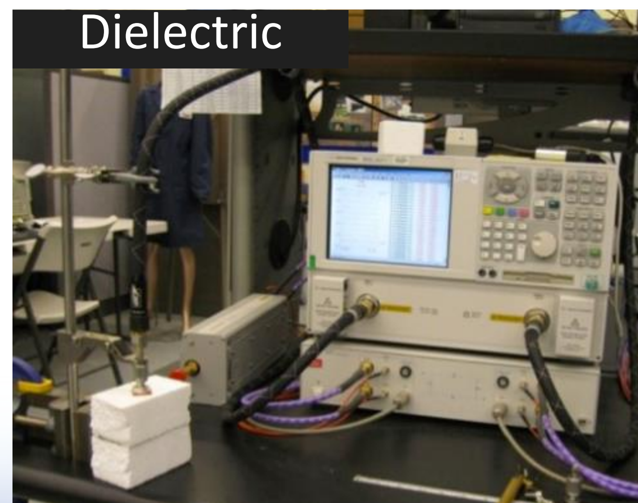
- Coordination Aging and NDE
- Sensitivity analysis of key indicators
- Correlation of destructive and non-destructive data
- Assessment of NDE methods







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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, UT, …) at local area identified with bulk tests.
- **Repair/replace** where indicated. Consider also replacement in similar environments even if no degradation is observed.

Condition-Monitoring Techniques for Electric Cables Used in NPPs
(NRC Reg Guide 1.218)

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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 Scope:

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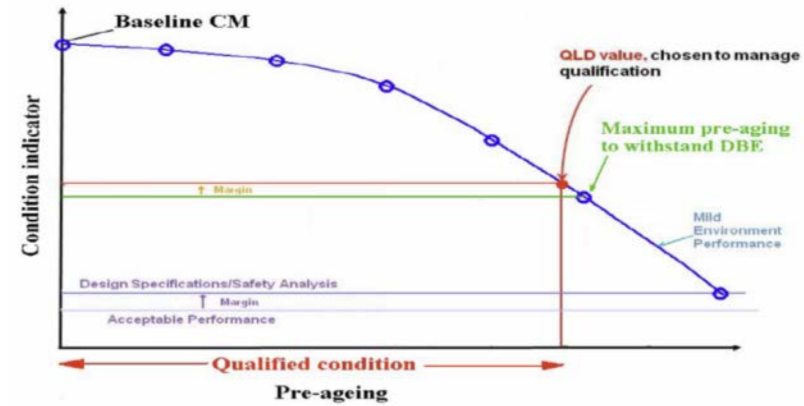
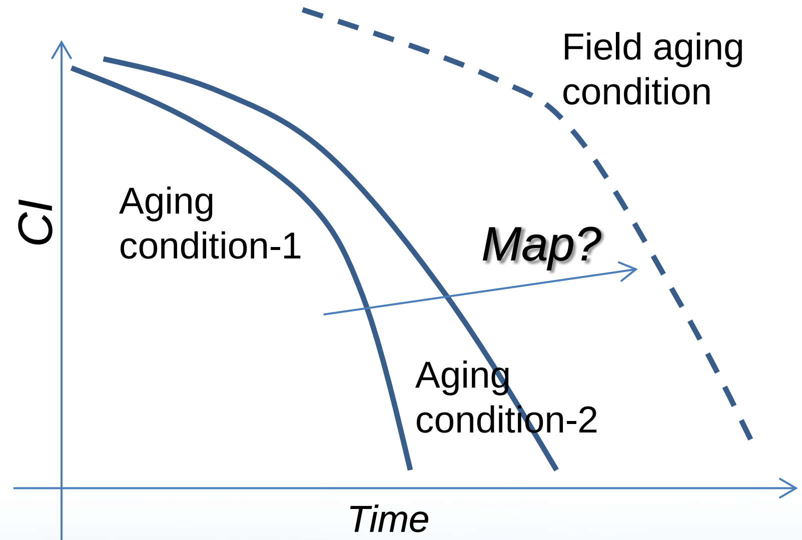
- Identify key indicators of aging
  - Determine measurements capable of "early warning" of condition degradation
  - Correlate aging with macroscopic material properties
- Advance state-of-the-art and develop new/transformational NDE methods
  - Enable in-situ cable condition measurements
  - Demonstrate 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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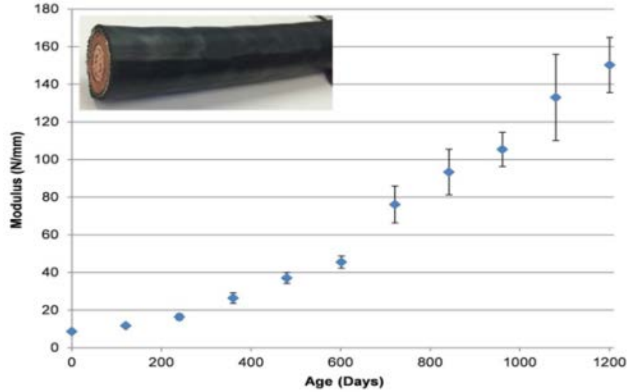
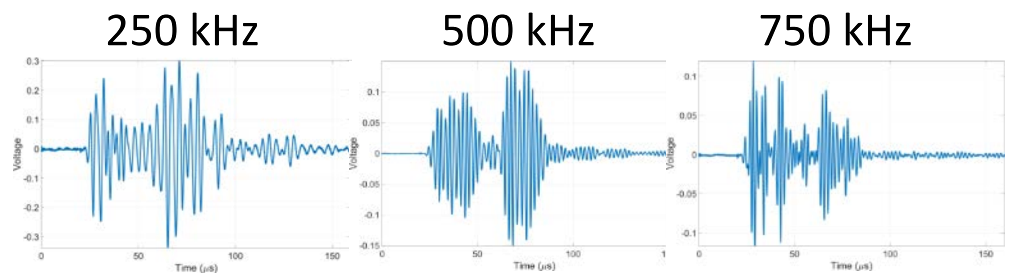
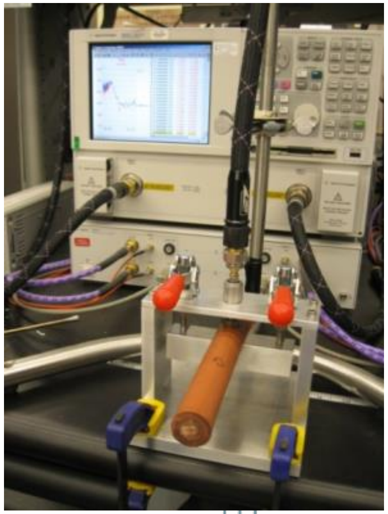
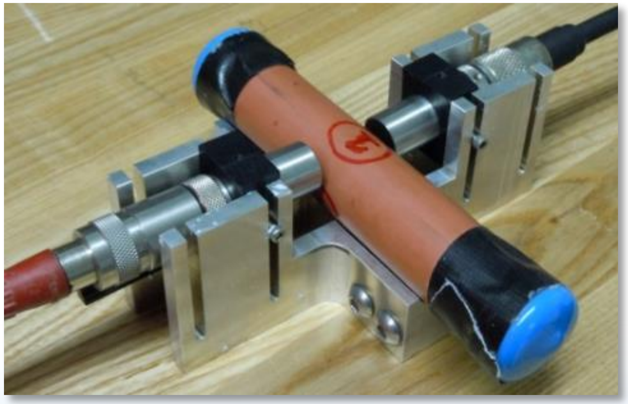
Local Spot Measurements

- Indenter
- Capacitance
- Acoustic
- Dielectric Constant









Full Cable Measurements

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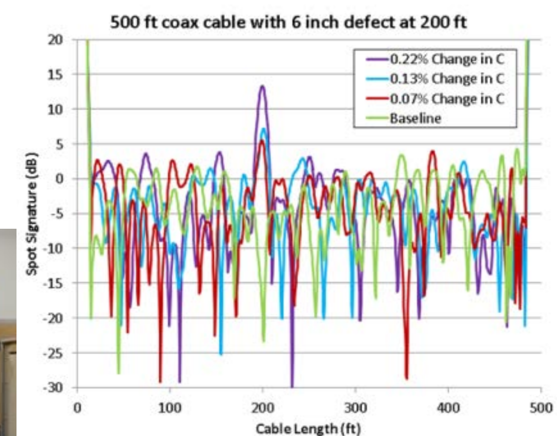
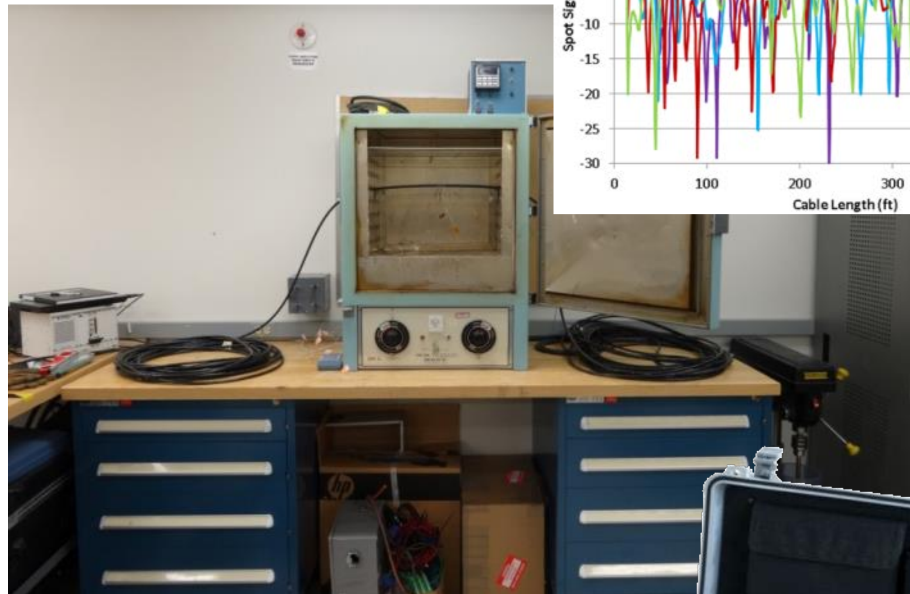
- Frequency Domain Reflectometry
- Dissipation Factor (tan δ)
- High Pot
- Partial Discharge





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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

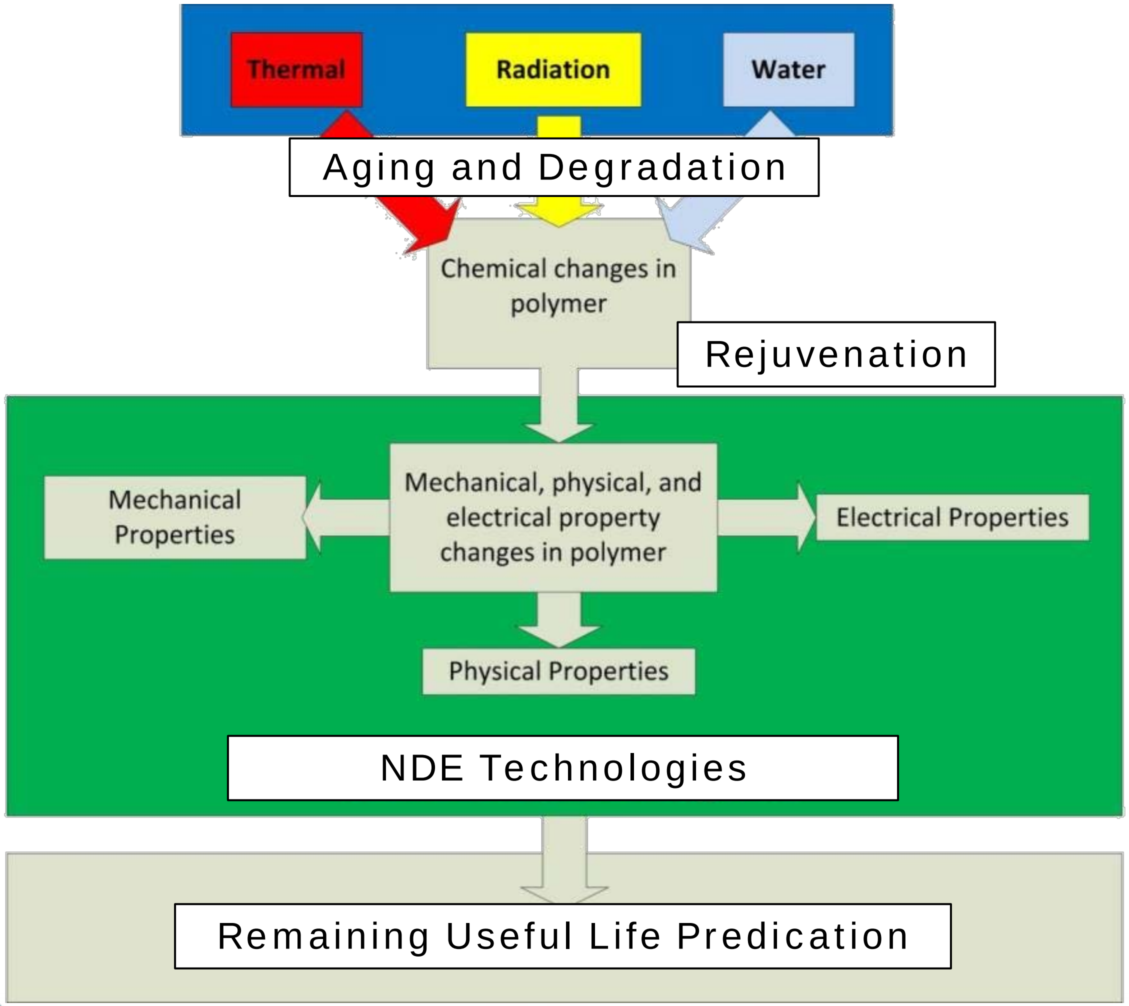
Cable Program Summary

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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Leo.Fifield@pnnl.gov