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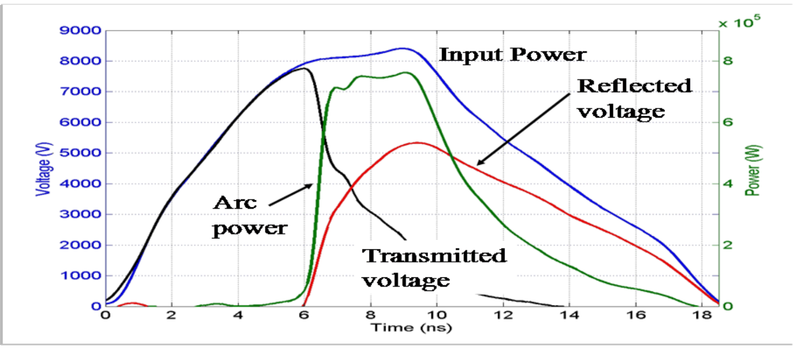

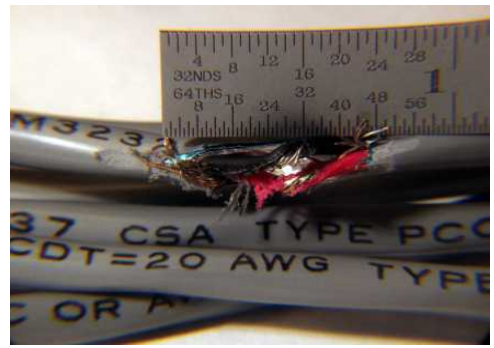

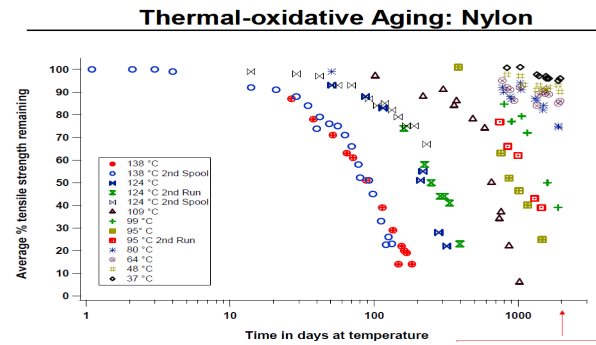

Research Recommendations Relevant to Aging Mechanisms and Condition Monitoring in Submerged Medium Voltage Cables

Robert Bernstein, Jason Neely, and Samuel Durbin

USNRC Headquarters

August 11th, 2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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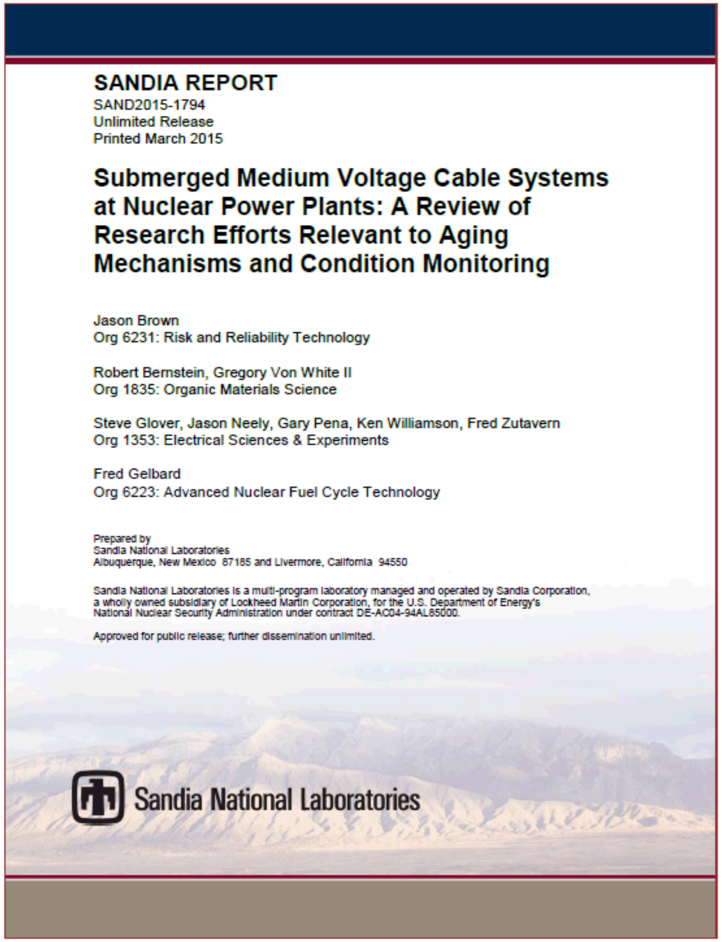
Outline

- Project Objectives
- Approach to Addressing Objectives
- Overview of Findings
- Recommended path forward
  - Material science
  - Condition monitoring
- Remaining useful life
  - Predict and prevent system failures
- Summary


SANDIA REPORT
SAND2015-1794
Unlimited Release
Printed March 2015

Submerged Medium Voltage Cable Systems at Nuclear Power Plants: A Review of Research Efforts Relevant to Aging Mechanisms and Condition Monitoring

Jason Brown
Org 6231: Risk and Reliability Technology

Robert Bernstein, Gregory Von White II
Org 1835: Organic Materials Science

Steve Glover, Jason Neely, Gary Pena, Ken Williamson, Fred Zutavern
Org 1353: Electrical Sciences & Experiments

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Org 6223: Advanced Nuclear Fuel Cycle Technology

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*This presentation is intended to compliment material in SAND2015-1794

Project Objectives

- To establish and document the state-of-the-art in
  - Science behind aging and degradation of submerged cables including various EPR blends and XLPE
  - Cable condition monitoring and assessment
- To suggest a method for quantifying cable condition: *An Aging Metric*
- To recommend an R&D path forward to advance capabilities in accelerated aging (simulated submerged conditions), condition monitoring and assessment

Approach to Addressing the Objectives

- Sandia assembled a team of experts in:
  - Risk, Reliability and Safety
  - Organic Materials Sciences (accelerated aging of insulation polymers)
  - High Voltage Electrical Sciences (experts in lighting, breakdown, dielectric properties)
  - Nuclear System surety
- Sandia corresponded with experts identified by NRC and presented at ICC Spring 2014
- Sandia deliverable underwent external review by experts identified by NRC

Complexity of the Problem Spans Material, Electrical, and Reliability Sciences

- Significant amounts of research has been conducted to address cable aging and its complexities
- Identification of a consistent End-of-Life (EOL) criteria is needed
- Advances in accelerated aging need to:
  - Link stressors to aging mechanisms
  - Enable accelerated aging that is consistent with field aging
  - Enable diagnostic and lifetime analysis development
- Advances in condition monitoring (CM) require:
  - Identification of the most sensitive markers that correlate to EOL
  - Selection of diagnostics that are sensitive to aging markers
  - Develop analysis techniques that predict remaining useful life with confidence/uncertainty measures

RECOMMENDED PATH FORWARD

Phased Technological Approach

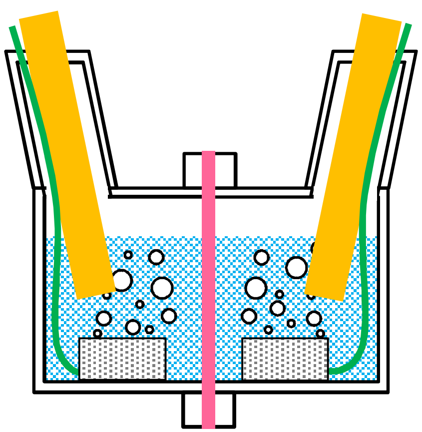
- Phase 1 – Literature Review (Complete)
  - Identified current status of research and path forward
  - Fundamental studies needed to systematically understand variables/stressors
- Phase 2 – Isotopic Plaque Testing and CM Diagnostic Development
  - Study role of molecular dioxygen versus water
  - Develop CM diagnostics to measure the presence of water trees and bulk degradation
- Phase 3 – Down-Select Aging Stressors and CM Diagnostics
  - Additional plaque testing to define key parameters for new accelerated aging protocol
  - Down-select CM diagnostics based on complimentary characterization of bulk and local degradation
  - Develop new test vessel for advanced aging studies

Phased Technological Approach (cont'd.)

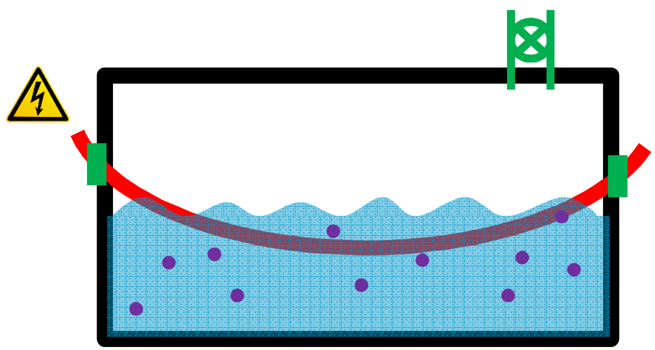
- Phase 4 – Accelerated Aging Protocol Development
  - Transform from plaque to cable sample testing
  - Develop new accelerated aging protocol
  - Produce cable samples aged to various stages of "life" for CM evaluation
- Phase 5 – Remaining Useful Lifetime (RUL) Model Development and Validation
  - Validate initial Phase 3 data with field-returned samples
  - Complete comprehensive, empirical database to fully inform RUL models

Various Testing Vessels

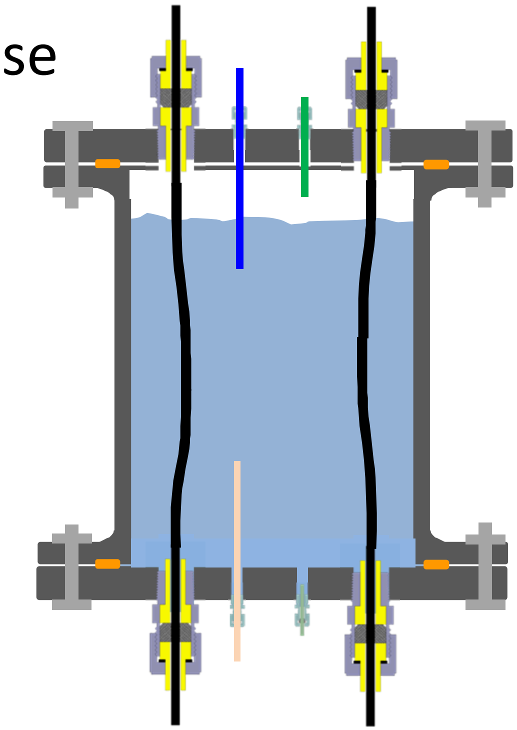
- Conceptually easy, technically challenging
  - Multi-disciplinary design required
- Each vessel represents different testing phase
  - Provide reinforcing, confirmatory research with separate effects testing



Plaque Testing



Unpressurized Cable Testing



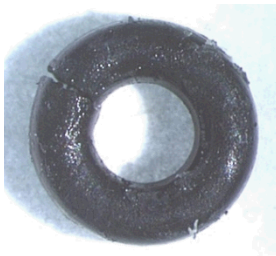
Pressurized Cable Testing

Research Roadmap

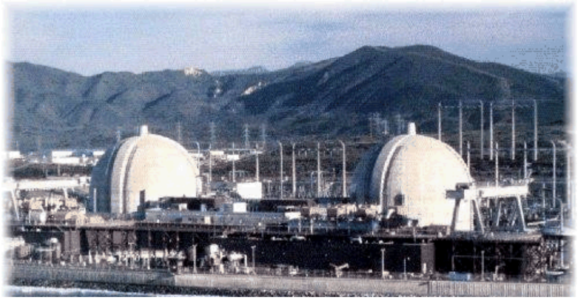
	Phase II	Phase III	Phase IV	Phase V
Accelerated Aging	Test apparatus development; Isotopic plaque testing	Continued plaque testing with additional stresses and "multi-stress" scenarios	Accelerated aging protocol development for TELA	Continue TELA development and engage standards community to replace AWTT, ACLT
	Development of laboratory method to view water-based degradation in EPR	Develop a new vessel for wet pressurized cable aging		
Cable Management Program		Community outreach activities for support of standard EOL and RUL definition development	Consensus building activities for development of standard EOL and RUL definitions	Remaining Useful Life Model Development
Condition Monitoring Tests	Testing of virgin and field and lab aged cable samples using bulk CM methods	Down select of CM methods for development of multi-test diagnostic method	Continued development of multi-test bulk CM diagnostic, inc TELA samples	Field testing of multi-test bulk CM diagnostic method(s)
	Investigate new methods of detecting local degradation on field-aged cables	Down select of CM methods for local degradation detection	Continued development of local degradation detection methods, inc TELA samples	Field testing of newly developed local degradation test method(s)

MATERIAL SCIENCE AND ACCELERATED AGING

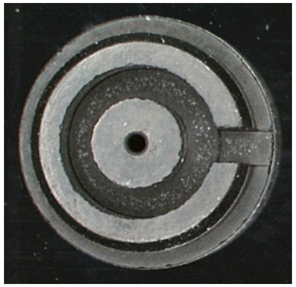
Organic Materials Aging and Degradation Is Relevant to Many High-Consequence Systems



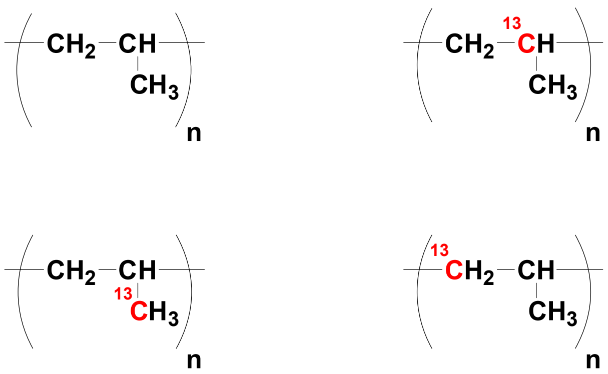
O-rings



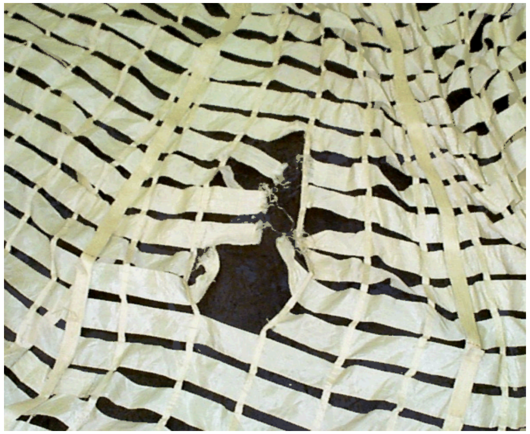
Nuclear Power Plant Cable Insulation



Shorting Plugs



Labeled Polymers



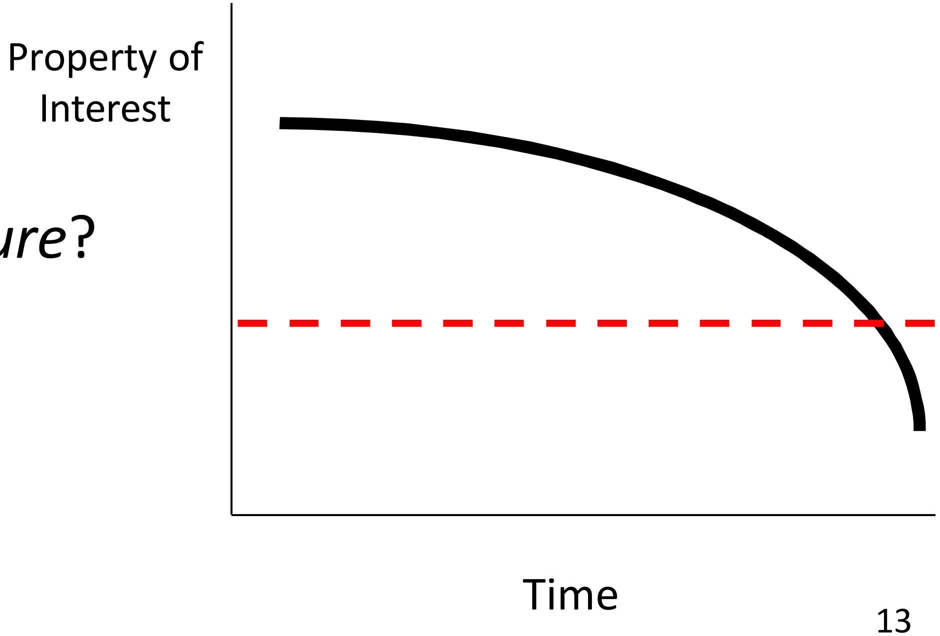
Textiles

Goals of a Material Aging Program

Objective: Provide a technical basis to predict performance as a function of time

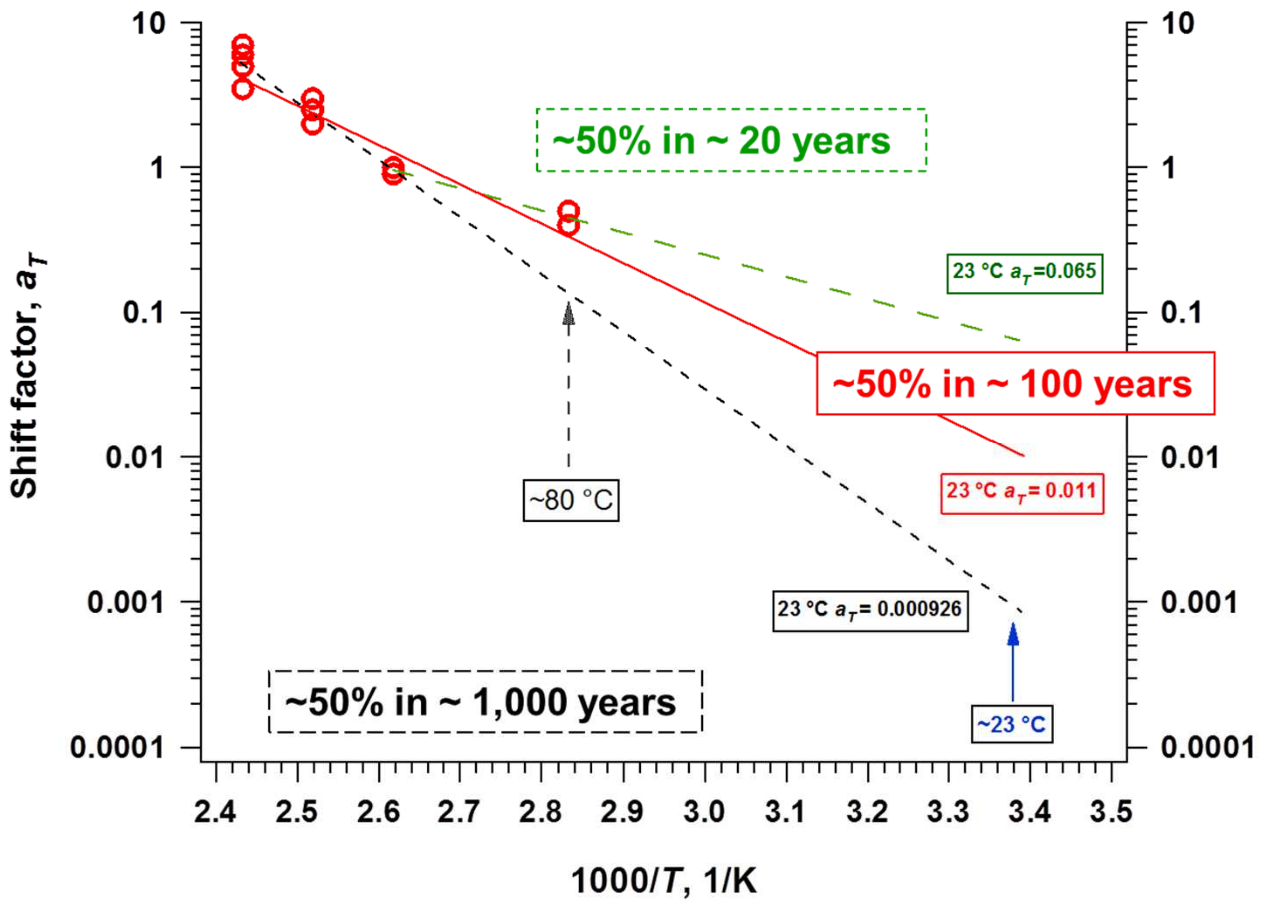
Usually multi-year programs modeled after previous programs resulting in material performance predictions validated with field returned samples

- What is the performance *measure*?
- What is the performance *limit*?
- Basis for "Lifetime" predictions



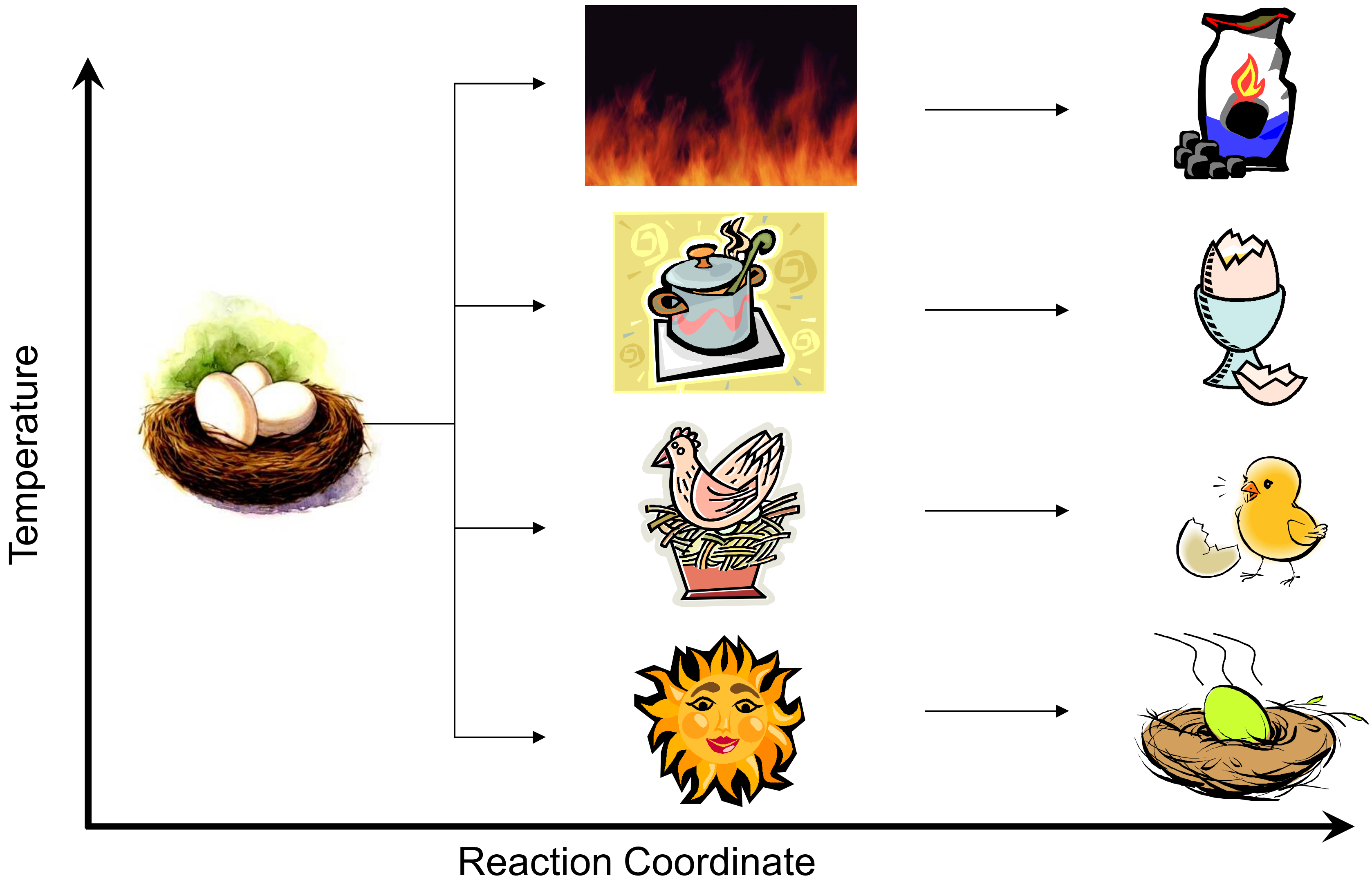
Valid Accelerated Aging Requires Understanding of the Chemistry

Conclusions derived from initial high temperature, short duration can be misleading



Bernstein, R.; Gillen, K. T. Polymer Degradation and Stability, Predicting the Lifetime of Fluorosilicone O-rings 2009, 94, 2107-2133.
Bernstein, R.; Gillen, K. T. "Fluorosilicone and Silicone O-ring Aging Study," Sandia National Laboratories, SAND2007-6781, 2007.

The Acceleration of 'Time' Can Have Several Results



Isotopic Labeling can Provide Insight into Oxidation Based Aging

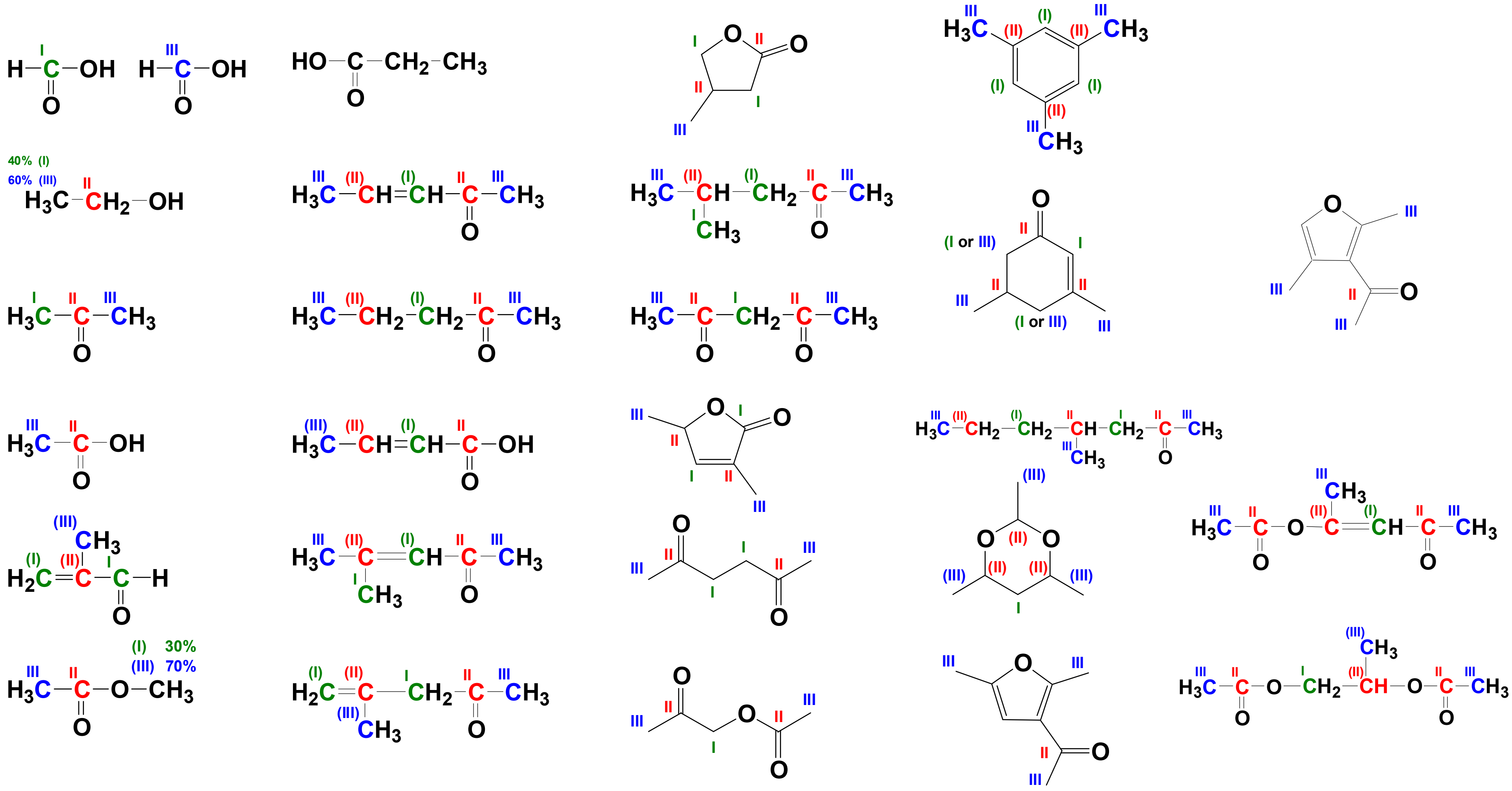
- First step: understand the source of ‘oxidation’
  - Is it oxygen (O_2) or water (H_2O)? Is there a synergism?
  - Are they interconnected? What is relationship?
- Utilizing isotopic labeling, coupled with analytic studies can answer this question
- Oxygen 16 (normal) vs Oxygen 18 (heavier, non-radioactive isotope)

H_2O vs $H_2{}^{18}O$

O_2 vs ${}^{18}O_2$

Argon

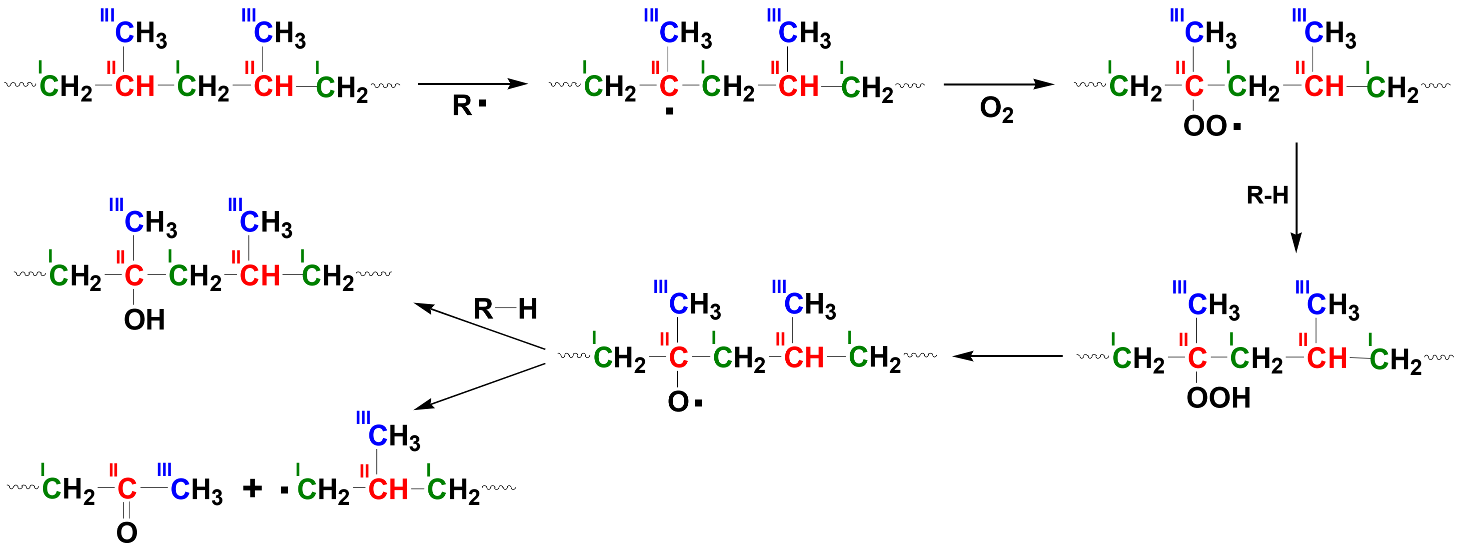
The Chemistry of Thermal-Oxidative Degradation - Extensively Studied in Some Cases



Bernstein, R.; Thornberg, S. M.; Assink, R. A.; Irwin, A. N.; Hochrein, J. M.; Brown, J. R.; Derzon, D. K.; Klamo, S. B.; Clough, R. L., The origins of volatile oxidation products in the thermal degradation of polypropylene, identified by selective isotopic labeling, *Polymer Degradation and Stability,* **2007**, *92*, 2076-2094

Reaction Mechanisms Are Often Unknown

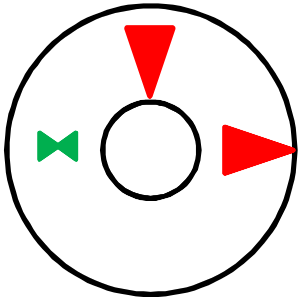
- Reactions take more than one step
- It is possible to have more than one plausible reaction sequence for a given result
- Better understanding requires identification of reaction intermediates



Thornberg, S. M.; Bernstein, R.; Derzon, D. K.; Irwin, A. N.; Klamo, S. B.; Clough, R. L. *Polymer Degradation and Stability*, The Genesis of CO_2 and CO in the Thermooxidative Degradation of Polypropylene 2007, 92, 94-102.

Water Trees

Comparison between EPR and Unfilled XLPE		
	EPR	Unfilled XLPE
Tree Shape	spherical	narrow and long
Water absorption	greater	lesser
Vented Trees	rarely found	found



Notional schematic of vented (red) and bow-tie (green) trees

Demonstrates mechanistic differences between materials
Probably even intra-material type

Boggs, S.; Xu, J. "Water treeing - Filled versus unfilled cable insulation," *IEEE Electrical Insulation Magazine*, 17, 23-29, 2001.

Degradation Similarities

- Data reveals that carboxylate ions, trace of ketones and esters, and <u>sulfate ions</u> were all present within or near the surface of the water trees

- Oxidative products appear (by spectroscopy) to be similar to those from other degradation pathways
  - Thermal-oxidative, photochemical, gamma-irradiation

- Analytical Differences Laboratory vs. Field Aging

- <u>Any theory needs field aged validation/verification</u>

Patsch, R. *IEEE Conference on Solid Dielectrics,* Water Treeing in Cable Insulation -Are Laboratory Tests Meaningful? **1988**, 242-245.
Xu, J. J.; Boggs, S. A. *IEEE Electrical Insulation Magazine,* THE CHEMICAL NATURE OF WATER TREEING - THEORIES AND EVIDENCE **1994**, *10*, 29-37.

Key Stressors Have Been Suggested

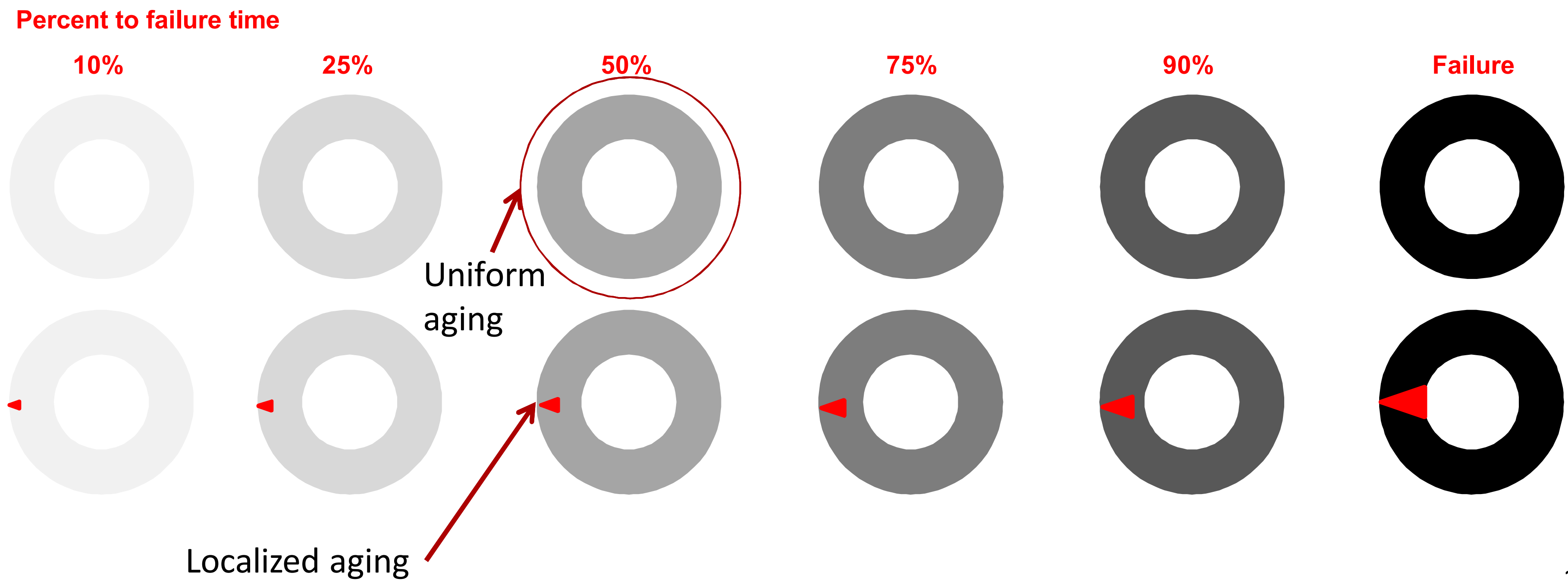
- Water:
  - Submerged or wet; solubility key issue?
  - Water line (triple point) issues
  - Clearly ‘older’ steam cured method and ‘cleanliness’ impacted performance
- Soluble Ions:
  - Ions clearly a major influence
  - Exact role not clear; but have a significant role
  - Always present
- Electrical Parameters:
  - *Electric Field*
  - Rate of change
  - Magnitude
  - Duration
  - Frequency

Stressors that can Impact Dielectric Aging

Number	Stressor	Source
1	Moisture	From humidity, ground water, or rain
2	Oxygen	From air, from water
3	Ions	Many sources
4	Triple points	Manufacturing defect, cable degradation, water interface
5	Electric field impulse	Lightning, line transients
6	Mechanical stress	Installation, manufacturing defect, degrading mechanical support
7	High electric field	Manufacturing defect, installation, cable degradation
8	Temperature	Enclosures, sources, loads
9	Oscillating electric field	Power system
10	High gradient electric field	Lightning, fault, switching equipment

Incremental Laboratory Aging Would Impact Material Science and Condition Monitoring

- Better understand the linearity of the aging process
- Better understand the impact of combined stressors on aging
- Provide materials for condition monitoring sensitivity analysis
- Provide a data base for the end of life definition
- Provide a data base for the remaining useful life analysis



Candidate Aging Test Matrix

Controls Single Variate Multi-Variate

	Stressor								
1	Moisture		X	X	X	X	X	X	X
2	Air (oxygen)	X	X	X	X	X	X	X	X
3	Elevated Temperature			X	X	X	X	X	X
4	Elevated Voltage (E-field)			X	X	X	X	X	X
5	Ions				X				
6	Mechanical stress (tight coil)					X			
7	High electric field (unshielded)						X		
8	Triple Points							X	
9	Electric field impulse (Lightning)								X

Examples of Aging Mechanisms Linked to Detectable Markers

Number	Category of Degradation	Marker	Test(s)
1	Thermo-oxidative aging jacket	Material hardening	Indenter test
	Thermo-oxidative aging dielectric	Low frequency dielectric loss	Dissipative methods
	Thermo-oxidative aging dielectric	Changes in capacitance	LIRA
	Thermo-oxidative aging dielectric	PD activity in response to voltage application	Partial Discharge
2	Mechanical Damage	Crack, break in dielectric	Resistance, TDR, PASD
3	Water tree growth	Low frequency Dielectric loss	Dissipative methods
		High frequency dielectric loss	DTDR, PASD
		Increased conduction currents	Resistance, VLF tan δ
4	Corrosion	Increased resistive loss (heat)	Infrared emission (IRT)

Additional Notable Areas for Consideration

- Rejuvenation Fluids:
  - Useful information; not fully realized
- Voids:
  - Voids known to be in insulation; high pressure aging postulated closing them
  - Void growth could be condition monitoring parameter
  - Not practical for field, but for laboratory?
- Defects:
  - Manufacturing processes
  - Installation
- Physical Stress:
  - Aging under ‘stress’ a potential degradation acceleration; path forward not clear
- ‘Pressure’ Aging:
  - High water pressure experiments performed, data suggest trying low pressure
  - Oxygen pressure?

Suggested Needs

- Accelerated Aging
  - Accelerated aging protocols useful for ‘lifetime’ predictions
  - ACLT and AWTT useful for comparison but not predictions, new method needed
- Mechanistic Understanding
  - Extensive studies, lack of fundamental understanding of degradation mechanisms
  - Mechanism(s) not understood; little insight into aging methodologies
  - Lack of understanding of parameters that ‘drive’ degradation
    - Magnitudes
    - Synergism
  - Mechanistic understanding needed to help acceleration (very complex)
  - Systematic and controlled environments over extended timeframes
- Definition
  - ‘End of life’ need ‘definition’ (see condition monitoring slides)
- Detection
  - Enhanced ability to detect and quantify (number, size) of water trees, voids, or defects
  - Rapidly, non-destructive and over large lengths of cable

Areas to Explore and Develop

- High volume, multi-variable testing apparatus
- Fundamental understanding of material aging mechanisms
- New accelerated aging method; working toward ‘predictions’
- Scanning techniques to determine insulation condition; need help

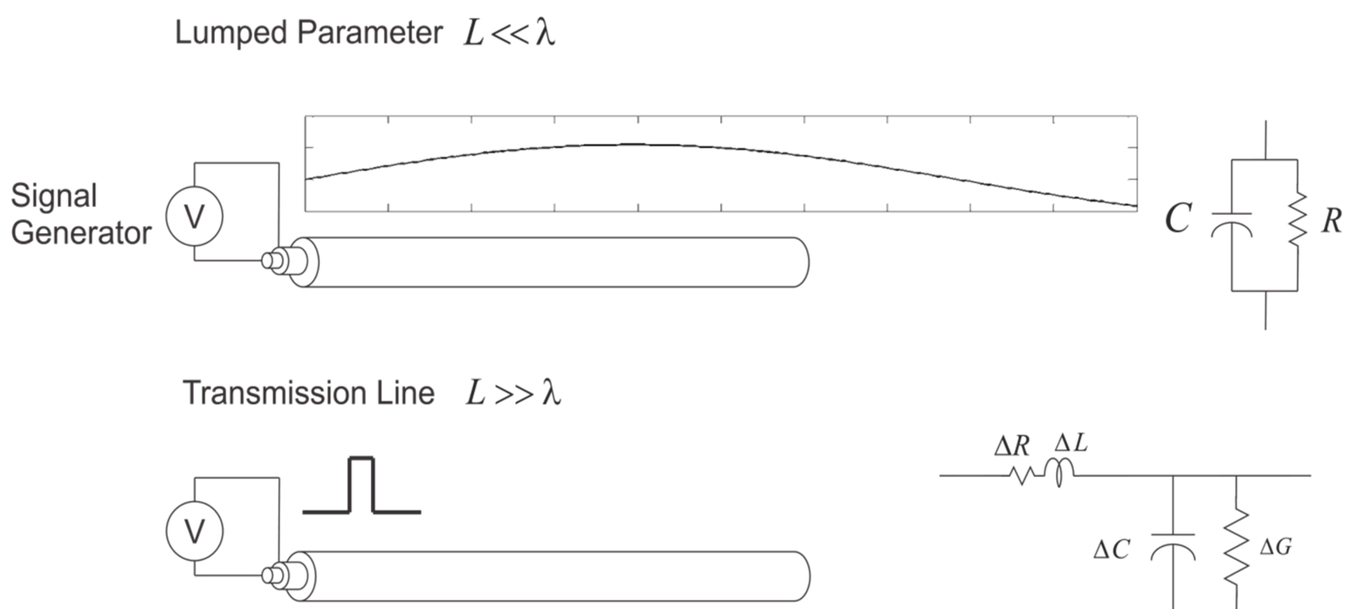
CONDITION MONITORING

Condition Monitoring

- Detect environmental conditions that accelerate aging
  - Excessive temperature
  - Water submergence or high humidity
- Detect changes in cable condition that correlate with trends in the degradation of dielectric strength over periods of time
  - Changes are in physical and/or electrical properties
  - Logistical Advantages/Disadvantages to each method
  - Properties are material dependent (EPR vs XLPE)
- Bulk vs. localized aging and degradation
- In this review, we provide
  - A summary of noteworthy condition monitoring advances
  - An approach to combining the results of multiple condition monitoring schemes to predict end-of-life (EOL)

Electrical Testing Basics

- Three basic principles dominate the success of electrical testing schemes
  - (1) **Sensitivity** of the electrical phenomenon to the condition indicator
  - (2) **Attenuation** of signals that result from interactions with degraded regions of cable
  - (3) **Bandwidth** of the electrical test; *bulk* versus *local* condition monitoring



Visual Inspection Methods

- Background
  - Regarded as the simplest and most common method of inspection [1]
  - Walkthrough procedures have been documented [2-3]
  - NESCC noted that "…universal procedures for walk downs of cable installations are needed to help pinpoint the locations of trouble."[4]
  - No academic literature was identified quantifying the efficacy of visual inspection methods
- Applicability to Submerged Cable
  - 'Unaided' inspection plausible in manways
  - Illuminated borescope allows visual access to submerged ducts

Reproduced from [1]

[1] Shumaker,B.D.; Campbell,C.J.; Sexton, C.D.;Morton, G.W.; "Cable Condition Monitoring for Nuclear Power Plants," *Future of Instrumentation International Workshop (FIIW),) 2012*, pp.1-4, Oct. 2012.

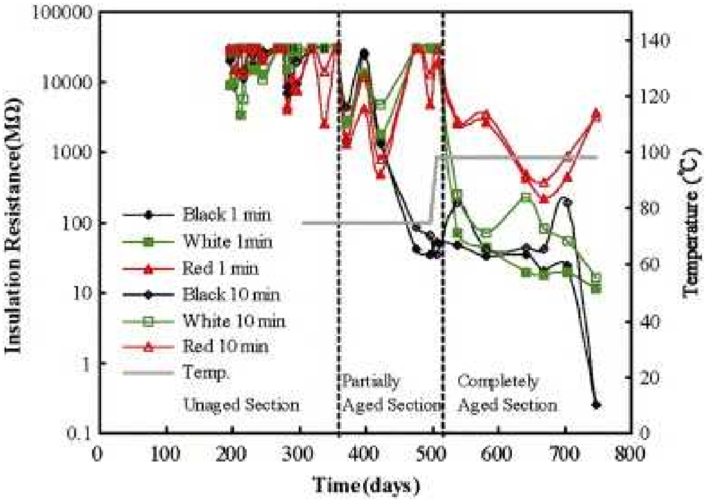
[2] **IAEA Nuclear Energy Series No. NP-T-3.6, "**Assessing and Managing Cable Ageing in Nuclear Power Plants," International Atomic Energy Agency, May 2012

[3] **1011223,** "Aging Identification and Assessment Checklist: Electrical Components,," EPRI, Palo Alto, CA and Altran Corporation, Boston, MA, 2005.

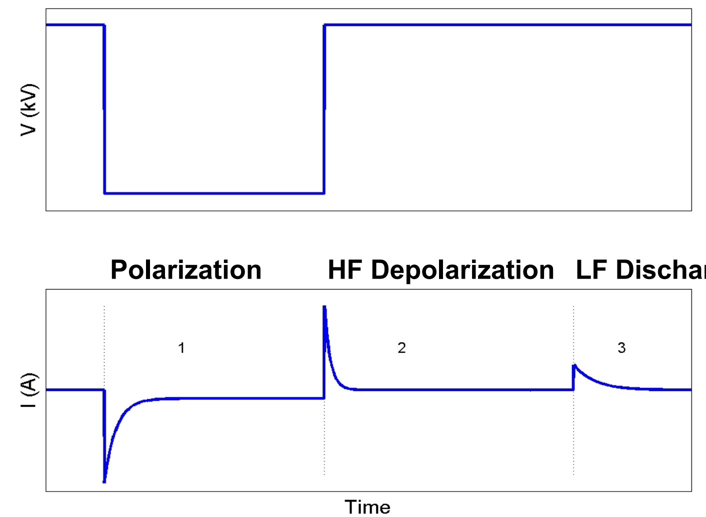
[4] **Nuclear Energy Standards Coordination Collaborative (NESCC),** "Electrical Cable Aging and Condition Monitoring Codes and Standards for Nuclear Power Plants: Current Status and Recommendations for Future Development," January 2014.

CM Methods for Bulk Aging Assessment

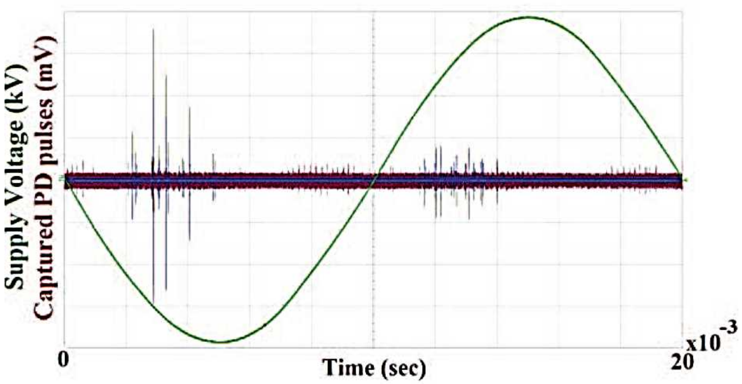
DC Insulation Resistance



Polarization/Depolarization Current



Partial Discharge

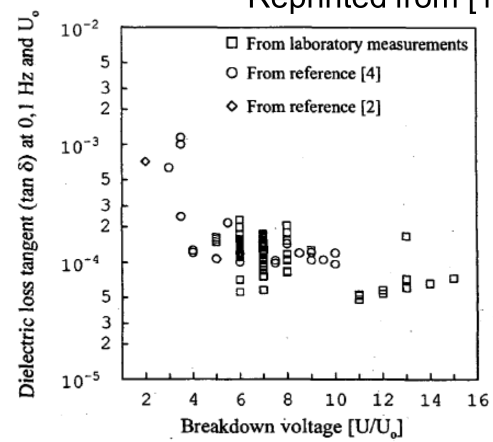


Dissipation Factor Tests

Reprinted from [1]

$$\varepsilon = \varepsilon' - j\varepsilon''$$

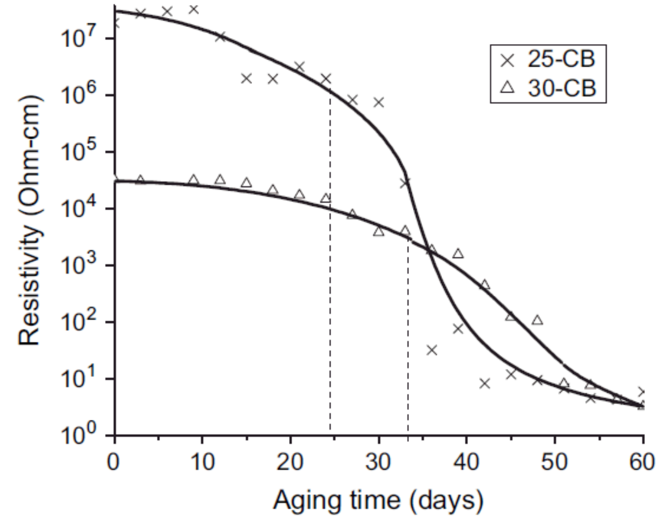
$$\tan\delta = \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'}$$

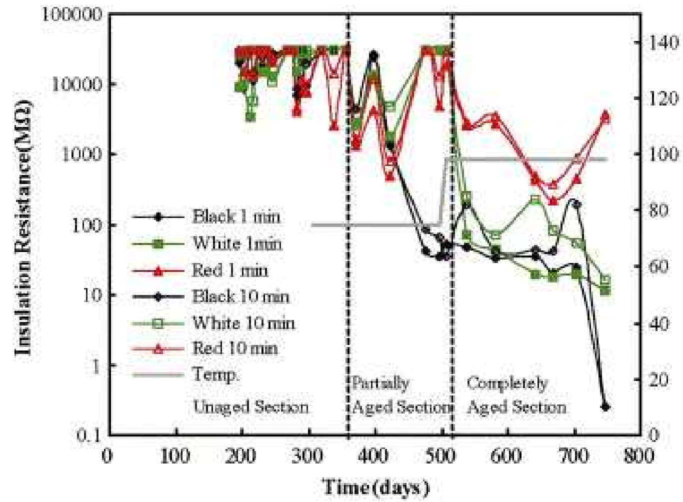


[1] Hvidsten, S.; Benjaminsen, J.T., "Diagnostic testing of MV XLPE cables with low density of water trees," *Electrical Insulation, 2002. Conference Record of the 2002 IEEE International Symposium on,* pp.108-111, 7-10 Apr 2002.

DC Insulation Resistance

- Background
  - Simplest in situ electrical test
  - Regarded as pass/fail; not trendable
- Recent Advances
  - Large gradual changes in electrical resistivity detected in thermally aged carbon black filled EPR [1]
  - Electrical resistivity found to be trendable in degradation of submerged lab aged cable [2]



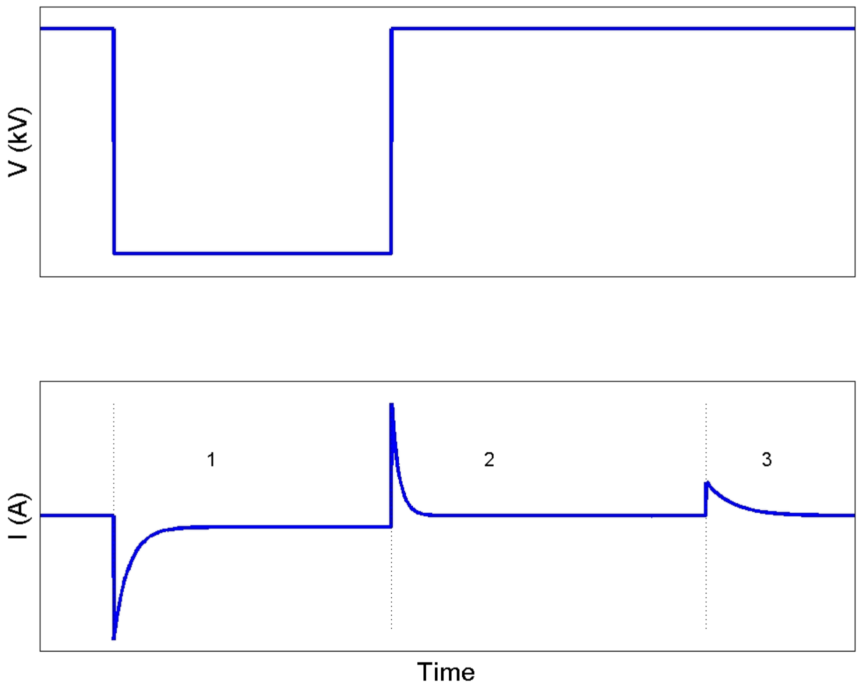


[1] Yangyang Sun, Shijian Luo, Ken Watkins, C.P. Wong, "Electrical approach to monitor the thermal oxidation aging of carbon black filled ethylene propylene rubber," *Polymer Degradation and Stability*, Volume 86, Issue 2, Pages 209-215, November 2004.

[2] Y.T. Hsu, K.S. Chang-Liao, T.K. Wang, C.T. Kuo; Monitoring the moisture-related degradation of ethylene propylene rubber cable by electrical and SEM methods, Polymer Degradation and Stability, Volume 91, Issue 10, October 2006, Pages 2357-2364, ISSN 0141-3910

Polarization/Depolarization Methods

- Cable is charged and discharged
- Changes in dielectric
- Popular everywhere… except the US



Partial Discharge (PD) Monitoring

- A PD is an electrical discharge that does not bridge the electrode gap
  - Pico-Coulomb scale, 10-100ns FWHM duration [1]
- PD monitoring is a technique that correlates PD activity with the phase of the voltage on the cable to monitor condition
  - Online techniques use the service voltage to stimulate PD activity
  - Offline techniques use externally applied voltages on the cable
- Commercialized systems using sensitive voltage monitors and frequency-domain methods can detect PD activity and severity at 500 feet or more
- PD monitors can be permanently installed in the system
  - Continuous monitoring
  - Emerging denoising techniques and automated pattern recognition

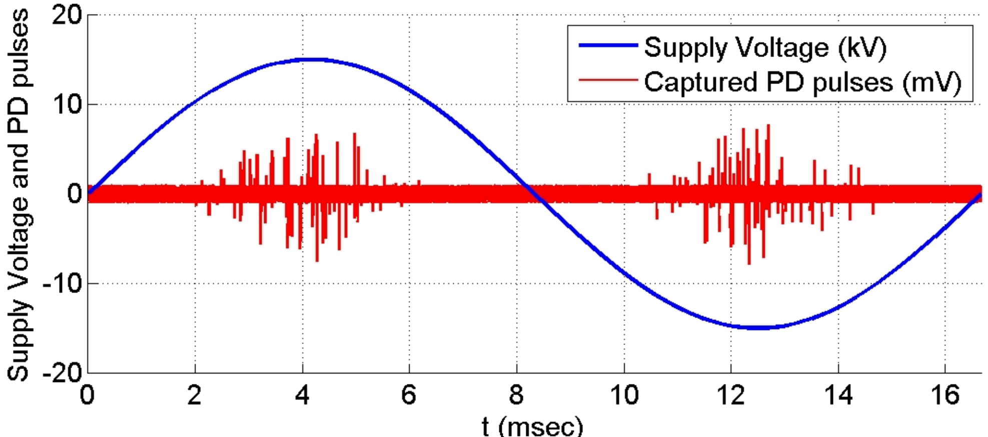


Illustration of PD transients correlated with voltage phase angle

[1] F.H. Kreuger, Partial Discharge Detection in High - Voltage Equipment", Butterworth & Co. (Publishers) Ltd, 1989.

Dissipative Methods Are Good at Finding Degradation of Submerged Cables

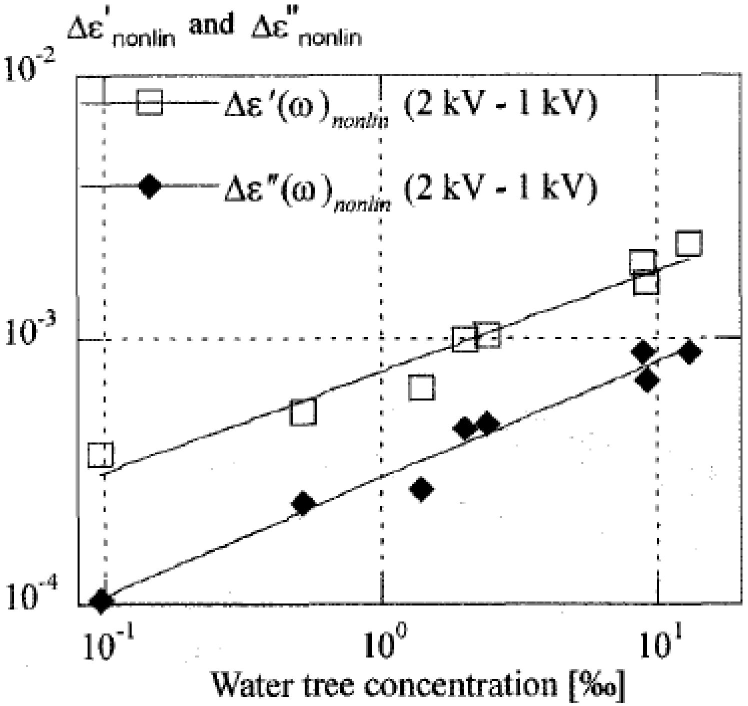
- Tests that measure dissipation factor of dielectrics
  - Changes in loss factor of the dielectric can be attributed to aging/degradation

$$\varepsilon = \varepsilon' - j\varepsilon''$$

$$\tan\delta = \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'}$$

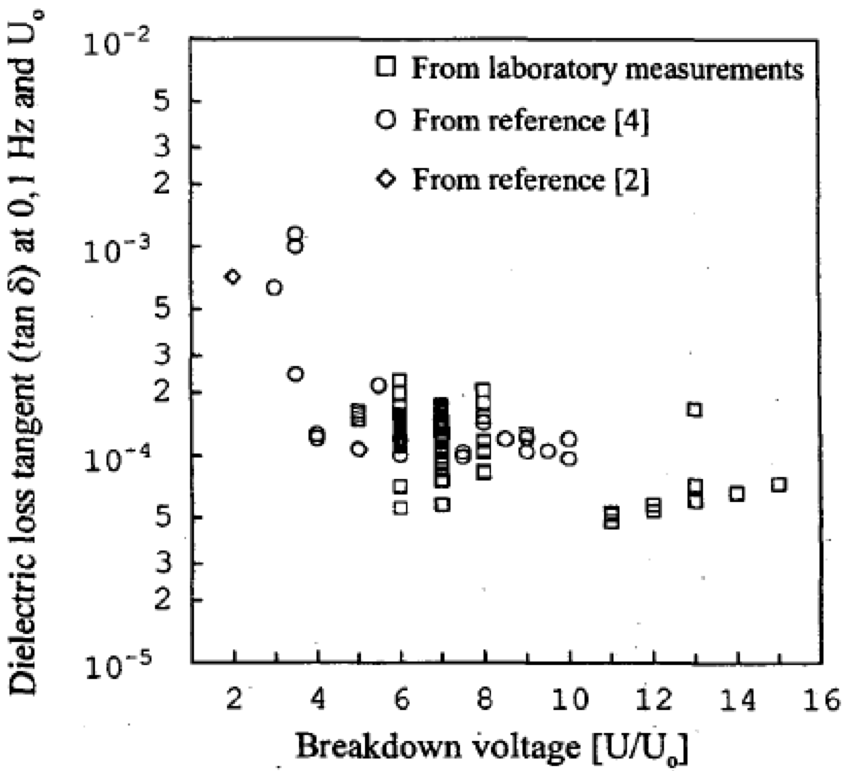
  - Low frequency Tan δ correlates with water tree degradation
- Family of testing methods include
  - "Tan δ" testing
  - Delta Tan δ testing
  - Dielectric Spectroscopy

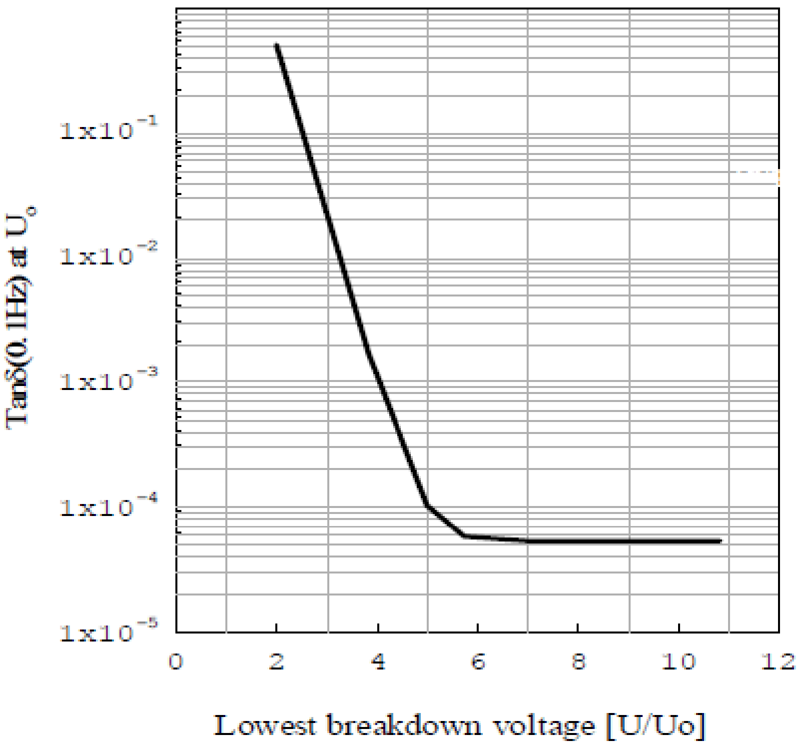
Reproduced from [1]



[1] Werelius, P.; Tharning, P.; Eriksson, R.; Homgren, B.; Gafvert, U., "Dielectric Spectroscopy for Diagnosis of Water Tree Deterioration in XLPE Cables," *IEEE Trans. on Dielectrics and Electrical insulation,* Vol. I, No. 1, pp. 27-42, Feb. 2007.

Tan δ Results Correlate with Minimum AC Breakdown Voltage

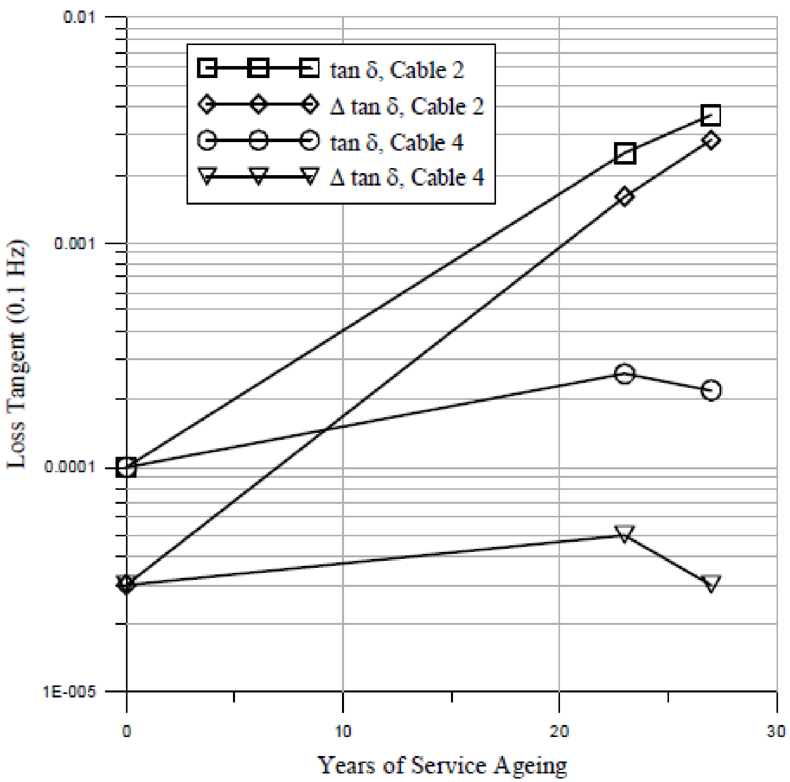




[left] Hvidsten, S.; Benjaminsen, J.T., "Diagnostic testing of MV XLPE cables with low density of water trees," *Electrical Insulation, 2002. Conference Record of the 2002 IEEE International Symposium on,* pp.108-111, 7-10 Apr 2002.
[right] Skjølberg, J.; Hvidsten, S.; Farmeo, H., "Experience from on-site condition assessment of XLPE MV cables," *Electrical Insulation, 2006. Conference Record of the 2006 IEEE International Symposium on,* pp. 432-435, 11-14 June 2006.

Dissipative Methods Are Trendable

- Applicability to Submerged Cable
  - Sequential measurement of Tan δ has been used to predict life



Werelius, P.; Tharning, P.; Eriksson, R.; Homgren, B.; Gafvert, U., “Dielectric Spectroscopy for Diagnosis of Water Tree Deterioration in XLPE Cables,” *IEEE Trans. on Dielectrics and Electrical insulation,* Vol. I, No. 1, pp. 27-42, Feb. 2007.

CM Methods for Local Degradation Detection

- Differential TDR
  - New method demonstrated with XLPE
  - Needs to be evaluated with EPR
- Pulse Arrested Spark Discharge (PASD) TDR
  - Commercial method used on aircraft LV wire (shielded and unshielded)
  - Needs to be evaluated on MV cable
- LIRA
  - Demonstrated for LV cables with thermal/mechanical damage, shielded and unshielded
  - Demonstrated for detecting water tree degradation in XLPE cable
  - Needs to be evaluated for EPR
- Flash Thermography
  - Commercial method for detecting water degradation of composites
  - May be used to quantify water ingress in MV cable jackets

Time Domain Reflectometry (TDR) Methods

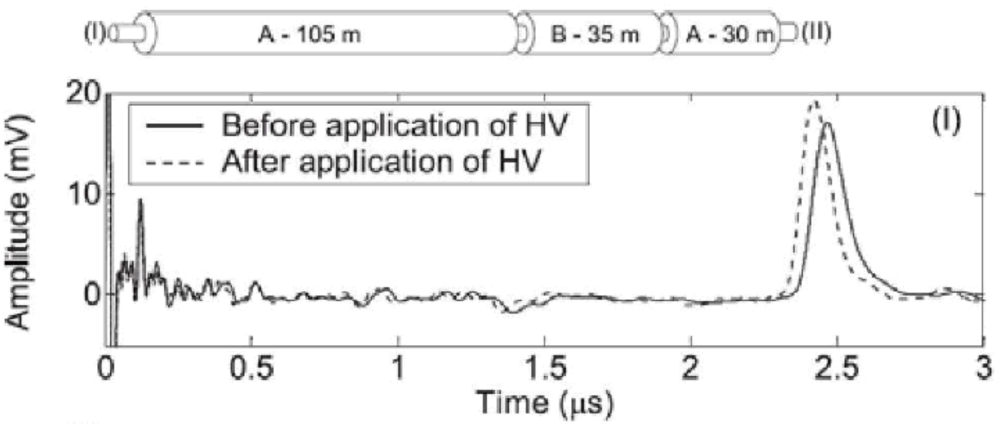
- Conventional TDR successful in detecting gross damage, localized damage in submerged environments
  - Severe mechanical damage
  - Thermal cracking
  - Submergence
- Can locate damaged sections to within a foot
- Not indicated for detecting water trees
  - "With a TDR alone, it is not possible to locate faults with resistance values greater than ten times the characteristic impedance [of the cable] …"[1]
  - Corrosion on the shield causes attenuation in the cable, limiting detection of reflected signal [2]

[1] **IEEE STD 1234-2007,** "IEEE Guide for Fault Locating Techniques on Shielded Power Cable Systems," *37,* pp.1, 2007.
[2] **3002000557, "**Plant Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants (Revision 1)," EPRI, Palo Alto, CA, June 2013.

Differential TDR Methods

- Recent research has established that high-frequency permittivity of water-tree degraded XLPE cable may be altered with application of high-voltage [1-2]
- A *Differential TDR* method has been developed that "… compare[s] the propagation properties for different applied voltages on the cable."
- Modeling and simulation efforts have begun to study water tree degraded cable

Reproduced from [2]



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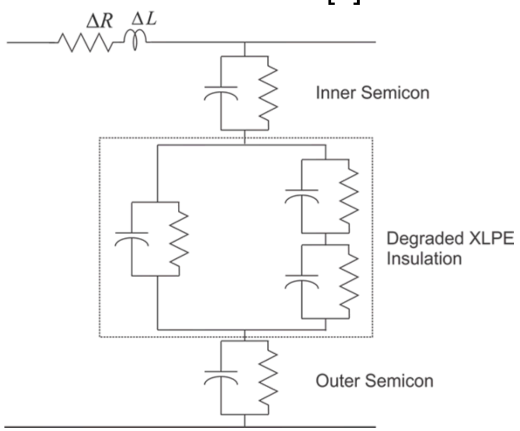

[1] Papazyan, R.; Eriksson, R.; "High Frequency Characterization of Water-treed XLPE Cables," *Proceedings of the 7th"; International Conference on Properties and Applications of Dielectric Materials,* Nagoya, June 2003.
[2] Eriksson, R.; Papazyan, R.; Mugala, G., "Localization of Insulation Degradation in Medium Voltage Distribution Cables," *Industrial and Information Systems, First International Conference on Industrial and Information Systems*, pp.167-172, Aug. 2006.
[3] Kuan, T.M.; Ariffin, A.M.; Sulaiman, S.; Md Thayoob, Y.H., "Wave propagation characteristics of polymeric underground cables," *Power Engineering and Optimization Conference (PEOCO), 2011 5th International,* pp.410-415, 6-7 June 2011.

Differential TDR Methods

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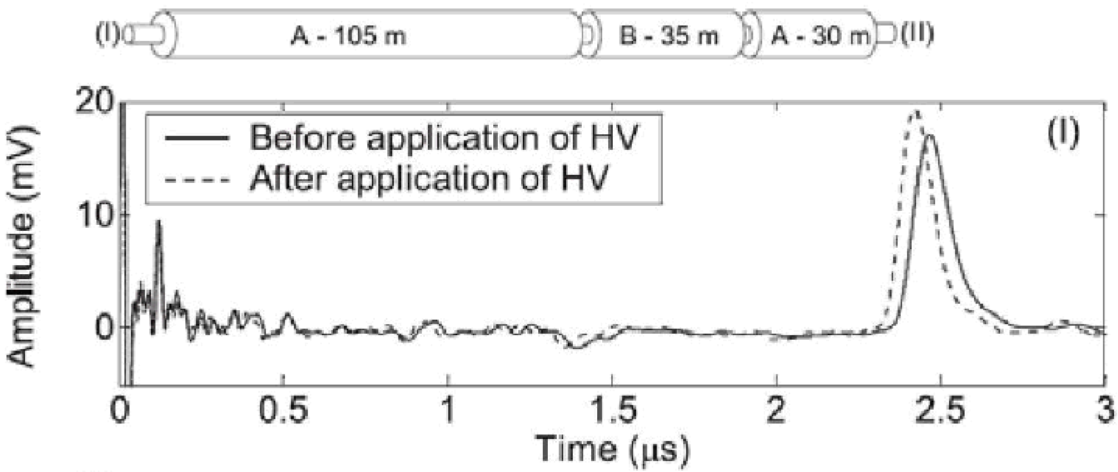
- A *Differential TDR* method has been developed that "… compare[s] the propagation properties for different applied voltages on the cable."
- Modeling and simulation efforts have begun to study water tree degraded cable
- High bandwidth and improved sensitivity

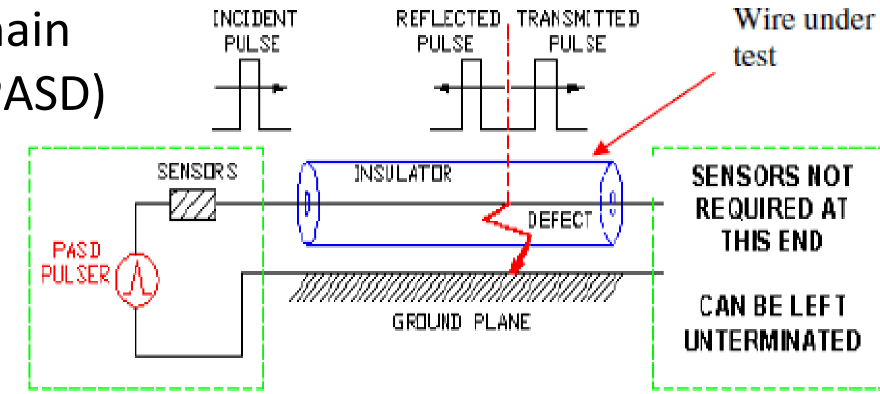
Reprinted from [2]



[1] Papazyan, R.; Eriksson, R.; "High Frequency Characterization of Water-treed XLPE Cables," *Proceedings of the 7th*"; *International Conference on Properties and Applications of Dielectric Materials,* Nagoya, June 2003.
[2] Eriksson, R.; Papazyan, R.; Mugala, G., "Localization of Insulation Degradation in Medium Voltage Distribution Cables," *Industrial and Information Systems, First International Conference on Industrial and Information Systems*, pp.167-172, Aug. 2006.

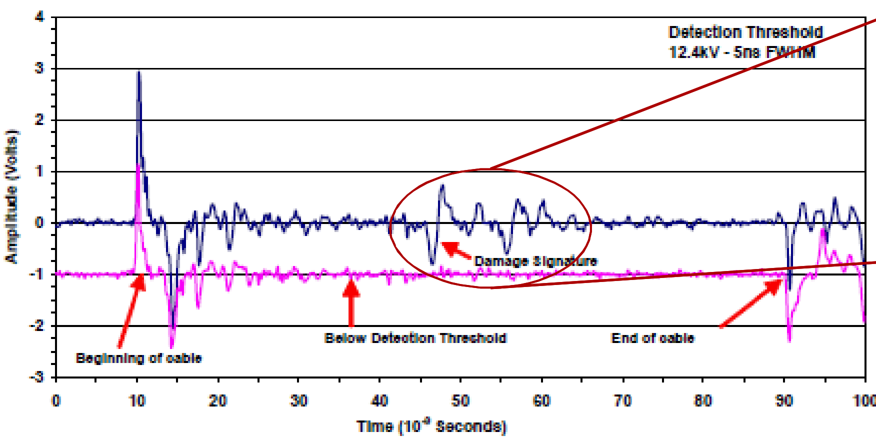
Pulse Arrested Spark Discharge TDR Method

- Recently developed high voltage time domain scheme: Pulse Arrested Spark Discharge (PASD)
  - Low voltage (100 V) then high voltage pulses (1-15 kV) are launched down cable
  - Electrical breakdown results in impedance discontinuity
  - High Bandwidth, Improved sensitivity, addresses attenuation issues
  - High power (kW), but low energy (mJ)



Reprinted from [1]

Mechanical damage



[1] **SANDIA REPORT SAND2005-2638,** "Final Report on Development of Pulse Arrested Spark Discharge (PASD) for Aging Aircraft Wiring Application," R. Kevin Howard, Steven F. Glover, Gary E. Pena, Matthew B. Higgins, Larry X. Schneider and Thomas R. Lockner, September 2006.

Frequency Domain Reflectometry

- Line resonance analysis (LIRA)
  - Furthest along
  - Background
    - 10 – 15 years mature
    - Aviation
  - Provides spatial information
- Low energy “chirp” or range of frequency (“white noise”)
- Used in concert with radar for localization
- Several reports on low voltage cabling
  - Limited studies on MV cables are promising, should be studied in greater detail

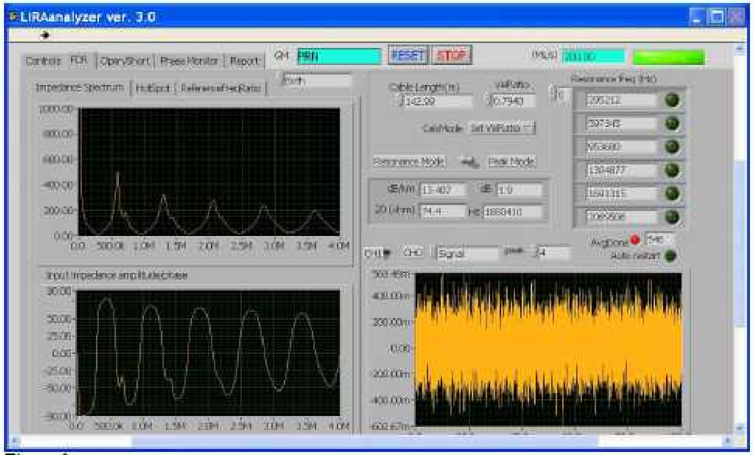
Line Resonance Analysis (LIRA)

Reprinted from [1]

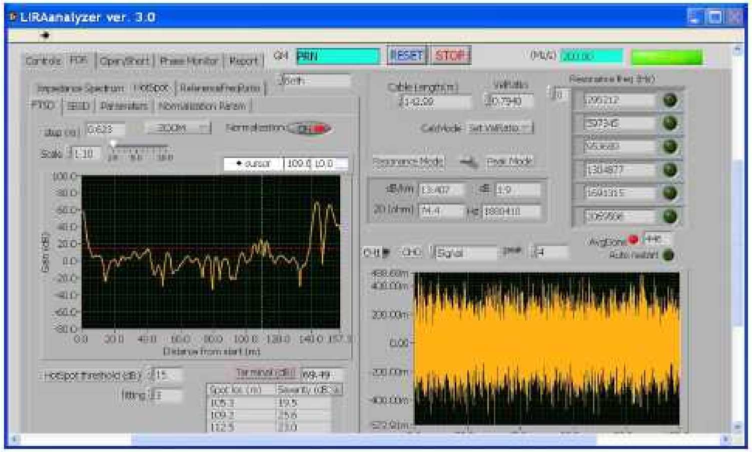
- Proprietary method that evaluates line impedance spectrum from noise measurements [1-2]
- Originally indicated/demonstrated for detecting gross mechanical damage, thermal and radiation degradation of low voltage cables [1-2]
- Demonstrated in laboratory and in situ
- Reported detection of water tree degradation in 5kV XLPE submerged cable [3]

$$|F(\omega)|$$

$$\angle F(\omega)$$



$$|f(d)|$$



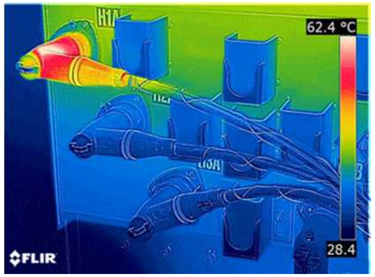
[1] **NKS-157,** "Wire System Aging Assessment and Condition Monitoring (WASCO)"; Paolo F. Fantoni, Nordic nuclear safety research, ISBN 978-87-7893-221-1; 2007.

[2] **1015209,** "Plant Support Engineering: Line Impedance Resonance Analysis for the Detection of Cable Damage and Degradation," EPRI, Palo Alto, CA, 2007.

[3] Fantoni,P.;Juvik,J.I.;"Condition Monitoring of Electrical Cables using Line Resonance Analysis (LIRA)"; Insulated Power Cales, 8th International Conference on; JiCable; Versailles, France; 2008.

Infrared Thermography

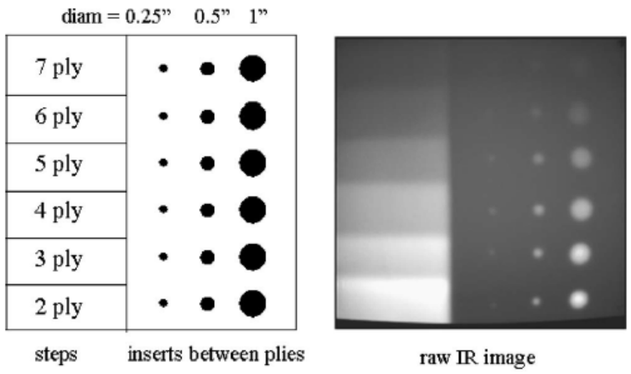
- Classical IR Thermography
  - Anomalous heating may indicate damage
  - Typically requires line-of-site or view port
  - Advanced image processing may resolve thermogram through walls
- Flash Infrared Thermography/Videography
  - Test surface is heated with a flash lamp
  - Asymmetrical cooling reveals subsurface defects



Thermal imaging being used to identify a potentially faulty connection. [Flir.com]

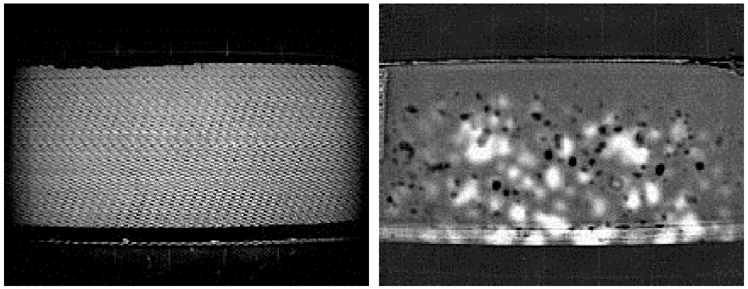
Thermal imaging of a cable fault inside a concrete structure [1]

Graphite epoxy sample [2]



Carbon epoxy composite

Thermal Image   Thermal Image after flash



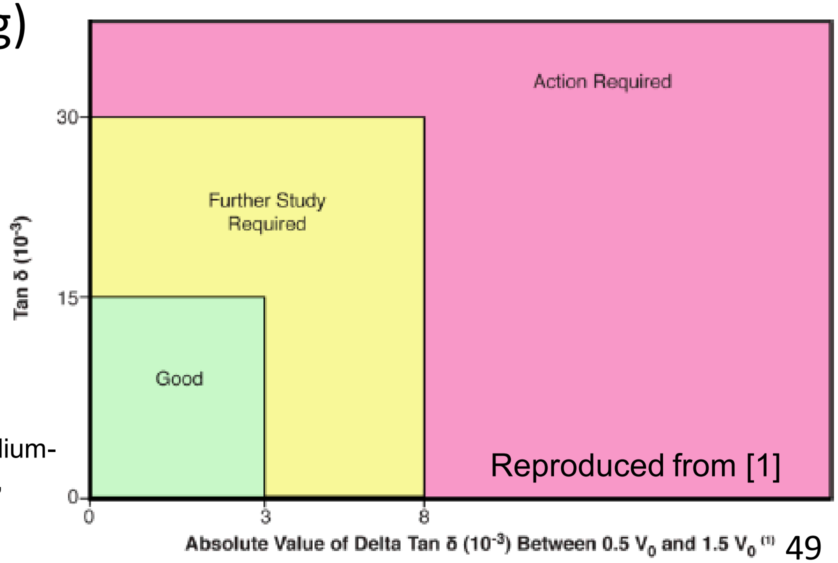
[Courtesy of Thermal Wave Imaging ThermaLogix.com]

[1] M. S. Jadin, S. Taib, S. Kabir;"Infrared Thermography for Assessing and Monitoring Electrical Components within Concrete Structures," *Progress in Electromagnetics Research Symposium (PIERS), Proceedings of the,* Marrakesh, Morocco, March 2011.
[2] S. Shepard, J. Hou, J. Lhota, J. Golden; "Automated Processing of Thermographic Derivatives for Quality Assurance," *Optical Engineering*, Vol 45, No 5, May 2007.

REMAINING USEFUL LIFE

Quantifying MV Cable Condition

- Majority of the literature indicates a two-tier: pass/fail or three-tier condition grading scheme: *good*, *medium*, *replace*
- Typically, criteria are based on measurement thresholds
  - PD pulses, Tan δ values, among others
- Currently no universally accepted *end-of-life* criteria has been defined; several have been cited
  - Breakdown voltage (inferred or verified with Withstand testing)
  - Water tree length (laboratory aging)
  - Insulation resistance
- No elegant way of combining multiple test results has been identified



Reproduced from [1]

[1] **3002000557,** "Plant Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants (Revision 1)," EPRI, Palo Alto, CA, June 2013.

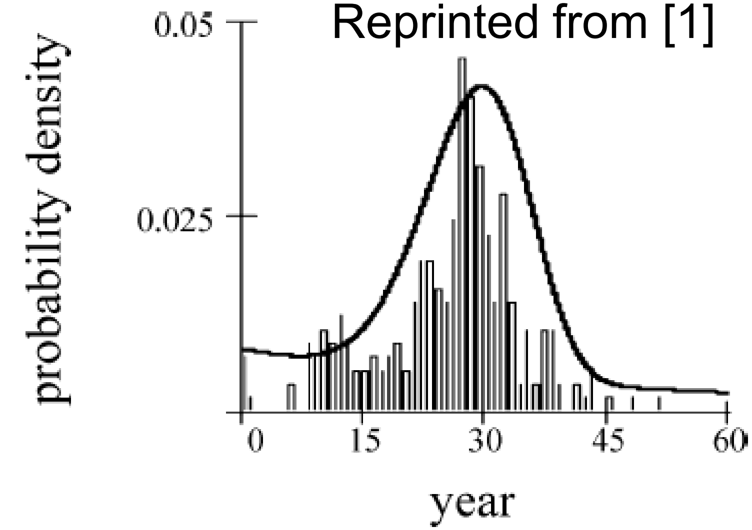
Condition Monitoring as an Assessment of *Reliability*

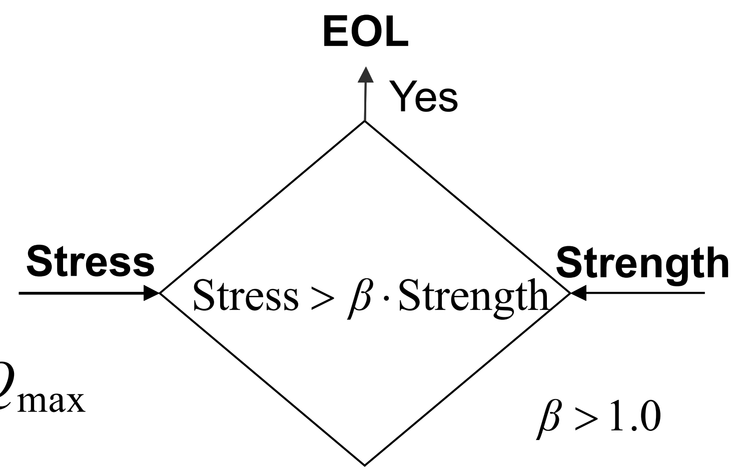
- What is the probability of failure?

$$P(\text{Failure} \mid \text{some time period}) < P_{\min}$$

- Failure vs *End-of-Life*
- *Remaining Useful Life* (RUL) defined as the time before the cable has reached *End-of-Life* (EOL)
  - Cable condition may be quantified by considering its likelihood to reach *End-of-Life* within a specified time [2]

Reprinted from [1]



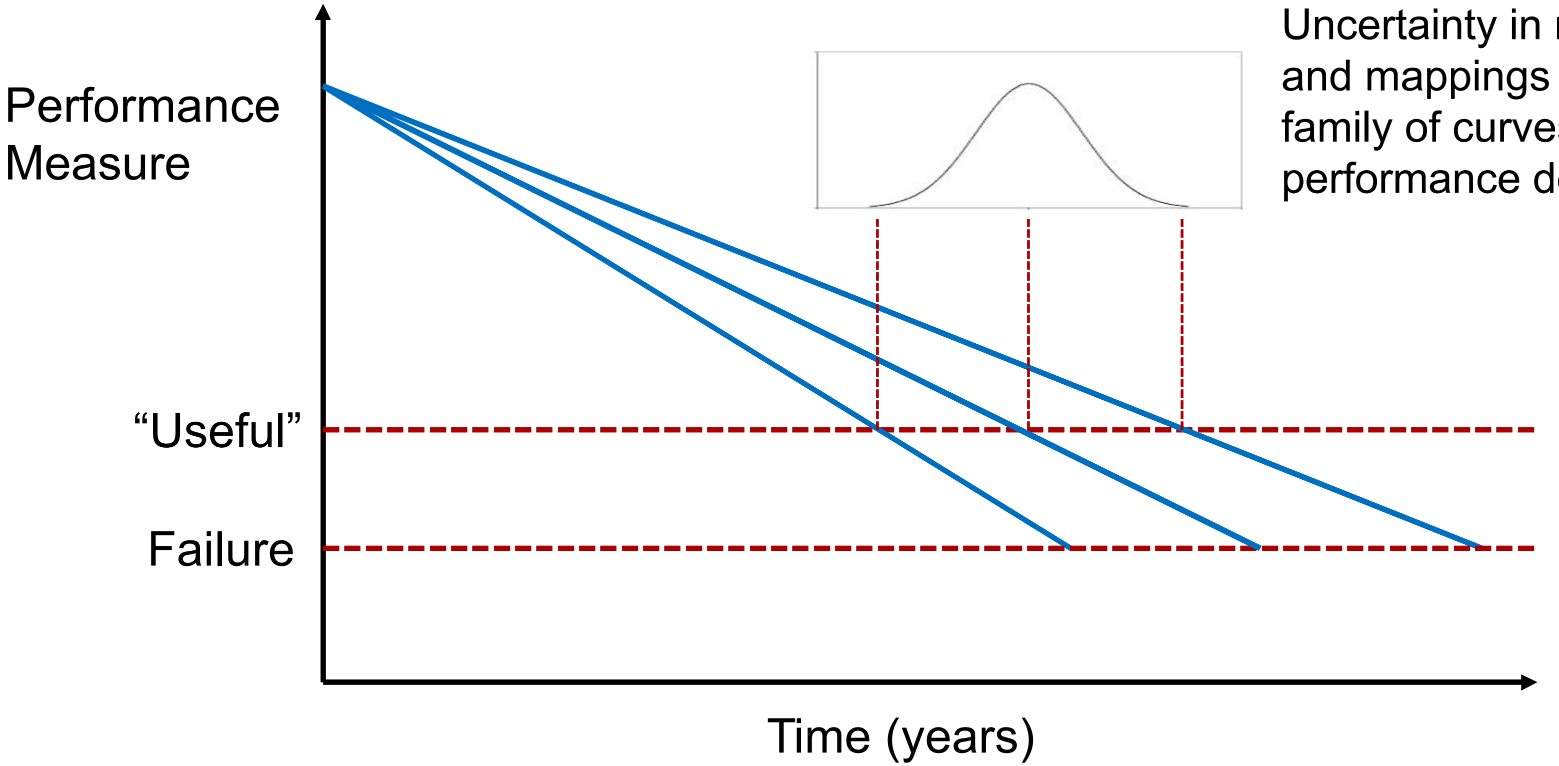


$$E(RUL(t_k)) \leq RUL_{\min} \quad \text{or} \quad P(RUL(t_k) < T_{\min}) > Q_{\max}$$

[1] Zhang, X.; Gockenbach, E., "Assessment of the actual condition of the electrical components in medium-voltage networks," *Reliability, IEEE Transactions on*, vol.55, no.2, pp.361-368, June 2006.
[2] K. Le Son, M. Fouladirad, and A. Barros. "Prognostic maintenance policy based on remaining useful life estimation," *ESREL (European Safety and Reliability Conference) PSAM11,* p.10, Helsinki, 25 June 2012.

Remaining Useful Life (RUL) Estimation

- By trending the results of condition monitoring methods while considering the error



Uncertainty in measurements and mappings implies a family of curves predicting performance degradation

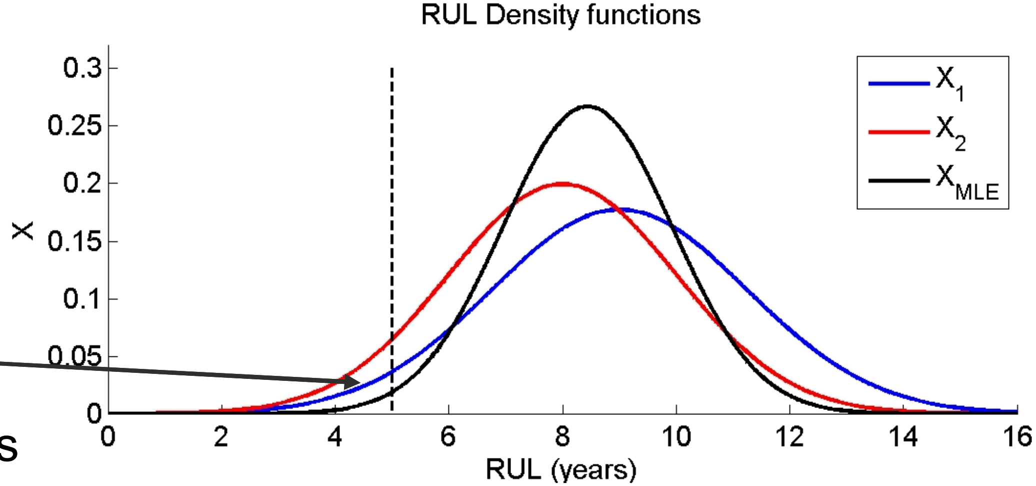
Remaining Useful Life (RUL) Estimation

- Field of *Reliability Engineering* deals with the prediction and prevention of system failures
- Maximum Likelihood Estimation (MLE) of remaining useful life gives a quantifiable measure of reliability
  - Combine Life Models and trendable tests to improve RUL estimate
  - Established test results need to be mapped to RUL estimates
  - Using Lifetime models, the effect of mitigation strategies may be assessed

$$X_{MLE} = \hat{\sigma}^2 \left(\frac{X_1}{\sigma_1^2} + \frac{X_2}{\sigma_2^2} \right)$$

$$P\left(RUL(t_k) < 5\text{yrs}\right) > Q_{\max}$$

Area under the curve for $T_{\min}$ = 5 years



In Summary

- Accelerated Aging
  - Accelerated aging protocols useful for ‘lifetime’ predictions
  - ACLT and AWTT useful for comparison but not predictions, new method needed
- Mechanistic Understanding
  - Extensive studies, lack of fundamental understanding of degradation mechanisms
  - Mechanism(s) not understood; little insight into aging methodologies
  - Lack of understanding of parameters that ‘drive’ degradation
    - Magnitudes
    - Synergism
  - Mechanistic understanding needed to help acceleration (very complex)
  - Systematic and controlled environments over extended timeframes
- Definition
  - ‘End of life’ needs definition
- Detection
  - Enhanced ability to detect and quantify (number, size) of water trees, voids, or defects
  - Rapidly, non-destructive and over large lengths of cable

Research Roadmap

	Phase II	Phase III	Phase IV	Phase V
Accelerated Aging	Test apparatus development Isotopic plaque testing Development of laboratory method to view water-based degradation in EPR	Continued plaque testing with additional stresses and “multi-stress” scenarios Develop a new vessel for wet pressurized cable aging	Accelerated aging protocol development for TELA	Continue TELA development and engage standards community to replace AWTT, ACLT
Cable Management Program		Community outreach activities for support of standard EOL and RUL definition development	Consensus building activities for development of standard EOL and RUL definitions	Remaining Useful Life Model Development
Condition Monitoring Tests	Testing of virgin and field and lab aged cable samples using bulk CM methods	Down select of CM methods for development of multi-test diagnostic method	Continued development of multi-test bulk CM diagnostic, inc TELA samples	Field testing of multi-test bulk CM diagnostic method(s)
	Investigate new methods of detecting local degradation on field-aged cables	Down select of CM methods for local degradation detection	Continued development of local degradation detection methods, inc TELA samples	Field testing of newly developed local degradation test method(s)