Progress in the Investigation of Nuclear Power Plant Cable Aging

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Nuclear Power Plants (NPPs)

- 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

*SAND 96-0344
Polymer Cable Materials

**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)

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Cables in US Plants
36% of cables are XLPE
36% of cables are EPR
5% of cables are SiR

Cables in Containment
90% of units have XLPE
70% of units have EPR
30% of units have SiR

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1NUREG/CR-7153, Vol.5 2013
2EPRI TR-103841, Rev.1 1994
Polymer Degradation (Aging)

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)
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?
Gamma Exposure Capabilities

PNNL
High Exposure Facility (HEF)
- Temperature control through mechanical convection ovens
- Dose rates from 1 to 100krad/h

ORNL
High Flux Isotope Reactor (HFIR) Spent Fuel Gamma Irradiation Facility (GIF)
- Dose rate variable with spent fuel life
- Can be between 3krad/h to 10Mrad/h
- Position of sample holder can allow for multiple dose rates and temperatures to be measured in single run
Polymer Aging Characterization and Testing Laboratory at PNNL

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 microscopic
- Photographic documentation booth
Inhomogeneous Aging Study
Understanding of Mechanisms

- Diffusion Limited Oxidation
- Nucleation of Degradation
- Effect of Sample Geometry
Microstructure Analysis
Imaging and Quantifying Degradation

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

XMT of EPR

Modulus, MPa

NUREG/CR-7153, Vol. 5

ATR FTIR

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

- Aging and NDE
  - Shielded and Un-shielded cables
- Sensitivity analysis of key indicators
- Correlation of destructive and non-destructive data
- Assessment of NDE methods
  - Line resonance analysis (LIRA)
Cable Program Summary

Cable Stressors

Chemical Changes

Changes in Properties

Correlation to Remaining Life

Aging and Degradation

Chemical changes in polymer

Rejuvenation

Mechanical, physical, and electrical property changes in polymer

Physical Properties

Mechanical Properties

Electrical Properties

NDE Technologies

Remaining Useful Life Predication

GAPS

Detailed Understanding

Effective Treatments

Key indicators of cable aging

Transformational NDE

Methods for Life Prediction

LWRS NDE R&D Roadmap PNNL-21731 2012
Questions?

L W R S
Light Water Reactor Sustainability

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