Outline

- Overview of NIST/Polymeric Materials Group
- Electrical Cables in Nuclear Power Plants
  - Background
  - Current Status
- Research Project
Engineering Laboratory Mission

To promote U.S. innovation and industrial competitiveness in areas of critical national priority by anticipating and meeting the:

- measurement science and
- standards

needs for technology-intensive manufacturing, construction, and cyber-physical systems in ways that enhance economic prosperity and improve the quality of life.
Polymeric Materials Group
Materials and Construction Research Div.

- Service life prediction of high performance polymers and composites
- Development of metrologies and methodologies for the characterization of high performance polymers and composites
“Current estimates of service life are crude and there is little or no correlation between laboratory and field exposure.”  Rilem State of the Art Report, 1999
Reliability-Based SLP Methodology

Outdoor Exposure

Laboratory Exposure

Databases
Predictive Models

Basis for the Coatings Service Life Prediction Consortium
Integrating Sphere-based UV Chamber

NIST SPHERE

- Simulated Photodegradation via High Energy Radiant Exposure
- 2 m integrating sphere
- 8400 W UV $\Rightarrow$ ~22 “SUNS”
- 95% exposure uniformity
- Visible and infrared radiation removed
- Temperature and relative humidity around specimens precisely controlled
- Capability for mechanical loading

- Martin and Chin, U.S. Patent 6626053
Reliability-Based SLP Methodology

Outdoor Exposure Chambers

Coatings Service Life Prediction

Lab: 25°C, 100% ND (16)
35°C, 4RH, 4WL, 100% (64)
45°C, 2RH, 4WL, 100% (32)
55°C/75%RH, 60% ND (16)

Outdoor: G4-17 (56)

* Linkage of outdoor and laboratory data sets
Cables in NPPs

- Categories
  - Medium voltage power (2.4 kV to 34 kV)
  - Low voltage power (<1 kV)
  - Control
  - Instrument
  - Panel and hook-up wire
  - Specialty
  - Security
  - Telephone
  - Lighting
  - Grounding

Distribution of circuit cables:

20% instrument; 61% control; 13% AC power; 1% DC power; 5% communication

Medium voltage cable includes metallic shield (helically wound tapes, distributed drain wires, longitudinally corrugated copper, concentric neutral wires)
# Cables in NPPs

## Table 2.2. Main Usage of Polymeric Cable Materials in NPPs

<table>
<thead>
<tr>
<th>Material</th>
<th>Insulation</th>
<th>Jacket</th>
<th>Extent of use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-linked polyethylene/polyolefin (XLPE/XLPO)</td>
<td>✓</td>
<td></td>
<td>wide</td>
</tr>
<tr>
<td>Low and high molecular weight polyethylene (LMWPE, HMWPE)</td>
<td>✓</td>
<td></td>
<td>some</td>
</tr>
<tr>
<td>Ethylene propylene based elastomers (EPR, EPDM)</td>
<td>✓</td>
<td></td>
<td>wide</td>
</tr>
<tr>
<td>Chlorosulphonated polyethylene (CSPE), also known as Hypalon®</td>
<td></td>
<td>✓</td>
<td>wide</td>
</tr>
<tr>
<td>Ethylene vinyl acetate (EVA)</td>
<td>✓</td>
<td>✓</td>
<td>some</td>
</tr>
<tr>
<td>Polyvinyl chloride (PVC)</td>
<td>✓</td>
<td>✓</td>
<td>wide</td>
</tr>
<tr>
<td>Silicone rubber (SiR)</td>
<td>✓</td>
<td>✓</td>
<td>some</td>
</tr>
<tr>
<td>Polyether ether ketone (PEEK)</td>
<td>✓</td>
<td></td>
<td>limited</td>
</tr>
<tr>
<td>Ethylene tetrafluoroethylene (ETFE), also known as Tefzel®</td>
<td>✓</td>
<td></td>
<td>limited</td>
</tr>
<tr>
<td>Polyphenylene oxide (PPO), also known as Noryl®</td>
<td>✓</td>
<td></td>
<td>limited</td>
</tr>
<tr>
<td>Butyl rubber (BR)</td>
<td>✓</td>
<td>✓</td>
<td>limited</td>
</tr>
<tr>
<td>Polyimide, also known as Kapton®</td>
<td>✓</td>
<td>✓</td>
<td>limited</td>
</tr>
<tr>
<td>Polychloroprene, also known as Neoprene®</td>
<td>✓</td>
<td></td>
<td>limited</td>
</tr>
<tr>
<td>Polyethylene terephthalate (PETP), also known as Mylar® (used as a tape wrap)</td>
<td>✓</td>
<td></td>
<td>limited</td>
</tr>
</tbody>
</table>

Additives: anti-oxidants, flame retardants, fillers, plasticizers

Newer halogen free materials

*from IAEA*
WHAT IS THE PROBLEM? WHY IS IT HARD TO SOLVE?

• Safety and performance concerns about electric cables (low and medium voltage) in aging nuclear power plants

• Many cables are inaccessible or are a part of underground cable circuits

• Large number of cables at plants, need to identify those cables at greatest risk based on cable function and its environment (temperature, moisture, radiation, voltage)

• Lack of minimally invasive testing methods for medium voltage cables

• Unknown aging effects of newly developed insulation materials-zero halogen

• Selected codes and standards currently used for new nuclear energy facilities are outdated
  – 4 to 11 years since revisions; many rescinded.

• Lacking standards:
  – acceptance criteria for non-destructive tests
  – tests of unshielded cables
• Agencies and industry formed working groups and are conducting research

• US NRC and DOE
  – Sandia National and Argonne National Laboratories
    • Cable degradation mechanisms
  – Electric Power Research Institute (EPRI)
    • Cable aging management—guidance documents for low and medium voltage cables in 2010
  – Brookhaven National Laboratory
    • Nuclear Energy and Infrastructure Systems Division
    • Plant Aging and License Renewal

• Insulated Cable Engineers Association (ICEA), National Electrical Manufacturers Association (NEMA), Underwriters Laboratories, Inc. (UL)—main SDOs for cables in general (not necessarily NPPs)

• IEEE and Nuclear Power Engineering Committee (NPEC) Aging—"general “ (liaison between ANSI, ASME, ANS, ASTM and ISA)
  – ANS, IEC, ASME, ISA, HFES, EPRI, INPO, NEI, NIRMA, DOE, and US NRC
  – IEEE subcommittee-3 Working Group 3.4, resulting in IEEE Std 1205-2000 (Guide for assessing, monitoring, and mitigating aging effects on Class 1E equipment used in nuclear generating stations)
    • Update process to current industry practices to show relationships between process steps and update corresponding guidance discussions; new guidance and limitations for Arrhenius and radiation dose age modeling for remaining equip. life; condition monitoring approaches; update example assessments and attributes of an effective aging management program.

• Organization for Economic Cooperation and Development- Nuclear Energy Agency (OECD-NEA)
  – Stress Corrosion Cracking and Cable Aging Project (SCAP)- Japan funds

**Members**: Belgium, Canada, Czech Republic, Finland, France, Germany, Japan, Mexico, Norway, Korea, Spain, Sweden, Switzerland, Slovak Republic, US, Ukraine; **Observers**: International Atomic Energy Agency (IAEA) and European Commission (EU)

• International Atomic Energy Agency (IAEA)
  – Nuclear Power Engineering
    • Instrumentation and Control Technologies

• Nuclear Energy Institute (NEI)—policy organization for nuclear technologies industries
HOW IS IT SOLVED TODAY?

- **Aging factors**
  - Polymer system
  - Pre-service and service environment
  - Time scale

- **Conditions of concern**
  - Temperature
  - Radiation
  - Oxygen
  - Water vapor in containment - low RH; wet-well cables up to 80% RH; ground apps-submergence;
  - Mechanical influences: vibration, connect/disconnect, installation bends

- **Aging Changes**
  - Tensile strength decrease
  - Hardness increase
  - Density increase
  - Electrical property changes - small dielectric loss increase

- **Determination of Service Life**
  - Checked cables in-service
  - Accelerated exposure (Arrhenius model)
  - Thermal aging: 50°C to 160°C (depends on cable rating and material)
  - Radiation: Sandia’s low intensity cobalt array (LICA) (10 rad/h versus 50 rad/h)
  - Moisture: inside containment, RH not a factor; wet well cables exposed to up to 80% RH; during service RH exposure possible

- **Condition Monitoring Testing Methods**
  - Visual inspection
  - Mechanical: elongation at break, tensile strength, compressive modulus
  - Electrical: insulation resistance, dielectric strength, dielectric loss, LIRA (Line Resonance Analysis) [new (2005) transmission line theory; hot spot detection], tan δ testing, very low frequency (VLF) withstand testing
  - Physical/chemical: FTIR, OITT (oxidation time/temperature), swelling ratio, gel fraction, mass loss, acoustic velocity assessment, visco-elasticity, NMR, density, partial discharge
WHAT ARE THE GAPS IN THE RESEARCH?

- Determination of aging mechanisms for:
  - Low voltage cables under wet conditions
  - High voltage cables under temperature, radiation, and wet conditions
  - Newly developed insulation materials
- Determination of extended SL of currently aged cables
- Determination of the effectiveness of cable splicing and aging processes
- Standardization of procedures for condition monitoring test methods
  - Calibration of equipment and optimization of test parameters
  - Optimization of acceptance criteria
- Develop standard sampling techniques for microsampling methods
  - Acceptable to operators and regulators
- Develop training materials for NPP operators
Research with US NRC

• **Assessment of Electrical Cable Condition Monitoring Tests**
  
  – **Objective:** Selected condition monitoring tests (CMTs) evaluate a set of commercial electrical cables, each exposed to static, well-controlled exposure conditions. Each cable will be:
    
    • characterized to establish baseline values for cable properties using the set of predetermined CMTs
    
    • subjected to a series of static, well-controlled temperature, relative humidity/water immersion and operational aging radiation exposure environments
    
    • periodically removed from each exposure environment and evaluated using the predetermined CMTs
    
    • analyzed to assess temporal changes in cable performance and CMT results
    
    • related to cable electrical performance to establish acceptance criteria for each CMT
Research with US NRC

CONDITION-BASED QUALIFICATION

- Baseline Condition Monitoring ($CM_0$)
- Mild Environment Performance
- QLD value, chosen to manage qualification
- CM after operational aging to identify QLD ($CM_{Post-Aging}$)
- CM to verify post DBE performance ($CM_{Post-QBE}$)
- CM to verify performance after post-accident period
Task 1: Establish baseline values for a number of cable properties using a suite of predetermined condition monitoring tests

- **Cable Materials**
  - crosslinked polyethylene (XLPE)
  - ethylene propylene rubber (EPR)
  - silicone rubber (SR)
  - chlorosulphonated polyethylene (CSPE/Hypalon)

- **Cable Specifications**
- Instrumentation, Control, and Power
  - **Power**: 6 to 8 AWG; 500 V, 1000 V, 5 kV
    - ohmic heating
  - **Control**: 500 V
- **General**:
  - Shielded: 3 conductor or 3 conductor + ground; twist shielded pair (1000V)
  - One single conductor cable (12 AWG)
  - ‘in-service’ cables from Zion NPP in IL

- **CMTs**
- **Mechanical Methods**
  - Elongation at Break
  - Compressive Modulus

- **Electrical Methods**
  - Time Domain Reflectrometry
  - Line Resonance Analysis
  - Partial Discharge

- **Phys.-Chem. Methods**
  - Fourier Transform Infrared Spectroscopy (FTIR)
  - Oxidation Time/Temperature
  - Mass Loss
Research - Specifics

Task 2: Conduct temperature, relative humidity/water immersion, and radiation exposure environments

- Water submergence experiments at ambient temperature (27°C).
- Radiation exposure: total radiation dose for operational aging = 50 MRad (500 kGy) with a dose rate of <100 Gy/h
  - temperature and RH will be controlled simultaneously
    - University of Maryland College Park (Al-Sheikhly Co-60 source)
- Energized cable experiments will also be explored
- Accident conditions of radiation (LOCA) will be examined in a later phase
Research - Specifics

- **Tasks 3 and 4:** Monitor changes in cable properties versus exposure time; quantitatively characterize cable degradation mechanism(s)
- At predetermined exposure times, cable specimens characterized using CMTs
  - Many CMTs are materials characterization methods currently used in our laboratory
    - elongation at break - dynamic mechanical analysis (DMA)
    - compressive modulus - nanoindentation
    - mass loss - thermal gravimetric analysis (TGA)
    - chemical composition - infrared spectroscopy
  - Additionally, exposed specimens quantitatively characterized using a variety of analytical instruments including, but not limited to:
    - differential scanning calorimetry (DSC) - glass transition temperature ($T_g$)
    - moisture content analysis
    - morphological changes
      - scanning electron microscopy (SEM)
      - laser confocal microscopy
      - atomic force microscopy (AFM)
• **Task 5: Relate condition monitoring test results to cable electrical performance and establish acceptance criteria for condition monitoring tests**
  
  – CMT results correlated against well-established cable failure performance data
  
  – Cable failure determined from electrical output tests which measure performance capability
    • voltage
    • capacitance
    • impedance measurements
  
  – CMT data collected from EPRI, IAEA, and NRC used to improve the statistics of this evaluation, keeping in mind that the data collected from these organizations may not have used the same experimental parameters as what was used in the proposed study.
Research

ANSI / NIST
Nuclear Energy Standards Coordination Collaborative

• **Task Group:** *Electrical Cable Aging and Condition Monitoring Codes and Standards for Nuclear Power Plants*

• Establish coordination and consistency of safety and non-safety related electrical cable requirements in nuclear power plants.

• Identify new design requirements for electrical cables, particularly for those involving new polymeric components, and develop a plan to incorporate these new requirements into codes and standards.

• Identify and review all U.S. Nuclear Regulatory Commission (NRC) Regulatory documents related to electrical cables for nuclear power plants.

• Identify and review all non-NRC standards documents, such as Institute of Electrical and Electronics Engineers (IEEE), Institute of Electrochemical Commission (IEC), National Electrical Manufacturers Association (NEMA), Insulated Cable Engineers Association (ICEA), and Underwriters Laboratory (UL), related to electrical cables.