Service Life of Electrical Cable and Condition Monitoring Methods

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Outline

- Background
  - Electrical Cables in Nuclear Power Plants
  - Condition Monitoring and Assessment Research
- Standards Engagement
- Cable Condition Monitoring Project Plan
- Summary

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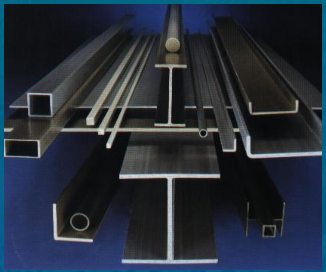


- Service life prediction of high performance polymers and composites

- Development of metrologies and methodologies for the characterization of high performance polymers and composites

WHAT IS THE PROBLEM?

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

- Cables in NPPS are very important safety components - provide power to safety-related equipment, used for instrumentation and control of safety functions.
- A variety of environmental stressors exist in NPPs – **radiation, temperature, moisture, chemical spray, mechanical stress** – all of which can cause degradation that may go undetected.
- Electrical cables often overlooked in aging analyses and condition monitoring evaluations - passive components, not considered to require inspection and maintenance.

Cables in Nuclear Power Plants

- 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

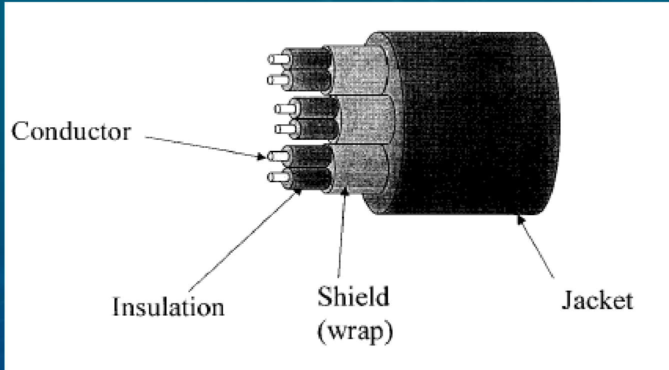


FIG. 2.1. Structure of a twisted pair shielded instrumentation cable (schematic).

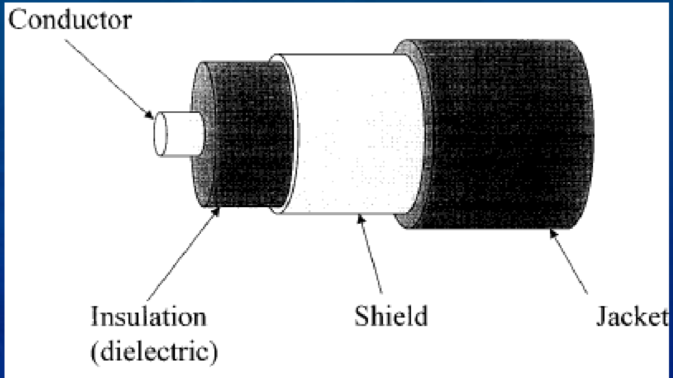


FIG. 2.2. Structure of a co-axial instrumentation cable (schematic).

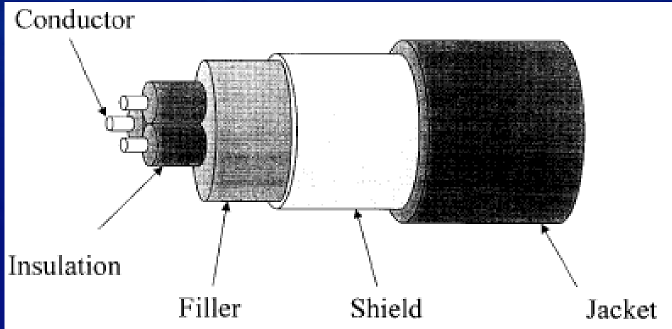


FIG. 2.3. Structure of a multiconductor shielded control cable (schematic).

Cables in NPPs

TABLE 2.2. MAIN USAGE OF POLYMERIC CABLE MATERIALS IN NPPs

Material	Insulation	Jacket	Extent of use
cross-linked polyethylene/polyolefin (XLPE/XLPO)	✓		wide
low and high molecular weight polyethylene (LMWPE, HMWPE)	✓		some
ethylene propylene based elastomers (EPR, EPDM)	✓		wide
chlorosulphonated polyethylene (CSPE), also known as Hypalon®		✓	wide
ethylene vinyl acetate (EVA)	✓	✓	some
polyvinyl chloride (PVC)	✓	✓	wide
silicone rubber (SiR)	✓	✓	some
polyether ether ketone (PEEK)	✓		limited
ethylene tetrafluoroethylene (ETFE), also known as Tefzel®	✓		limited
polyphenylene oxide (PPO), also known as Noryl®	✓		limited
butyl rubber (BR)	✓	✓	limited
polyimide, also known as Kapton®	✓	✓	limited
polychloroprene, also known as Neoprene®		✓	limited
polyethylene terephthalate (PETP), also known as Mylar® (used as a tape wrap)			limited

- Many contain additives, which may vary from one version of the product to another:
  - anti-oxidants
  - flame retardants
  - fillers
  - plasticizers
- Some newer cable materials are halogen free

from IAEA

HOW IS IT ADDRESSED TODAY? BY WHOM?

Sandia National Laboratories

BROOKHAVEN NATIONAL LABORATORY

Argonne NATIONAL LABORATORY

ICEA

EPRI ELECTRIC POWER RESEARCH INSTITUTE

NEMA Setting Standards for Excellence

UL

IEEE Advancing Technology for Humanity

NEA Nuclear Energy Agency

IAEA.org International Atomic Energy Agency

NEI NUCLEAR ENERGY INSTITUTE

HOW IS IT ADDRESSED TODAY?

- Aging Factors and Conditions
  - Pre-service and service environment
  - Temperature
  - Water (liquid and vapor)
  - Radiation
  - Oxygen
  - Mechanical stresses

- Property Changes due to Aging
  - Tensile strength decrease
  - Hardness increase
  - Density increase
  - Electrical property changes-small dielectric loss increase

- Determination of Service Life
  - In-service inspection of connected eqpt
  - Accelerated exposure, thermal aging
  - Radiation
  - Moisture

- Condition Monitoring Test Methods
  - Visual inspection
  - Mechanical: elongation at break, tensile strength, compressive modulus
  - Electrical: insulation resistance, dielectric strength, dielectric loss, line resonance analysis, tan δ, partial discharge
  - Physical/chemical: FTIR, OIT (oxidation time/temperature), swelling ratio, gel fraction, mass loss, acoustic velocity assessment, visco-elasticity, NMR, density, time domain reflectometry

ANSI / NIST Nuclear Energy Standards Coordination Collaborative

- **Task Group Formed in 2011:**

  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 new polymeric components, and develop a plan to incorporate these new requirements into codes and standards.

- **Identify and review** all NRC regulatory documents related to electrical cables for nuclear power plants.

- **Identify and review** all non-NRC standards documents – IEEE, IEC, NEMA, ICEA, UL - related to electrical cables.

Standards Reviewed

Cable Assemblies

Std Number	Standard Title
IEEE 317	IEEE Standard for Electric Penetration Assemblies in Containment Structures for Nuclear Power Generating Stations
IEEE 323	IEEE Standard for Qualifying Class 1E Equipment of Nuclear Power Generating Stations
IEEE 344-1975	RECOMMENDED PRACTICE FOR SEISMIC QUALIFICATION OF CLASS 1E EQUIPMENT FOR NUCLEAR POWER GENERATING STATIONS
IEEE 383	IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations
IEEE 572	IEEE Standard for Qualification of Class 1E Connection Assemblies for Nuclear Power Generating Stations
IEEE 627-2010	IEEE Standard for Qualification of Equipment used in Nuclear Facilities
IEC 60780	Qualification of Electrical Equipment of Safety Systems in Nuclear Power Plants

Fiber Optics

Std Number	Standard Title
EIA 472000-A: 1985	Cables, Generic Specification For Fiber OpticNow TIA 4720000:1993
	Generic Specification For Fiber Optic Cable
IEEE 1682-2011	IEEE Standard for Qualifying Fiber Optic Cables, Connections, and Optical Fiber Splices for Use in Safety Systems of Nuclear Power Generating Stations
IEEE 1428-2004	Guide for Installation Methods for Fiber Optic Cables in Electric Power Generating Stations and in Industrial Facilities

Fire-Related Standards

Std Number	Standard Title
NFPA 701	Standard Methods of Fire Tests for Flame Propagation of Textiles and Films
IEEE 634-2004	IEEE Standard Cable-Penetration Fire Stop Qualification Test
UL 94	Standard for Safety of Flammability of Plastic Materials for Parts in Devices and Appliances testing (plastic r
IEEE 383-1974	older version discussed flame performance
UL VW-1	Vertical Wire Flame Test
IEEE 1202-1991	Flame Testing Of Cables for Use in Cable Tray (check most recent--2006)
UL 1581	Reference Standard for Electrical Wires, Cables, and Flexible Cords
UL 1685	similar IEEE 1202
NFPA 262	Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces
UL 1666	Test for Flame Propagation Height of Electrical and Optical-Fiber Cables Installed Vertically in Shafts

Standards Reviewed

Design and Installation

Std Number	Standard Title
IEEE 336-2010	Recommended Practice for Installation, Inspection, and Testing for Class 1E Power, Instrumentation, and Control Equipment at Nuclear Facilities
IEEE P422 (IEEE422-1986)	IEEE Guide for the Design and Installation of Cable Systems in Power Generating Stations (currently in revision)
IEEE 690	Standard for the Design and Installation of Cable Systems for Class 1E Circuits in Nuclear Power Generating Stations
IEEE 1185	IEEE Recommended Practice for Cable Installation in Generating Stations and Industrial Facilities
IEEE 525	IEEE Guide for the Design and Installation of Cable Systems in Substations
NEMA/ICEA WC 3,5,7,8	(relevant to old plants but not for new construction)
NEMA WC74-2006/ANSI/ICEA S-93-639	Shielded Power Cables 5,000 - 46,000 V
NEMA WC70-2009/ANSI/ICEA S-95-658	Non-Shielded Power Cables Rated 2000 V or Less
NEMA WC71-1999/ICEA S-96-659	Non-Shielded Power Cables Rated 2001 - 5000 V
ANSI/ICEA S-97-682-2007	Utility Shielded Power Cables Rated 5 Through 46 kV
NEMA WC57-2004/ICEA S-73-532	Standard for Control, Thermocouple Extension and Instrumentation Cable (Rev. 2, 2004)
UL 83	Thermoplastic-Insulated Wires and Cables (applies to thermoplastics but not used in NPP)-move to non Class 1e
UL 44	Thermoset-Insulated Wires and Cables
UL 1072	Medium-Voltage Power Cables
UL 1277	Standard for Electrical Power and Control Tray Cables with Optional Optical-Fiber Members
UL 1569	Metal-Clad Cables

Service Life Prediction

Std Number	Standard Title
IEEE 775	IEEE Guide for Designing Multistress Aging Tests of Electrical Insulation in a Radiation Environment
IEEE 1205	IEEE Guide for Assessing, Monitoring, and Mitigating Aging Effects of Class 1E Equipment used in Nuclear Power Generating Stations
IEEE 400	IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems
IEEE 400.1	IEEE Guide for Field Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5 kV and Above With High Direct Current Voltage
IEEE 400.2	IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency
IEEE 400.3-2006	IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment
IEC 61244-2	Long-term radiation ageing in polymers - Part 2: Procedures for predicting ageing at low dose rate (this is due for updating in 2012)
IEC 62582	Nuclear Power Plants - Instrumentation and control important to safety - Electrical equipment condition monitoring methods - Part 1: General
	Part 2: Indenter Modulus
	Part 3: Elongation at Break (due to be published early 2012)
	Part 4: Oxidation induction techniques(just published)
IEC 62465	Nuclear Power Plants-Instrumentation and control important to safety- Management of aging of electrical cabling systems (published 2011)

NRC Documents Reviewed

RG	Standard Title	IEEE Std to which it is based
RG 1.63	Electric Penetration Assemblies in Containment Stuctures for Nuclear Power Plants	IEEE 317-1983
RG 1.89	Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants	IEEE 323-1974
RG 1.211	Qualification of Safety-Related Cables and Field Splices for Nuclear Power Plants	IEEE 383-2003
RG 1.156	Qualification of Connection Assemblies for Nuclear Power Plants	IEEE 572-2006
RG 1.100	Seismic Qualification of Electrical and Active Mechanical Equipment and Functional Qualification of Active Mechanical Equipment for Nuclear Power Plants	IEEE 344-1987
		IEEE 627-2010
Safety Guide 30		IEEE 336-1971
RG 1.75	Criteria for Independence of Electrical Safety Systems	
RG 1.131	Qualification Tests of Electric Cables, Field Splices, and Connections for Light-Water-Cooled Nuclear Power Plants	
DG-1240; RG 1.218	DRAFT REGULATORY GUIDE: (Proposed new regulatory guide) Condition Monitoring Program for Electric Cables Used In Nuclear Power Plants	
NUREG/CR-0381	A Preliminary Report on Fire Protection Research Program Fire Barriers and Fire Retardant Coatings Tests	
NUREG/CR-0654	Nuclear Power Plant Fire Protection - Fire-Hazards Analysis (Subsystems Study Task 4)	
NUREG/CR-1682	Electrical Insulators in a Reactor Accident Environment	
NUREG/CR-2927	Nuclear Power Plant Electrical Cable Damageability Experiments	
NUREG/CR-6794	Evaluation of Aging and Environmental Qualification Practices for Power Cables Used in Nuclear Power Plants	
NUREG/CR-7000	Essential Elements of an Electric Cable Condition Monitoring Program	
NUREG/CR-7010	Vol. 1 Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE) Volume 1: Horizontal Trays (Draft Report for Comment)	
NRC INFO NOTICE 2010-26	Submerged Electrical Cables	
NRC INFO NOTICE 93-33	Potential Deficiency of Certain Class 1E Instrumentation and Control Cables	
NRC GENERIC LETTER 2007-01	Inaccessible or Underground Power Cable Failures that Disable Accident Mitigation Systems or Cause Plant Transients	
SUM REP/GEN LET 2007-01	"Inaccessible or Underground Power Cable Failures that Disable Accident Mitigation Systems or Cause Plant Transients"	

Non-NRC Documents Reviewed

Standard Number	Standard Title
SAND2005-7331	Nuclear Energy Plant Optimization (NEPO) Final Report on Aging and Condition Monitoring of Low-Voltage Cable Materials
SAND 2010-7266	Review of Nuclear Power Plant Safety Cable Aging Studies with Recommendations for Improved Approaches and for Future Work
PNL-10717	A Review of Information for Managing Aging in Nuclear Power Plants
EPRI TR106394	Evaluation of Gases Generated by Heating and Burning of Cables
EPRI 1022638	Plant Engineering: 2011 Complete Product List
EPRI 1000444	Fiber Optic Cables in High Voltage Environments
EPRI1002036	Extruded Dielectrics for Transmission Cables Evaluation of Aging Models
EPRI 1002037	Review of Materials and Materials Technologies for Transmission Cable Applications
EPRI 1003062	Natural Versus Artificial Aging of Electrical Components
EPRI 1008211	Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets
EPRI 1008560	Equipment Failure Model and Data for Underground Distribution Cables A PM Basis Application
EPRI 1010497	Formation of Nanovoids in Extruded Dielectrics Caused by Mechanical Fatigue and Fracture
EPRI 1011273	Procedures for the Examination of the Metals Used in Electrical Power Cables
EPRI 1011873	Cable Polymer Aging and Condition Monitoring Research at Sandia National Laboratories Under the Nuclear Energy Plant Optimization (NEPO) Program
EPRI 1020804	Plant Support Engineering: Aging Management Program Development Guidance for AC and DC Low-Voltage Power Cable Systems for Nuclear Power Plants
EPRI 1020805	Plant Support Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants
EPRI 1011629	instrument control (must pay for)
EPRI 113557	Assessment of Insulation Quality in115 kV XLPE Cables
IAEA TECDOC1147	Management of ageing of I&C equipment in nuclear power plants
IAEA TECDOC1188	Assessment and management of ageing of major nuclear power plant components important to safety: In-containment instrumentation and control cables: VI and II
JNES2009	Aging Management of Nuclear Power Plant
JNES-SS-0903	The Final Report of the Project of Assessment of Cable Aging for Nuclear Power Plants

Task Group Findings and Path Forward

- After review, found that most standards actually revised or were under revision.
- New standards are also being created to monitor the condition of electrical cables
- Recommended looking outside conventional standards for electrical cables:
  - Military Specifications, other non-Class 1E requirements
  - Research Documents
  - DOE-Sandia, Brookhaven, etc.; NRC document, EPRI reports
- ***Challenge*** : *New versus Old NPP Construction*
- ***Challenge***: *Qualification of cables upon accident conditions*
- ***Challenge***: *SDOs want NRC to cite* most recent version of standards in licensing process

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 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

Research

Assessment of Electrical Cable Condition Monitoring Tests (sponsored by U.S. NRC)

- **Objectives**:
  - To confirm the adequacy of condition monitoring under normal operational and LOCA conditions
  - To confirm the condition-based qualification methodology
  - To confirm acceleration factors for accelerated aging tests and validate service life prediction.

Research

Assessment of Electrical Cable Condition Monitoring Tests (sponsored by U.S. NRC)

- **Experimental approach:**
  - Cables subjected to a series of static, well-controlled temperature, relative humidity and operational aging radiation exposure environments
  - Periodically removed from each exposure environment and evaluated using the predetermined CMTs against baseline values
  - Relate cable electrical performance to acceptance criteria for each CMT

Research

Task 1: Establish baseline values for 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)
  - 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

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

Table 3. Proposed Aging Conditions.

Temperature (°C)	Relative Humidity (%)
30	20
42	50
55	80
27	water submerged

- Simultaneous temperature, moisture, and radiation exposure:
  - total radiation dose for operational aging = 50 MRad (500 kGy) with a dose rate of $<$100 Gy/h
- Energized cable experiments will also be explored
- Loss of Coolant Accident (LOCA) conditions will be examined in a later phase

Research

Tasks 3 and 4: Monitor changes in cable properties vs. exposure time;

Quantitatively characterize cable degradation mechanism(s) to establish appropriate conditions for accelerated aging

- At predetermined exposure times, characterize cable specimens using CMTs.
- Additionally, chemical, physical, and morphological characterization of exposed specimens will be carried out using a variety of analytical instruments including, but not limited to:
  – Infrared, UV-visible, and Raman spectroscopy
  – Thermal Analysis
  – Moisture sorption analysis
  – Scanning electron microscopy
  – Laser confocal microscopy
  – Atomic force microscopy
- Laboratory aged cables will be compared with field-aged materials

Research

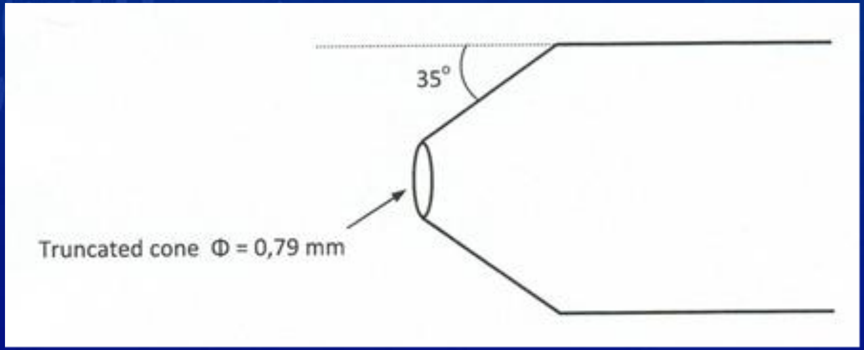
Task 5: Relate condition monitoring test results to cable electrical performance and establish acceptance criteria for condition monitoring tests

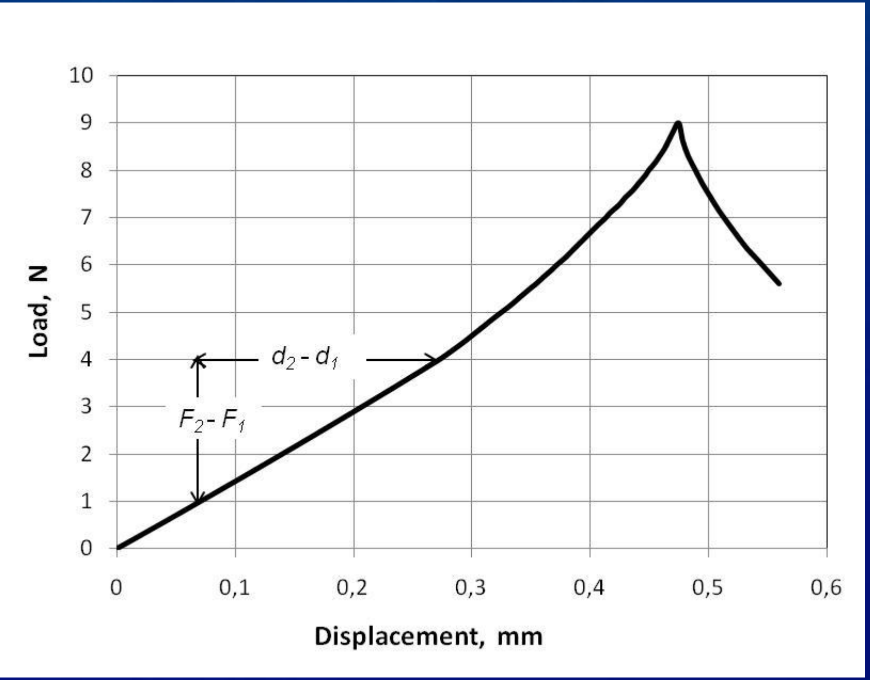
- CMT results will be correlated against well-established cable failure performance data
- Cable failure determined from electrical output tests which measure performance capability
  - voltage
  - capacitance
  - impedance measurements
- CMT data collected from EPRI, IAEA, and NRC used to improve the statistics of this evaluation; however, data from these sources may not have used the same experimental parameters .

Methods

IAEA Round Robin

- **Indenter** **IEC/IEEE 62582-2**
- 5.1 ± 0.1 mm/min and a maximum force of 10 N
- $IM = (F_2 – F_1)/(d_2-d_1)$



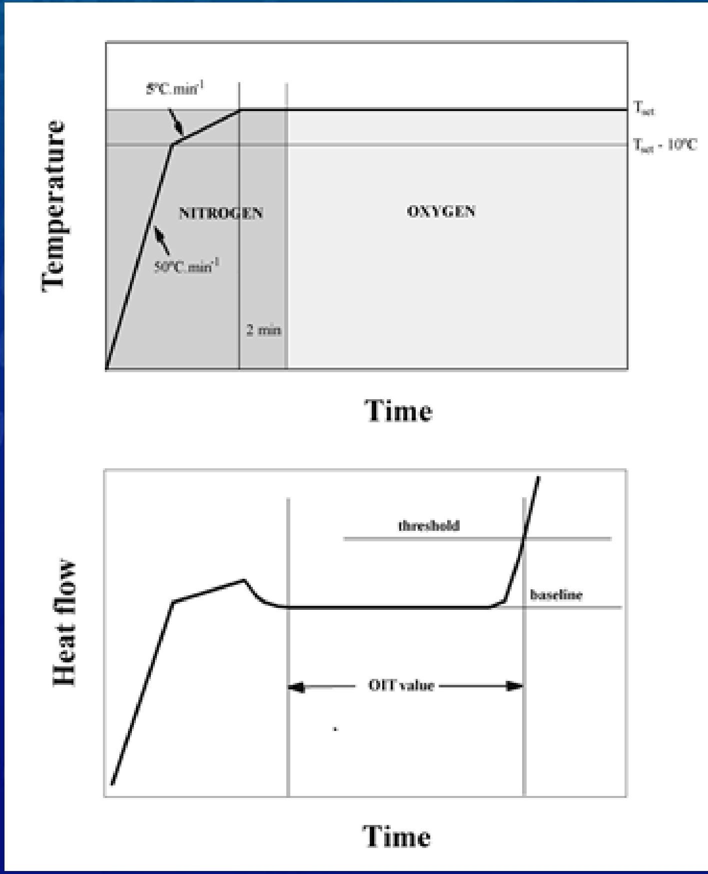


Methods

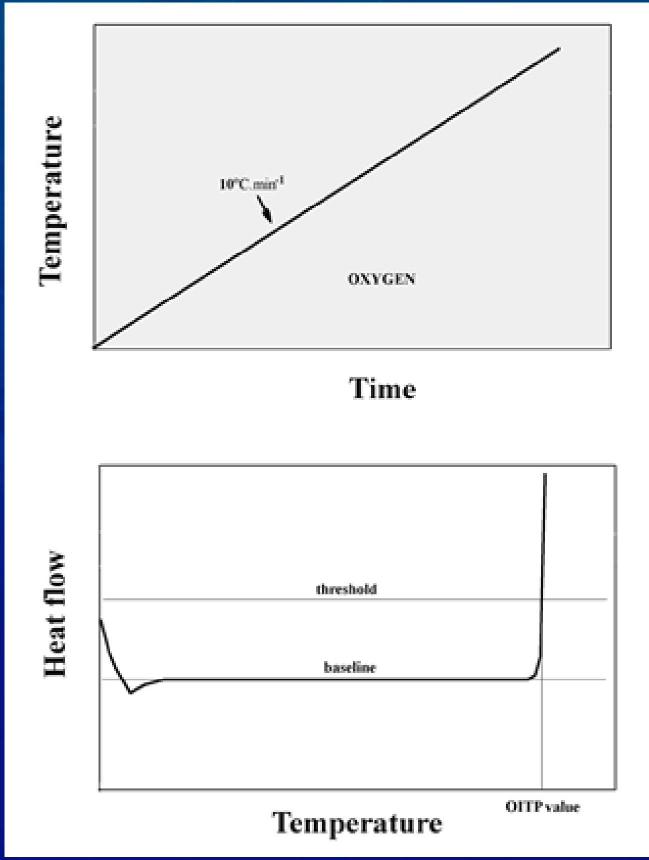
IAEA Round Robin

- **Oxidation induction time/temperature (OIT/OITP) IEC/IEEE 62582-4**
- N_2- 50°C/min until 10°C below set temp, 5°C/min to set temp, hold 2 min
- Switch to O_2, monitor time to oxidize

Time



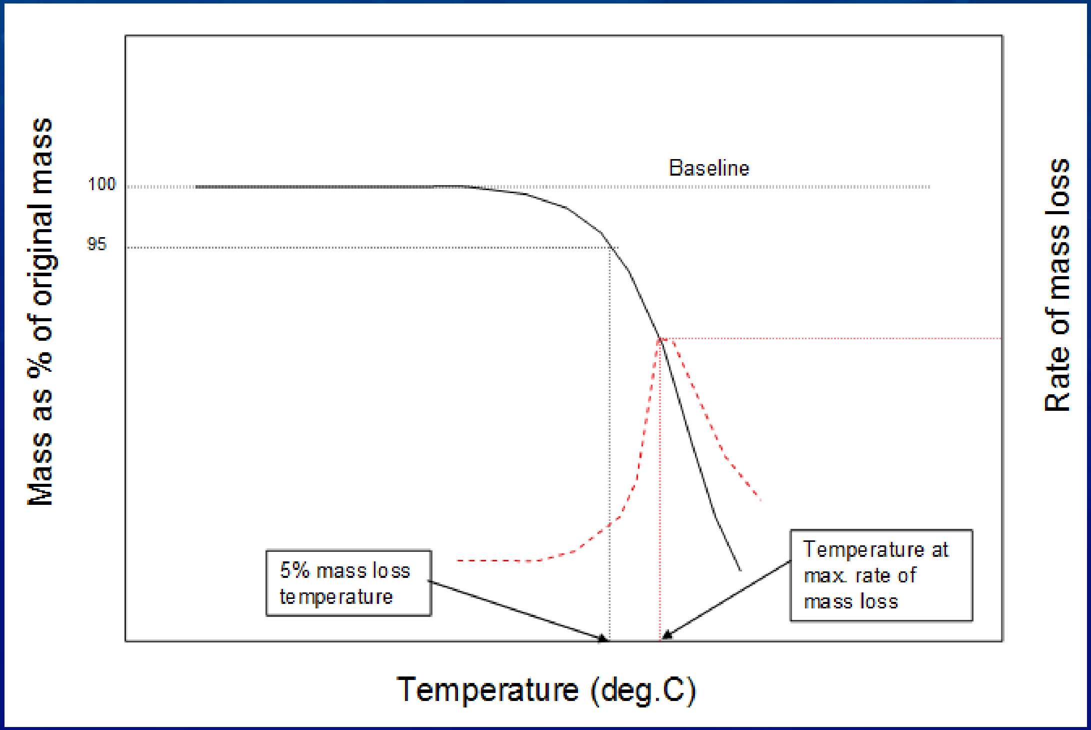
Temperature



Methods

IAEA Round Robin

- **Weight Loss- TGA**
  - N_2-10°C/min
  - temperature at maximum rate of weight loss
  - temperature at 5% weight loss

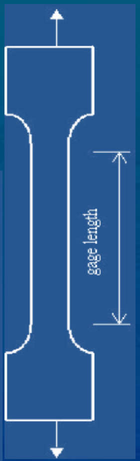


Methods

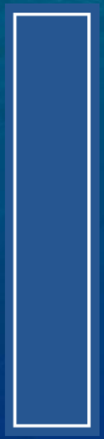
IAEA Round Robin

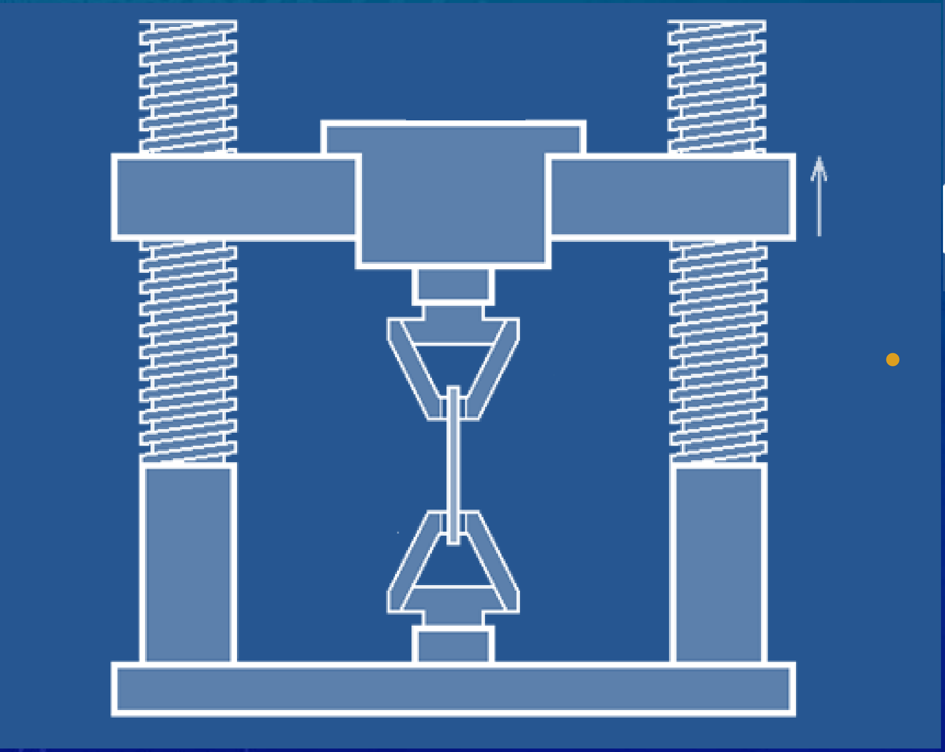
- **Density**
- weigh specimen in air and in distilled (or de-ionized water) using an analytical balance

Results Mechanical Testing-*Tensile testing*



Test Sample Types





Universal Testing Machine

IEC/IEEE 62582-3
ASTM D-412-C

- **Measures:**
  - Ductility, via elongation at break
  - Rigidity, via elastic modulus
  - Strength, via ultimate and yield strength
  - Toughness, via area under stress/strain curve

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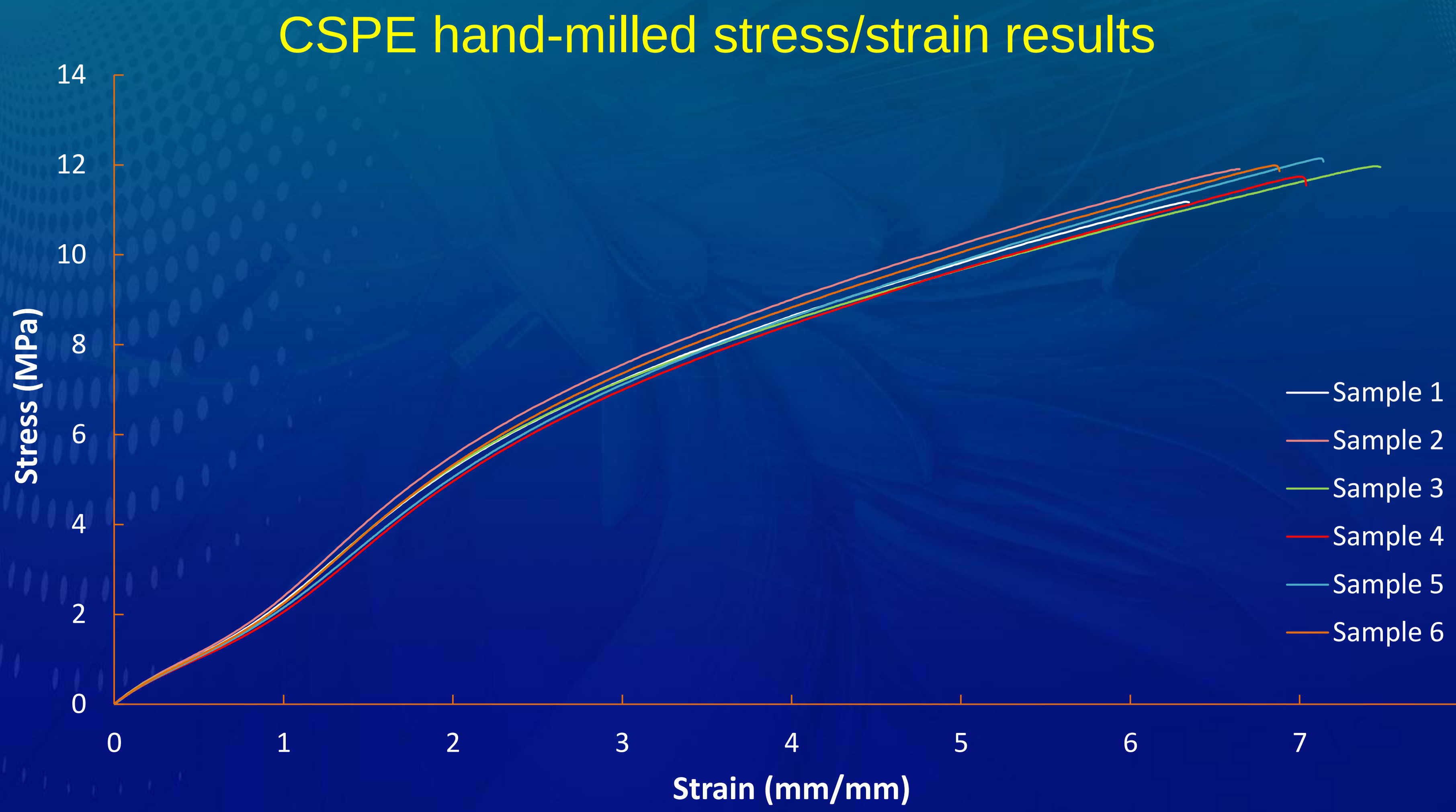
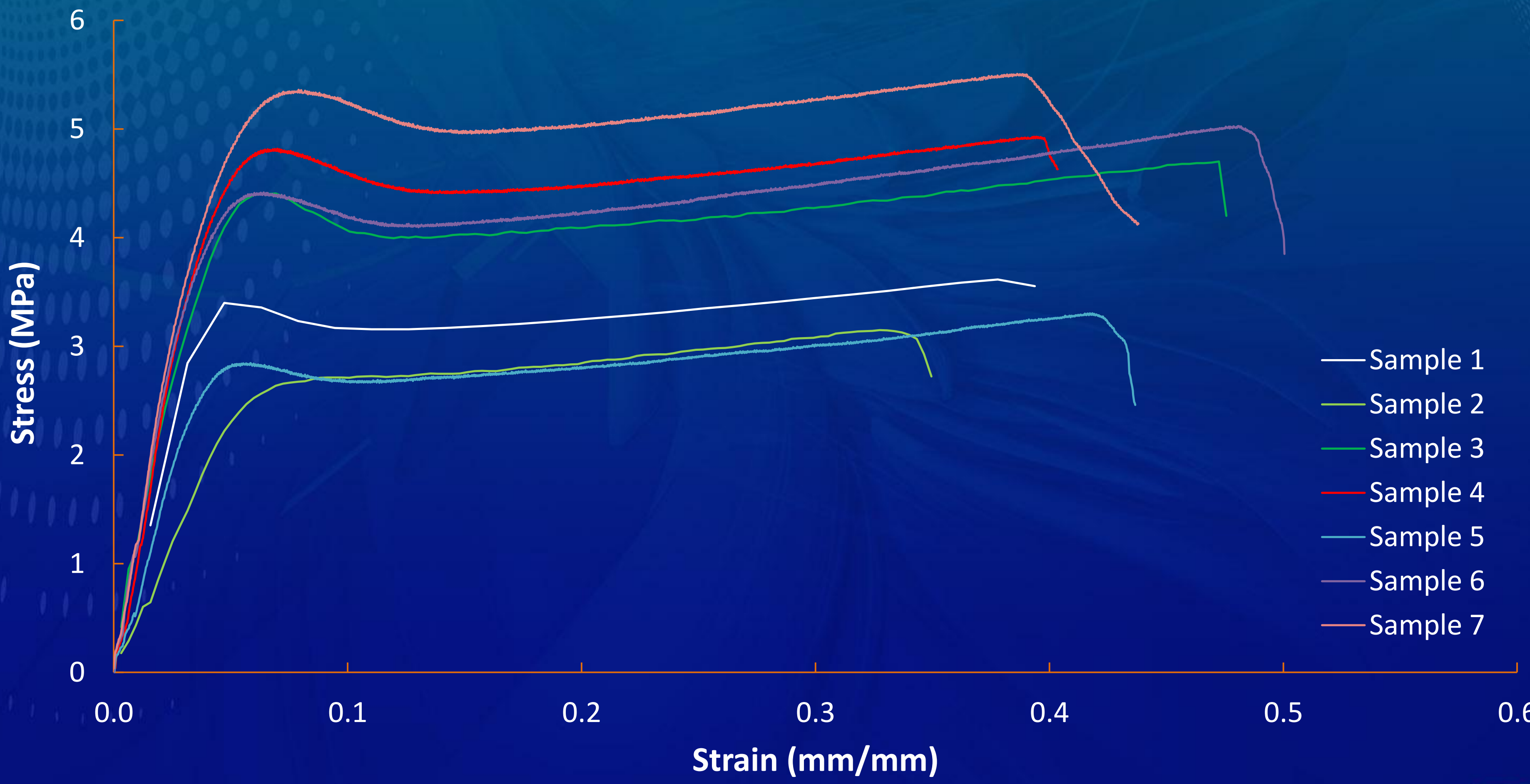
Results Mechanical Testing-*Tensile testing*



Results Mechanical Testing-*Tensile testing*

XLPE hand milled stress/strain results



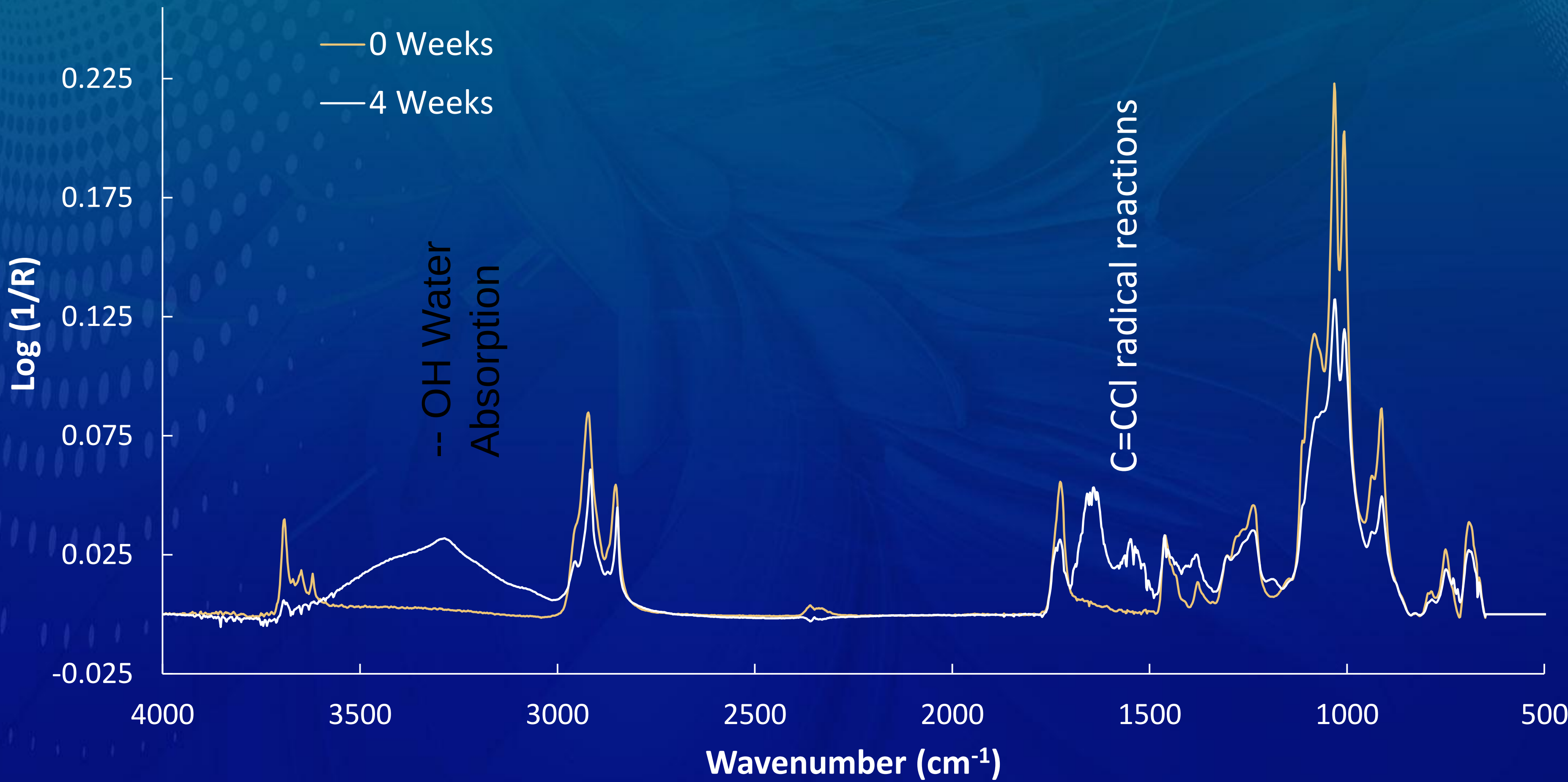
Results Mechanical Testing- *Summary*

- **Gripping**
  - Challenge: either break or slip
  - Experimentation: various grips and arrangements
  - Result: constant-pressure pneumatic grips on order
- **Extension**
  - Challenge: measure extreme extension
  - Experimentation: video capture and software quantification
  - Result: laser extensometer installed/to be tried

Results Chemical Analysis-

Fourier Transform Infrared Spectroscopy (FTIR)

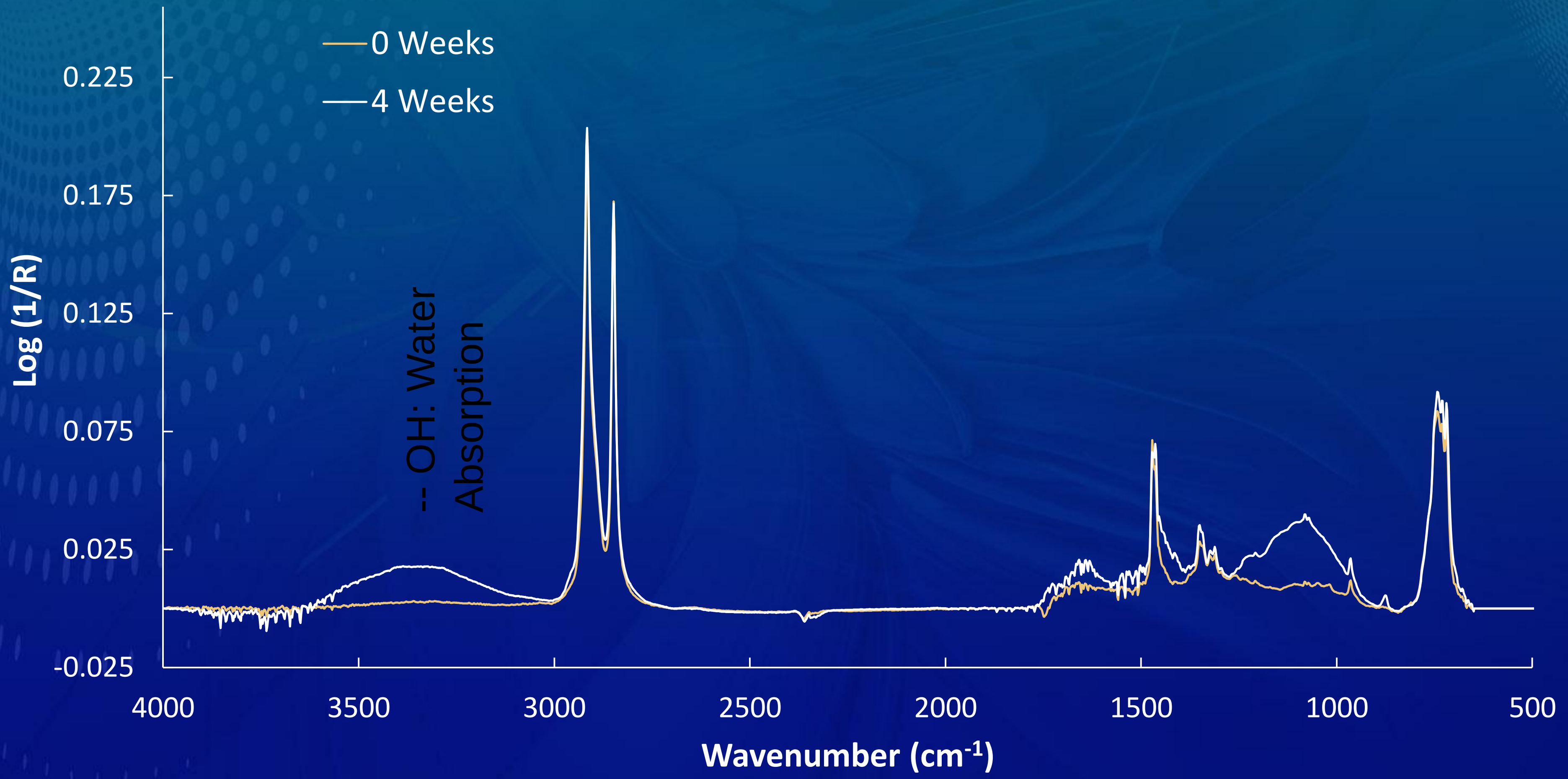
CSPE: *unaged vs 4 weeks submerged*



Results Chemical Analysis-

Fourier Transform Infrared Spectroscopy (FTIR)

XLPE: *unaged vs 4 weeks submerged*



XLPE Density decrease: peak ratio of 1460 cm-1 :730 cm^{-1}

Results Chemical Analysis- *Fourier Transform Infrared Spectroscopy (FTIR)*

- CSPE: Water absorption, C=C formation
- XLPE: Water absorption, possible sulfonyl chloride contamination

- Investigate Raman Spectroscopy
  - Complement FTIR
  - Analysis in water possible

Summary

- Service lives and condition of NPP cables are critical to their safety and performance.
- Engaged with standards organizations to determine NPP cable research and standards needs, and develop plan for research and transferring results into published standards
- Project underway with U.S. NRC to confirm adequacy of current condition monitoring tests and to establish appropriate conditions and parameters for accelerated aging.

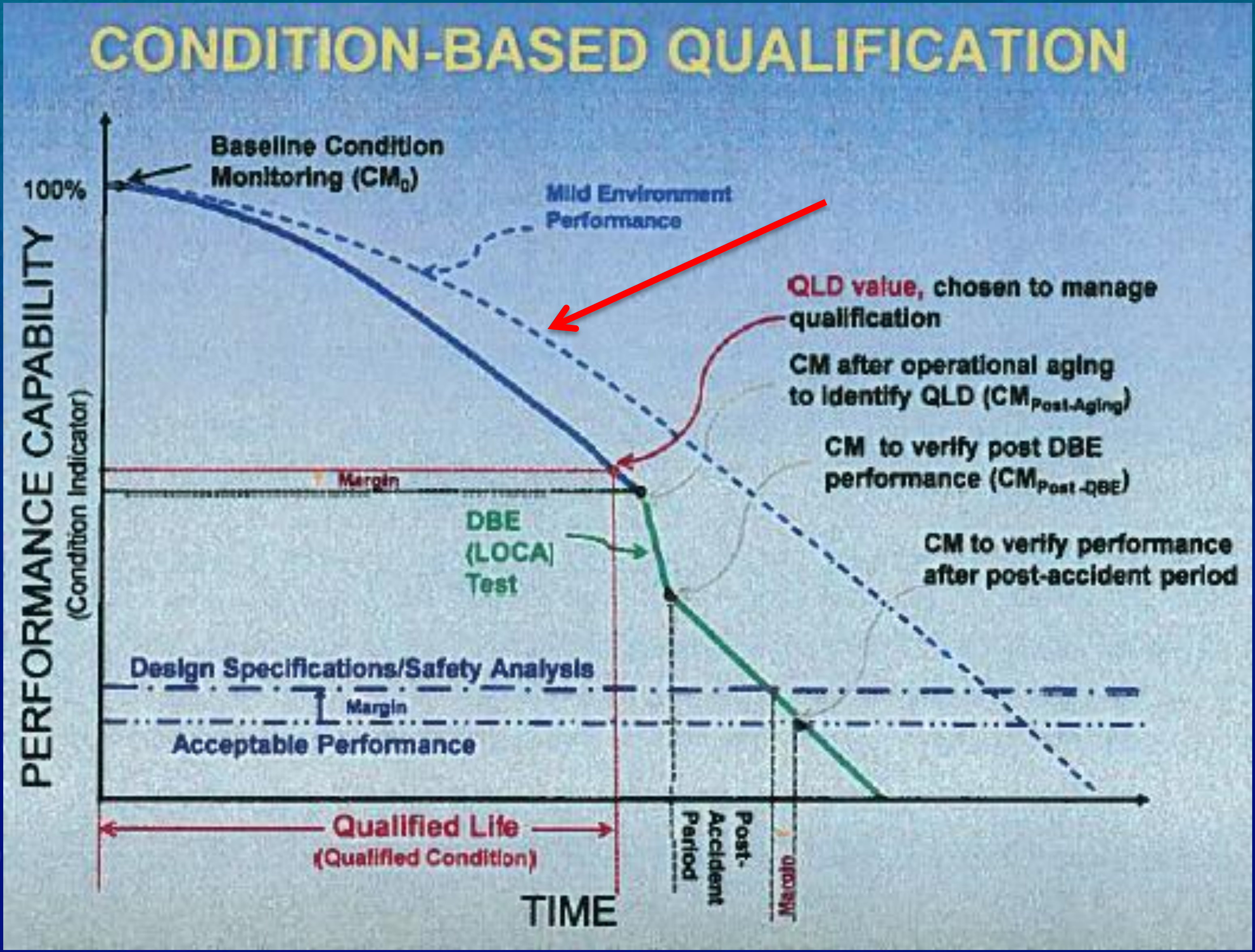
Acknowledgements

U.S. NRC Research Funding

(through interagency agreement with NIST)

Guest Researchers

Research



from US NRC

Research

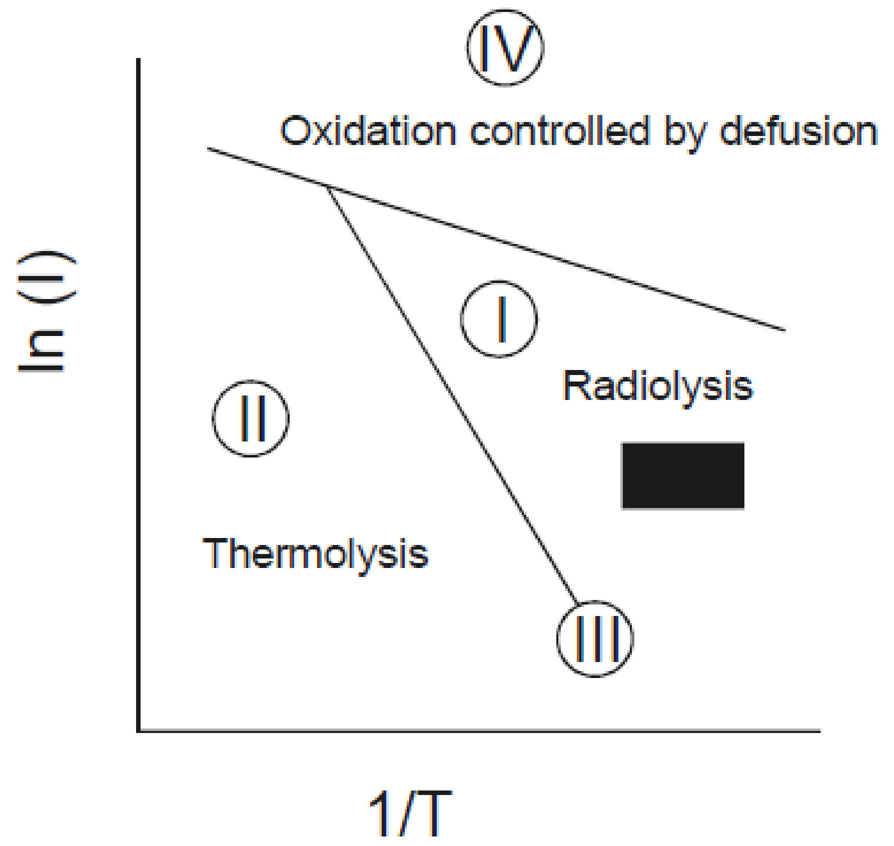


FIG. 3.1. Schematic diagram showing the dominant ageing mechanisms for different conditions of dose rate I and temperature T (Domain (III) represents the boundary between domains (I) and (II). Ageing mechanism = f (ln I, 1/T) [3.1, 2.2]. The black square represents the service conditions in an NPP.

from IAEA