IN-SITU Cable Condition Monitoring Using Fourier Transform Near-Infrared (FT-NIR) Spectroscopy

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Outline

- Introduction
- FT-NIR
- Experimental details
- Results and discussion
- Conclusions
- References and acknowledgements

Introduction

(FT-NIR in Nuclear Industry Historical Perspective)

- **1995 - Ontario Hydro supported three projects for condition monitoring (chemical analysis, indenter, and spectroscopic methods – FT-NIR)**
- **1996 - Several manufacturers were evaluated and FT-NIR from Bruker Optics was purchased and in house development started**
- **1998 - Condition monitoring was put on hold due to a pressing need for identification of cables**
- **1999 - An identification model was developed and audited for implementation and FT-NIR has since been used to scan thousands of cables in CANDU plants**
- **2007 - Condition Monitoring revived**

Non-Nuclear Applications Patents awarded to NIR Technologies Inc.

United States Patent No. US 7,329,547 B2 (Feb. 12, 2008)

Canadian Patent No. 2,404,891 (Nov. 18, 2003)

Introduction
(FT-NIR - Chemical Method)

Known advantages

- Non-destructive, non-intrusive
- IN-SITU, portable, cost effective and easy to use
- Results generated instantly

Hypothetical advantages

- Accurate, repeatable, using separate, similar tools (i.e.: same Mfr)
- May be more broadly applied than other chemical methods

Disadvantages

- Does not work with black materials, no reflectance
- Alternative method available for black materials but not fully developed as FT-NIR measurements are local only
- Matrix dependent, therefore requires careful attention when developing reference library

Introduction
(Preliminary Investigations)

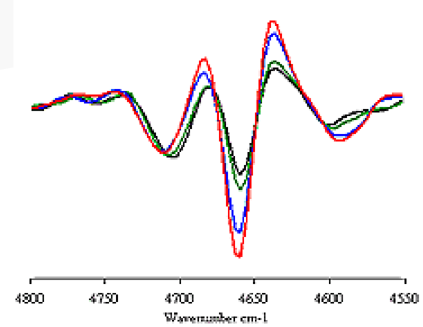
Objectives

- Determine feasibility of using FT-NIR for condition monitoring
- Determine sensitivity of FT-NIR to changes due to radiation and thermal ageing

Limitations

- Small number of incrementally aged specimens available (PVC and XLPE only)
- Previous chemical testing limited to plasticizer content (PVC)

FT-NIR
(Theory)



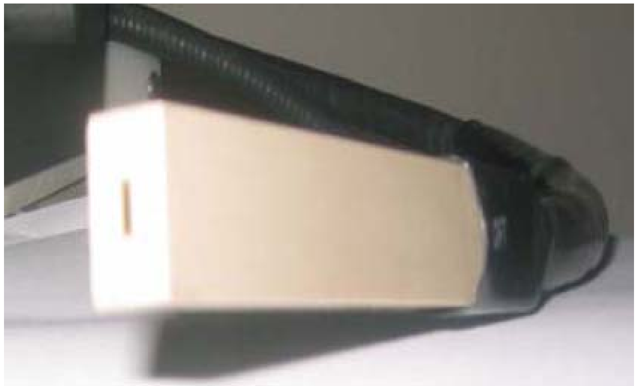
- **Measurements of energies (near infrared light) absorbed or transmitted by a sample which is proportional to the vibration (stretching and bending) of chemical bonds such as C-H, O-H, N-H**
- **Provides the chemical 'finger-print' of a material at the molecular level which is unique to a specific material formulation at any given point in time**
- **The chemical 'finger-print' changes with chemical changes to molecules i.e., radiation or thermal ageing**
- **Measurements can be taken in absorption or transmission**
- **Complex 'finger-prints' can be analyzed using Chemometric Analysis**

FT-NIR
(Apparatus)

Main Components

- **Bruker Optics FT-NIR Spectrometer (Matrix-F), weighs about 17 kg**
- **Custom designed probe from Remspec Corp.**
- **OPUS software for scanning and analysis**
- **Laptop**

Fibre optic probe can be as short as 1 meter or as long as 10 meters.



Instrument and laptop can be operated during field operation using UPS to move the instrument from one location to another

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Experimental details
(Method/Analysis)

- FT-NIR scanning range 4,000 – 14,000 cm^{-1}, each measurement typically takes 25 seconds. All samples were scanned at ambient temperature of 20 to 25°C
- Spectral analysis was carried out and FT-NIR response was compared to Elongation at Break data
- FT-NIR response for PVC data was also compared to plasticizer data
- No OIT/OITP data available for XLPE

Experimental details
(Specimen Description)

Cable #	Mfr	Configuration	Type	Jacket	Insulation	Service Condition s
2	X	14C#16AWG (3 colors)	I&C	FRPVC	FRPVC	Negligible radiation, Low Temperature
1	Y	14C#16AWG (3 colors)	I&C	FRPVC	FRXLPE	Negligible radiation, Low Temperature
7	Y	3C#2AWG (2 colors)	Power	FRPVC	FRXLPE	Unknown, but common along entire length

- **Cables cut into equal lengths and tied around a mandrel**
- **Copper conductors extracted for cable# 1 & 2 (1 wire from each colour), insulation tubes are used as elongation specimen, rebundled within jackets, sealed with silicone RTV for ageing**
- **Cable#7 (1 from each colour) aged as-received, dumbbell-shaped specimens were cut from insulation for elongation testing**

Experimental details
(Specimen Ageing)

Ageing Phase	Ageing Conditions
Baseline	Natural, 17 yrs, negligible radiation, low temp
Radiation	14 Mrads (Gamma @ 44krads/hr)
Thermal, 1st increment	255 hrs @ 100 °C
Thermal, 2nd increment	480.5 hrs (cumulative)@ 100 °C
Thermal, 3rd increment	750.5 hrs (cumulative)@ 100 °C
Post-DBA transient*	284 hrs (additional) @ 90 °C (Transient was approx. 6 hrs @ 115 °C with short interval up to 130 °C)

* DBA simulation included saturated steam and elevated pressure

- **E_a of 0.86 eV was bounding, not specifically derived**
- **Specimens stored for 8 years prior to NIR measurements**

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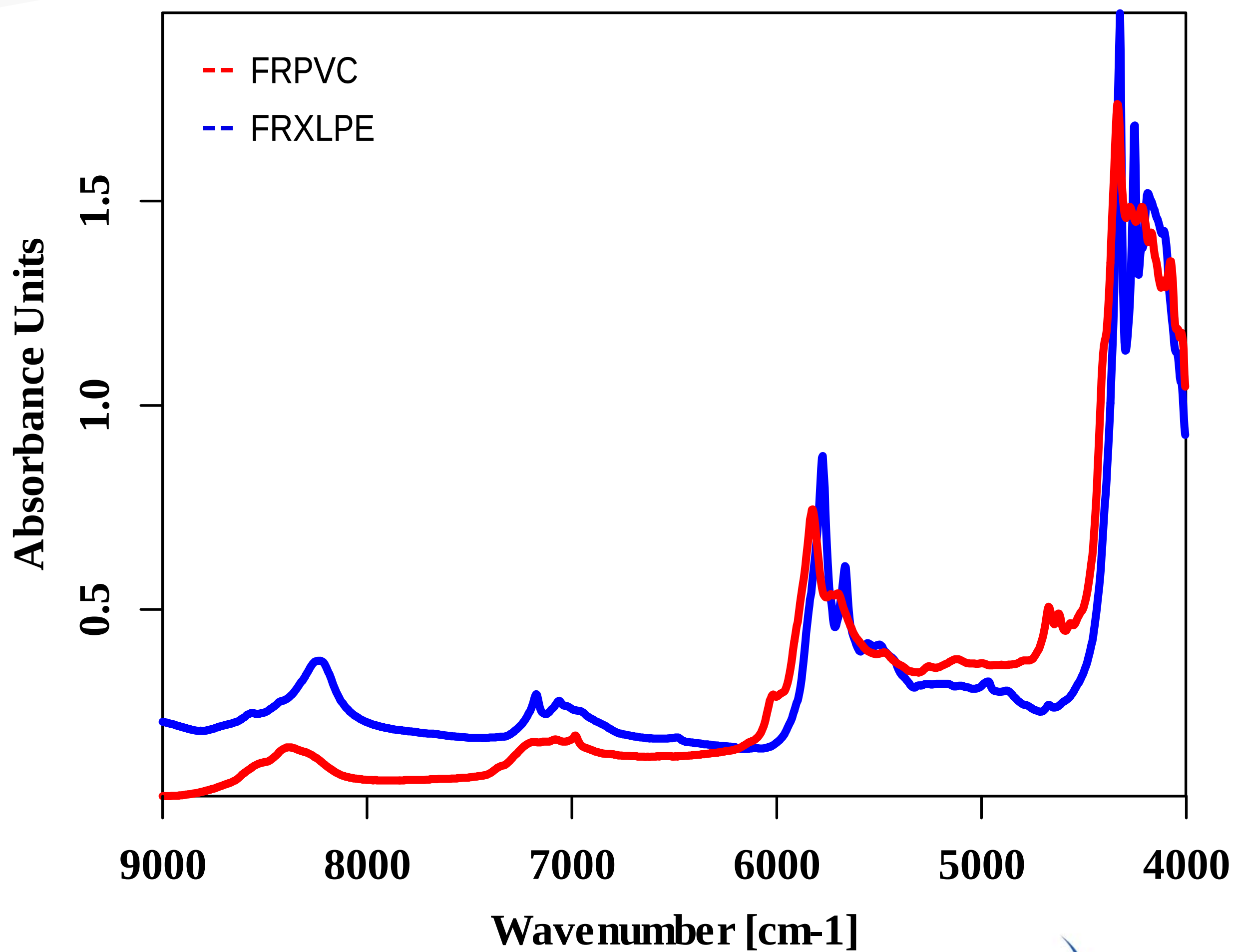
Results and Discussion
(Absorption Spectra)



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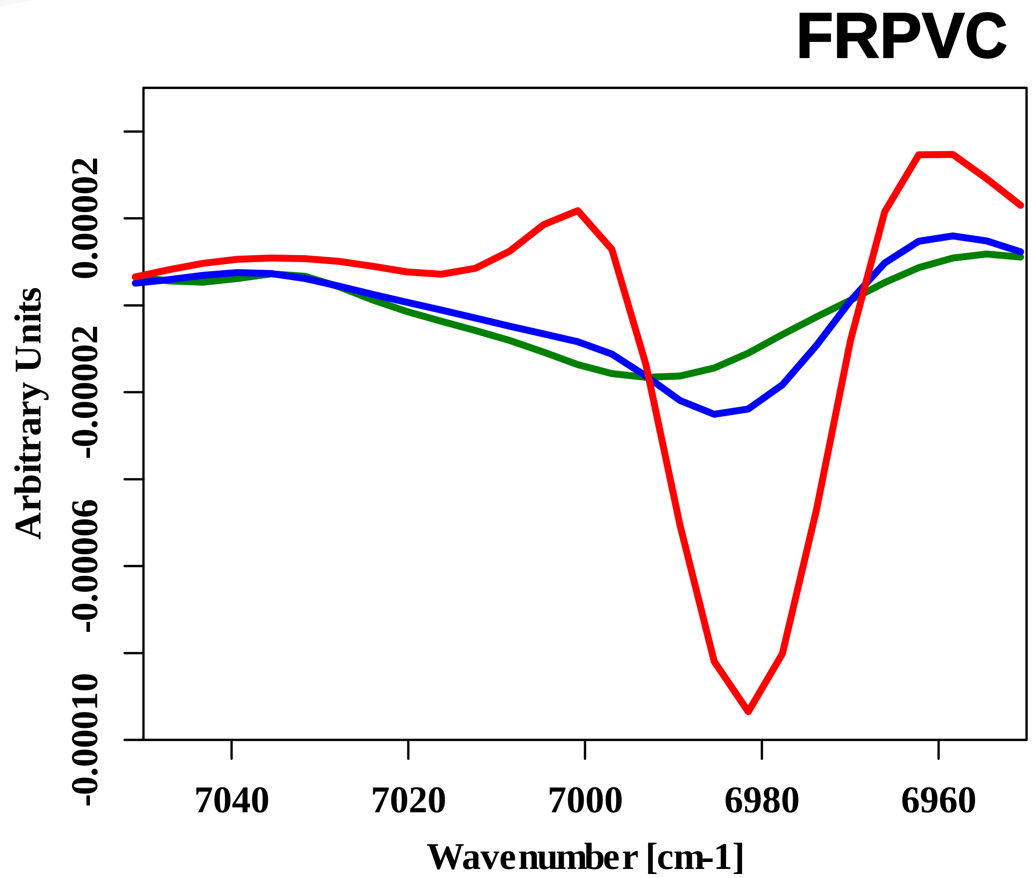
Results and Discussion
(2nd Derivative Spectra)



-- Baseline -- Post Radiation -- Post Thermal

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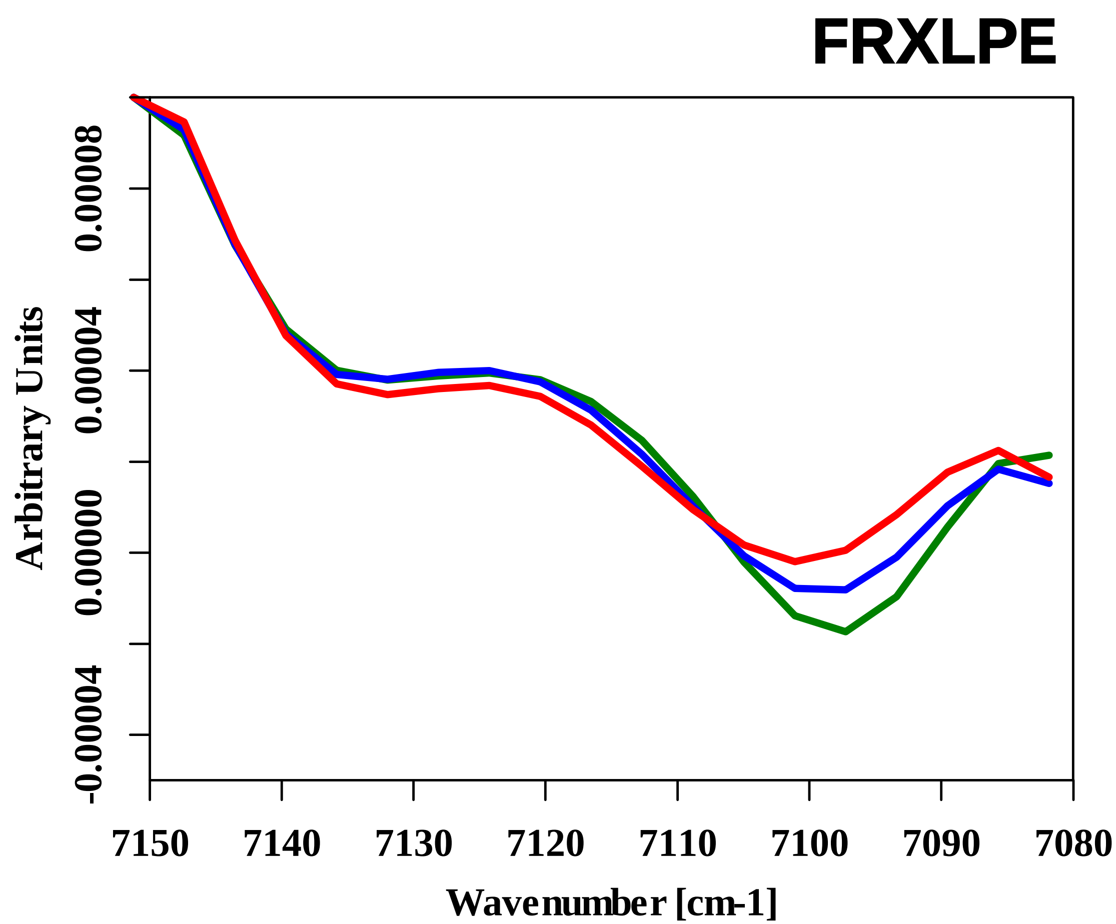
Results and Discussion

(2nd Derivative Spectra)



-- **Baseline** -- **Post Radiation** -- **Post Thermal**

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Results and Discussion
(Factorized Analysis)

- **Average spectrum for each Group, baseline, post-radiation, thermal ageing 1st increment, thermal ageing 2nd increment, post-thermal, and post-LOCA was assessed with respect to different components (known as vectors)**
- **Vectors are mathematical expressions used in quantifying changes and differences between data sets and may represent more than one component**
- **Once a factorized analysis for a particular group of cables has been established the future scans can be compared to the reference materials incorporated in the factorized analysis model**

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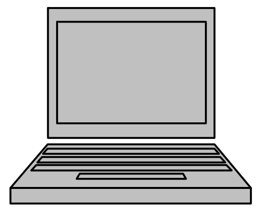
Results and Discussion
(Factorized Analysis)



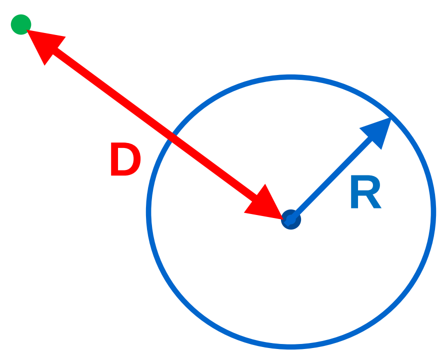
Database established for specific material
In range (i.e.) Humidity: 5 to 35%
Temperature: 5 to 50°C

Thermal Effects

Radiation Effects

Other variables:
-Probe Length

Measured Value



Threshold Value (R)

To confirm the condition of the cable:
Hit Quality (**D**) <= Threshold Value (**R**)

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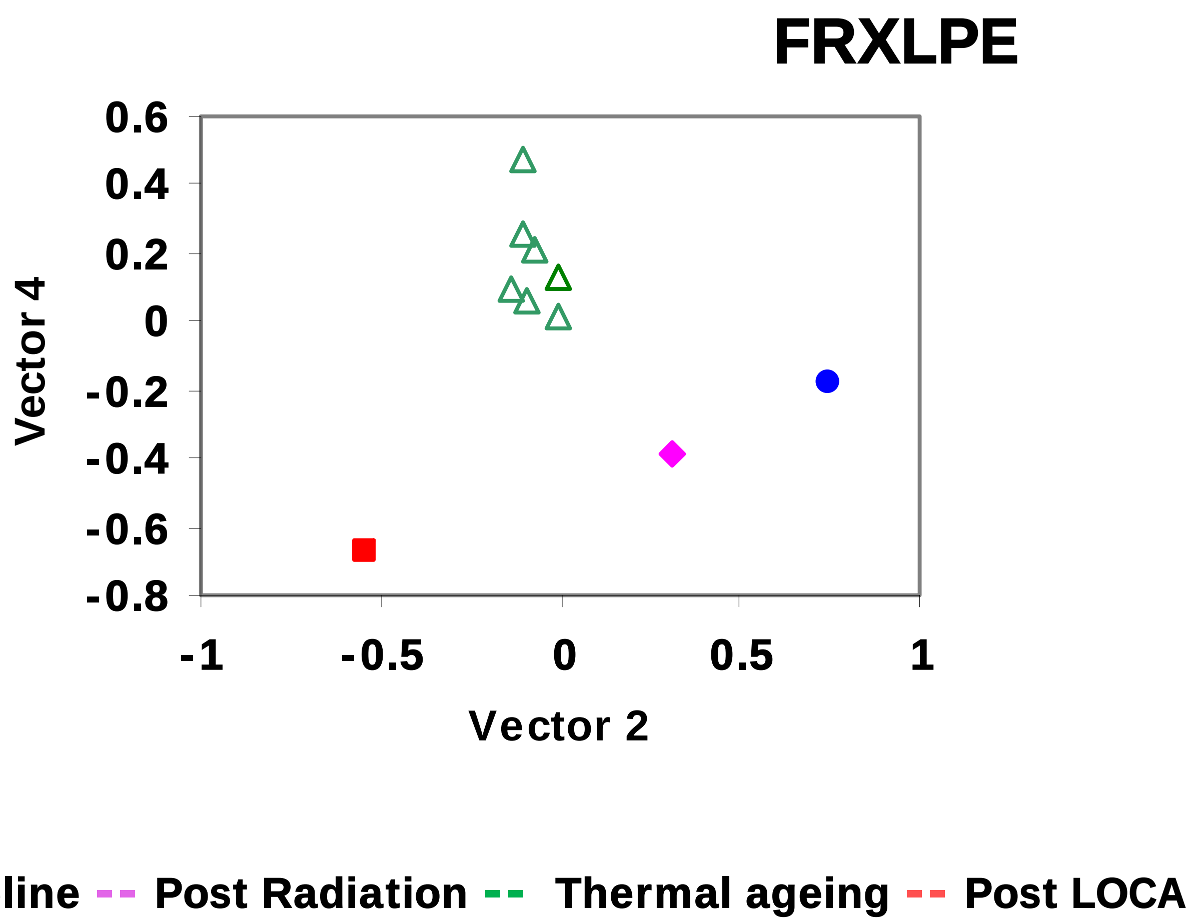
Results and Discussion
(Factorized Analysis)



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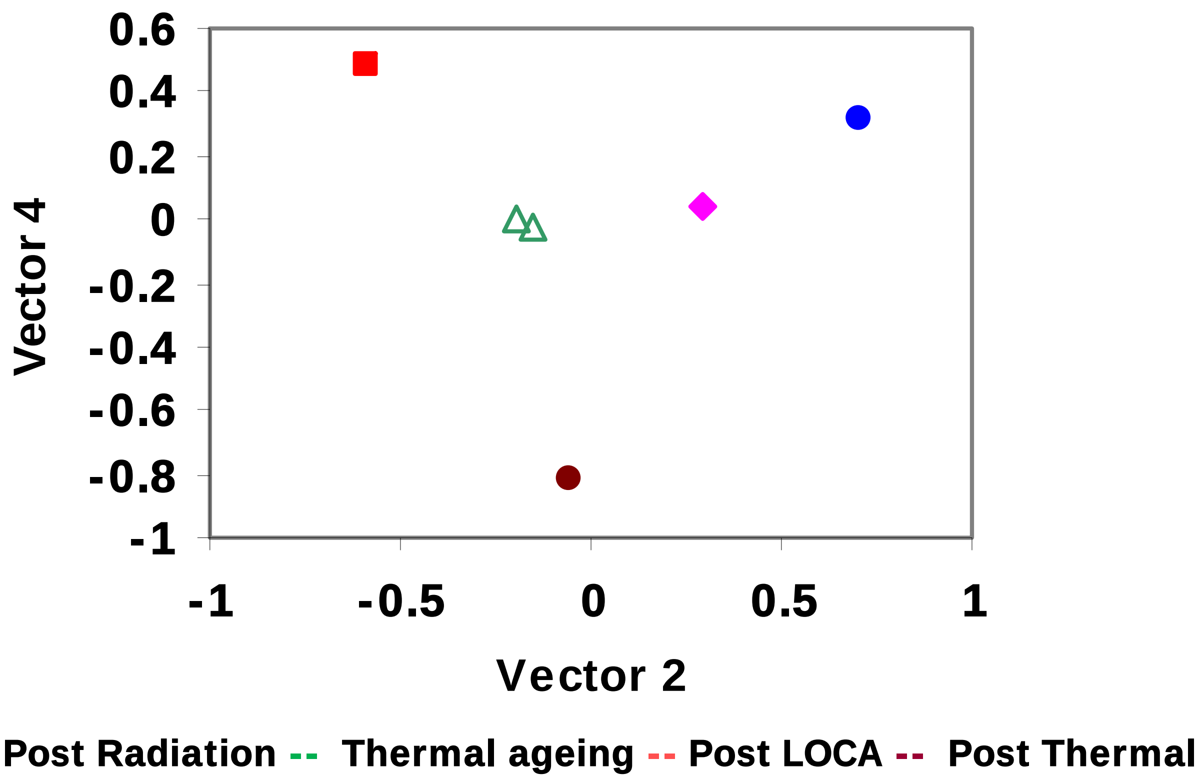
Results and Discussion
(Factorized Analysis)



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Results and Discussion
(Factorized Analysis)

Identification Report FRXLPE Base Line Sample

Identical To: Group 2 Cable 1, Base Line

Hit No.	Hit Quality	Reference File	Threshold
1	0.021403	BaseLine.100	0.092561
2	0.444252	Post Radiation.100	0.137538
3	0.816729	Post Thermal.100	0.060856
4	0.825758	Thermal 2nd Inc.500	0.070036
5	0.860556	Thermal 1st Inc.500	0.049324
6	1.336133	Post LOCA.100	0.100741

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Results and Discussion
(Factorized Analysis)

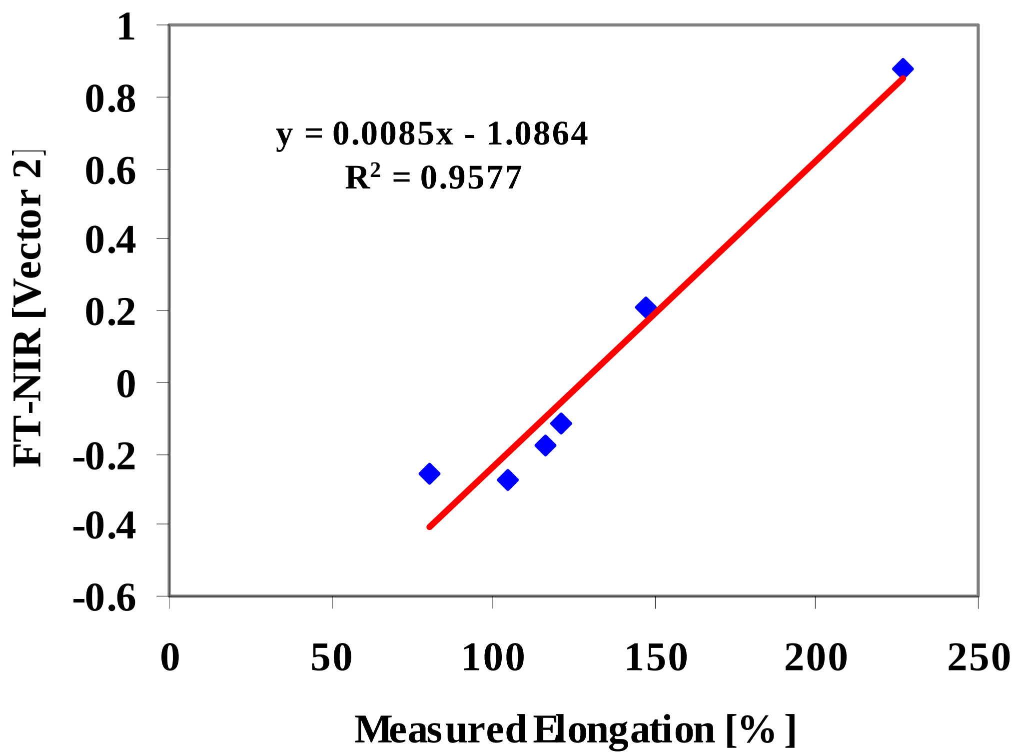
FRXLPE

Repeatability

Repeat No.	Hit Quality	Reference File	Threshold
1	0.05	BaseLine.100	0.092561
2	0.072	BaseLine.100	0.092561
3	0.054	BaseLine.100	0.092561
4	0.099	BaseLine.100	0.092561
5	0.055	BaseLine.100	0.092561
Average	0.066		
Variance	0.000		
Standard Dev	0.030		

Results and Discussion
(FRPVC properties)

% Elongation (EAB)



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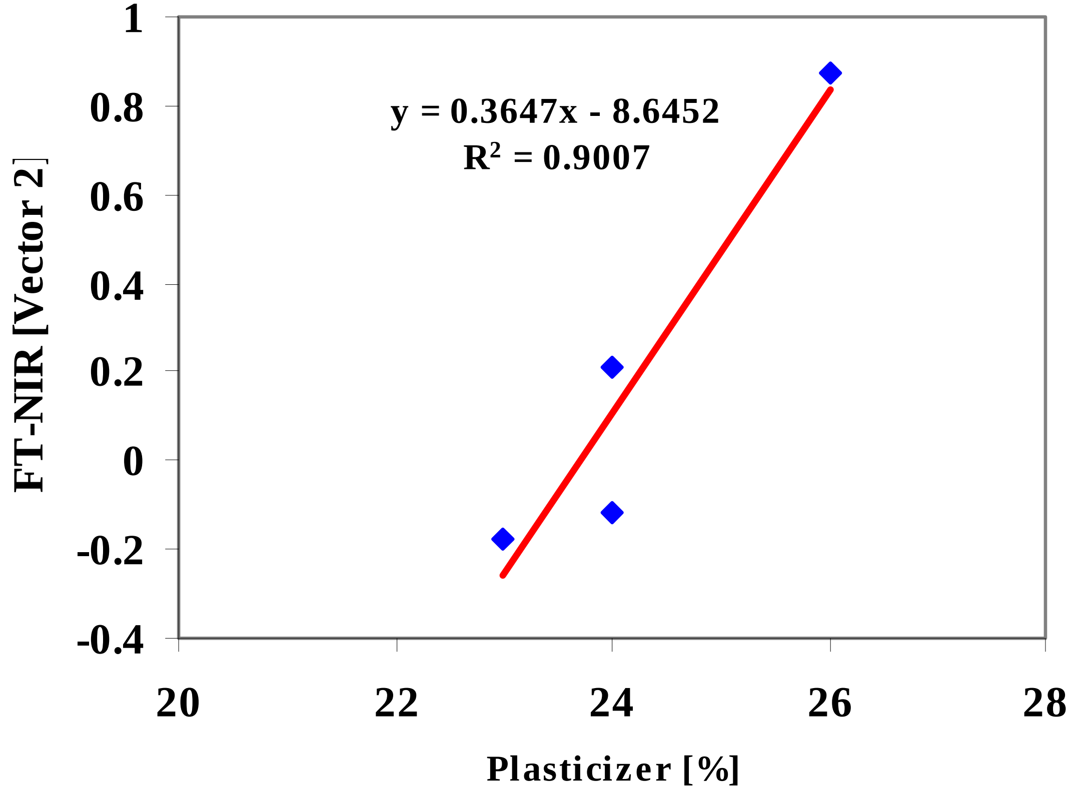
Results and Discussion
(FRPVC properties)

Plasticizer Content



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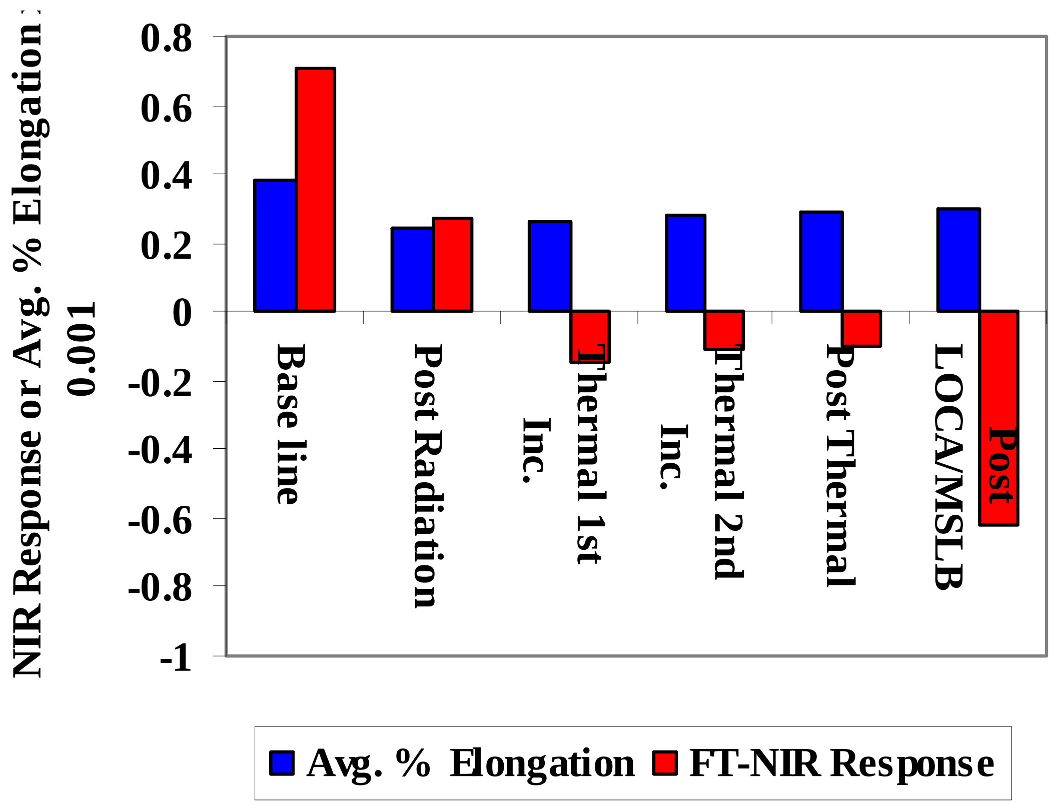
Results and Discussion
(FT-NIR vs Elongation)

Cable 1 (FRXLPE)



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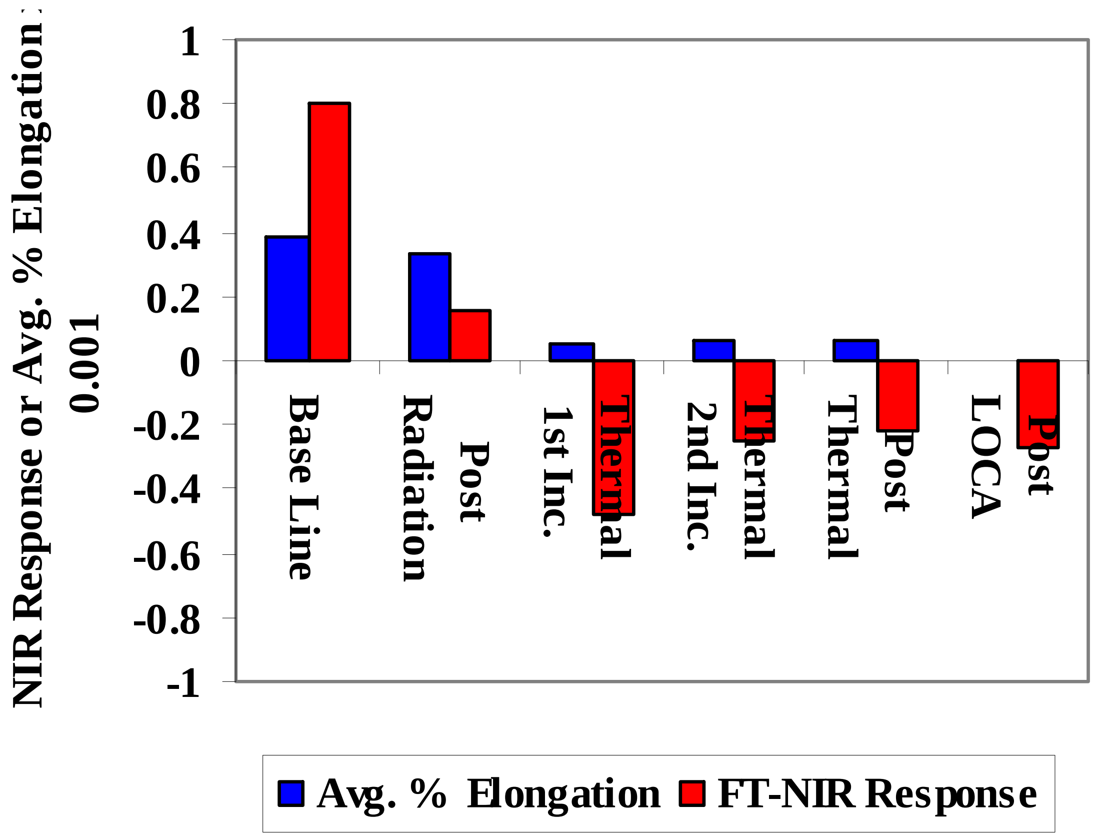
Results and Discussion
(FT-NIR vs Elongation)

Cable 7 (FRXLPE)



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Conclusions

- **FT-NIR very effective in tracking degradation in PVC and correlated well with Elongation at Break and plasticizer content data**
- **FT-NIR responded better than Elongation at Break for the first three stages (base line, post radiation and 1st thermal increment). However, small changes was observed between 1st, 2nd and 3rd thermal increments.**
  - **It is recognized that EAB is not a good condition indicator for XLPE**
  - **Ageing increments not representative of natural ageing and too large for trending**
- **Repeatability is achievable (FT-NIR is matrix dependent environmental conditions during scanning must be incorporated into the reference model)**

Conclusions
(Where to from here?)

- **Better ageing study designs are necessary to capture the early changes in the artificially aged cables**
- **Establish base line measurements for critical samples (a key to the future assessment)**
- **Test ranges of environmental factors that influence spectra**
- **Verify repeatability and identify parameters that need to be incorporated into a model for transferability between two instruments**
- **Investigate sensitivity to stabilizer/anti-oxidant content (OIT/OITP comparisons) - availability of samples**
- **If warranted, develop new tool for black insulations**

References and Acknowledgements

- IAEA, "*Assessment and management of ageing of major nuclear power plant components important to safety: In-containment instrumentation and control cables*", IAEA-TECHDOC-1188, v1, 2000.
- Subudhi, M., Brookhaven National Laboratory, "*Literature Review of Environmental Qualification of Safety-Related Electric Cables*", BNL-NUREG-52480 (NUREG/CR-6384), v1, 1996.
- Identification of Nuclear Cables Using a Non-Destructive, Non-Intrusive Near Infrared (NIR) Spectroscopy Technology (OPT Report: 6692-000-1998-RA-0001-R01), 1999.
- Identification of Cable Insulation at Bruce Power (Units 3 & 4), Bruce Power Document Reference: Bruce 'A' NK21-REP-03651-00002, NIR Identification of Cable Insulation at Bruce 'A' , Rev. 0, 2004.
- RCM Technologies, "*Qualification Test Report for Harsh Environment Testing of Cables for Point Lepreau and Gentilly-2 Stations*", Rpt. 13010-QTR, Rev. 02, 2003.

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The authors gratefully acknowledge Milad Debly of NB Power for generously providing permission to use their aged cable specimens and condition monitoring data. The contribution made by Aaron Law to this presentation are also appreciated.

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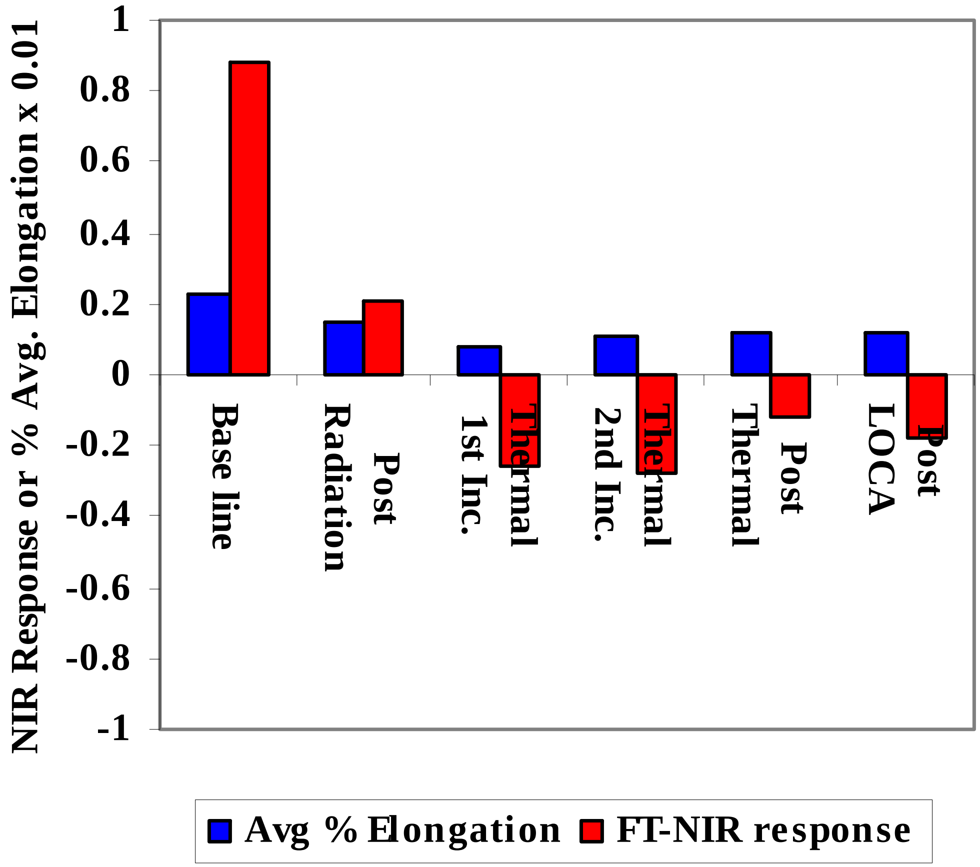
Questions?!?

FT-NIR vs Elongation

Cable 2 (FRPVC)



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Factorized Analysis

Identification Report FRXLPE
Post Radiation Sample

Identical To: Group 2 Cable 1, Post Radiation

Hit No.	Hit Quality	Reference File	Threshold
1	0.064653	Post radiation	0.137538
2	0.378062	Base line	0.092561
3	0.430845	Post thermal	0.060856
4	0.439855	2nd Inc. thermal	0.070036
5	0.474585	1st Inc. thermal	0.049324
6	0.949752	Post LOCA	0.100741

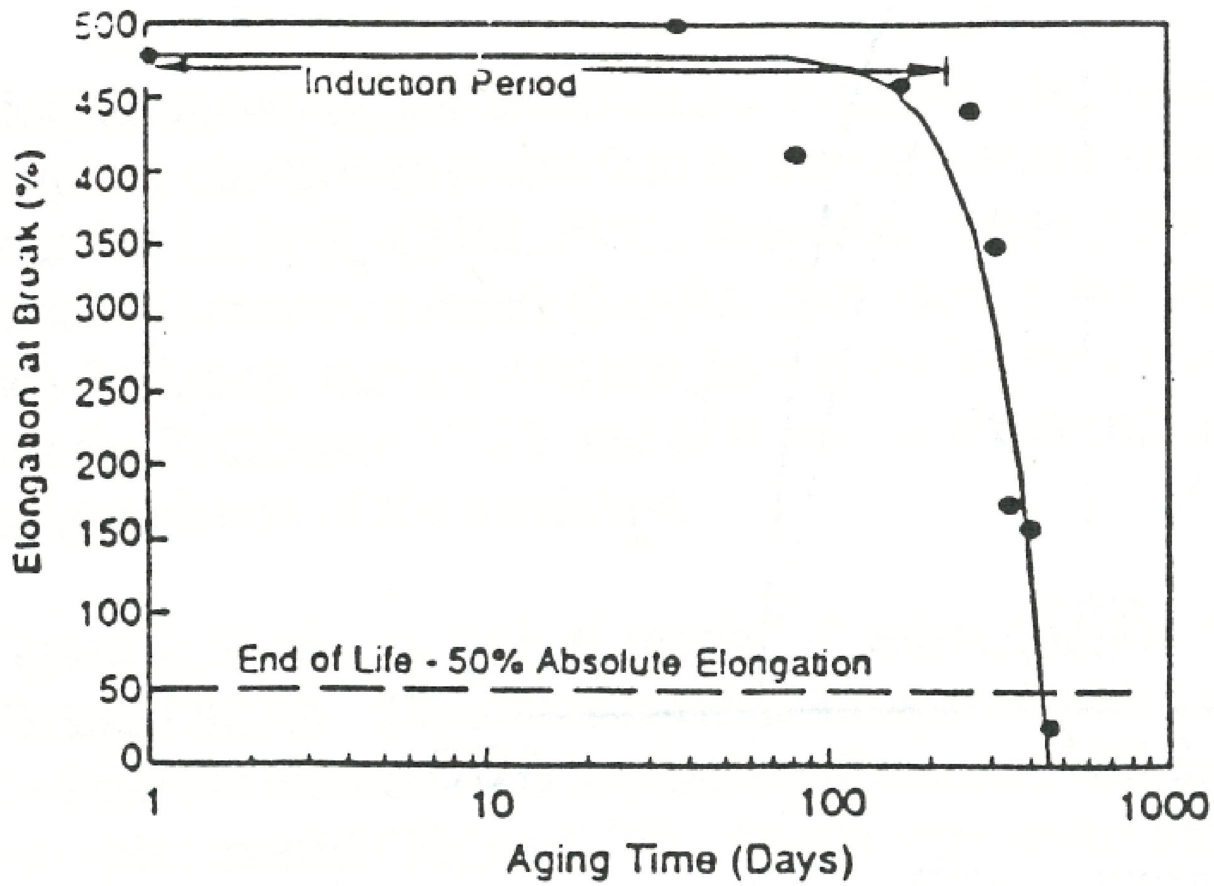
Factorized Analysis

Identification Report FRXLPE Post LOCA Sample

Identical To: Group 2 Cable 1, Post LOCA

Hit No.	Hit Quality	Reference File	Threshold
1	0.084123	Post LOCA	0.100741
2	0.401655	1st inc. thermal	0.049324
3	0.436327	2nd inc. thermal	0.070036
4	0.445327	Post thermal	0.060856
5	0.817297	Post radiation	0.137538
6	1.250974	Base line	0.092561

XLPE (EAB vs Ageing Time)



Source: EPRI TR-102399, 1993.

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