CABLE CONDITION MONITORING USING NON-DESTRUCTIVE AND NON-INTRUSIVE FOURIER TRANSFORM NEAR INFRARED (FT-NIR) SPECTROSCOPY

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Abstract:

The potential of using Fourier transform near infrared (FT-NIR) spectroscopy to monitor cable insulation condition and trend age-related degradation was investigated. The FT-NIR chemical finger-prints of PVC and XLPE cable insulation were significantly altered due to degradation resulting from irradiation and thermal aging. These spectral changes were correlated to critical property changes, i.e., average % elongation. The FT-NIR technique showed promise as an alternative to more traditional destructive chemical monitoring methods. The nuclear power industry is currently seeking cost-effective, non-destructive tools to support cable condition monitoring (CM) programs, now becoming recognized as essential to supporting plant life extensions and new builds.

1. Introduction

Most cable EQ programmes to date have been designed to support a qualified life of 30 or 40 years. As many plants consider extending operation to 60 years or more and analysis is used to extrapolate qualified life, the uncertainties inherent in the original sequential accelerated aging programmes become more pronounced. Also, as new plant construction is planned, modern equipment will require EQ and the most appropriate time to establish condition monitoring data is during their EQ test programmes. In response to these concerns, newly revised technical standards more explicitly recognize condition monitoring and “qualified condition” as a valid alternative, or complementary approach, to the traditional qualified life method of addressing ageing degradation. Regulators are also strongly encouraging incorporation of CM into aging management programmes.

Much industry effort and resources have been committed to developing effective CM methods but no one method has yet been demonstrated to suitably address all cable materials and issues [1, 2]. Instead, multiple methods must be integrated into an overall CM programme. The currently available CM methods may be divided into 4 categories; visual, electrical, mechanical and chemical, each having its strengths and weaknesses. This paper specifically investigates the potential of FT-NIR as an effective chemical CM method without many of the disadvantages of the chemical methods most widely used currently; namely OIT, OITP, plasticizer content and TGA.

The desirable attributes of any CM method are as follows:

a) Non-intrusive
b) Reproducible/repeatable
c) Non-destructive
d) Unaffected by, or may be adjusted for, environmental variations
e) Sensitive to rate of degradation
f) Applicable to a wide range of materials
g) Portability of test equipment
h) Assesses the entire length of cables
i) Cost-effective
j) Reliably detects characteristic assuring DBA survival (i.e. qualified condition)

It is the purpose of this paper to explore the hypothesis that FT-NIR is capable of satisfying all desirable CM attributes, with the exception of (h). Until now, the use of FT-NIR in the Canadian Nuclear industry has been limited to verifying material chemical formulation for the purpose of establishing similarity to test specimens [3,4].

FT-NIR optically scans insulation using a portable tool that is easily transported to the field and a probe that may be applied to the surface of insulation of energized cables/wires. Therefore, it inherently satisfies items (a), (c), (g) and (i) which the other methods do not, since they require material micro-samples for removal to a lab for destructive testing. Also, recent industry investigations have revealed that the current chemical methods may be vulnerable to variation in results without strict procedural controls to ensure identical test processes from one time and lab to the next. Without these controls attributes (b) and (j) are significantly challenged. With respect to repeatability of FT-NIR various cable insulation have been scanned as monthly check standards to make sure if the FT-NIR instrument is within the specified parameters. No one current chemical CM method satisfies (f). None of the chemical CM methods satisfies item (h).

2. Methods and Materials

To assess the effectiveness of FT-NIR as a CM technique, it was necessary to obtain incrementally aged material specimens. It normally takes many months to perform accelerated ageing of these specimens. Fortunately, Point Lepreau Generating Station (PLGS) had recognized that cable CM would be an essential part of supporting plant life extension and that early collection of condition data from the field was necessary to develop the degradation trends for prediction of remaining cable life. Collection of field data commenced in 1995 and the first phase of lab testing to define material degradation rates was completed in 2002 at RCMT [5]. PLGS generously offered the incrementally aged specimens from this test programme for the purpose of this study.

Although ten cable specimens were subjected to ageing trend tests, only three different cables having two different insulation materials, polyvinylchloride (PVC) and cross-linked polyethylene (XLPE) were selected for this study (Table 1). These cable specimens were selected because they represented generic insulation materials that are in wide industry use and would be expected to benefit most from a CM programme. These were abandoned cables that had been installed in the plant for 17 years.

Table 1 Cables used in this study

Cable #	Mfr	Configuration	Insulation/ Jacket	Type	Normal Service Conditions
2	X	14C#16AWG	FRPVC/ FRPVC	Ctl	Negligible radiation; Common, low temperature
1	Y	14C#16AWG	FRXLPE/ FRPVC	Ctl	Negligible radiation; Common, low temperature
7	Y	3C#2AWG	FRXLPE/ FRPVC	Pwr	Unknown but common across entire specimen

2.1 Specimen Preparation

Cables 1 and 2 were cut into 14 equal length specimens and cable 7 was cut into 10 equal lengths (because it was a short sample). In cable 1 and 2 specimens, one wire of each colour was removed and the copper conductors extracted to leave only the undamaged insulation tubes (as elongation test specimens). The insulation tubes were then rebundled within the jackets and the jacket slit and cable ends sealed with silicone RTV. Cable 7 specimens retained the conductor during aging following which dumbbell insulation specimens were cut for elongation tests.

The CM coupon specimens were tied together on a string and wrapped around a mandrel. These specimens were to be removed from the aging program at predefined points to collect incremental degradation data. Cables 1 and 2 also had 60 ft cable specimens wrapped on the mandrel to be used to monitor electrical performance during Design Basis Accident (DBA) simulation. Cable 7 was not monitored during DBA simulation testing. Cable specimen coupons were extracted at the completion of each phase of the ageing programme, summarized in Table 2, to collect CM data.

Table 2 Specimen Ageing Protocol

Ageing Phase	Aging Conditions
Baseline	Natural, 17 years, negligible radiation, low temp
Radiation	14 Mrads gamma @ < 44 krads.hr
Thermal, 1st increment	255 hours @ 100^{o}C
Thermal, 2nd increment	480.5 hours (cumulative) @ 100^{o}C
Thermal, 3rd increment	750.5 hours (cumulative) @ 100^{o}C
Post-DBA transient*	284 hours (additional) @ 90^{o}C (Transient was approx 6 hrs at 115^{o}C with short interval up to 130^{o}C)

* DBA simulation included saturated steam and elevated pressure. Cable 2 was exposed to an additional 115^{o}C for 5 hours.

2.2 Previously Collected Condition Monitoring Data

The Point Lepreau cable ageing programme collected various condition indication data for the aged cable specimens including, plasticizer content, compressive modulus (Indenter), insulation resistance, tensile strength, density and % elongation. However, no OIT data was collected. For the purpose of this study the % elongation has been included for comparison to NIR results. This is because % elongation has been recognized as the mechanical property that best indicates the ability of a cable to survive a DBA (assuming it can do so when new) [1, 2]. For previously qualified cables it was necessary to correlate condition indication (CI) data with % elongation data to estimate reliable service. However, for new qualification programs this may not be necessary providing the CI condition monitoring technique is capable of reliably detecting that the cable condition remains within that which was defined prior to exposing the cable to DBA conditions in the EQ test programme.

The Tinius Olsen Universal Tensile Testing Machine was used to perform elongation tests on each specimen group. The aged samples were stretched until failure and the results expressed in terms of % elongation. Elongation is defined as the change in length divided by the original length and expressed as a percentage (Table 3).

Table 3 Percent Elongation at Break Data [5]

Cable #	Insulation colour	% Elongation	
		sample	Average
2	Red, white, orange	Base line	227
		Post radiation	146
		Thermal 1st Inc.	80
		Thermal 2nd Inc.	105
		Post thermal	121
		Post LOCA	116
1	Pink. Green, Orange	Base line	384
		Post radiation	241
		Thermal 1st Inc.	259
		Thermal 2nd Inc.	279
		Post thermal	288
		Post LOCA	295
7	Pink, blue	Base line	382
		Post radiation	330
		Thermal 1st Inc.	58
		Thermal 2nd Inc.	57
		Post thermal	60
		Post DBA	Note 1

Note 1) The cable 7 specimen was so severely embrittled following DBA simulation that the conductor could not be removed to permit elongation testing without breaking the insulation.

2.3 FT-NIR Cable Insulation Scanning

Scanning and analysis of cable insulation was carried out according to NIR Technologies Inc.'s QA procedures [QA-NIR-003 and QA-NIR-004] using a square probe designed to maximise exposure of cable insulation to infrared light (Figure 1). A Bruker Optics FT-NIR Spectrometer (Matrix-F model) equipped with a custom designed rectangular probe from Remspec Corporation in combination with OPUS (Optics Users Software) software was used to obtain the spectra over the range 10,000-4000 cm^{-1} (1000-2500 nm). The fibre optic probe carrying the near infrared light was held against the insulation and on average five measurements of five scans per insulation were taken (for a total scan time of 25 seconds).

Figure 1 FT-NIR Spectrometer (inset the cable insulation probe)

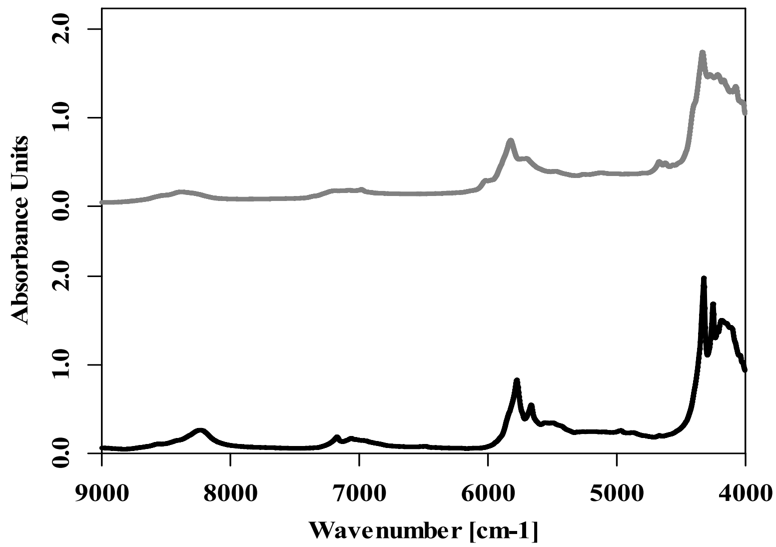
Spectrometer

Probe

3. Results and Discussion

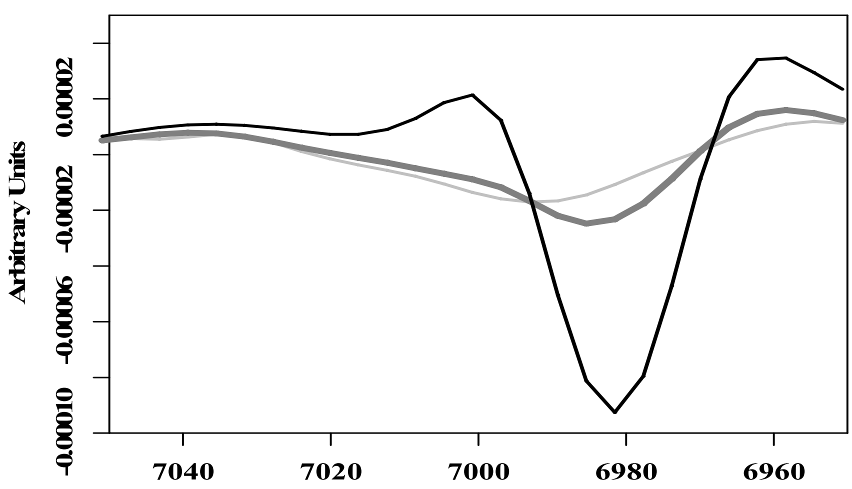
The FT-NIR spectra are composed of broad peaks due to combination and overtones of fundamental vibration in the infrared region. However, advances in instrumentation, computer power combined with chemometric analysis have made it possible to analyse the FT-NIR spectral finger prints. Figure 2 shows the absorption spectra for FRPVC (Cable # 2) and FRXLPE (Cable # 1). The absorption spectra of each material is a unique finger print of that material unless the chemical composition of that material has been altered i.e., thermal or radiation ageing. Using chemometric analysis available through the OPUS software, the second derivative spectra can be obtained that shows the differences more clearly. Figures 3 and 4 show the second derivative spectra for FRPVC and FRXLPE (base line, post radiation and post thermal samples) respectively.

Figure 2 Absorption Spectra for FRPVC and FRXLPE



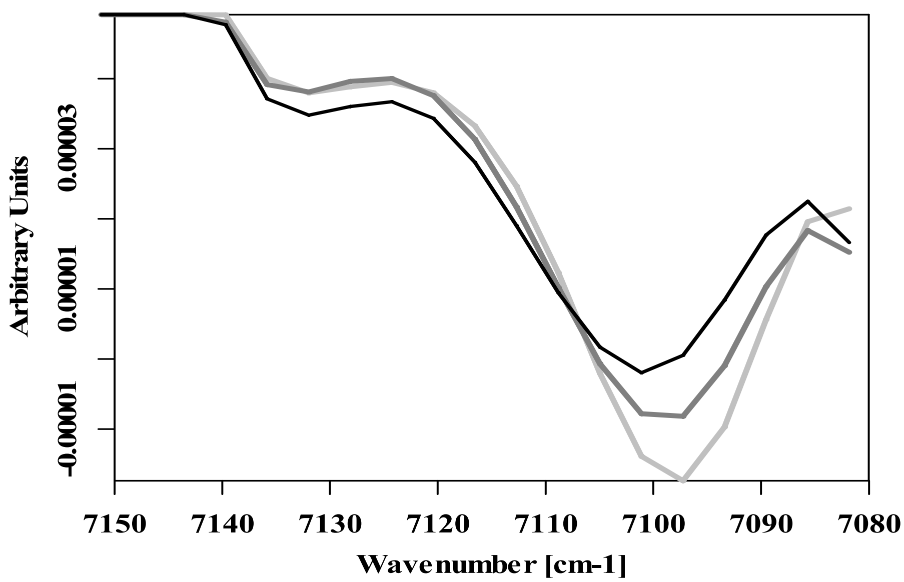
Grey = FRPVC and Black = FRXLPE

Figure 3 Second Derivative Spectra of FRPVC



Black = Base line, Charcoal = Post Radiation, and Grey = Post Thermal

Figure 4 Second Derivative Spectra of FRXLPE



Black = Base line, Charcoal = Post Radiation, and Grey = Post Thermal

3.1 FT-NIR Classification

Factorized analysis method available with OPUS software was used to classify the FT-NIR spectra of each cable at various ageing stages (baseline, post-radiation, thermal ageing 1st increment, thermal ageing 2nd increment, post-thermal, and post-DBA). In the factorized analysis, each average spectrum was assessed with respect to different components (known as vectors) present in each cable group. Several vectors combine together to form a classification model. Vectors are mathematical expressions used in quantifying changes and differences between data sets. Figures 5 and 6 show the factorized analysis for FRPVC and FRXLPE and as can be seen all samples at each stage of ageing can be distinguished from each other. The points presented in Figures 5 and 6 are averages of three different colour insulations (white, orange, and red for FRPVC or pink, green, and orange for FRXLPE). The chemical composition of all insulation in each cable is made of the same material. The effect of concentration of the colour pigment has very little effect if any on the spectrum. We chose these colours because the reflectance is affected by darker colours. In fact, black insulation absorbs the light and there is no reflectance and that is why black cables cannot be scanned by FT-NIR technology. No special precaution was undertaken before scanning the cable insulation, i.e., samples were scanned as received. 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 and report the comparison results. In fact, this is how the cable insulation classification (Qualification Groups) is achieved at both Ontario Power Generation and the Bruce Power nuclear stations [3,4].

Figure 5 Factorized Analysis of FRPVC (Cable 2)

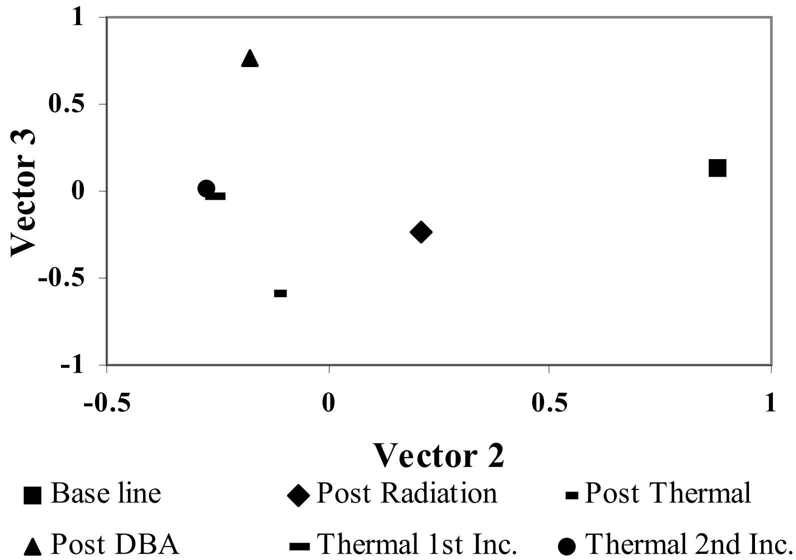
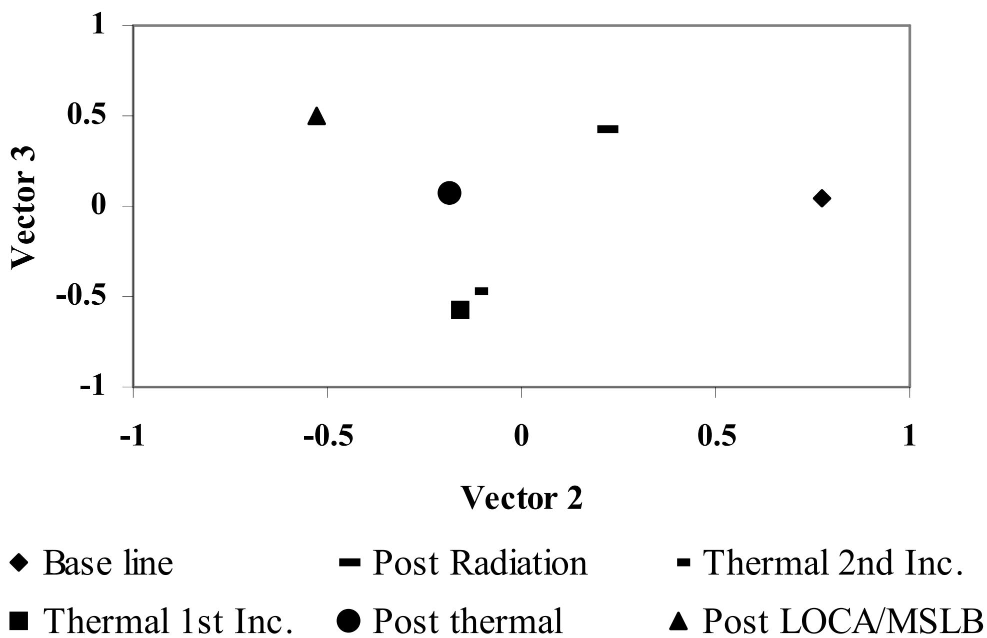


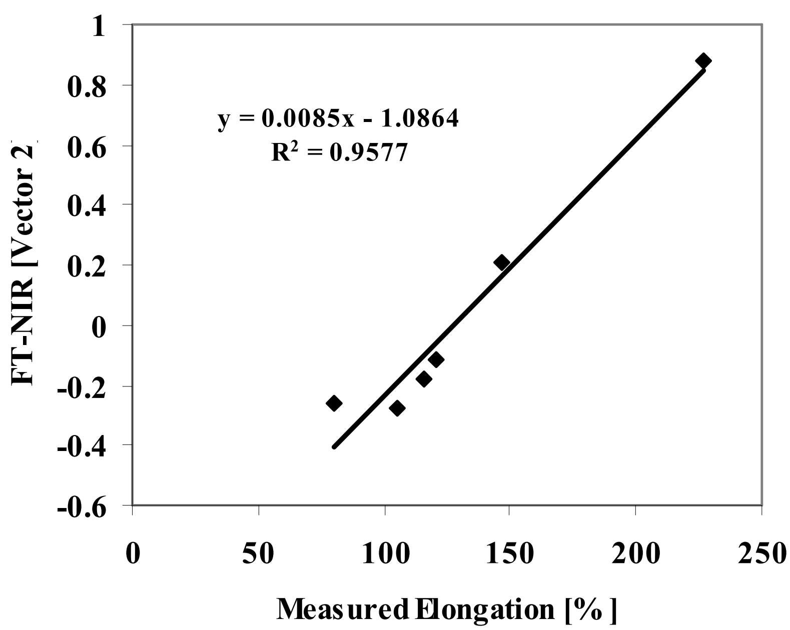
Figure 6 Factorized analysis of FRXLPE (Cable 1)



3.2 Correlation of FT-NIR results to average % elongation

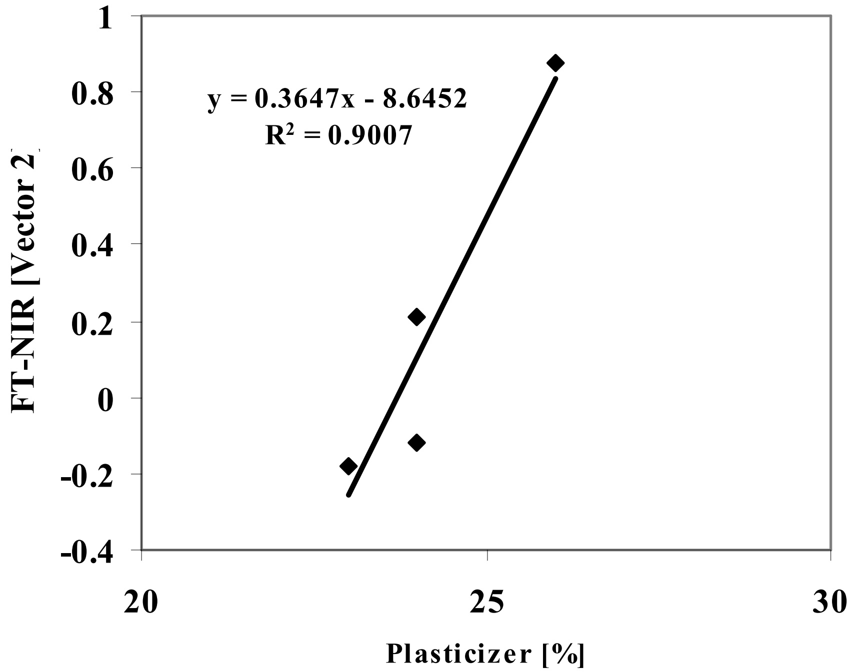
The results of FT-NIR (vector 2 values) were plotted against the average % elongation for the same set of aged samples. Figure 7 shows this correlation for FRPVC and as can be seen there is a good correlation coefficient of R^2=0.957 between the average % elongation (mechanical test) and the FT-NIR finger prints (chemical changes). In fact, the only value that is off is the thermally aged 1st increment that showed average % elongation of 80. Changing this value to 110 improved the correlation coefficient to (R^2=0.993). As indicated above chemical changes to each material is unique and, as a result, once a correlation between destructive test results and those from FT-NIR have been established, the model can be used in future for condition monitoring. This can simply be achieved by scanning the material non-destructively and comparing the vector 2 data to those in the model and predicting the status of the ageing within that particular cable.

Figure 7 Correlation of FT-NIR for FRPVC (Cable 2) to average % elongation



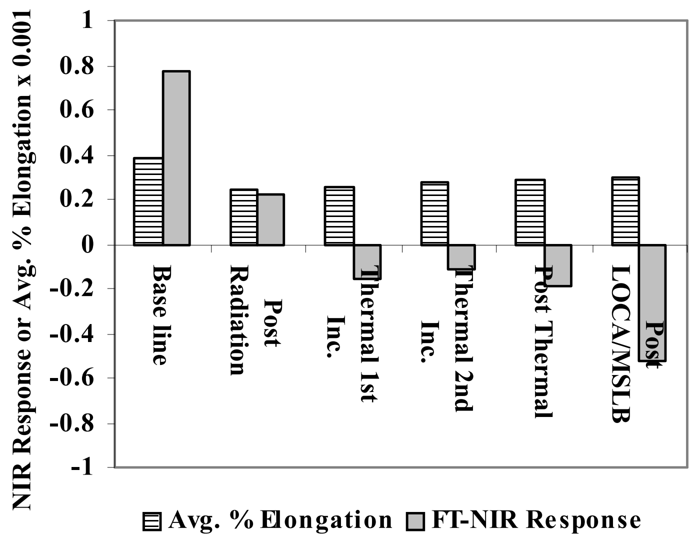
We also examined this correlation with % plasticizer content, once again a good correlation coefficient of R^2=0.90 was obtained (Figure 8).

Figure 8 Correlation of FT-NIR for FRPVC (Cable 2) to % Plasticizer Content



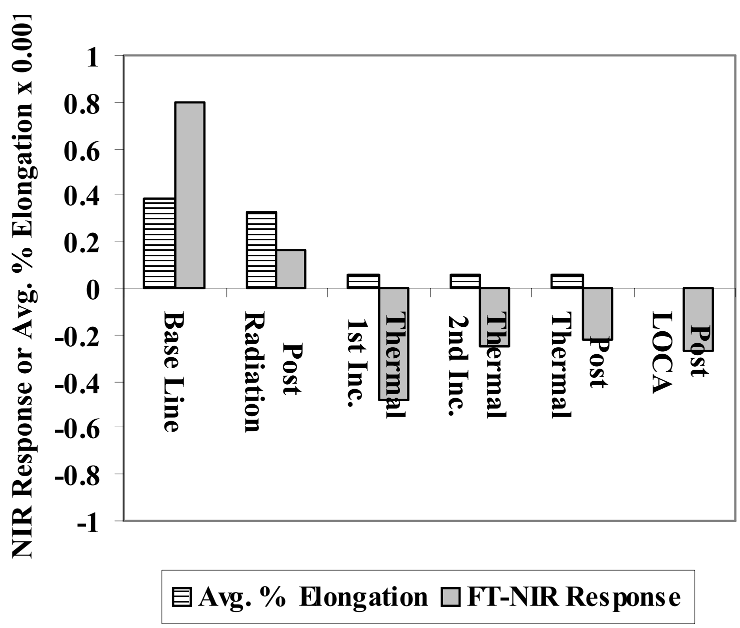
In contrast the Cable 1 FRXLPE insulation showed a sizeable drop in the average % elongation from 383% to 241% following radiation ageing but during the thermal ageing and post DBA it showed a slight increase. However, when vector 2 data for the FRXLPE cable insulation were plotted against the progressively aged specimen increments and compared to average % elongation, it clearly indicated that FT-NIR is very sensitive to the effects of ageing (see Figure 9). The above analysis shows the chemical changes in the FRXLPE as monitored by FT-NIR but the same cannot be tracked by average % elongation. This result indicates that the FT-NIR is sensitive in tracking chemical degradation in FRXLPE cable insulation prior to it manifesting in mechanical changes. The retention of average % elongation may be explained by internal cross-linking taking place following irradiation and 1st and 2nd increments of thermal ageing.

Figure 9 Correlation of FT-NIR data for FRXLPE (Cable 1) to Average % Elongation



We also examined the average % elongation data for cable 7 (FRXLPE) insulation with respect to changes in the FT-NIR response. Although both Cable 1 and 7 insulation were made of similar material by the same manufacturer, the average % elongation data showed totally different results (Figure 10). There is an initial drop following the radiation tests but a huge drop following the first incremental thermal ageing. Data were not obtained from the post-DBA sample since it was too severely embrittled. It is interesting to note that, despite a significant difference in % elongation results, FT-NIR data was very similar between cables 1 and 7.

Figure 10 FR-XLPE (Cable 7)



4. Conclusion

The FT-NIR fingerprint showed changes due to radiation, thermal and DBA ageing. These changes in the FT-NIR spectra were found to correlate very well with average % elongation for FRPVC with an R^2 value of 0.957. However, the same was not true for FR-XLPE, cable 1 where no significant elongation change occurred following the initial drop after radiation ageing and then remained constant throughout thermal and DBA ageing. In contrast, the FT-NIR response showed changes following each ageing increment with a continuous downward trend in the value of Vector 2. A similar FR-XLPE in a power cable showed a similar downward trend as observed with FT-NIR. These changes were material specific i.e., FRPVC or FRXLPE and it should not be assumed that can be applied universally e.g., to other PVC or XLPE materials. Once a cable condition monitoring model for a specific cable insulation has been established the follow up non-destructive and non-intrusive cable condition monitoring can be achieved easily.

Further research is necessary to explain the elongation trend discrepancies in the two FRXLPE cable insulations. In addition, it may be necessary to investigate if the sharp change following the 1st thermal ageing increment in Cable 7 was due to the early depletion of stabilizers and if FT-NIR may be as effective in tracking this as OIT. Since both of these methods track chemical changes such as depletion of stabilizers, anti-oxidants, it is anticipated that the FT-NIR can be as effective as OIT but without the disadvantages of destructive testing and strict procedural controls.

5. References

[1] International Atomic Energy Agency, “Assessment and management of ageing of major nuclear power plant components important to safety: In-containment instrumentation and control cables” IAEA-TECDOC-1188, Volume 1, December 2000

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Acknowledgements

The authors gratefully acknowledge Milad Debly of NB Power for generously providing permission to use their aged cable specimens and condition monitoring data.