Condition Assessment of Installed Nuclear Power Plant (I&C) Cables

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Condition Assessment (I&C Cables)

- **Destructive testing - Effective**
  - **Tensile Testing (All insulation types)**
  - **OIT (Oxidation Induction Time) (XLPE & EPR)**
  - **Plasticizer Content (PVC)**
  - **Gel Content (PVC & Butyl Rubber)**

- **Non-Destructive testing**
  - **Visual Inspection (All insulation types)**
  - **EPRI Indenter (PVC, Hypalon, & Neoprene)**
  - **Near Infrared (NIR) Spectroscopy (XLPE, EPR, & PVC)**

- No single tool will provide the desired confidence.
- A combination of techniques will improve the accuracy of predictions.

Comparison of Insulation & Jacket Types Installed in US and CANDU (OPG and Bruce Power) Nuclear Plants

	US Plants		CANDU (OPG and Bruce Power)	
	Inside Vault	Outside Vault	Inside Vault	Outside Vault
Insulation	FRXLPE, FREPR, Composite: EPR/Neoprene, EPR/Hypalon, FRXLPE/Neoprene	FRXLPE, FREPR, Composite: EPR/Neoprene, EPR/Hypalon, FRXLPE/Neoprene	FRXLPE, FREPR	FRXLPE, FREPR, PVC
Jacket	Hypalon, Neoprene	Hypalon, Neoprene	PVC	PVC
40 Yr Irradiation Dose	< 10 Mrad	0.1 Mrad	50 Mrad	0.1 Mrad
Temperature (Max.)	40-50◦C	40-50◦C	40-50◦C	40-50◦C

In Darlington NGS (4 Units, Net Output 3,512 MW)

Limited number of insulation formulations (safety related cables)

Jackets provide mainly mechanical protection, and have several formulations

All insulated wires and the majority of jackets are yellow colored (non black). This facilitates visual inspection

Visual Inspection – PVC Jacket Aging

As Received

40 days @ 110°C

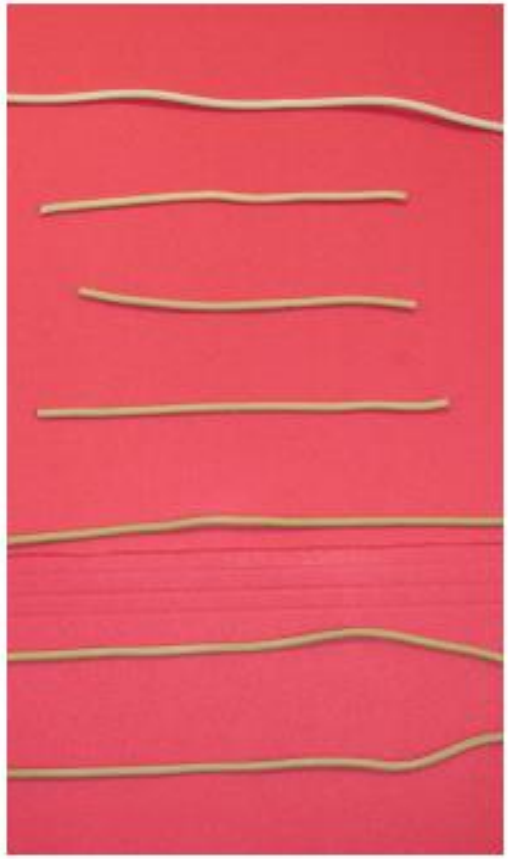
96 days @ 110°C

110 days @ 110°C

150 days @ 110°C

180 days @ 110°C

255 days @ 110°C



255 days @ 110˚C = 40 years @ 65˚C

Exposure to >100 Mrad needed for PVC jacket color change

Qualitative indicator of thermal aging

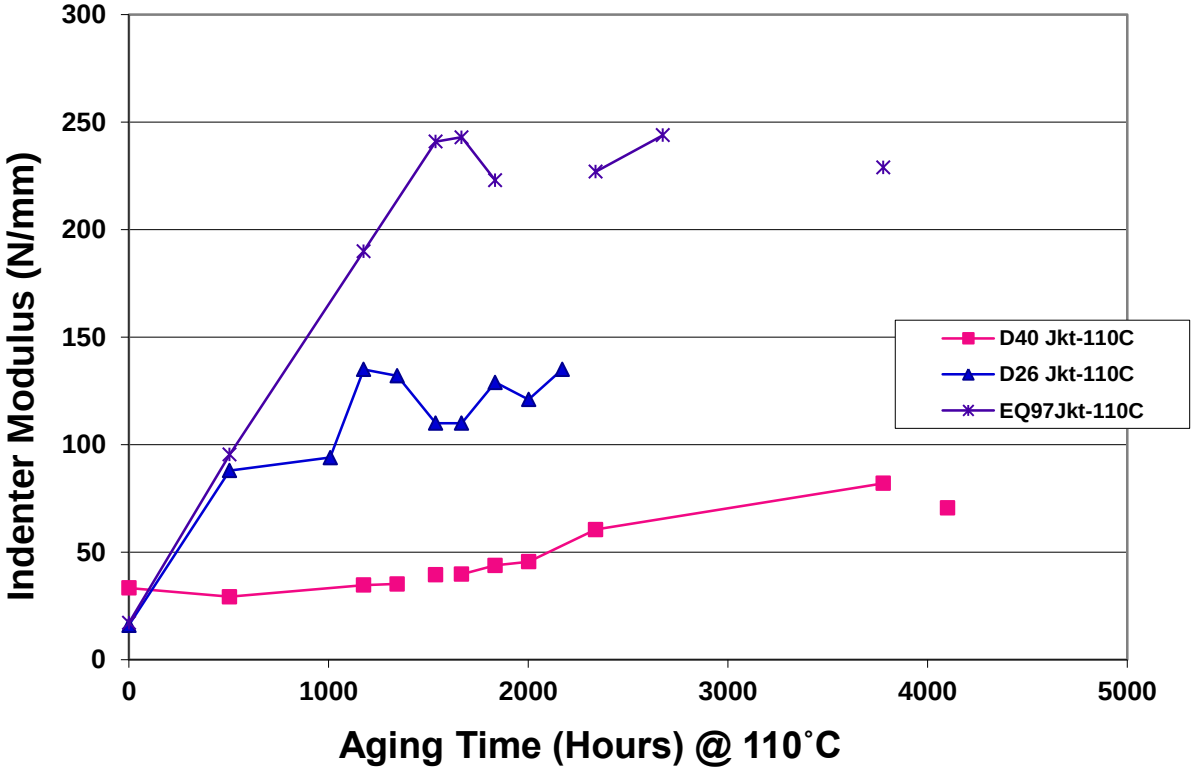
Non-Destructive Technique – Cable Indenter

The Indenter Tool as used in the lab

The Indenter Tool in a cable tray as used in the field

Suitable for: Thermal aging of PVC, Neoprene & Hypalon materials
Not Suitable for Radiation: >100 Mrads required for indication
Quantitative indicator of thermal aging

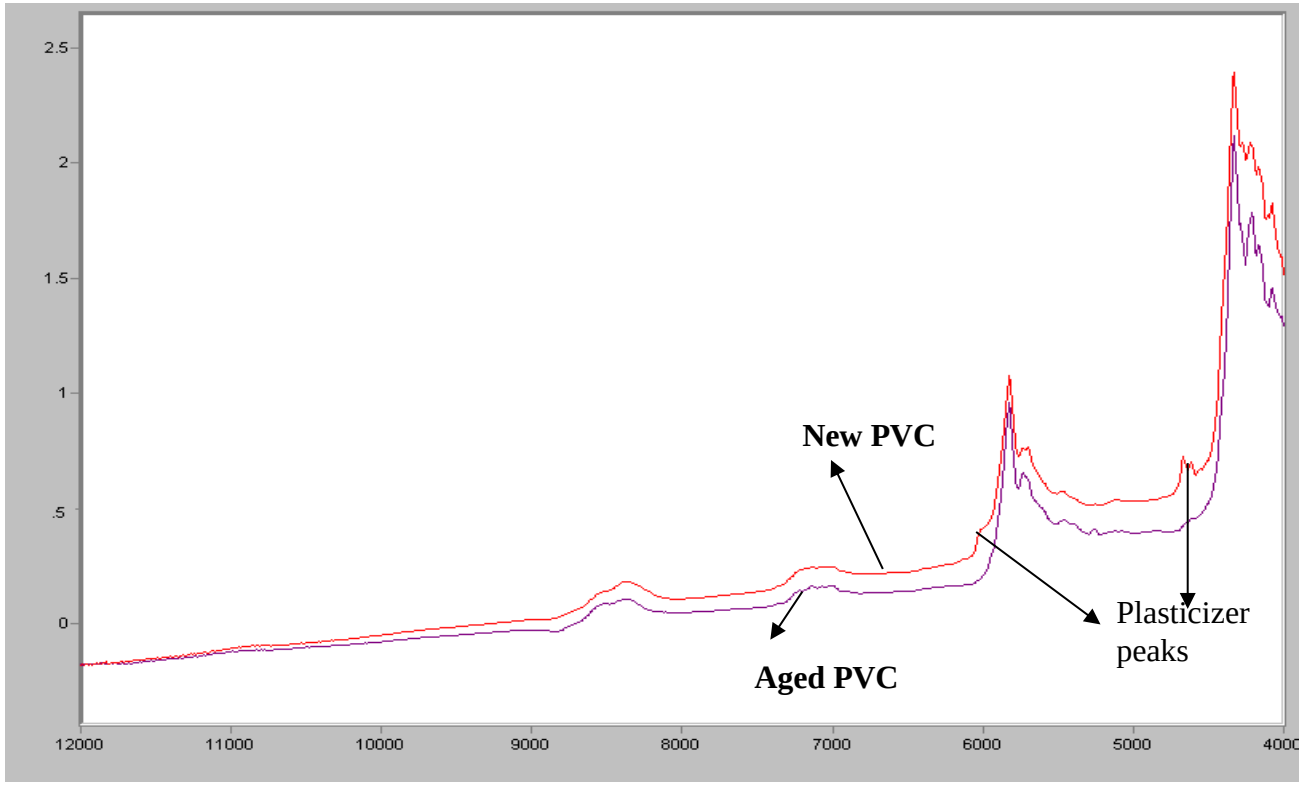
Indenter Modulus of 3 Yellow PVC Jackets



- Indenter Modulus > 100 N/mm = Hot Spot (Insulation must be checked)
- **Modulus increase correlates with aging time**
- **Good indicator of the condition of PVC cables used outside containment**
- **Eg.: Cable EQ97 ages rapidly i.e., If it shows minimal or no aging then other cables in that location must be ok (thermally)**

Non Destructive Technique - NIR Spectroscopy

NIR Change with Thermal Aging for PVC

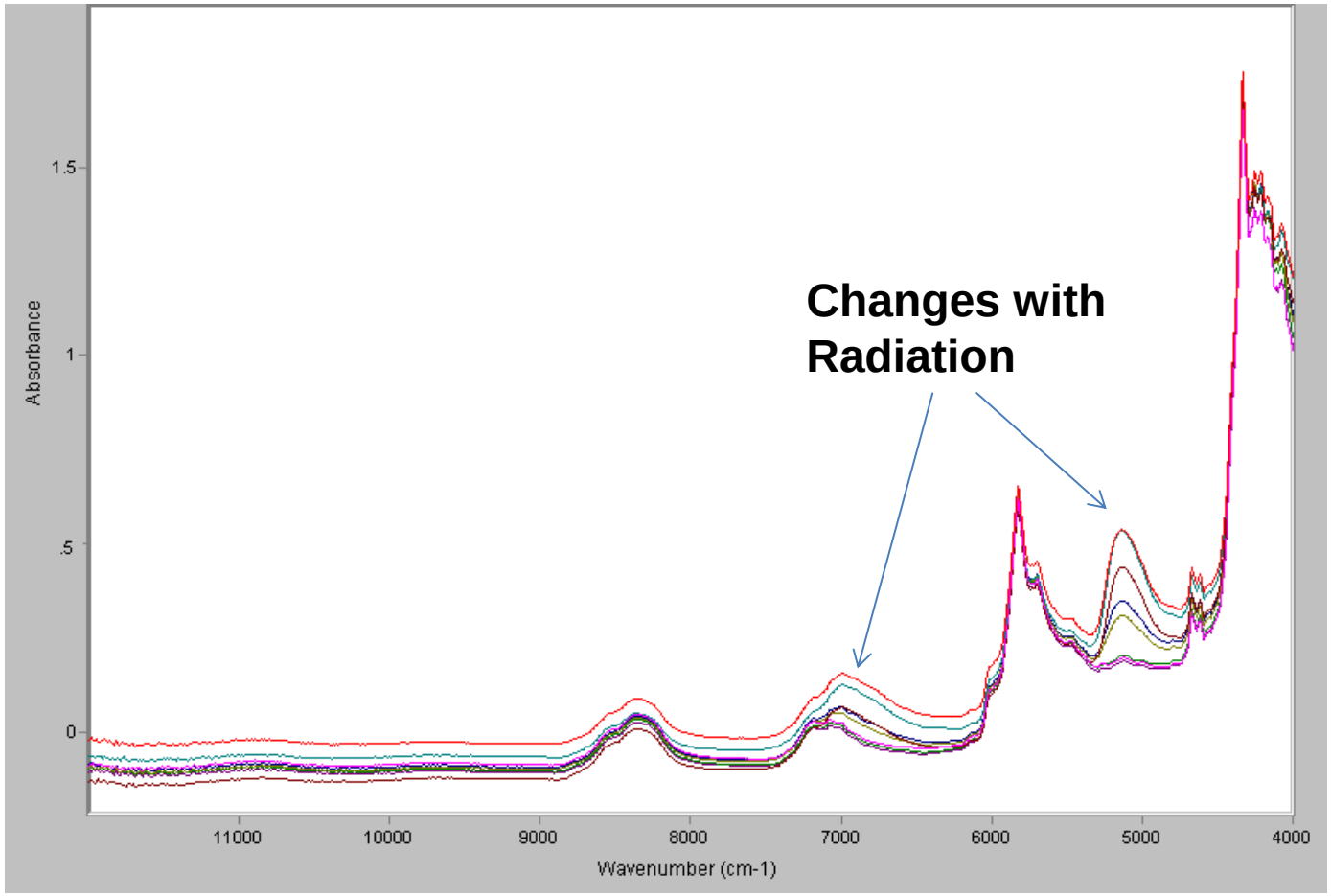


Intensity of the plasticizer peaks decrease with aging

(Normal plasticizer content >30% by weight)

NIR technology monitors loss of plasticizers – Primary thermal aging mechanism for PVC

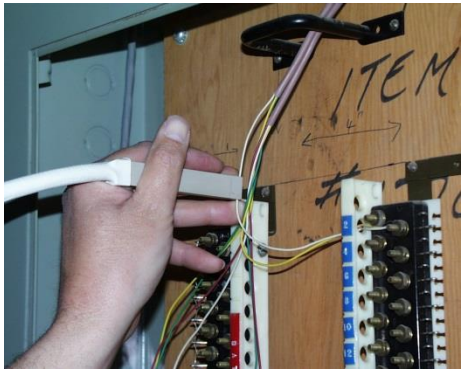
NIR Change with Radiation Aging for PVC (0 to 60 Mrad)



NIR monitors degradation due to exposure to radiation

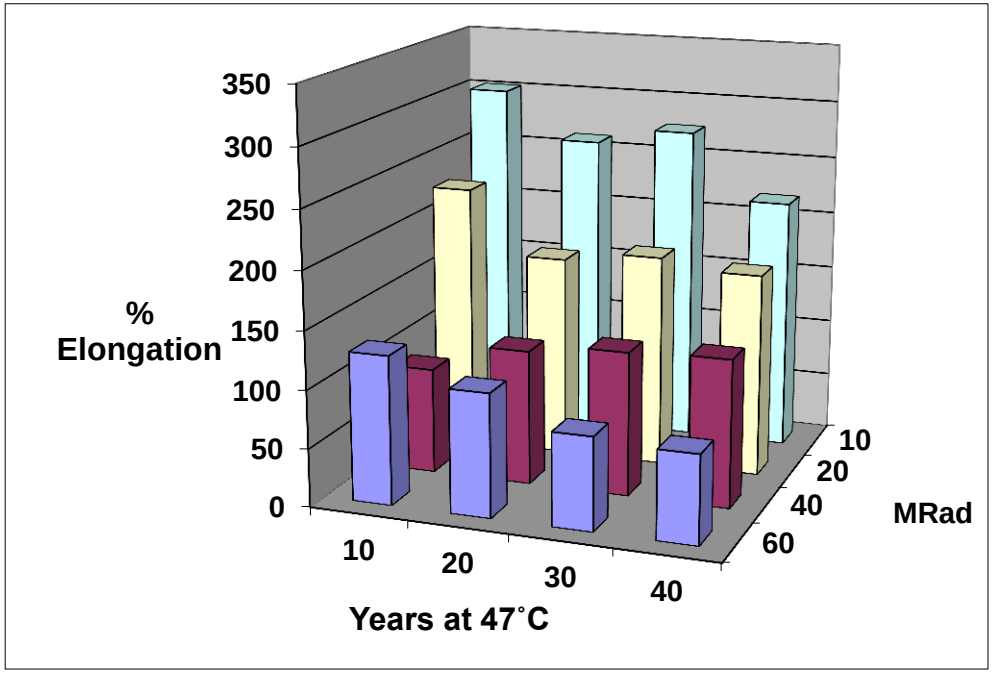
NIR (Near Infrared) Technology

- **Non-destructive – *Light Colors only***
- **Materials absorb IR at characteristic frequencies**
- **Capable of discriminating between formulations**
- **NIR is field proven technology in CANDU plants**
  - **Rugged instrumentation**
  - **Flexible, fiber-optic probe for easy access to cables**
  - **Used on > 10,000 in-service cable insulations in CANDU plants**



Elongation-at-Break – Acceptance Criteria

Elongation values of XLPE 1,2,3 insulation after irradiation exposure to 10, 20, 40, and 60 Mrad plus thermal aging equivalent to 10, 20, 30, and 40 years at 47◦C.



Elongation-at-break is very sensitive to both radiation & thermal exposure
Acceptance Criteria : 50% Absolute Elongation (for LV, XLPE & EPR Cables)

Kinectrics has developed aging models which can predict elongation values based on NIR spectroscopic changes

Construction of NIR Models - Samples

- **Most Common LV Safety Related Cable Insulation Types:**
  (a) XLPE 1,2,3,35, 38 (b) EPR 3,4,5 (c) XLPE 30
- **Cables Purchased from Canada Wire, Phillips, Pirelli, Shawflex, Alcan, & Northern Telecom between 1970 to 1995**
- **NIR Models constructed with insulation samples:**
  - **Naturally aged samples removed from Pickering, Darlington, & Bruce Power**
  - **Accelerated thermally aged samples (110 to 140◦C in air and under high O_2 pressure)**
  - **Accelerated Irradiation samples (Up to 100 Mrads @ 0.02 Mrad/h in air and under high O_2 pressure at room temperature)**
  - **Irradiated and also Thermally aged**

  Insulated wires of different thickness (#16 AWG to 8 AWG)

  Complete cables & Insulated wires alone (i.e., jackets removed)

- **Determined elongation at break values for all the above samples**
- **Collected NIR spectra of all the above samples**

Construction of NIR Models - Chemometrics

Partial Least-Squares (PLS)

NIR monitoring of aging based on spectral analysis in combination with mathematical (statistical) analysis of measured spectra.

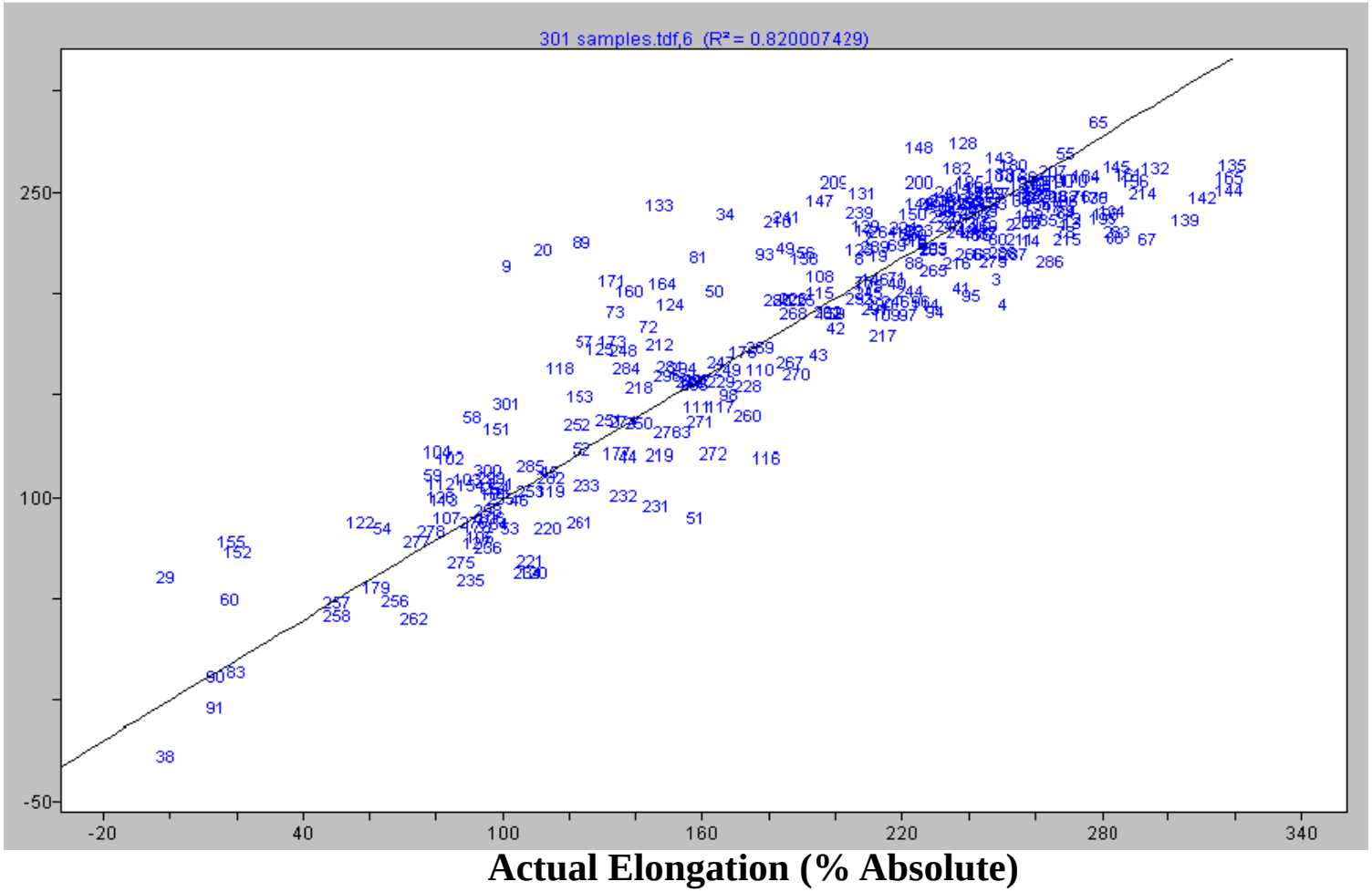
Calibration Models

NIR spectral data correlated with elongation at break

Applicability of Models- Mahalanobis distance (M-Dist.)

Statistical measure of how distant the samples are from the calibration set

NIR Prediction Model – EPR 3,4,5 Insulation



Actual elongation values Vs predicted for thermal, radiation, and radiation plus thermal aged EPR 3,4,5 insulated wires (removed 13 outliers out of 301 samples) $R^2 = 0.82$

Verification of NIR Models–Sacrificial Cable Spool

- Twelve (12) XLPE 30, XLPE 1,2,3 & EPR 3,4,5 insulated sacrificial cables (un-energized) placed in DNGS vault (Unit 4) during construction in 1984-1990
- Plant operation started 1992
- 3 to 6’ sections removed for destructive analysis in 2004 and 2014
- Cables underwent 12 and 22 years of field aging @ DNGS

- Temperature Range: 104F (40◦C)
- Radiation Exposure: 0.66 to 50 Mrad (22 yr estimated dose from EQ room condition manual)

Verification of NIR Models

Visual Inspection of 22-Yr Field Aged Cables

Photograph 1: K-504228-Cable -1

Photograph 2: K-504228-Cable #2

Photograph 4: K-504228-Cable #4

Photograph 5: K-504228-Cable #5

Photograph 8: K-504228-Cable #8

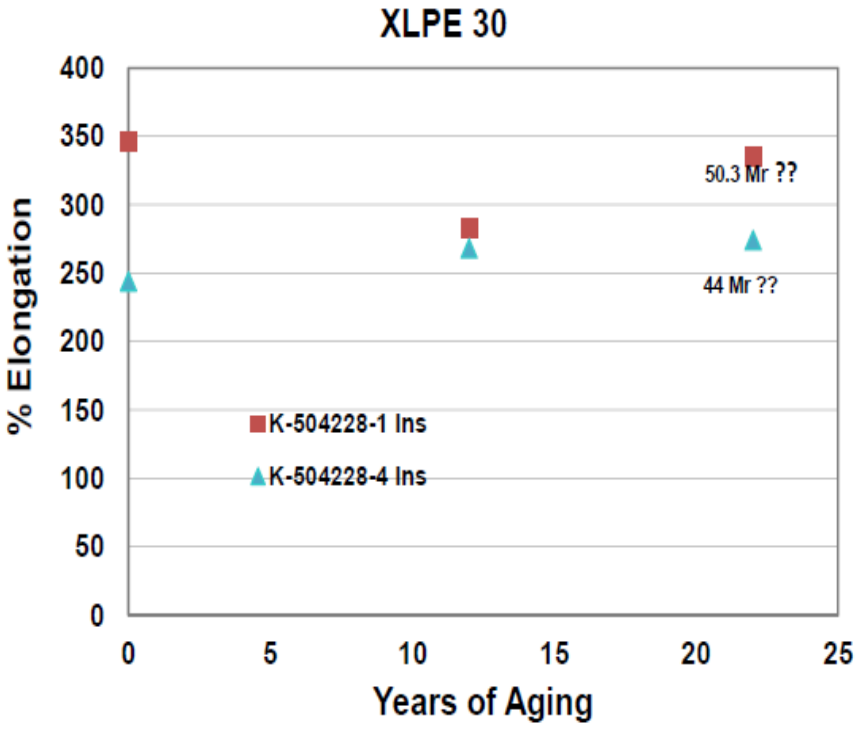
Photograph 9: K-504228-Cable #9

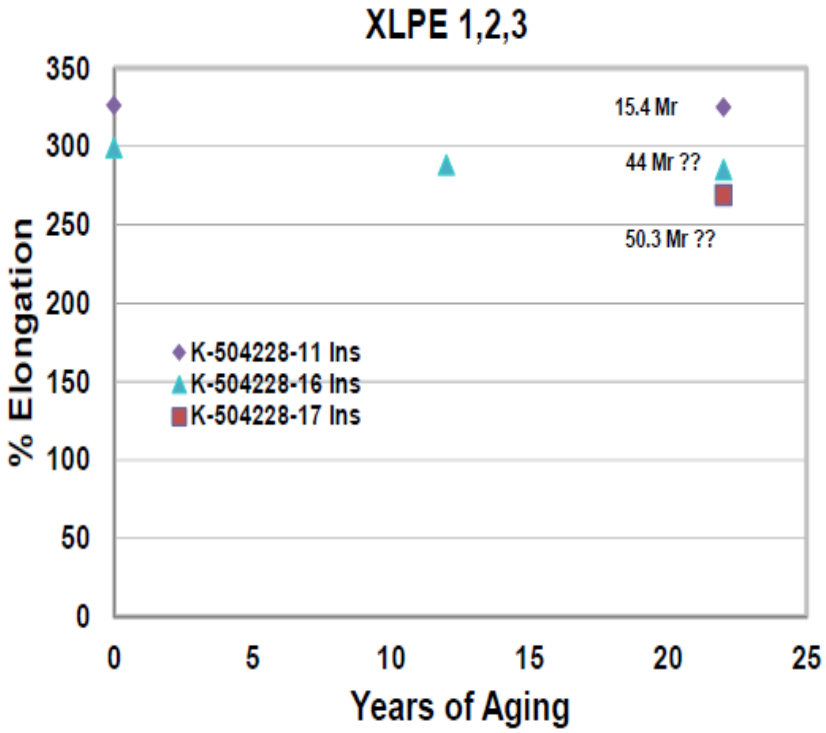
Photograph 16: K-504228-Cable #16

Photograph 17: K-504228-Cable #17

Photograph 12: K-504228-Cable #12

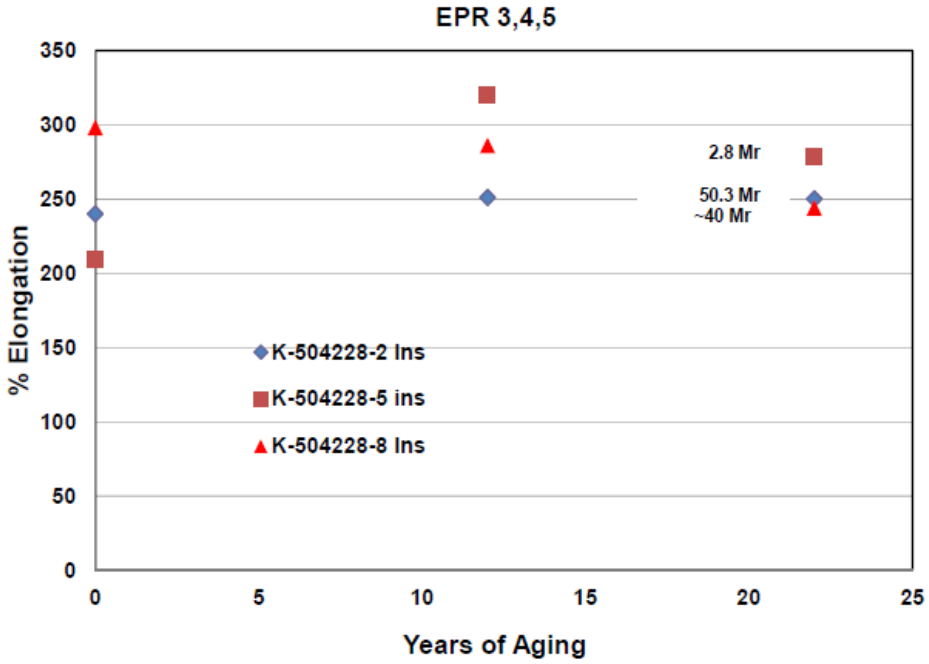
Elongation at Break Values of XLPE 30 & XLPE 1,2,3 Insulations (New, 12-Yr Aged and 22-Yr Aged)

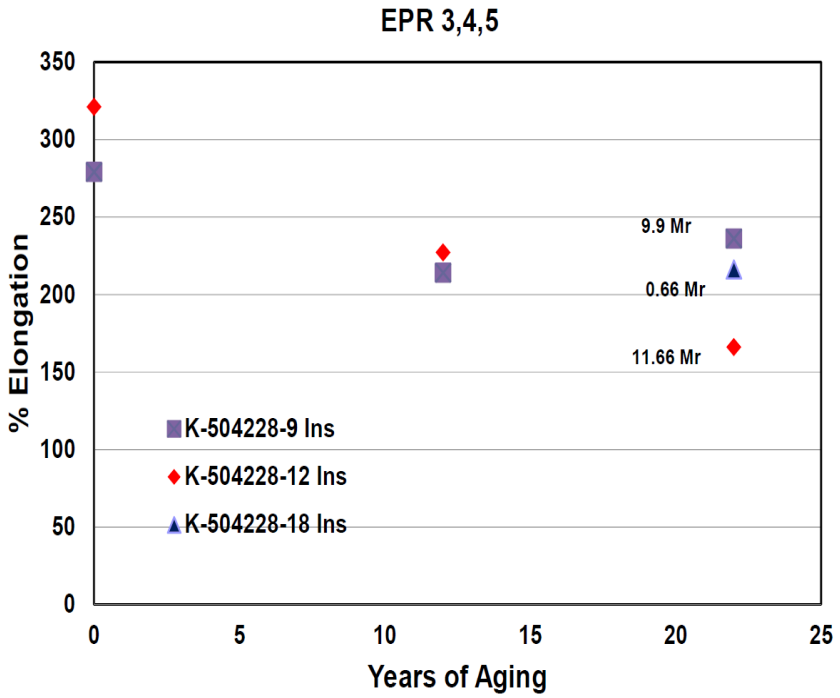




Estimated Radiation Dose (in Mrads) ?? from EQ Room Condition Manual
?? At this level of irradiation Elongation values should have dropped to ~100%

Elongation at Break Values of EPR 3,4,5 Insulations (New, 12-Yr Aged, and 22-Yr Aged)





Estimated Radiation Dose (in Mrads) ?? from EQ Room Condition Manual
?? At this level of irradiation Elongation values should have dropped to ~100%
K-504228-12 Ins - Elongation reduction due to composite insulation

Verification of NIR Models

NIR Predicted Elongation Vs Actual (Work done in 2007)

KINECTRICS

12yr Field Aged Cables From DNGS Vault

Cable Number	Cal Model	NIR Pred_Value (% Elongation)	M_Distance	Actual (% Elongation)	Insulation Type
K-010171-1	EPR 3,4,5 Elong.	-271	310	Not Applicable*	XLPE 30
K-010171-2	EPR 3,4,5 Elong.	276	5.4	251±11	
K-010171-4	EPR 3,4,5 Elong.	-292	377	Not Applicable*	XLPE 30
K-010171-5	EPR 3,4,5 Elong.	200	1.2	320±21	
K-010171-8	EPR 3,4,5 Elong.	282	1.1	286±13	
K-010171-9	EPR 3,4,5 Elong.	239	0.69	214±12	
K-010171-10	EPR 3,4,5 Elong.	215	0.91	197±22	
K-010171-11	EPR 3,4,5 Elong.	-329	381	Not Applicable*	XLPE 30
K-010171-12	EPR 3,4,5 Elong.	186	1.6	227±21	
K-010171-15	EPR 3,4,5 Elong.	200	1.3	227±15	
K-010171-16	EPR 3,4,5 Elong.	-210	112	Not Applicable**	XLPE 1,2,3

* Requires XLPE 30 Cal Model

** Requires XLPE 1,2,3, 35 Cal Model

Verification of NIR Models

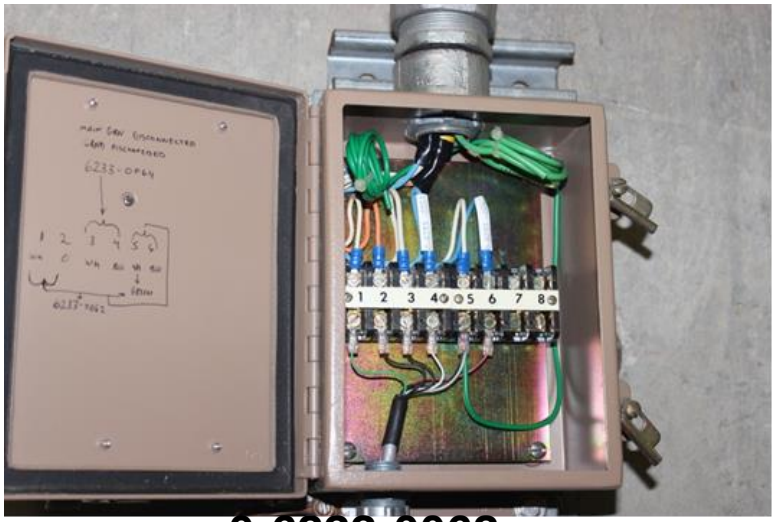
NIR Predicted Elongation Vs Actual (Work done in 2014)

KINECTRICS

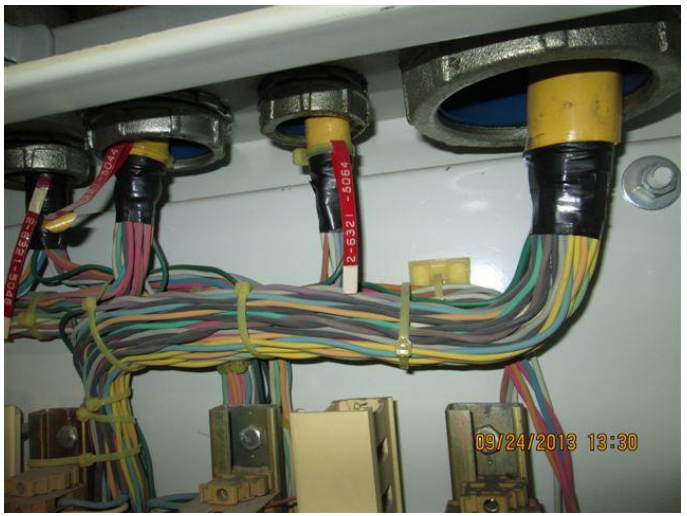
22yr Field Aged Cables From DNGS Vault

Cable Number	Insulation ID	Cal Model	Actual Elongation %	NIR Predicted Elongation at Break %	M-Distance
K-504228-1	XLPE 30	XLPE 30 Elong.	335±42	301	0.68
K-504228-2	EPR 3,4,5	EPR 3,4,5 Elong.	250±13	238	1.5
K-504228-4	XLPE 30	XLPE 30 Elong.	276±18	307	0.83
K-504228-5	EPR 3,4,5	EPR 3,4,5 Elong.	279±12	242	0.73
K-504228-8	EPR 3,4,5	EPR 3,4,5 Elong.	244±21	235	1.02
K-504228-9	EPR 3,4,5	EPR 3,4,5 Elong.	236±16	224	1.1
K-504228-10	EPR 3,4,5	EPR 3,4,5 Elong.	199±10	217	1.94
K-504228-11	XLPE 1,2,3,35	XLPE 1,2,3,35 Elong.	325±33	290	0.69
K-504228-12	EPR 3,4,5	EPR 3,4,5 Elong.	166±10	Dark Insulation	
K-504228-16	XLPE 1,2,3,35	XLPE 1,2,3,35 Elong.	285±33	257	0.61
K-504228-17	XLPE 1,2,3,35	XLPE 1,2,3,35 Elong.	269±11	326	2.86
K-504228-18	EPR 3,4,5	EPR 3,4,5 Elong.	216±27	240	0.58

Condition Assessment of In-Service Cables (DNGS) Subjected to Radiation



0-6233-0062



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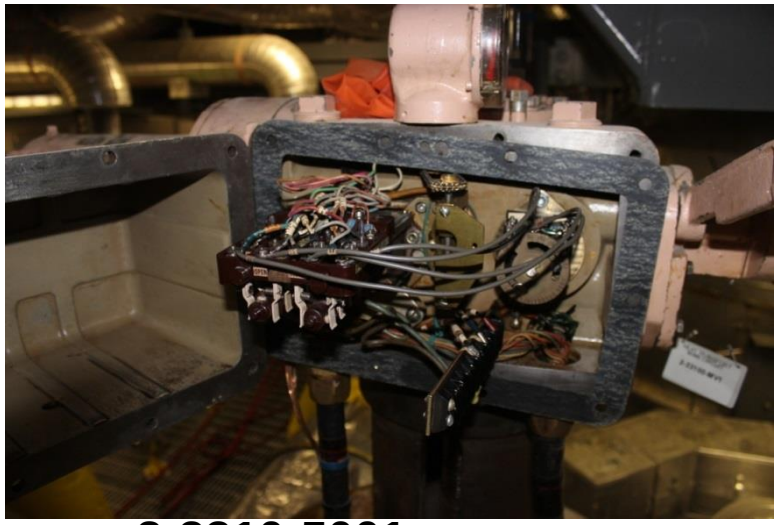

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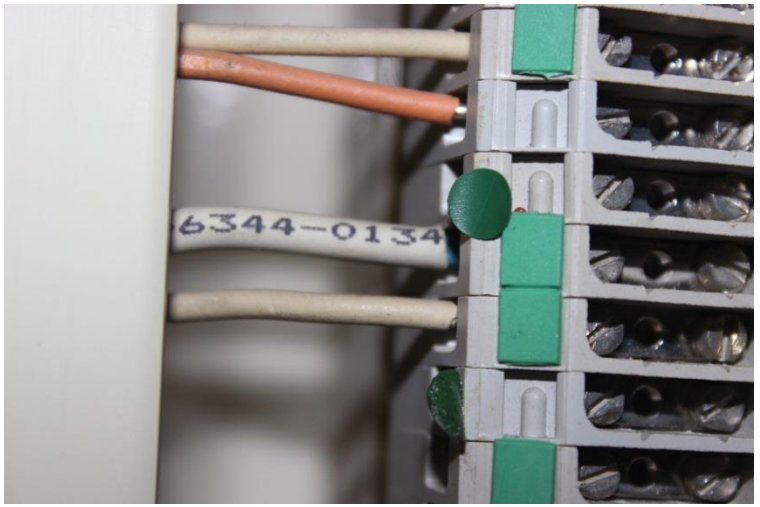

0-6344-0134

Condition Assessment of In-Service Cables @ DNGS

KINECTRICS

Cables Subjected to Predominantly Radiation Environment

Cable Number	Insulation ID	IM (N/mm)[1] Jacket	Typical Indenter Modulus @ 25°C Jacket (N/mm)	NIR Predicted Elongation at Break (Ins) %	Elongation Values of 22Yr Field Aged Spare Cables (Ins) (%)	Test Date
0-6233-0062	XLPE 30	23.7	20.5 to 27.8	322	276 to 335	30-Jul-2013
2-6022-9055	Unknown PVC	15.3	Not known Values similar to un aged PVC	N/A	N/A	25-Jul-2013
2-6321-5055	Kapton	N/A	Not Applicable	N/A	N/A	17-Sep-2013
2-6321-5064	XLPE 1,2,3,35,38	No Access	19.3 to 30.6	269	269 to 325	24-Sep-2013
2-3211-5004	XLPE 1,2,3,38	No Access	N/A	314	269 to 325	16-Oct-2013
2-3310-5001	XLPE 1,2,3,38	No Access	19.3 to 30.6	294	269 to 325	13-Sep-2013
0-6344-0134	XLPE 30	20.3	20.5 to 27.8	327	276 to 335	03-Dec-2013

1 Average of 5 Measurements, Force Range: 4.5 to 8.5 N, Ambient field temperature 25 to 27°C
N/A: Not Applicable

Conclusions

- ***Condition of PVC, XLPE, and EPR insulations can be assessed by nondestructive in-situ techniques – Visual, Indenter, and NIR spectroscopy.***
- ***Visual and Indenter methods can identify hot spots and determine the extent of thermal aging.***
- ***NIR spectroscopy can be used determine the extent of aging of cables used inside & outside containment.***
- ***Laboratory and field analysis indicates that the most common safety related I&C cable types @ DNGS are minimally aged after 22 years of service.***
- ***EQ Room Condition Manual (RCM) estimated radiation dosage appears to be higher than laboratory and field analysis indicates.***

OPG Dose Estimates - Historical

- Dose estimation was based on startup survey data, fixed area gamma monitors and 1 year passive monitoring in the vault at the approximate locations
- However, cables span various quadrants but average dose data was used
- Based on Kinectrics cable evaluations, Darlington cable dose estimates appear overly conservative

Darlington Path Forward

- Darlington will be installing 16 dosimeters throughout the vault in D1641 in key locations which do not have Fixed Monitors
- These dosimeters will allow the RCM to be revised to reflect the most accurate dose estimates