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Ageing Management of Cable in Nuclear Generating Stations

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EXECUTIVE SUMMARY

Power, control and instrument cables are intrinsically important to safe and reliable nuclear power plant (NPP) operation. International experience has indicated that, as operating plants have aged, the number and rate of cable failures has increased, implying that degradation due to ageing may be a contributing factor. With extension of plant life beyond the original design life of cables, the risk of failure rates increasing due to ageing degradation also increases and this may introduce new challenges to long term plant safety and reliability. Based on analysis of the available international and Canadian NPP cable failure history, the majority of cable failures have been related to random installation/maintenance damage or age-induced degradation due to adverse service conditions, particularly medium voltage (MV) cables in submerged environments. There has been no indication that cables in typical low stress environments are prematurely failing due to ageing.

The nuclear power industry has recognized that a comprehensive and coordinated cable ageing management program is needed to provide reasonable assurance that age-related degradation does not significantly affect the long term safe and reliable operation of NPPs [13.4][13.7][13.17][13.35]. Much effort and resources have been dedicated over the past 20 years to establishing the bases for such a program.

Information was gathered from representatives of the operating Canadian NPPs related to their experience with cable reliability and current programs or practices employed to address cable ageing [13.112][13.113][13.114][13.115][13.116]. Canadian NPP configurations and cable failure experience was assessed against international research, experience and regulatory guidance. It was concluded that the current international guidance on cable ageing management is generally appropriate and recommended for Canadian NPPs.

Recommendations for Canadian regulatory guidance were developed on this basis and core program elements established consistent with USNRC regulatory guide RG1.218 [13.35]. The following 11 core elements were defined as essential to an effective cable ageing management program (Section 12).

1. Definition of scope of cable to be addressed by program
2. Develop and maintain a database of all cables to be monitored
3. Characterize and monitor service environments.
4. Identify stressors and expected ageing mechanisms.
5. Select condition monitoring techniques suitable to monitored cables.
6. Establish baseline condition of monitored cables.
7. Identify cable characteristics/ageing effects monitored by each CM technique
8. Periodically perform CM tests and inspections on cables.
9. Periodically review and incorporate plant and industry experience.
10. Periodically review, assess, and trend the condition of monitored cables.
11. Identify degraded conditions and define/take corrective actions

Section 6 through 10 provide a review of Canadian NPP cable ageing management practices against the above CAMP core elements. While information from the NPPs was limited, it could be determined that none of the NPPs currently have a comprehensive CAMP that addresses all of the above core element requirements. Program gaps vary between NPPs but further information and analysis is required to accurately define the full extent of the gaps.

1.0 INTRODUCTION

1.1 Purpose

The objective of this study is to provide the background and technical basis supporting regulatory guidance, consistent with the requirements of CNSC regulatory document RD-334 [13.150], pertaining to the recommended core elements of a cable ageing management program in Canadian Nuclear Power Plants (NPPs). Significant international research and operating experience on cable ageing has been gathered over the past 20 years. This international experience has been reviewed against the current practices and configuration of Canadian NPPs to confirm applicability as a technical basis for establishing a systematic approach to cable ageing management in Canada.

A cable ageing management program (CAMP) must provide reasonable assurance that age-related degradation of cable does not significantly affect the long term safe and reliable operation of the plant. While existing plant EQ programs specifically address ageing of cables that are credited with safety functions in harsh environments, a more comprehensive cable ageing management program is necessary to also address those cables that affect safety and reliability under normal and abnormal operating conditions. Condition monitoring (CM) testing methods may be used to track and trend age-induced degradation of cables for the purpose of managing ageing; however, it is not the intent of a CAMP to test and monitor the condition of every cable within its scope. Rather, the majority of cables within a CAMP, in typically benign plant environments and operating conditions, may be addressed by representative cables in bounding conditions [13.35]. The objectives of a CAMP are best realized by focusing effort and resources on cables of concern [13.7]. By focusing on cables in worst-case environments, confidence is provided that other similar cables in less severe conditions are in satisfactory condition.

1.2 Background

Electric cables have typically been viewed as reliable, maintenance free components. With few exceptions, this has been the experience during the original design life of NPPs where the cables have been properly applied and operate in service conditions anticipated during design. However, in the past 5-10 years, reports of increased cables failure rates have emerged, primarily in adverse service conditions and particularly with respect to medium voltage cables operating in submerged conditions (Section 4.0). As NPP licensees apply to extend the operating life of their plants for 20 years or more beyond the original design life, the nuclear power industry has recognized the increased need to address the potential safety and reliability impacts of cable ageing degradation[13.1][13.4][13.14][13.17][13.35].

Since cables are ubiquitous across safety-related systems and all subject to reduced reliability with age, prognostic techniques are needed to provide sufficient foreknowledge of emerging ageing problems to permit planning and implementation of corrective actions. Care should be taken to ensure that monitoring methods themselves do not degrade the plant condition or operational reliability beyond the offsetting benefit of the data. Therefore, wherever possible, non-intrusive and non-destructive techniques should be favored. Since cables traverse many environmentally diverse zones it is also necessary to include techniques for identifying localized hot spots or adverse environments that may degrade the cable more rapidly or in concert with other ageing mechanisms.

Most Canadian cable EQ programs to date have been designed to support a plant design life of 27 or 40 years [13.53]. As many plants consider extending operation to 60 years or more and analysis is used to extrapolate qualified life, margins are eroded and the uncertainties inherent in the original sequential accelerated ageing programs become more pronounced [13.7].

As new plant construction is planned, modern equipment will require EQ and the most appropriate time to establish condition monitoring data is during EQ test programs. In response to these concerns, modern EQ standards more explicitly recognize condition monitoring and "qualified condition" as a valid complementary approach, or even preferred alternative, to the traditional qualified life method of addressing ageing degradation (Section 5.4). Similar approaches may be used for mild environment cables with some caution that the selected critical properties and their end points may be different (Section 4.3).

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. Instead, multiple methods must be integrated into an overall program. The currently available CM methods may be divided into 4 categories; visual, electrical, mechanical and chemical, each having its strengths and weaknesses.

The desirable attributes of any CM method are as follows [13.4][13.17]:

- Reliably detects characteristic relevant to continued performance with a well defined end condition
- Non-intrusive
- Non-destructive
- Reproducible/repeatable
- Unaffected by, or may be adjusted for, environmental variations
- Sensitive to rate of degradation and providing sufficient lead time to incipient failure to implement preventative actions
- Applicable to a wide range of materials applicable to NPP
- Portability of test equipment
- Assesses the entire length of cables and identifies location of defects
- Cost-effective and relatively simple to apply in field
- Immediately available

It is also essential that the techniques used are accurate and repeatable from the lab to the field and between labs. Round robin tests revealed that subtle differences in the procedures used by various labs/providers to collect material condition data can provide different results thus preventing their integration into a common program [13.8]. To address this, a new set of joint IEEE/IEC standards [13.100][13.101][13.102][13.103]

[13.104] are in development to standardize the processes for these methods to facilitate repeatability and interchangeability of data, regardless of the source. It is advisable to integrate these controls into any new cable condition monitoring program.

1.3 Importance of Cable Ageing Management

Power, control and instrument cables are intrinsically important to safe and reliable plant operation. International experience has indicated that as operating plants have aged, the number and rate of cable failures has increased, implying that degradation due to ageing may be a contributing factor (Section 4.0). With extension of plant life, the risk of failures rates increasing due to ageing degradation also increases and this may introduce new challenges to long term plant safety (Figure 1.1).

Defense-in-depth is the fundamental safety principle underlying the safety technology at NPPs. The defense-in-depth concept provides a series of overlapping measures and features that, when properly applied, ensure that no single human or equipment failure will result in harm to the public. Design provisions for normal operating and safety systems ensure that the three basic safety functions (control reactor power, cool fuel and confine radioactive materials) are preserved.

During normal and abnormal operation, plant safety function availability is generally protected from single cable failures by redundancy, separation and diversity of safety related systems and functions. Often, diversity in redundant systems is limited to the system operating principles and end devices but not extended to the cables which support those systems. This probabilistic reliability model is supplemented by a deterministic environmental qualification (EQ) program intended to address global events, such as a LOCA or SSLB, that may introduce harsh environments transcending the normal reliability barriers and result in common cause concurrent failures [13.11]. The NPP EQ programs are explicitly required to account for age-related degradation as it pertains to increased vulnerability to harsh environments, although many Canadian cable EQ test programs were designed to support a qualified life of only 27 or 40 years [13.53]. Condition monitoring may be required to extend qualified life based on condition [13.4]. However, it may be argued that even in mild environments, age-related degradation alone may become a common cause of concurrent failures if failure rates are permitted to increase as a result of inadequate monitoring and management as they enter the wear-out phase of the reliability bathtub curve (Figure 1.1) [13.11]. Cables outside the EQ program are not generally subjected to the same systematic approach and rigor with respect to ageing management.

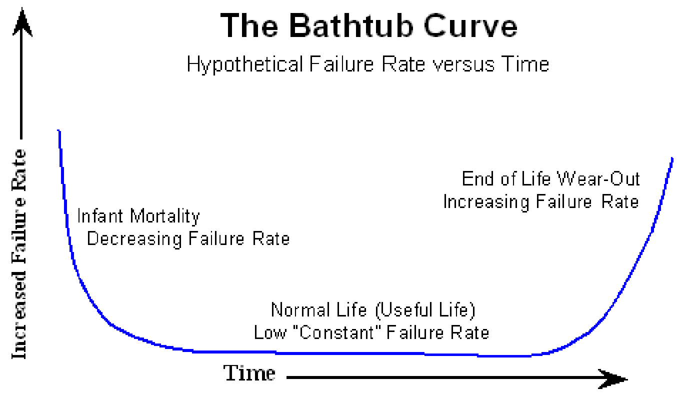


Figure 1.1 - Typical Bathtub Curve Used for Reliability Models

The first (infant mortality) phase of the curve illustrates the risk of early failure due to installation errors/damage, major manufacturing defects, etc. These failures are typically addressed by pre-installation screening (QA, receipt inspections, work controls, etc) and pre-operational testing (return-to-service tests, commissioning tests, etc). All of the operating NPPs are beyond this phase for bulk cabling and it is only relevant to new cable installations looking forward.

The second (normal life) phase of the curve represents the useful lifetime period with a relatively steady failure rate. Failures in this region are commonly referred to as “random failures” due to variations in material properties, manufacturing processes, isolated/localized events, etc. Failures during this phase are regarded as independent of degradation due to ageing and this relatively steady failure rate is addressed by the plant reliability analysis [13.11].

The third (wear-out) phase represents an increasing failure rate due to gradual age-related degradation. It is this phase that a cable ageing management program is intended to address. If failure rates are permitted to increase due the common cause of age-related degradation, then this may have a negative impact on defense-in-depth by increasing the probability and frequency of process system transients or failures and increasing the probability of mitigating component failures. A properly implemented defense-in-depth strategy is indicated by a smooth and steady NPP operation with little or no need to call upon safety systems [13.11].

There are plant cables that are not credited with a direct or supporting nuclear safety function but are significant with respect to reliable plant operation. Failure of these cables may result in plant trips or transients which introduce safety challenges. Many of these cables may be exposed to adverse service conditions which promote age-related degradation and failure. It is important to overall plant safety that ageing degradation in these cables is addressed prior to its resulting in failure during operation.

1.4 Scope

This study addresses plant electric power, control and instrument cables up to 15 kVAC and 250 VDC. Cabling internal to equipment is not included. Cabling accessories, such as splices, terminal blocks, connectors, etc are also outside the scope and are considered as cable interfaces. The scope of the cable ageing management assessment is safety related cables, and cables supporting reliable plant operation, including Class IV power. EQ cables are a subgroup of safety related cables and, by definition, must be enveloped by the plant cable ageing management program. However, since regulatory direction requiring management of EQ cables already exists and is currently addressed by plant EQ programs, the focus of this report is on cables outside the EQ programs.

Representatives of all 7 operating Canadian NPPs were interviewed to determine their experience with cable reliability what programs or practices may be employed to address cable ageing. An assessment of the current status of cable ageing management in the international nuclear industry is based on experience from research, cable failures, guidance and regulation drawn from open literature from organizations such as the USNRC, IAEA, NEA, EPRI and limited proprietary literature from COG.

2.0 APPROACH/ METHODOLOGY

The approach used to develop a set of recommendations for cable ageing management involved 4 main steps.

1. Collect and review current international industry information
2. Collect and review current domestic NPP information
3. Comparative analysis of international and domestic information
4. Develop recommendations for Canadian cable ageing management

There are many volumes of research and development information published over the past 20+ years devoted to identifying cable ageing characteristics, CM methods, ageing management strategies and collection of failure data (Section 13). In the beginning, the publications were primarily informative, but have become more instructive in recent years to support plant life extension activities. Open literature from organizations such as the USNRC, IAEA, NEA, and EPRI was collected for review. Limited proprietary literature from COG was also obtained and reviewed. However, the sheer volume of past work precludes a full review of every document.

The past 5-10 years has seen a flurry of activity in developing cable ageing management information, to support the many applications for plant life extension. Many of these publications build upon earlier reports to define the current situation. In these cases, attention is focused on the more recent publication. There were few direct reports of cable failures in open literature. As a result, relevant summary information from the NEA [13.1] was used to develop conclusions.

Interviews were conducted with representatives of all 7 Canadian NPPs to determine their cable failure experience and the extent of programs or procedures each has implemented to manage ageing of cables. Information provided by the plants was accepted at face value and supporting documentation was not sought or reviewed for verification. Each NPP was provided a transcript of their interview to confirm that details were accurately recorded and statements properly interpreted. All NPP comments were incorporated into the final interview notes [13.107 through 13.123]. Each NPP representative was asked for the following:

- Types of cables used and their function (overall plant):
  - A list of safety related and non-safety related cables and their types, all voltages, and
  - Non-safety related cables that may have operational significance, confine to Class IV systems, including controls.
- Relevant data on cable failure incidents.
- Existing ageing management programme for cables addressing following:
  - Scope,
  - Preventive actions to minimize control and ageing degradation to detect ageing effects,

    - Monitoring and trending ageing effects,
    - Mitigating ageing effects,
    - Acceptance criteria,
    - Corrective actions, and
    - Quality management.
- Technical basis for the adopted activities.
- Utilisation of feedback from the results of Research and Development, codes and standards.
- Trending degradation mechanisms, and consolidation of appropriate maintenance.
- Information on safety implications of improper ageing.

Cable failure and reliability information was gathered from the NPPs and compared to that experienced internationally to determine if the driving forces for international CAMPs is relevant to Canadian NPPs (Sections 6 to 10). Analysis of similarities and differences in plant configurations and experience was performed to confirm that the current international guidance for development of a CAMP is applicable and effective for Canadian NPPs. On this basis, the recommended core elements of an effective CAMP are provided in Section 12.

The NPPs were also requested to provide information related to plant programs and activities to identify, track and mitigate age-related cable degradation with a view to identifying gaps in their programs. However, none of the NPPs could provide a discrete list of safety related and operationally important cables and neither had a complete and coordinated cable ageing management program. Without a reasonably mature and coordinated program, and limited proactive ageing management activities, it was impractical to provide a useful point-by-point gap analysis. Instead, the cable maintenance and testing activities at each plant were compared to the recommended CAMP core elements to identify where some may be effectively integrated into a CAMP (Sections 6 to 10).

3.0 CABLING SYSTEMS DISCUSSION

3.1 Cable Construction

Insulated cables are used to transmit energy from one location to another. The amount of energy transmitted varies through several orders of magnitude. In a NPP the amount of energy transmitted by any one cable varies from 10^{-12} watts to 10^{6} watts. The transmission of this energy from the source of the energy to the end device is necessary to ensure the safe and reliable operation of a NPP. Due to the great range of energy being transmitted different types of insulated cables are used depending on the requirements of the specific application.

Almost all installed cables in nuclear power plants consist of a copper conductor surrounded by an insulated elastomeric material. These conductors are frequently bundled together with an elastomeric jacket. There are some exceptions to this type of construction which are discussed later. Cables which transmit large amounts of energy are classified as power cables as their function is usually for the sole purpose of transmitting energy from one location to another. These cables normally operate at voltages between 120V and 15kV in a typical NPP. Cables which transmit low levels of energy are normally used for plant control functions classified as Control Cables and normally operate at the millivolt level to 120V. These control cables have a set of specialized cables which are utilized for special applications where signal integrity is important. These cables are known as instrument/signal cables.

Power cables frequently contain additional features to deal with high operating voltages.

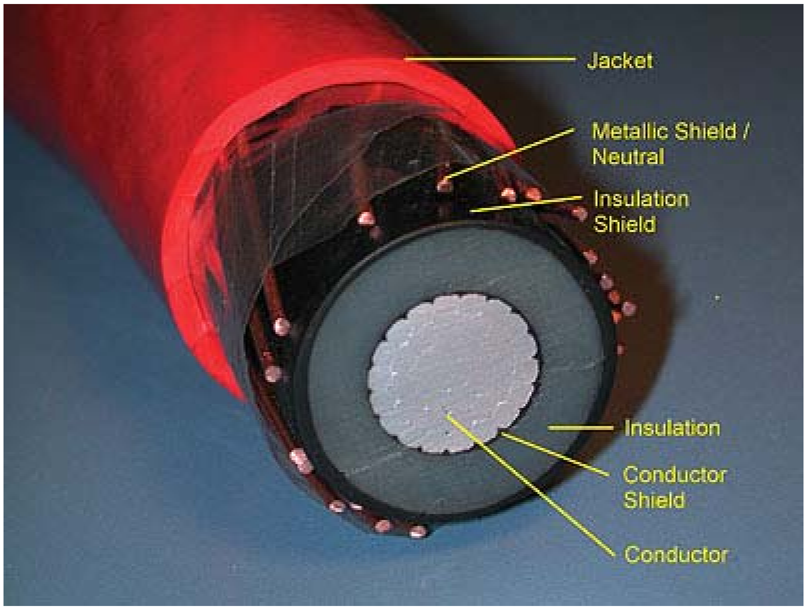


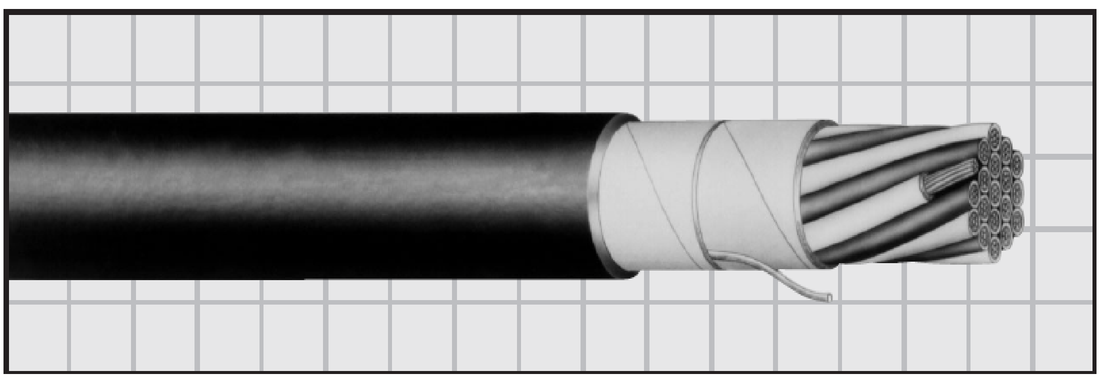
Figure 3.1 Typical Single Conductor Medium Voltage Power Cable

The differentiating features of a power cable are the larger conductor size required to carry the current necessary to meet the load, voltage and short circuit requirements of the application. The conductor shield reduces the voltage stress on the insulation by removing the insulating air between the conductor and the insulation. Insulation thickness will vary with the operating voltage of the cable. The insulation and metallic shield controls the voltage gradient across the cable insulation to prevent surface tracking on the cable insulation. In some cases where neutrals are used oversized insulation shields are utilized to carry the neutral current. Conductor shields and insulation shield are usually present on cables rated at 5kV or greater. There are several types of cable finishes which consist of jackets and armours. The most prevalent finish in Canadian NPPs is an extruded cable jacket which, in addition to protecting the cable, insulates the insulation shield from ground. Power cables operating at voltages of less than 1kV are not supplied with conductor or insulation shields.

Control cable can be divided into 2 classifications: general purpose cables and instrument/signal cable. General purpose cable is very similar to low voltage power cable and uses a very similar type of construction; that is an insulating material directly extruded over a conductor. In most NPPs general purpose control cables are of 2 types:

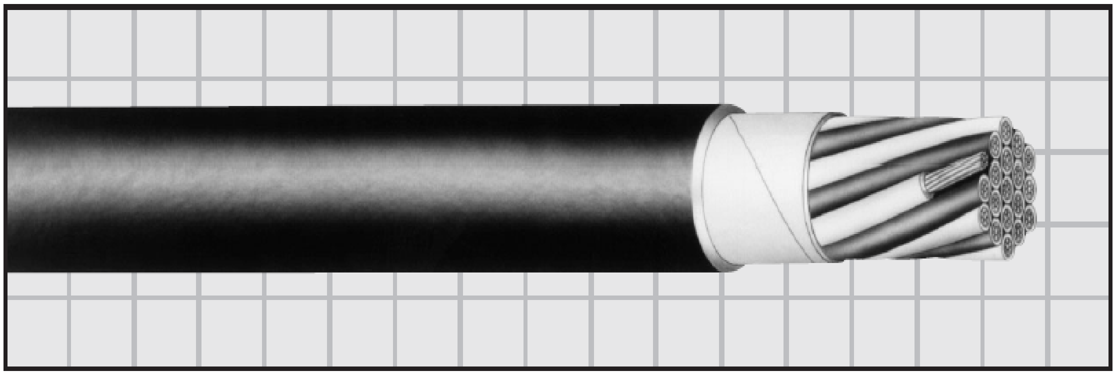
- 600V insulated unshielded control cable with an overall jacket
- 300V insulated twisted pair cable with an overall shield and jacket.

The 600V insulated cable is used primarily on circuits operating at 120VAC and the 300V cable is used on 48VDC control circuits.



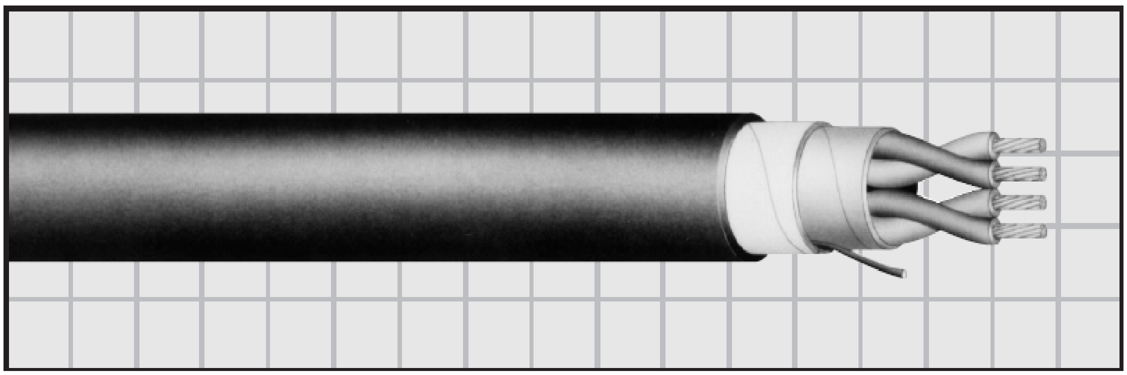
Sample Instrumentation Cable 600 V, Multi-conductor Shielded (from Rockbestos Firewall® III)

Figure 3.2 - Typical Shielded Control Cable



Sample Instrumentation Cable 600 V, Multi-conductor Unshielded (from Rockbestos Firewall® III)

Figure 3.3 - Typical Unshielded Control Cable



Instrumentation Cable 600 V, Multi Unshielded pairs with Overall Shield (from Rockbestos Firewall® III)

Figure 3.4 - Typical Control and Instrument/signal cable

Instrument/signal cables are associated with control and communication circuits which require specialized cables to deal with high frequency or requirement for low signal to noise applications. In these cases, depending on the specific application, conductors for each application (i.e. individual shielded and twisted pairs) or coaxial cables are used. A typical coaxial application in NPPs is Ion Chamber instrument/signal cables. These cables frequently require that the jacket be electrically intact to protect the overall cable shield from uncontrolled ground currents.

In a typical NPP, a number of specialized cables with different methods of construction may exist. These include mineral-insulated copper-covered cable, cable bus assemblies, heat tracing cables, fibre optic, and bare and insulated copper grounding cables.

The most common forms of insulation found in Canadian nuclear power plants are listed below. This information is taken from sections 6 through 10 of this report. Short forms for the compounds align with Canadian NPP usage. Chemical names for compounds align with those in IAEA-TECDOC-932 [13.10].

- Polyvinyl chloride (PVC) and Flame-Retardant Polyvinyl chloride (FRPVC)
- Cross-linked Polyethylene (XLPE) and Flame-retardant Cross-linked Polyethylene (FRXLPE)
- Ethylene Propylene Rubber (EPR) and Ethylene Propylene Diene-Monomer (EPDM)
- Magnesium oxide (MgO) found in MICC cable
- Polyethylene (PE) Thermoplastic found in co-axial cables
- Silicone rubber (SiR) found in high temperature applications
- Tefzel a copolymer of ethylene and tetrafluoroethylene (ETFE)
- Polytetrafluoroethylene (PTFE) (FEP) commonly referred to as Teflon
- Halar, a copolymer of ethylene and chlorotrifluoroethylene (E-CTFE)
- PEEK (Polyether ether ketone)
- Kapton a polyimide impregnated tape insulation usually found in high temperature applications
- Butyl Rubber
- Oil impregnated Paper (PILC) insulated lead covered
- Ethyl Vinyl Acetate (EVA) a copolymer of ethylene and vinyl acetate

Table 3.1 identifies typical application for each type of cable insulation. The capability of the insulation electrically and thermally establishes the service to which cable insulation can be used. Cost is also a factor.

Table 3.1 - Typical Applications for Cable Insulation Types

Insulation	MV Power	LV Power	Building Services	Control	Instrument / Signal
PVC/FRPVC		Yes		Yes	Yes
XLPE/FRXLPE	Yes	Yes	Yes	Yes	Yes
EPR/EPDM	Yes	Yes		Yes	Yes
MgO (MICC)		Yes	Yes	Yes	Yes
PE					Yes
SiR		Yes			
ETFE		Yes		Yes	Yes
PTFE				Yes	
E-CTFE				Yes	Yes
PEEK				Yes	Yes
Polyimide (Kapton)				Yes	Yes
Butyl Rubber	Yes				
Paper/oil (PILC)	Yes				
EVA				Yes	Yes

There is a wide number of cable finishes used in Canadian NPPs. These are frequently referred to as jackets, sheaths, armours, and braids. By far the most common finish is an extruded elastomeric jacket. The vast majority of cables are finished with a FRPVC jacket. More recent cables have been supplied with a Chlorosulfonated Polyethylene (CSPE, trademark Hypalon) or Cross-Linked Polyolefin (XLPO) jackets. Armoured finishes are present and are usually “TECK” cable which has an outer PVC jacket, and interlocking aluminum armour and an inner PVC jacket. In older plants aluminum sheath armour with a PVC jacket are found.

3.2 Stressors, Ageing Mechanisms and Failure Modes

Stressors in cable service conditions which potentially impact cable ageing can be divided into two categories.

1. Environmental stressors: continuously exist in the ambient environment surrounding the cable, such as heat, radiation, moisture, etc.
2. Operational stressors: induced by the system and day-to-day operation of the cable and plant, such as high voltage, electrical transients, ohmic heating due to loading, chemical contamination and flexing/vibration, etc.

Cables are always exposed to more than one stressor simultaneously and these multiple stressors may work in synergy or opposition when inducing material degradation. Error induced degradation/damage, such as design, installation, maintenance and manufacturing deficiencies are not strictly stressors; however, they may act as precursors to premature cable failure by exposing critical cable materials to increased stress or reduced margin to failure in cable properties. Where error induced degradation results in immediate or near term cable failure this is not related to ageing. However, in some cases, if a cable is damaged or not properly applied, installed or manufactured, it may operate for an extended period of time; but when combined with an adverse operational or environmental stressor may result in premature ageing and cable failure.

By their nature, these error based events tend to be isolated, localized and randomly distributed. Therefore, defense against these types of events adversely affecting continued plant safety and reliability is provided by probabilistic reliability based barriers, such as redundancy and separation (Section 1.3). The primary barriers to the occurrence of these types of events are plant Design, Maintenance, Operations and Procurement controls and Quality Assurance.

Cable ageing mechanisms are those chemical and physical processes, such as oxidation, cross-linking, scission, etc, which occur in a material as the result of a stressor being applied to a cable. The cable material properties are changed by the ageing mechanism which results in changes to cable performance. An example of this would be radiation making a cable insulation material more brittle. The cable then would be more prone to failure as a result of loss of elasticity and inability to accommodate cable movement.

Cable failures occur when one or more of the cable components fail in a manner such that the cable is no longer able to perform its essential function. This includes the conductor, the voltage shields, the insulation and the cable finish/jacket (Table 3.2).

Table 3.2 Summary of Stressors and Potential Ageing Mechanisms in Cables

Sub-part	Material	Stressors	Potential Ageing Mechanisms	Potential Ageing Effects	MV	LV	I&C	Comments
Insulation	Various polymer materials (e.g., XLPE, EPR, PVC)	Elevated temperature Elevated radiation fields	Embrittlement Cracking	Decrease in dielectric strength Increase in leakage currents Eventual failure	●	●	●	Elevated temperature due to combination of external environment and internal ohmic heating (power cables only).
	PVC	Temp >80C >15Mrads	HCl evolution Salt formation	Decrease in dielectric strength Increase in leakage currents	●	●	●	Elevated temperature due to external environment and internal ohmic heating (power cables only).
	Various polymer materials that are permeable to moisture	Wetting	Moisture intrusion	Decrease in dielectric strength Increase in leakage currents Eventual failure	●	●	●	Long term operation in wet or submerged condition can lead to water treeing.
	Various polymer materials that do not contain a tree retardant additive	Wetting concurrent with voltage	Electrochemical reactions Water treeing	Decrease in dielectric strength Increase in leakage currents Eventual failure	●			Tree retardant additives can mitigate this aging mechanism.
	Various polymer materials that have voids or other imperfections	Voltage Electrical transient	Partial discharge (corona) Electrical treeing	Decrease in dielectric strength Increase in leakage currents Eventual failure	●			Insulation must contain voids or other imperfections.
	Various polymer materials (e.g., XLPE, EPR)	Handling, physical contact, or abuse during maintenance, operation, or testing activities	Mechanical damage including crushing, bending, tensile deformation	Decrease in dielectric strength Increase in leakage currents Eventual failure	●	●	●	Only applicable to cables installed in accessible locations.
	Various polymer materials (e.g., XLPE, EPR)	Installation damage	Mechanical damage including crushing, bending, tensile deformation	Decrease in dielectric strength Increase in leakage currents Eventual failure		●	●	
Jacket	Various polymer materials (e.g., CSPE, Neoprene)	Elevated temperature Elevated radiation fields	Embrittlement Cracking	Loss of structural integrity Increased intrusion of moisture and contaminants into the cable interior	●	●	●	The primary function of the cable jacket is to provide mechanical protection to the cable during installation. A secondary function is to mitigate intrusion of contaminants to the interior of the cable.
	Various polymer materials (e.g., CSPE, Neoprene)	Handling, physical contact, or abuse during maintenance, operation, or testing activities	Mechanical damage including crushing, bending, tensile deformation	Loss of structural integrity Increased intrusion of moisture and contaminants into the cable interior	●	●	●	Only applicable to cables installed in accessible locations.
	Various polymer materials (e.g., CSPE, Neoprene)	Installation damage	Mechanical damage including crushing, bending, tensile deformation	Loss of structural integrity Increased intrusion of moisture and contaminants into the cable interior	●	●	●	
	Various polymer materials (e.g., CSPE, Neoprene)	Electromechanical forces due to electrical transient	Mechanical damage	Loss of structural integrity Increased intrusion of moisture and contaminants into the cable interior	●			Can occur if cable has conducted a high-magnitude fault current.
	Copper	Wetting due to	Corrosion	Increased electrical	●	●	●	Internal ohmic heating on

Conductor	Aluminum	moisture intrusion Condensation	Oxide formation Loosening of connectors	resistance Increased ohmic heating				MV & LV power cables only.
	Copper Aluminum	Vibration	Metal fatigue Loosening of connectors	Increased electrical resistance Degraded connector contact	●	●	●	Applicable to portion of cables near load terminations.
	Aluminum	Compressive forces	Cold flow Loosening of connectors	Loss of contact on connectors Increased electrical resistance Increased ohmic heating	●	●	●	Applicable to aluminum conductors with static mechanical connectors. Internal ohmic heating on MV & LV power cables only.
	Copper Aluminum	Electromechanical forces due to electrical transient	Mechanical damage including fatigue, bending, cracking Loosening of connectors	Loss of structural integrity Broken conductor strands	●			Can occur if cable has conducted a high-magnitude fault current.
	Copper Aluminum	Handling, physical contact, or abuse during maintenance, operation, or testing activities	Mechanical damage including fatigue, bending, tensile deformation, cracking Loosening of connectors	Loss of structural integrity Broken conductor strands Open circuit		●	●	
	Copper Aluminum	Installation damage	Mechanical damage including fatigue, bending, tensile deformation, cracking Loosening of connectors	Loss of structural integrity Broken conductor strands Open circuit		●	●	
Shield	Copper tape Copper wire	Wetting due to moisture intrusion	Corrosion Oxide formation	Loss of structural integrity Increased insulation degradation due to partial discharges Decreased EMI protection	●		●	Partial discharge applicable to MV power cables only. Decreased EMI protection applicable to I&C cables only.
	Semi-conducting polymers	Elevated temperature Elevated radiation fields	Embrittlement Cracking	Loss of structural integrity Increased insulation degradation due to partial discharges Decreased EMI protection	●		●	
	Copper tape Copper wire	Handling, physical contact, or abuse during maintenance, operation, or testing activities	Mechanical damage including crushing, bending, tensile deformation, cracking	Loss of structural integrity Broken conductor strands Decreased EMI protection		●	●	Decreased EMI protection applicable to I&C cables only.
	Copper tape Copper wire	Installation damage	Mechanical damage including crushing, bending, tensile deformation, cracking	Loss of structural integrity Broken conductor strands Decreased EMI protection		●	●	Decreased EMI protection applicable to I&C cables only.
Sheath	Lead	Alkaline environment (e.g., free line from concrete ducts)	Corrosion	Loss of structural integrity Increased intrusion of moisture and contaminants into cable interior	●			Applicable to MV power cables.

1. Table 3.2 adapted from NUREG/CR-7000, Table 2.1 [13.17].

Failures of the cable conductor result from a variety of issues. Degradation could occur from flexing/vibration due to equipment operation. Flexing failures also occur as a result of aggressive handling during installation and maintenance. Failures which result from flexing may be realized as failure of the conductor or failure of the insulation. The failure of the insulation may be further facilitated by embrittlement of the insulation resulting from thermal or radiation ageing. The failure could also be assigned to improper selection of the cable type to deal with flexing or improper installation to address the flexing.

The ageing of cable insulation manifests itself from the action of the ageing mechanisms acting over a period of time in combination with the service stressors to modify the performance of the insulating material. Most cable insulation is composed of a polymeric compounds or a copolymer of different compounds. In addition, additives are found in the cable insulation to impart specific properties to the insulation. The additives provide specific properties to the material such as fire retardancy, antioxidation and colour. These compounds are vulnerable to the stressors of radiation, temperature, electrical stress and humidity. It should be noted that electrical stress is usually only a factor in cables operating at voltages in excess of 1kV [13.8]. The effects of ageing on the insulating material manifest themselves in the following ways:

- Decrease in tensile elongation and tensile strength
- Change in the hardness of the material either softer or harder
- Evolution of hydrochloric acid (e.g. PVC)
- Change in density
- Change in electrical properties of the insulation (dielectric).
- The absorption of water and salts (water trees)
- Chemical contamination resulting from internal or external exposure

These changes in material properties if allowed to progress far enough will ultimately result in the failure of the cable.

An ageing mechanism of particular interest is the development of water trees in cables located in wet areas. A review of OPEX indicates this is a significant threat to plant cables which are subject to submersion (Section 5.2). It should be noted that water tree development takes a substantial amount of time. Long term wetting is required for the development of trees. Cable which are only occasionally wetted, such as in drained manholes are not considered to be submerged as long as the wetting is for a short period of time. Water is known to be drawn to the highest voltage stress point of the cable. The water will draw salts along with the water. Water and voltage must be present for damage to occur. Cables which are rarely energized are less prone to water treeing. Water trees in themselves do not cause a cable failure but water trees weaken the electrical performance of the cable insulation. With voltage stress water trees will change to electrical trees. An electrical tree will, in a relatively short period of time, result in a cable failure. This type of failure is found in both XLPE and EPR cables, with earliest onset of failure depending on the particular vintage and variation in material. Cables manufactured in the 1970's and 1980's are the most prone to this type of failure but the failure mode will still occur in cables of more recent manufacture. This is less probable for cables operating at 1 kV or less due to lower voltage stresses. Further guidance on the susceptibility of MV cables to water degradation and failure is available in EPRI 1020805 [13.64].

Each type of cable insulation will be prone to chemical changes from oxidation, radiation etc. The underlying chemical and physical changes are important in the development of ageing management tools. A basic understanding of these mechanisms is necessary to select the appropriate tool and to help in the interpretation of the results from testing programs. Information regarding failure mechanisms is provided in IAEA -TECDOC 1188 Volume 1 [13.7].

Cable jackets, while normally not critical to the cable operation, are required for the function of the cable in certain instances. In some cases the electrical performance of the jacket is required to prevent circulating current in the cable shields of medium voltage power cables and to limit noise in instrument/signal cables. The materials used in cable jackets in Canadian NPPs are effectively the same or similar to those used in cable insulation; hence the ageing mechanisms are similar. Cable jackets by their location are prone to damage as a result of installation, handling and ongoing maintenance activities.

While the transfer of energy from one location to another is the primary function of cables installed in NPPs, there are other types of degradation which could affect the cables' ancillary functions. For any particular cable these can be found in the original cable specification. Two specific areas of importance in NPPs are described below.

In Canada, cables are also part of the Containment boundary. Cables are required to enter into the various containment structures. In all Canadian NPP, except Darlington, this is accomplished by using the CANDU style cable penetration. There are several variants of this design but all designs effectively share a similar approach where epoxy is moulded over a cable. In some cases the epoxy is moulded directly over the cable insulation to make the cable penetration. In this case, the sealing of the cable strands (when present) and the dimensional stability of the insulation is important to the function of the cable. Where this is the case, the Containment function of the cable insulation may be monitored using condition indicators (e.g. compressive modulus, OIT, etc) that are linked to mechanical integrity of the insulation, such as elongation-at-break, where necessary. In some plants, silicone grease air tight (SGAT) cable has been used to seal the strands. In newer plants, stranded conductors are eliminated and the penetration is formed by moulding to a solid conductor.

Cables installed in Canadian NPPs are required to be Fire Retardant [13.105]. It has been reported that some utilities replace cables with cracked jackets due to concerns with respect to the impact of the cracked jacket on fire retardancy [13.7]. However, data collected from various countries has indicated that, for the bulk cable materials of concern in Canadian NPPs (i.e. XLPE, EPR, EVA and PVC), ageing has no adverse effect on material fire properties [13.1].

3.3 Cable Routing and Environments

In a typical Canadian NPP, cables are present in almost all physical locations of the power plant. This leads to a large variation of type and amplitude of ageing stressors. Cables can run through a large number of plant areas and the stressors on any one cable circuit can vary greatly over its length. The stressors which typically change over the route of any one cable are:

- Temperature
- Radiation
- Humidity/submergence
- Chemical contamination
- Presence of chemical by-products from cable ageing

The presence of submergence has been identified by operating experience (OPEX) to be a contributing factor to the failure of cables [13.43]. The submergence of cables frequently occurs from cables being routed in below ground cable ducts, trenches and manholes. In addition, cable can become submerged if routed in conduits which do not have adequate provision for drainage.

An extreme example of the degree to which a cable circuit environment can change over it length is the reactor flux measurement horizontal ion chamber signal. The ion chambers are mounted on the outside wall of the reactor in a tube contained within the shield tank. In this location the ion chambers are exposed to the high radiation fields and the elevated temperature of the shield tank. Due to these extreme conditions, the Ion Chambers are supplied with integral mineral insulated and jacketed cables as the radiation fields exceed those for which most polymeric compounds can withstand. These mineral insulated cables are routed through shielding material to the outside of the shield tank into the reactor vault. Once in the reactor vault, the mineral insulated cable is connected to a polymeric coaxial cable. In the reactor vault the cables are subjected to the normal elevated radiation and temperature conditions of the vault as well as the elevated radiation and temperature radiation levels found in the post LOCA (Loss of Coolant Accident). The cable then is routed through a CANDU style cable penetration into the reactor auxiliary bay which has a mild radiation exposure but has relatively high normal temperatures and in some CANDU designs the cable is exposed to the elevated temperatures which result from a Main Steam Line Break accident. From the reactor auxiliary vault the cable is routed into a protected mild area to the ion chamber signal amplifier.

4.0 CABLE CONDITION MONITORING

4.1 Description and Purpose

The IAEA [13.12] defines condition monitoring (CM) as "*Continuous or periodic tests, inspections, measurement or trending of the performance of physical characteristics of structures, systems and components to indicate current or future performance and potential for failure*." Condition monitoring provides a means to evaluate the level of degradation in cables and, where appropriate techniques exist, trend degradation over time. This can provide the NPP with a powerful prognostic tool to anticipate future age-related failures and initiate preventative actions.

Condition monitoring involves the observation, measurement and/or trending of one or more "condition indicators (CI)" correlated to the physical condition of the cable and its current and/or future functionality under expected service conditions, including accident conditions where applicable [13.17][13.95]. To be effective, CIs must be leading indicators of adverse change in condition and directly related to the ability to function. For EQ cables, the CI must also be correlated with the degree of degradation experienced due to normal service ageing simulation in a fully sequential EQ test program [13.99]. The CI must be modeled against the ageing critical characteristics of the cable and an end condition/acceptance criterion must be established. Measured changes must be large enough to distinguish the degree of degradation and be consistent enough to predict end condition in time to implement corrective actions prior to failure.

4.2 Considerations

No one CM method has yet been demonstrated to suitably address all cable materials and issues. Instead, a suite of methods must be integrated into an overall program to provide the necessary insight into the condition of cables. The currently available CM methods may be divided into 4 categories; visual, electrical, mechanical and chemical, each having its strengths and weaknesses.

The desirable attributes of any CM method are as follows [13.4][13.17]:

- Reliably detects characteristic relevant to continued performance with a well defined end condition
- Non-intrusive
- Non-destructive
- Reproducible/repeatable
- Unaffected by, or may be adjusted for, environmental variations
- Sensitive to rate of degradation and providing sufficient lead time to incipient failure to implement preventative actions
- Applicable to a wide range of materials applicable to NPP
- Portability of test equipment
- Assesses the entire length of cables and identifies location of defects
- Cost-effective and relatively simple to apply in field
- Immediately available

It is also essential that the techniques used are accurate and repeatable from the lab to the field and between labs or service providers. Long term life cycle management strategies must consider obsolescence [13.5][13.150] and this includes the potential loss of access to CM technologies and data due to the unavailability of a single proprietary CM service provider. This risk may be mitigated by preference of CM techniques with broad support and use in the industry and technologies and data available from multiple sources/providers, where effective CM method options are available. Round robin tests revealed that subtle differences in the procedures used by various labs/providers to collect material condition data can provide different results thus preventing their integration into a common program [13.8]. To address this, a new set of joint IEEE/IEC standards [13.100][13.101][13.102][13.103][13.104] are in development to standardize the processes for these methods to facilitate repeatability and interchangeability of data, regardless of the source. It is advisable to integrate these controls into any new cable condition monitoring program.

4.3 Harsh vs. Mild Environments

A cable AMP is intended to support the continued reliability of all cables with safety functions or that are otherwise important to reliable and safe plant operation throughout the design life of the NPP. The ageing management of safety-related cables in a harsh DBA environment is addressed within the plant EQ program [13.99]. The basis for qualification requires a rigorous documentation of empirical evidence, analysis and traceability. EQ cable condition acceptance criteria must be linked to the ability of the cable to function throughout the harsh DBA conditions [13.106]. Ageing management of cables in a mild environment does not demand the same level of rigor as EQ cables and provides more flexibility for the use of well supported engineering judgment and industry operating experience. Although cables in mild environments are not exposed to a significant change in ambient environmental conditions following a DBA, they may experience much more severe system-induced stressors due to operational requirements than those during normal operation and surveillance tests [13.4].

4.3.1 EQ Cables

It is important to remember that the primary objective when environmentally qualifying cables is to demonstrate that they will continue to function within specification during exposure to a harsh DBA environment. Independent of age-related degradation, cable insulation performance will deteriorate in high temperature and steam/pressure environments due to inverse insulation resistance vs. temperature (IR vs. T) characteristics or other vulnerabilities to the acute effects of the DBA stressors [13.88]. In fact, IEEE requires that both aged and unaged specimens be tested since ageing effects, up to a point, may actually improve DBA performance and mask failure modes [13.97]. It is not the intent of ageing management to preclude harsh environment effects or improve DBA performance. The purpose of ageing management, in the EQ context, is to assure that the performance demonstrated during DBA testing is not compromised by allowing the condition of cables in service to deteriorate beyond that of the age-conditioned test specimens.

CSA Standard N290-13 [13.106] permits the use of CM in validating qualified life and refining ageing predictions; however, it provides no guidance as to how it is to be applied. IEEE Std 323 [13.99] permits condition-based qualification as an alternative or adjunct to the traditional "qualified life" approach to EQ age management and provides some general guidelines. It defines condition-based qualification as "*qualification based on measurement of one or more condition indicators of equipment, its components, or materials for which an acceptance criterion can be correlated to the equipment's ability to function as specified during an applicable design basis event*". IAEA Report NP-T-3.6 [13.4] provides detailed guidance in how to integrate condition-based qualification into a cable EQ test program.

To address the potential deleterious effects of cable ageing, fully sequential EQ testing requires that cable specimens be put in an end-of-life condition prior to exposure to DBA simulation [13.97]. Age conditioning of cables to simulate an end-of-life condition has typically addressed both radiation and thermal stressors, where applicable. Thermal ageing has traditionally been based on Arrhenius methodology and radiation ageing has been achieved by exposure to the required total integrated radiation dose. The radiation ageing may have been separated into normal dose and accident dose exposures; however, sometimes both normal and accident dose may have been combined in a single test phase.

Most EQ cable test programs in the past did not measure the condition of the cable before DBA simulation. The conventional method of ensuring that the end condition is not exceeded in service has been by assignment of a qualified thermal life at a given service temperature relative to the time at accelerated ageing temperature, using the Arrhenius model, and to ensure that total applied normal and accident radiation doses are not exceeded. Experience has indicated that this method was applied with sufficient margin and conservatism to be very effective through the original design lives of NPPs. However, margins and conservative assumptions have been eroded to address many of the uncertainties associated with test processes, field conditions and life extension. With the advent of new and effective CM methods, condition based qualification has become recognized as a superior method of assuring that cable condition does not degrade beyond that of the EQ test specimen through direct monitoring and measurement of essential cable properties [13.4].

One of the key aspects to consider when selecting CM techniques and acceptance criteria is that the condition indicator must be linked to a cable property relevant to its capability of continued performance in its expected service conditions. Electrical properties are the ultimate concern, and these may be adequate indicators of reliable service in typical environments of low severity; however, they are not typically sensitive to gradual degradation that would challenge a cable's ability to survive a sudden harsh or severe environment. In harsh DBA environments involving pressure, steam and/or flooding, mechanical failure is generally considered a precursor to electrical failure of low voltage cables. For most EQ cables, a nominal value of 50% absolute elongation-at-break has been generally accepted to provide sufficient condition margin for insulation to flex without cracking. Experience has indicated that this target criterion is conservative for most cables but values and properties may need to be adjusted based on application or material [13.7][13.23][13.39][13.76]. Since elongation-at-break is a destructive test, in-service cables typically require use of other CM techniques that are correlated to elongation-at-break [13.4].

Although elongation-at-break is relevant to ageing mechanisms associated with most EQ cables, some cable insulation materials are vulnerable to competing ageing mechanisms that create challenges to a cable's ability to perform throughout a harsh environment, independent of mechanical condition. For example, PVC insulated cables are known to produce hydrochloric acid (HCl) at ageing temperatures above 80^{o}C and/or a total integrated radiation dose above 15 Mrads, gamma [13.7][13.60]. The HCl results in production of conductive salts and may increase vulnerability to electrical failure when exposed to steam. Below a sustained normal service temperature of 80^{o}C and total integrated dose of 15 Mrads, which would represent the majority of in-service PVC cables, elongation-at-break remains the dominant ageing degradation concern for PVC due to migration of plasticizers [13.4][13.60]. The ability to survive accident temperatures and radiation doses above these conditions must be demonstrated by DBA simulation and is independent of CM.

Cable ageing characteristics must first be established and condition indicators modeled against critical property degradation to enable the use of CM in determining and predicting continued cable performance in service. During an EQ test program, specimens are aged incrementally and condition indicators are measured following each incremental ageing phase to provide a model of the ageing characteristics against which field CM measurements may be analyzed. Following all normal service age conditioning, CM data are collected to determine the qualified condition (Figure 4.1, Point B).

IEEE [13.99] defines "qualified condition, as "*the condition of equipment, prior to the start of a design basis event, for which the equipment was demonstrated to meet the design requirements for the specified service conditions*". Qualified life is analagous except measured in time and based on a mathematical model which theoretically represents the point where the same equipment condition is attained. Neither CSA [13.106], nor IEEE [13.99], require margin to be applied to qualified life, nor its equivalent, qualified condition. However, IAEA [13.4] requires that a margin be applied to the measured condition and defines this as the "Qualified Level of Degradation (QLD)". In either case, practical application of CM requires that an administrative limit be applied that defines a condition at which action is initiated to ensure that the QLD is not exceeded. This administrative limit should be based on the rate/trend of degradation, time between CM measurements and time required to implement necessary actions.

Collection of CM data for service other than normal service age-conditioning is not mandatory for condition based qualification. However, CM data collected following accident radiation may be used to redefine a qualified condition for cables with safety functions restricted to DBAs that do not include radiation stressors, such as secondary side line breaks. Figure 4.1 also demonstrates that normal and accident radiation doses cannot be combined in a single phase with condition based qualification.

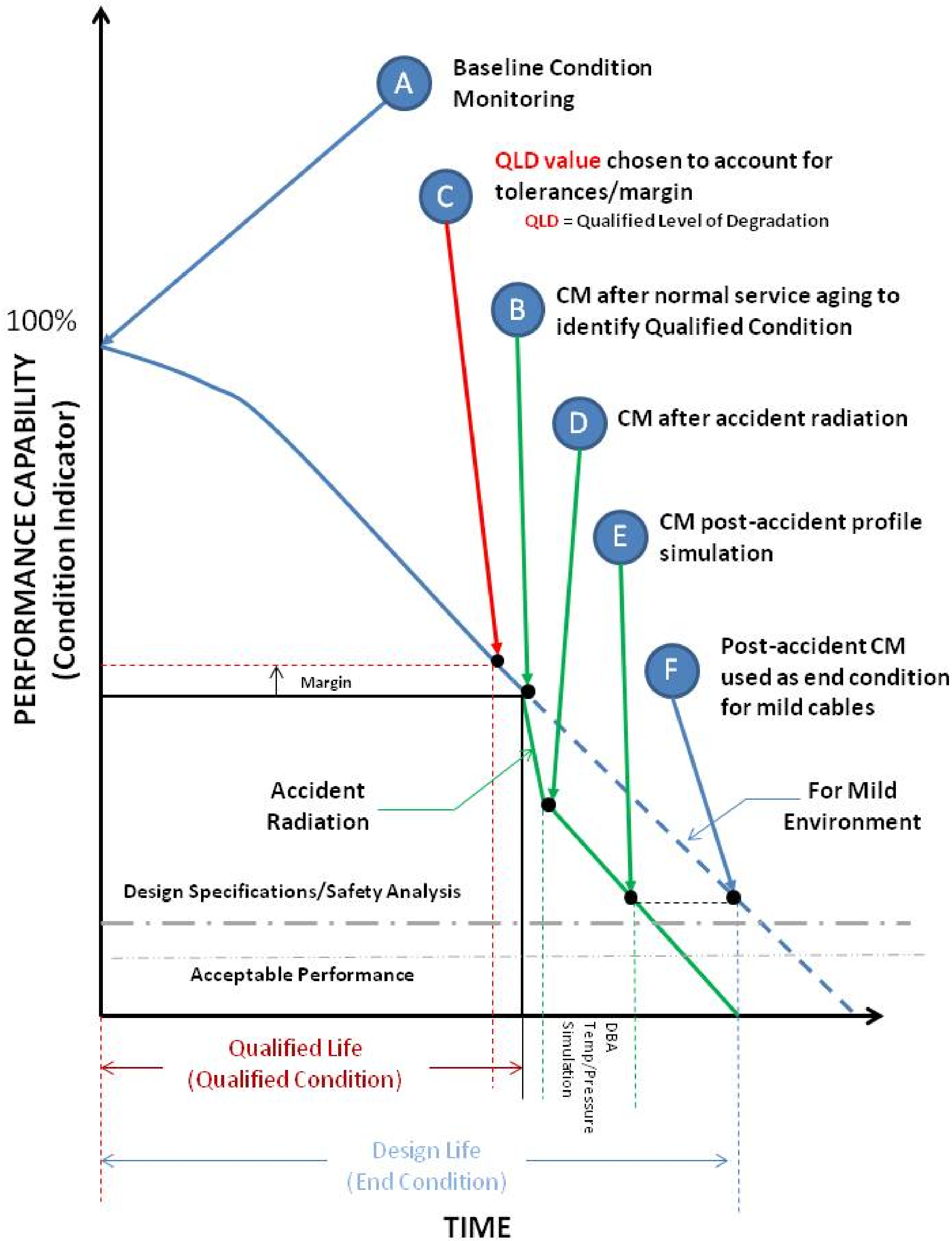


Figure 4.1 Condition Based Qualification (Adapted from NP-T-3.6, Figure 3.1 [13.4])

4.3.2 Mild Environment Cables

A mild environment is one that does not change significantly as a result of a DBA [13.99], however, this does not mean that all mild environment cables operate in benign service conditions. Qualification of cables in mild applications is established by conformance to the design/purchase specifications containing the functional requirements and service conditions under normal and anticipated operational events combined with well supported maintenance/surveillance programs [13.4]. Cables in a mild environment do not require a qualified life, or qualified condition, where they are operated within the limits established by applicable specifications and standards. The more appropriate service limitation is design life (see Figure 4.1). Failures associated with unanticipated conditions should be evaluated to determine if the root cause requires corrective actions to prevent the occurrence of common cause failures [13.97]. This approach has been considered generally adequate because such components can be serviced even following a DBA [13.4].

Absence of a harsh environment facilitates greater flexibility in cable ageing management. Cable condition acceptance criteria need not be linked to survival during peak DBA stressors, such a steam and pressure, and increased use of engineering judgment may be adopted. The NPP may choose an approach similar to EQ cables but DBA testing is not required. Where similarity to EQ cables is demonstrated, the existing CM data for the EQ cable may be used. In this case, the qualified condition (or qualified life) would be a conservative acceptance criterion. This may be adjusted based on post-radiation or post-DBA condition if CM data is collected at these points in the test program (See Figure 4.1).

4.4 Cable Monitoring Methods and Techniques

Available cable CM techniques generally involve the measurement/assessment of one or more of four categories of condition indicators; 1) electrical properties, 2) mechanical properties, 3) chemical or physical properties, or 4) physical condition/appearance. Since no single technique effectively predicts cable performance under DBA conditions, a suite of CM techniques is typically required to adequately assure continued reliable service.

These CM techniques are applied within the framework of cable ageing management strategies intended to increase the effectiveness of the program while minimizing operational burden. A logical approach would be use inexpensive, easily implemented screening techniques to identify early indicators of ageing on a large population of the cables within the program. This may be supplemented with increasingly intrusive and expensive techniques to provide improved ageing trend resolution to validate the conclusion of broad based testing or where cable ageing is evident or expected. When cable ageing management is anticipated during new plant construction, cable deposits may be installed in “worst case” environments to envelope the expected ageing effects of all plant cables and provide sacrificial coupons for destructive testing. Older NPPs may be able to define effective “cable deposits” by the identifying abandoned cables in bounding environments.

Guidance in selection of CM techniques is provided in EPRI 1022969 [13.61], IAEA-TECDOC-1188 [13.7], IAEA NP-T-3.6 [13.4], IEC/IEEE 62582-1 [13.100], NUREG/CR-7000 [13.17], BNL-90735-2009-IR [13.148], and USNRC Regulatory Guide 1.218 [13.32]. Guidance on ageing management strategies is provided in IEEE Std 1205-2000/Cor 1-2006 [13.95][13.96], IAEA NP-T 3.6 [13.4] and EPRI Reports 1021629 [13.63], 1020805 [13.64], 1020804 [13.65], TR-109619 [13.89].

Selected examples of CM techniques from the above literature are provided in sections 4.4.1 and 4.4.2. The described techniques are those in use, or in development, in the nuclear power industry and most applicable and effective with respect to the cable types identified in Canadian NPPs (Table 3.1). Each technique has its advantages, disadvantages and limitations that must be considered in concert with plant specific design, installation and operational factors when developing a CM program. Summaries of the in-situ and laboratory CM techniques are provided in Appendices A and B, respectively. The described CM methods are not intended as a comprehensive list and the above references provide guidance on several additional troubleshooting techniques that may be used to confirm and locate failures once the diagnostic methods indicate a significant problem. NPPs are encouraged to remain aware of research which may provide improved methods that warrant incorporation into the cable ageing management program.

4.4.1 In-situ CM Techniques

4.4.1.1 Visual Inspection

Visual inspection is simply a visual and/or tactile examination of accessible cables to identify changes in physical appearance, surface texture and damage. It is a very powerful, effective and inexpensive screening technique commonly used to provide a qualitative assessment of cable degradation. This is a non-destructive and non-intrusive technique that may be applied to all types of cables. Visual inspection may be aided with the use of flashlights, mirrors, magnifying glasses or even illuminated borescopes to access hard to reach locations such as inside conduits or cable trays.

Visual inspection is valuable as a relative assessment and screening tool, particularly at the beginning of a cable ageing management program during walk downs, to identify areas where significant ageing is occurring and to flag these areas for application of more sophisticated diagnostic CM techniques. For visual inspections to be effective, inspection procedures must be formalized and personnel trained to recognize indications of ageing [13.4][13.7][13.79].

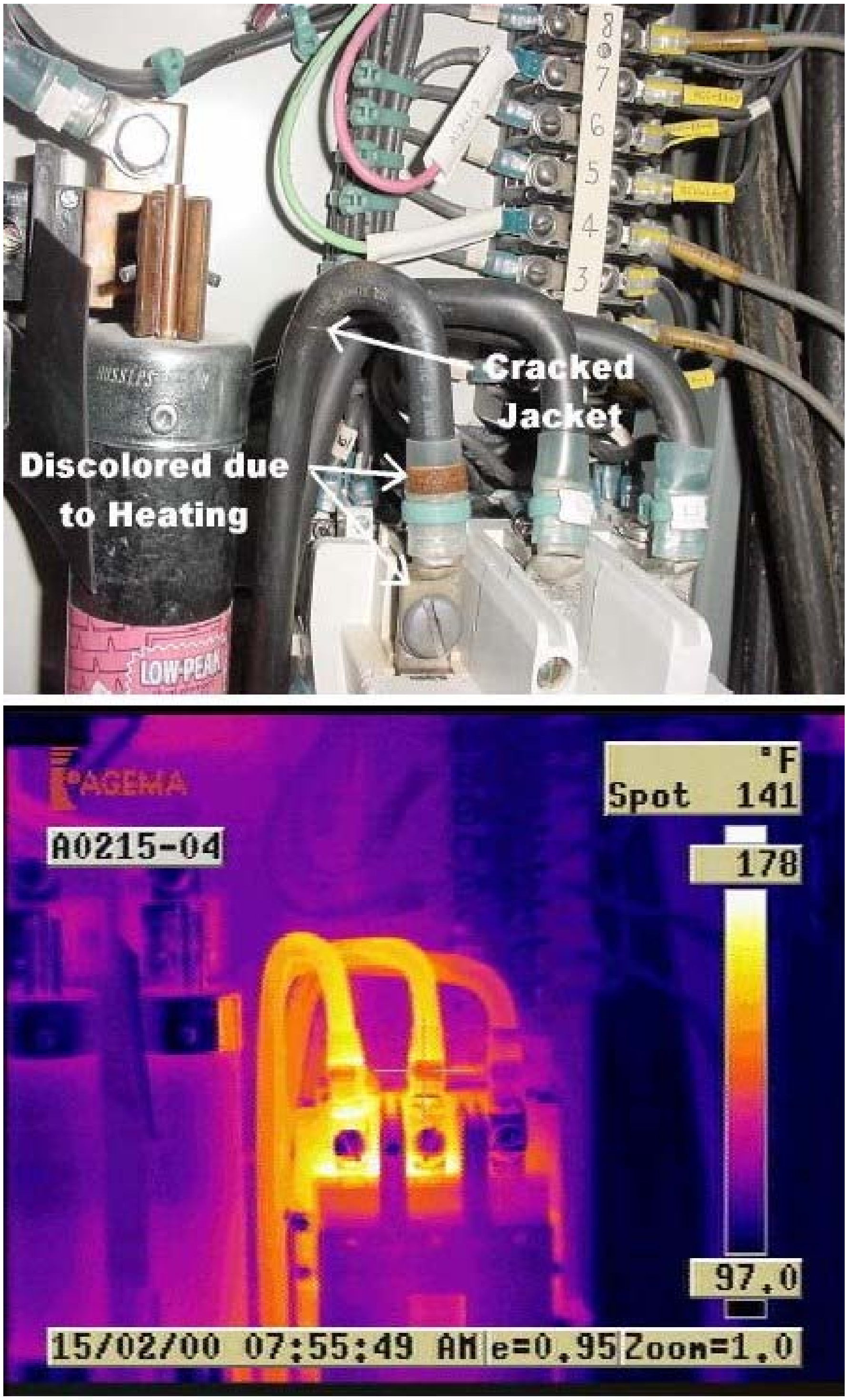
Since visual examination is limited to accessible cable components, it is typically limited to cable jackets, except where cable conductors are exposed in junction boxes or equipment. One example of how visual inspection may be used is with yellow PVC jackets. Most cables in Canadian NPPs have PVC jackets and many of these are yellow. Research by COG [13.56] has concluded that the yellow PVC jackets will remain unchanged when insignificant thermal ageing degradation has occurred and irradiation is below 20 Mrads. Where radiation is the only significant stressor, no colour change may occur until 30-50 Mrads. Therefore, in low radiation environments, jacket colour change may be used as a leading indicator of ageing degradation. In high radiation environments, jacket darkening may not occur until more advanced degradation has occurred.

Visual inspection is also effective in identifying cable damage that is unrelated to ageing. Examination may reveal physical damage or contamination from chemical spill that requires further assessment to determine if long term functionality may be affected.

4.4.1.2 Infrared Thermography

Infrared (IR) thermography is often listed a condition monitoring technique [13.4][13.17]. This is not entirely accurate since it does not collect data that directly indicates the condition of the cable. In reality, IR thermography is a screening technique used to collect data related to the service environments of cables, another essential element of the overall cable AMP. It is a non-destructive and non-intrusive cable ageing management tool that is independent of cable material. Collected data would be used to determine if specific cables operate in an adverse condition which may select the cables for condition monitoring.

Thermography is used to identify thermal hotspots that may facilitate localized accelerated degradation of cables. Particular concerns include power cable terminations, which may be subject to ohmic heating, and adjacent heat sources such as steam lines, which may raise ambient temperature (Figure 4.2). Thermographic surveys should be integrated into cable walk downs while equipment and systems of concern are operating in hot states. Electrical power equipment should be operating at typical normal load and steam lines should be at typical temperature. In some cases, thermal readings should be timed to occur during intermittent events, such boiler blow down. Where visual inspection suggests that thermal ageing may be more advanced than expected, a thermographic survey may be performed to determine if there are any unanticipated heat sources. Depending on the sensitivity and sophistication of the IR detector, temperature may be determined within a fraction of a degree.

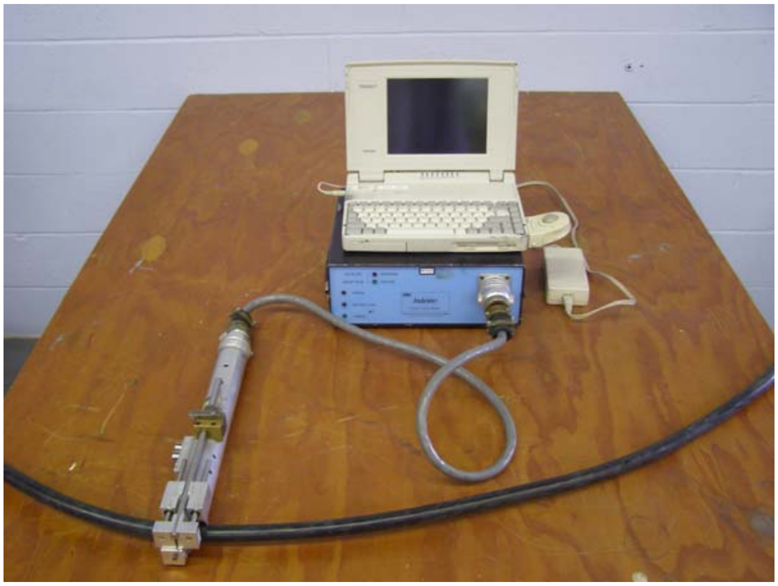


First photo shows cable degradation from local hot spots. Second photo shows thermograph of same cables. (Photo courtesy of Cooper Nuclear Station)

Figure 4.2: Infrared Thermograph Showing Overheated Motor Contactor Cables

4.4.1.3 Compressive Modulus (EPRI Indenter)

Compressive modulus is a mechanical test which uses an indenter to measure and track changes in material hardness, an indicator of embrittlement. A typical indenter uses an instrumented probe which is driven at a fixed velocity into the material and a load cell or similar force-measuring device, connected to the probe, which measures the applied force. Cable disconnection is not necessary. The probe's displacement is measured by an appropriate transducer. The point at which the tip of the probe is brought into contact with the material is sensed by a change in force. The travel and force are purposely limited to protect the material from permanent damage. The indenter modulus (IM) is calculated by dividing the change in force by the corresponding displacement during inward travel. When organic and polymeric materials age, they often harden which will result in an increase of indenter modulus. By monitoring changes in indenter modulus, estimates of degradation rates and levels induced by ageing can be made.



(courtesy: RCM Technologies)

Figure 4.3: Indenter

Good correlation between IM and degradation (changes in EaB) has been demonstrated for most common cable materials. Two notable exceptions are XLPE and radiation aged (> 15 Mrads) PVC [13.4][13.60]. It is primarily used for low voltage cables. Due to its non-destructive/non-intrusive nature, broad applicability and availability, ease of use, early availability and cost-effectiveness, the indenter is perhaps the most common and broadly applied diagnostic CM method used in NPPs to date [13.4][13.7]. Indenter measurements may be affected by specimen geometry, temperature, moisture content, vibration and surface contamination. IEEE/IEC 62582-2 [13.101] provides the necessary guidance to ensure accuracy and repeatability of IM data during modeling of specific cable material ageing characteristics and field measurements.

Field measurements require access to the surface of the material which typically limits indenter measurements to jacket materials, except inside junction boxes where individual conductors/wires are exposed. Nevertheless, the condition of cable insulation may be determined from indenter measurements on the cable jacket if a link is established between the ageing degradation of the jacket material and the degradation of the insulation. COG research has demonstrated that PVC jackets will age to their elongation limits much faster than their underlying XLPE and EPR insulations for thermal, radiation and combined environments [13.51]. It was also shown that PVC jackets will age at a similar or faster rate than the underlying PVC insulation for most PVC cable types where thermal ageing is dominant [13.53]. Indenter measurements performed on the jackets of many cables in Canadian NPPs may be used as a conservative leading indicator of insulation condition.

4.4.1.4 Recovery Time (AECL Portable Polymer Tester (PPT))

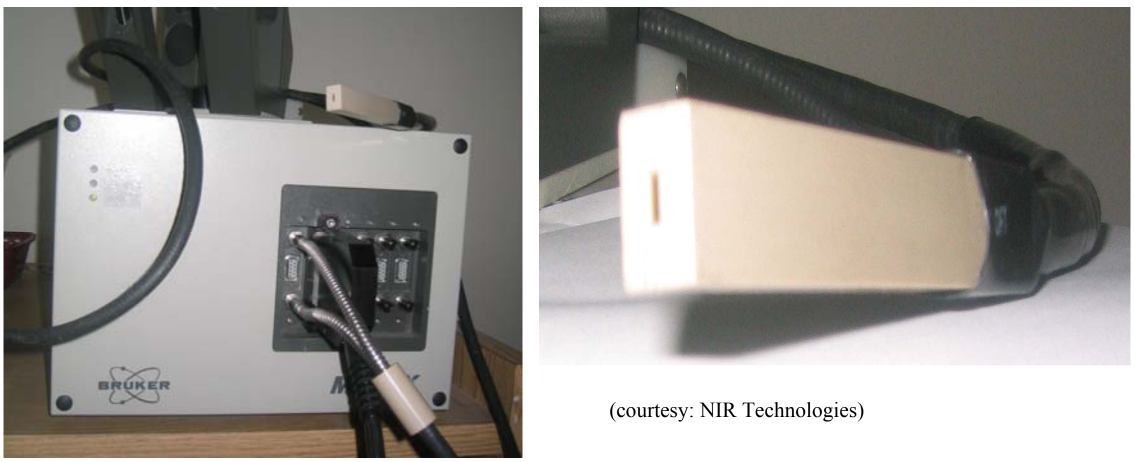
Recovery time is a mechanical test which measures the time for a material to recover from deformation following an indentation phase, a force relaxation phase and upon retraction of the indentation probe. This test is performed using a "Portable Polymer Tester (PPT)" currently being developed by AECL [13.52]. The AECL PPT is similar to the EPRI Indenter in physical appearance and practical field application but provides additional capabilities, including recovery time measurement.

Testing has indicated that recovery time is more sensitive to ageing degradation than compressive (indenter) modulus and, more notably, much more sensitive to ageing degradation in XLPE and irradiated PVC, with respect to correlation with EaB. Published research data does not indicate that there is a correlation with production of HCl and conductive salts in irradiated PVC, which is the ageing mechanism more relevant to electrical performance above 15 Mrads (section 4.3.1).

Further work is required to validate the AECL as an effective method and to determine if the potential benefits warrant its use over more proven and established methods, such as the EPRI indenter. The AECL PPT incorporates a temperature compensation feature to address the significant effect of temperature on recovery time measurements. Its accuracy and repeatability is affected by other environmental conditions and it is recommended that guidance be established, analogous to IEEE/IEC 62582-2 [13.101] for the Indenter, to ensure accuracy and repeatability of AECL PPT data during modeling of specific cable material ageing characteristics and field measurements.

4.4.1.5 *Fourier Transform Near Infrared Spectroscopy (FT-NIR)*

Fourier transform near infrared spectroscopy (FT-NIR) is a spectroscopic test method that is used with chemometric analysis to measure energies (near infrared light) absorbed or transmitted by a material which is proportional to the vibration (stretching and bending) of chemical bonds. It provides a chemical "fingerprint" of the material at the molecular level which is unique to the material formulation and is sensitive to material chemical changes, including those resulting from thermal and radiation ageing. The equipment includes a spectrometer unit connected to a non-metallic probe via a fibre optic cable (Figure 4.4). Data are collected by a laptop and an uninterruptible power supply (UPS) may be used to simplify operation and movement of the equipment in the field [13.133].



(courtesy: NIR Technologies)

Figure 4.4: FT-NIR Spectrometer and Probe

Research demonstrates that NIR is sensitive and effective in measuring and tracking thermal and radiation ageing related material changes in PVC and XLPE that can be correlated to EaB [13.53][13.51][13.133]. Recent COG research has not explicitly indicated that NIR is able to track creation of HCl and conductive salts in PVC, which is critical to DBA performance in high radiation locations; however, since the technique is sensitive to chemical changes this should be theoretically visible directly without correlation to a physical property [13.145].

FT-NIR has several advantages over indenter modulus and recovery time in that the probe is non-metallic and is simply applied to the available material surface, which does not require the same level of physical manipulation of the cables. The non-conductive probe simplifies measurements directly on exposed insulation, such as in junction boxers where there may be exposed conductors in live circuits. FT-NIR is the only identified non-destructive CM method that may be capable of measuring HCl and conductive salts in PVC.

One significant disadvantage of FT-NIR is that it is not effective on black materials. This eliminates it as a potential CM method where black cable jackets are used to infer insulation condition. However, some Canadian NPPs make extensive use of yellow jacket cables [13.53] where FT-NIR would be effective. It is also useful where colour-coded wire insulations are exposed, thus facilitating sampling. FT-NIR is material formulation dependent and ageing data must be based on specific cable type matrices. Since FT-NIR was used extensively to identify EQ cable formulation types at many Canadian NPPs over the past 10-15 years [13.60], some of the collected data may be useful in developing earlier baseline plant information for current comparison.

Accuracy and repeatability of FT-NIR data is dependent on the matrix and other factors, such as environmental conditions and measuring equipment configuration and calibration models (software). It is recommended that guidance be established, analogous to IEEE/IEC 62582-2 [13.101] for the Indenter, to ensure accuracy and repeatability of FT-NIR data during modeling of specific cable material ageing characteristics and field measurements.

4.4.1.6 Line Resonance Analysis (LIRA)

Line Resonance Analysis (LIRA) is an electrical test which uses the cable under test to modulate a high frequency white noise, low energy electrical signal [13.65]. Evaluation of the modulated signal for amplitude and phase differences of the frequency dependent resonances is capable of identifying termination points and impedance changes along the entire length of cable. Bulk damage, as well as localized damage (including cuts and gouges) and age-related degraded segments are able to be detected and located by the resonances. It is effective for dry cables but its effectiveness in providing indication of degradation due to wetted conditions in low voltage cables has not yet been demonstrated [13.67]. While LIRA is able to provide a reasonable assessment of the degree of damage, it is not able to adequately trend cable degradation for age-related damage. LIRA is a useful tool for identifying localized damage along cable sections that are not easily visible or accessible and thereby identify acute damage and potential “hot spots” for further evaluation and analysis using more sensitive CM diagnostic techniques [13.1][13.65].

The LIRA system may be used on adjacent conductors of any multi-conductor cable; no shield is required. The system requires access to the connections at one end of the cable, which may often require de-termination; however, if access is possible without de-termination, analysis of the results may be used to account for loads [13.35][13.65]. A thorough description of the technique and its application is provided in EPRI report 1015209 [13.67]. LIRA is still under development and its evolution should be followed to determine if its effectiveness may be expanded within the plant cable ageing management program [13.1].

4.4.1.7 Dielectric Loss-Dissipation Factor/Power Factor (Tan-δ)

Tan-δ testing is an electrical test that determines the ratio of the resistive leakage current through the insulation divided by the capacitive current. Testing may be performed at line or very low frequency (VLF) but VLF tests are preferred due to the more compact and portable size of the equipment[13.64]. Tan-δ is primarily useful with shielded medium voltage cables, particularly those in wet environments. The test should not be performed on low voltage cable cables or unshielded medium voltage cable due to physical safety concerns and unreliable test results [13.35].

Tan-δ is a bulk test and does not provide information related to degradation at a specific location along the cable. The test is effective in identifying distributed water-related damage prior to the onset of electrical trees. The progression of further degradation and subsequent electrical failure becomes more rapid once electrical trees have formed. Since Tan-δ provides an assessment of only the "average" cable condition, it does not discriminate between the presence of many widespread limited degradation and a few, or single, but significant flaws. Therefore, Tan-δ is typically used in conjunction with VLF withstand testing to reveal if severe localized damage is present. EPRI provides a detailed description of Tan-δ and its application in conjunction with VLF withstand in EPRI 1020805 [13.64]. EPRI 1025262 [13.61] has also recently been issued evaluating and validating Tan-δ using field implementation feedback. This report also provides insights gained and lessons learned from analysis of the test results and should be consulted before implementing this CM method.

4.4.1.8 Insulation Resistance (IR)

Insulation resistance is a common electrical test which applies a voltage between conductor and ground or between two conductors to determine the resistance of the insulation separating them. Some NPPs use ac and/or dc ground fault detection systems as a form of automated IR monitoring and fault detection. Insulation resistance is insensitive to radiation and thermal damage and ineffectual as a CM method under dry conditions since it is a lagging indicator of damage and failure [13.17]. However, it may be used as a leading indicator of cable insulation degradation in low voltage cables subjected to prolonged wetting [13.65]. Although IR measurements are common industry tests and simple to perform, they require the disconnection of cables.

A detailed description of IR testing and its application in a cable ageing management program is provided in EPRI 1020804 [13.65].

4.4.2 Laboratory CM Techniques

4.4.2.1 Elongation-at-Break (EaB)

Elongation-at-break is a mechanical diagnostic test technique that measures a material's resistance to fracture under applied tensile stress. It is a widely used and trendable benchmark for cable insulation. It is the primary condition indicator of cable survivability of EQ cables in a harsh environment since mechanical failure is generally considered a precursor to electrical failure of low voltage cables. Since EaB is a destructive test, in-service cables typically require use of other CM techniques that are correlated to EaB during modelling of cable ageing characteristics (see Section 4.3.1). However, in the plant, EaB may be measured directly where cables are available for couponing, such as cable deposits or abandoned cables. The direct use of EaB is not recommended for trending degradation of XLPE since it remains relatively constant for a long time and then rapidly declines [13.7]. Leading indication of failure may be inadequate.

The accuracy and repeatability of EaB test results are dependent on material formulation, sample collection and preparation, temperature, etc. IEC/IEEE 62582-3 [13.103] provides a standardized set of procedural controls that should be followed to ensure that data collected throughout the process of initial ageing characterization and field CM testing are calibrated.

4.4.2.2 Oxygen Induction Time/Temperature (OIT/OITP)

Oxygen Induction Time/Temperature are diagnostic chemical test methods that measure the loss of antioxidants in cable materials. Antioxidants are added to cable insulation and jacket materials to retard the onset of oxidation which degrades the material. By measuring the level of antioxidant remaining in the material, the remaining life of the cable can be estimated. There are two oxidation induction methods available, based on the time required to reach the onset of oxidation at a constant temperature (oxidation induction time – OIT) or based on the temperature at the onset of oxidation during a constant temperature ramp rate (oxidation induction temperature – OITP). The two methods are complementary, in that OITP is often effective in those materials where OIT is difficult to determine [13.102]. OIT/OITP requires correlation with a cable property that reflects cable functionality, such as EaB [13.7].

OIT/OITP is primarily suited to samples taken from materials that are polyolefin-based, such as PE and XLPE. It can also be used for some materials based on ethylene-propylene polymers, such as EPR and EPDM, and for some ethylene vinyl acetate EVA materials. It is particularly useful with PE and XLPE where the indenter and EaB are not effective. Since the point at which EaB begins to quickly decline is defined by the oxidation point, tracking the loss of antioxidants provides the necessary trending to be an effective prognostic tool. It is generally not suited for PVC or CSPE due to the corrosive byproducts evolved during the process [13.102].

OIT/OITP testing requires microsampling and therefore is destructive by definition. However, many consider it to be nondestructive since it requires only a very small sample that does not significantly damage the cable under test [13.17]. OIT/OITP results are affected by sample size and form, sample pan material, oxygen flow rate, stabilization time, test temperature and temperature ramp rate [13.7]. IEC/IEEE 62582-4 [13.102] was issued to provide guidance and standardize OIT/OITP methods to ensure reproducible results.

5.0 CABLE AGEING MANAGEMENT STATUS: INTERNATIONAL

5.1 Background

As NPP licensees apply to extend the operating life of their plants for 20 years or more beyond the original design life, the nuclear power industry has recognized the increased need to address the potential safety and reliability impacts of cable ageing degradation. Much effort and resources have been dedicated over the past 20 years to establishing the bases for such a program.

Electric cables have typically been viewed as reliable, maintenance free components. With few exceptions, this has been the experience during the original design life of NPPs where the cables have been properly applied and operate in service conditions anticipated during design. However, in the past 5-10 years, reports of increased cables failure rates have emerged, primarily in adverse service conditions and particularly with respect to medium voltage cables operating in submerged conditions.

5.2 Cable Failure History and Analysis

No single comprehensive databank of cable failures within the international nuclear power industry was available for review. Instead, the results of recent NEA efforts to collect cable failure information from several countries [13.1] are used as the primary basis for review and analysis. This is supplemented with other isolated known cable failure information as appropriate.

The majority of cable failure data presented in NEA/CSNI/R(2010)15 [13.1] was provided from U.S. NPP operating experience. In General Letter GL 2007-01 [13.40], the USNRC noted that, despite the relatively low number of cables subjected to submerged conditions at NPPs, there had been 25 reports of medium voltage AC and low voltage DC cable failures between 1988 and 2004. It was also acknowledged that there had been other non-reportable cables failures which suggested the problem was even larger. The USNRC requested licensees to provide their histories of related cable failures which resulted in the NRC identifying 269 cables failures from 64 sites (104 reactor units). Information Notice 2010-26 [13.43] was subsequently released which identified further failures and an increasing trend in failure rate.

The 269 reported failed cables were broken down as 209 normally energized, 15 normally de-energized and 45 unknown. Therefore, 93% of the 224 cables with known operating state were normally energized. Failure causes of the 15 normally de-energized cables were identified as water/moisture, manufacturing defects, installation errors and digs. Also, 125 cables were in service when they failed, 114 were not and 30 are unknown.

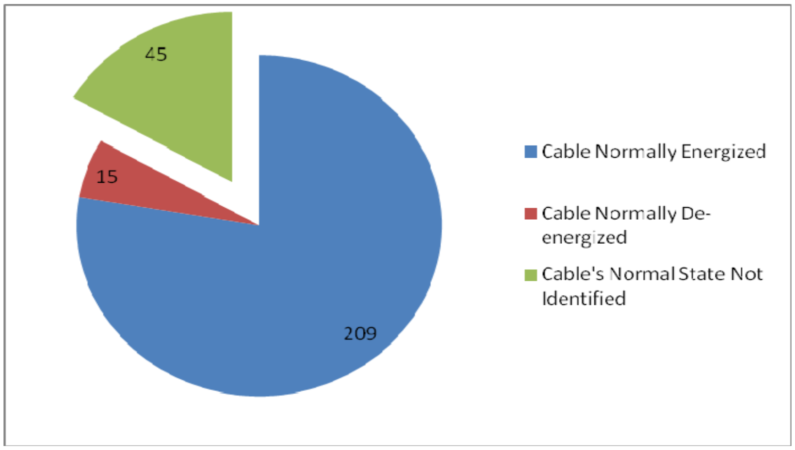


Figure 5.1 Cable Failures by Normal Service State

Figure 5.2 provides an estimate of the relative distribution of possible, probable and definitive causes and casual factors related to the cable failures. This distribution indicates that 86% of the failures were due to acute degradation as a result of failure of barriers such as design control, work control, manufacturing quality assurance or random events. Since the 15 known de-energized cable failures in Figure 5.1 were due to other reason, it is highly probable that the 14% of failures attributed to general or age-related chronic degradation in Figure 5.2 are associated with normally energized cables. Although specific details of the failures were unavailable for review, the overall impression of the data is that cables fail immediately due to acute damage from external processes or phenomena unrelated to "ageing" or are predisposed to failure from accelerated progressive degradation when exposed to adverse conditions, such as water, chemicals, high temperatures (in this case, ohmic heating), or misapplication. There is no indication that cables in dry, nominal, low stress environments are vulnerable to early failures due to ageing.

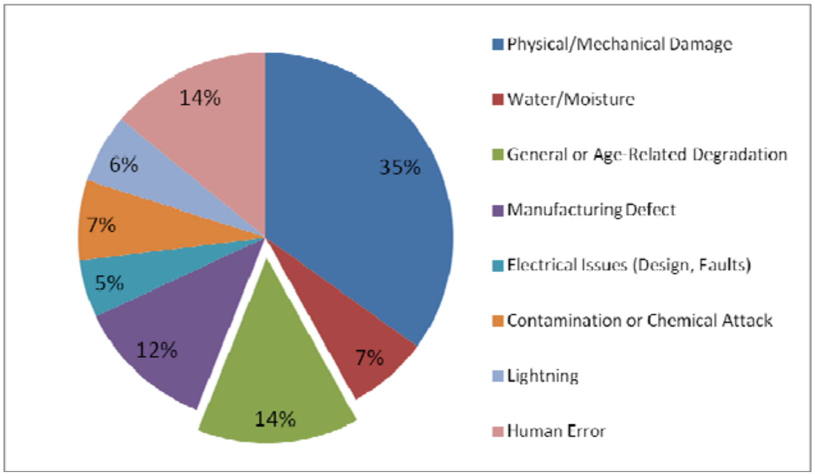


Figure 5.2 Causes and Casual Factors of Cable Failure

The data presented by the USNRC also indicated a definite increase in failure rate over time (Figure 5.3). The number of underground MV cable failures in the third decade of service was double that of the first decade. These service times at time of failure in are not inconsistent with the predicted times-to-failure for underground cables provided by EPRI Reports 1008560 [13.75] and 1020805 [13.6413.61].

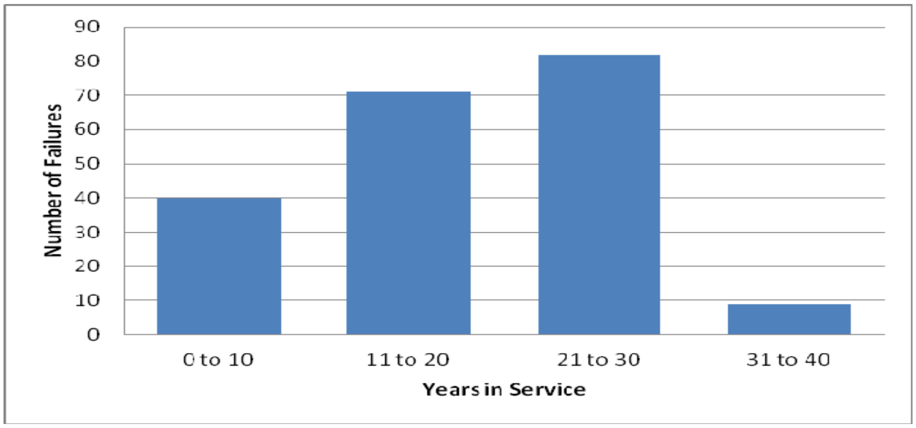


Figure 5.3 Underground MV Cable Failures per 10 Years of Service [13.1][13.17]

Several countries other than the U.S. provided the following cable failure information. Again, cable failure required the presence of adverse conditions or failure of work control or QA barriers. Information from Ukraine was less quantitative, but followed a similar pattern.

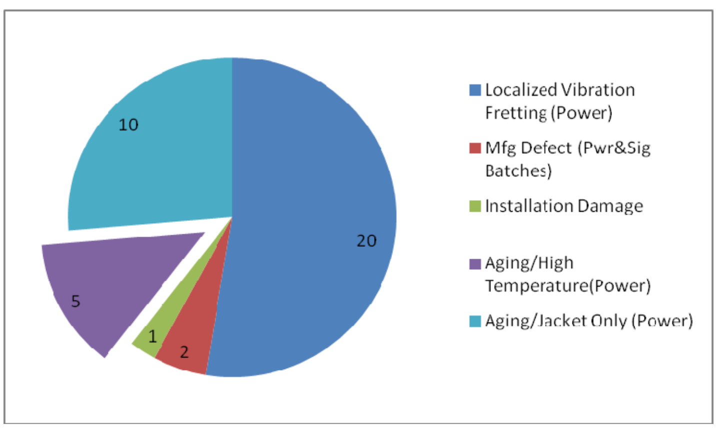


Figure 5.4 Cable Failures Other than U.S.

Individual reports of cable failures, other than inaccessible/buried cables were reviewed to determine if they may challenge the impressions provided by the data collected by the NEA.

USNRC Circular 77-06 [13.49] reported that one NPP experienced localized degradation of multiple cables due to contamination from leaking Electro-hydraulic Control (EHC) fluid. The EHC fluid damaged the PVC jackets Power, Control and Instrument cables but did not result in insulation damage or failures; however, some repairs were required. The problem was discovered visually during clean-up of the EHC fluid and would not have likely been discovered using available CM methods unless the condition was sufficiently protracted to result in insulation damage. The event was the result of acute degradation with immediate effects as the result of failure of unrelated systems and barriers and not related to exposure to chronic stressors.

USNRC Information Notice 86-49 [13.48] reported failure of a 4160V bus cable due to localized accelerated thermal ageing. The cable was exposed to elevated radiation heat from an adjacent 400F feed water line/flange which had its thermal insulation removed and not replaced following gasket replacement. This failure was due to age-related degradation facilitated by the introduction of an adverse condition (hot spot).

USNRC Information Notice 87-52 [13.47] reported that one utility had experienced failure of 9 of 91 Silicone Rubber (SR) insulated single conductor cables from two different manufacturers. The failures were discovered while performing high potential tests. Investigation suggested that the SR insulation is vulnerable to loss of dielectric integrity due to damage inflicted during handling. In this instance, cable failure is due to acute and immediate damage and not progressive degradation due to exposure to chronic stressors.

USNRC Information Notice 91-20 [13.46] reported the contamination of contactors in MCCs with a green liquescent substance leaching from PVC machine tool hook-up wire used in the Westinghouse MCCs. The green liquescent substance was determined to be PVC plasticizer contaminated with copper oxide salts. The substance was conductive when wet but may or may not be when dried and hardened, depending on the amount of copper oxide salts. Westinghouse indicated that the wires were likely manufactured in the mid-1960s but no controls or records of the materials and manufacturers were available. The PVC wiring within the MCCs was replaced with XLPE wiring. This particular event was confined to internal wiring of equipment and not necessarily representative of problems associated with ageing of general plant cabling. Regardless, the problem was less related to ageing effects on the cable itself than its contamination of exposed electrical parts within enclosed spaces.

USNRC Information Notice 2002-04 [13.42] reported failure of internal PVC wiring at breaker cubicles. The breaker cubicle had components on the door and internal with interconnecting wire that flexed each time the door was opened and closed. The failure root cause was attributed to the combined effects of age-related embrittlement of the PVC insulation and frequent flexing. Again, this event was confined to internal wiring of equipment and not necessarily representative of problems associated with ageing of general plant cabling. The failure required presence of an adverse condition (flexing) coupled with chemical ageing effects to induce failure.

Review of the available cable failure history suggests that there is little evidence of an increasing failure rate of general cabling that is in low stress service environments. The vast majority of failures indicate that an adverse service condition is required to induce or promote premature failure, either as an isolated immediate event or as a necessary precursor to accelerated ageing. There is evidence from the U.S. experience of an increasing trend in failure of power cables, particularly medium and high voltage cables, when submerged. However, outside of this, cable failure events appear relatively few in comparison to the large volume of cable in plant service. Again, in the majority of cases, cable failure required the presence of an adverse conditions, such as mechanical damage, high flex rates, chemical spills, water, hot spots, continuous energization/loading, etc or the failure of other barriers such as manufacturing QA, design controls, work controls, etc. While it is recognized that the scope of available cable failure information may be incomplete, it is apparent that any cable ageing management program must assign a significant emphasis on identifying situations where adverse conditions exist and focus efforts on these areas.

5.3 Regulatory

USNRC

The U.S. regulatory requirement regarding demonstration of continued reliability of NPP cabling is generally enveloped by 10 CFR 50.65 (commonly referred to as “the maintenance rule”) which requires that each licensee must monitor the performance or condition of structures, systems or components (SSCs) in a manner sufficient to provide reasonable assurance that they are capable of fulfilling their intended functions. An option is provided for the licensee to avoid monitoring if they can demonstrate that condition or performance of SSCs is effectively controlled by preventative maintenance.

The USNRC issued Regulatory Guide 1.160 [13.33] to provide guidance on interpretation of the maintenance rule and on acceptable ways of implementing it. The latest USNRC position on the subject was published with Draft Regulatory Guide DG-1278 [13.34], issued September 2011, proposing a revision to Regulation Guide 1.160 [13.33]. DG-1278 [13.34] indicates the USNRC’s endorsement of revision 4A of NUMARC 93-01, “Industry Guideline for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants”, issued April 2011, which provides methods for complying with 10 CFR 50.65. A key aspect of the application of the maintenance rule is that is it not limited to safety-related components but also includes nonsafety-related components :

i. *That are relied upon to mitigate accidents or transients or are used in plant emergency operating procedures (EOPs); or*
ii. *Whose failure could prevent safety-related SSCs from fulfilling their safety-related function; or*
iii. *Whose failure could cause a reactor SCRAM or actuation of a safety–related system.*

To provide guidance more specific to cables, the USNRC issued the following documents.

Regulatory Guide 1.218: Condition Monitoring Techniques for Electric Cables Used In Nuclear Power Plants, issued April 2012 [13.35]

The USNRC issued Regulatory Guide 1.218 to identify a method it considers acceptable for condition monitoring of electric cables for nuclear power plants, for those licensees choosing to use monitoring to meet the requirements of 10 CFR 50.65, "Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants." The guide provides a summary discussion of NUREG/CR-7000, Essential Elements of an Electric Cable Condition Monitoring Program [13.17], with a list of extracted condition monitoring techniques to be used where appropriate.

Regulatory Guide 1.218 provides the regulatory position that the following list of 11 elements constitutes an effective cable condition monitoring program.

1. Select cables to be monitored.
2. Develop database for monitored cables.
3. Characterize and monitor service environments.
4. Identify stressors and expected ageing mechanisms.
5. Select condition monitoring techniques suitable to monitored cables.
6. Establish baseline condition of monitored cables.
7. Identify cable characteristics and ageing effects being monitored by each selected condition monitoring technique. (*not listed in NUREG/CR-7000 [13.17], Table 5.1*)
8. Perform test and inspection activities for periodic condition monitoring of cables.
9. Periodically review and incorporate plant and industry experience.
10. Periodically review, assess, and trend the condition of monitored cables.
11. Identify degraded conditions and take prompt corrective actions. (*not listed in NUREG/CR-7000 [13.17], Table 5.1)*

It should be noted that elements "7" and "11" are not explicitly stated in the list of 9 essential elements list in NUREG/CR-7000, Table 5.1; however, they are inferred as an inherent part of the process.

Further, the USNRC regulatory position states that cable condition monitoring should be augmented for selected cables when the NPP has;

1. experienced failures of specific cable types connected to critical equipment,
2. operational history indicates failure of cables,
3. there is a locally adverse operating environment,
4. industry OPEX with similar equipment configuration and operating conditions indicate a need to augment CM

In other areas, CM may be limited to a representative sample of cables and frequency of CM may be adjusted based on plant specific cable test results and operating experience.

NUREG/CR-7000 – Essential Elements of an Electric Cable Condition Monitoring Program, issued January 2010 [13.17].

NUREG/CR-7000 lists nine essential elements (expanded to 11 in Regulatory Guide 1.218 above) for an effective cable condition monitoring program presented in this report are based upon the results of the NRC's electric cable and equipment research programs, industry guidance and standards, and the experience and observations of others who have studied or conducted electric cable condition monitoring and qualification testing. It provides guidance on the selection of cables to be included in the program, characterization and monitoring of cable operating environments and stressors, selection of the most effective and practical condition monitoring techniques, documentation and review of cable condition monitoring testing and inspection results, and the periodic review and assessment of cable condition and operating environments.

The guidance provided is very thorough and current and provides a reasonable basis for framing an equivalent cable ageing management program for Canadian NPPs. A full summary of the complete content of the document is unnecessary; however, there are key aspects of the guide that warrant discussion from a Canadian perspective.

The first, and perhaps most challenging, element of a cable AMP is defining the scope of cables to be monitored. NUREG/CR-7000 [13.17] recommends the following cables as candidates for a cable AMP program. The guide includes cable accessories, such as connectors, splices, fuse holders, etc in its scope. This report will focus on cables and address connections and accessories as cable interfaces.

Power and I&C cables with high safety significance, high plant risk significance, or are important to continued plant safe operation should form the core of the AMP. These cables are generally described as having either a direct safety-related function, are required to achieve and maintain safe shutdown, or are required to mitigate the consequences of a Design Basis Accident (DBA). Cables on the plant environmental qualification list (EQL) are an obvious subgroup of this set. The following cables may or may not be a subgroup.

a. Non-safety-related cables requiring EQ due to exposure to locally adverse service environments (e.g. normally submerged cables).
b. Cables required for plant to withstand station blackout.
c. Cables required to satisfy the fire protection regulations.
d. Cables within the scope of license renewal regulation. Guidance for these cables is provided in NUREG 1801 [13.15] (see later discussion). For the purpose of discussion, license renewal, in the U.S. context, is analogous to plant life extension.
e. Cables considered at risk based on operating experience.
f. Cables whose failure could result in a plant trip or transient.
g. Cables and wires internal to electrical, instrument or equipment enclosure, or equipment cabinets ARE NOT to be included as part of the cable AMP and should be addressed via equipment inspection, testing and maintenance activities.

The guidance and recommendations of NUREG/CR-7000 [13.17] are based on the U.S. experience and assumptions that plant cables are of construction and materials common to U.S. NPPs, namely copper or aluminum conductors and XLPE, EPR, SR or PE insulation. While these generic configurations are also common to Canadian NPPs, other insulation and jacket materials common to Canadian NPPs, such as PVC, are not addressed. Specialty, or less common, cable designs and insulations, such as Kapton, Tefzel, PEEK, butyl, etc are not discussed either. The guide also covers cable accessories such as splices, connectors, terminations, etc, which are outside the scope of this report.

A list of condition monitoring (CM) techniques, currently available and in common use, is provided based on the cumulative knowledge from research and experience of the international nuclear industry. The CM techniques discussed are a reasonably comprehensive total of available proven methods available for the common U.S. cable types. There are other less common CM methods and others under research and development in Canada, such as Near Infrared Spectroscopy (NIR) and a Deformation Recovery Time that also show promise. A summary of the CM techniques is provided in Appendix A.

NUREG 1801, Rev.2 – Generic Aging Lessons Learned (GALL) Report [13.15]

NUREG 1801 [13.15], or "the GALL Report' as it is commonly referred to, lists generic ageing management reviews (AMRs) of systems, structures, and components (SSCs) that may be in the scope of license renewal applications (LRAs) and identifies ageing management programs (AMPs) that are determined to be acceptable to manage ageing effects of SSCs in the scope of license renewal, as required by 10 CFR Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants." If an applicant takes credit for a program in the GALL Report, it is incumbent on the applicant to ensure that the conditions and operating experience at the plant are bounded by the conditions and operating experience for which the GALL Report was evaluated. If these bounding conditions are not met, it is incumbent on the applicant to address the additional effects of ageing and augment the GALL report AMPs as appropriate. If an LRA references the GALL Report as the approach used to manage ageing effect(s), the NRC staff will use the GALL Report as a basis for the LRA assessment consistent with guidance specified in the Standard Review Plan for License Renewal (NUREG 1800 [13.16]).

The latest updates to the GALL report were rolled out to LRAs via RIS 2011-05 [13.38]. Sections XI.E1, 2 and 3, define Cable AMP programs for cables that are not addressed by EQ programs. The cable AMPs are summarized as follows:

XI.E1: Applies to General Accessible Cabling (not EQ)

- Limited to cables exposed to adverse localized environments, such as temperature, radiation and moisture.
- Does not include actions to prevent or mitigate ageing degradation.

- Monitoring limited to visual inspection at localized high stress areas. First inspection to be prior to period of life extension and minimum 10 year intervals thereafter.
- Trending of degradation is not required, but recommended where possible.
- Any discovered anomalous conditions to be subject to engineering review and action, if necessary.

XI.E2: Applies to High Voltage, Low Current Signal Cables (not EQ)

- Limited to cables exposed to adverse localized environments, such as temperature, radiation and moisture.
- Does not include actions to prevent or mitigate ageing degradation.
- Monitor via review of calibration results or surveillance (SSTs) results if cables are in test circuit.
- Monitor via separate cable system test if cables are not in regular test circuit.
- First inspection to be prior to period of life extension and 10 year intervals thereafter.
- Trending of degradation is not required, but recommended where possible.
- Any discovered anomalous conditions to be subject to engineering review and action, if necessary.

XI.E3: Applies to Inaccessible or Underground Power Cables 400V and Above (not EQ)

- Focus is on cables that may be exposed to prolonged wetting or submergence.
- Cables that are rated as submarine or designed for continuous wetting or submergence are excluded.
- Inspection to identify areas of submergence.
- Actions are to be taken to correct and/or prevent or prolonged exposure to wetting.
- Submerged cables are to be tested for degradation and degradation is to be trended.
- First inspection to be prior to period of life extension and 6 year intervals thereafter.
- Any discovered anomalous conditions to be subject to engineering review and action, if necessary.

The above direction, provided by the USNRC to NPPs applying to extend the life of their plants and based on generic ageing lessons learned, suggests that the primary concerns with cable ageing are focused on those in high stress, adverse service conditions and not the vast majority of cables which are exposed to typical normal service environments. The dominant concern is with power cables, particularly medium voltage cables, that operate under prolonged submergence but are not designed/qualified for submergence. General cabling is of concern only if subjected to adverse service environments. It is also suggested that regular testing of instrument circuits may be an acceptable surveillance method if the cables are included in the test methods.

IAEA and NEA

NP-T-3.6 – (IAEA) Assessing and Managing Cable Ageing in Nuclear Power Plants [13.4]

This report was produced by experts and advisors from 18 different member countries. It provides guideline for qualifying and managing ageing of electric cables and builds on the substantial contribution of IAEA TECDOC-1188 [13.7,13.8]. This report also differentiates between the cable AMP approaches of operating NPPs and new builds. It concedes that more than 40 years of experience has shown that qualified cables have not tended to fail if properly sized, applied, installed and not exposed to service conditions more severe than assumed.

Unlike Regulatory Guide 1.218 [13.35] and NUREG/CR-7000 [13.17], this report focuses on the integration of condition based age management into a cable EQ program, rather than on providing guidance for establishing an overall plant cable ageing management program. The motivation for condition based qualification is to address life extension and uncertainties in the accelerated ageing process. Despite this, the report recognizes that the scope of cable ageing management needs extend beyond the list of EQ cables and that the methods for ageing management and Condition Monitoring of EQ cables may be extended to non-EQ cables, where appropriate. In many NPPs, specific cable types in EQ applications and those in non-EQ applications are not mutually exclusive. This is also true of Canadian NPPs.

NEA/CSNI/R(2010)15 – Technical Basis for Commendable Practices on Ageing Management – SCC and Cable Ageing Project (SCAP) [13.1]

This was an internationally coordinated project, involving 17 countries, to share their corporate knowledge and operating experience to understand cable failure mechanisms and identify effective techniques and technologies to effectively manage and mitigate active cable degradation in nuclear power plants. The specific objectives of the cable ageing portion of the project were to: i) establish a complete database with regard to major ageing phenomena for degradation of cable insulation through collective efforts by NEA members; ii) establish a knowledge base in these areas by compiling and evaluating the collected data and information systematically; iii) perform an assessment of the data and identify the basis for commendable practices which will help regulators and operators to enhance ageing management. The content is a collection of much of the information discussed separately here, in Section 5.0 of this report.

The following relevant observations and conclusions are extracted from the NEA report [13.1]:

- Past cable failure events are strongly linked to past manufacturing and installation practices.
- Ageing related cable failures are concentrated where adverse service environments exist.

- Ageing problems are best addressed through a systematic program which coordinates relevant activities.
- The CAMP should incorporate a process of continuous improvement through incorporation of OPEX and new research results.

5.4 Codes and Standards

As the value and demand for condition monitoring has evolved with NPP life extension, industry standards have been revised to incorporate guidance. In parallel, there is a general move to combine IEEE and IEC efforts and standards to standardize approaches internationally.

IEEE Std 1205 [13.95] was originally written to support license renewal (life extension) efforts. Its purpose is to provide guidance in assessing and monitoring ageing effects and in developing and implementing ageing management programs for Class 1E (safety-related) electrical equipment used in nuclear power generating stations. IEEE Std 1205 [13.95] is currently in a major revision to incorporate the following changes to make the guide more useful and applicable to electrical equipment.

- Incorporate Corrigendum 1 [13.96] and minor comments identified during the prior reaffirmation of the guide;
- Expand the usefulness of the guide to other non-power generating nuclear facilities and to non-Class 1E electrical equipment;
- Bring the standard up to date with current approaches used in the industry for developing and implementing an ageing management program;
- Update the bibliography;
- Add a new annex on how to adopt risk informed techniques into ageing management programs (if determined to be feasible);
- Update the annex on condition monitoring techniques; and
- Incorporate any other user feedback received that would help the guide to be more useful to the industry.

The revised standard is expected to be appropriate for implementation of a CAMP. It will be opened up to include all electrical equipment essential to reliable plant operation and not restricted to safety related cables. The stated purpose, to bring the standard up to date with current CAMP development approaches and CM techniques, is consistent with the indicated needs of the industry. The revised standard is expected to be issued in mid-2014; however, there is no current intention to issue it under a dual IEC/IEEE logo.

IEEE Std 323-2003 [13.99] added guidance on the use of condition based qualification as a alternative, or adjunct, to the traditional qualified life approach to managing ageing of EQ equipment. Efforts are currently underway to harmonize and combine IEEE Std 323 with IEC 60780 and issue them as a single dual logo standard for international use.

IEEE Std 383 [13.97] is in revision. There has been discussion about adding requirements to address long term water effects in cable qualification.

As part of the IAEA cable ageing research program, a set of round robin tests were performed to determine the effect of using multiple laboratories to produce CM data. The result was that results from different labs produced varied results for similar specimens. Therefore it was decided that strictly controlled processes were required to ensure that results of CM tests will be repeatable. A modular set of standards was developed cooperatively between the IEEE and IEC under a joint logo; IEC/IEEE 62582; Electrical Equipment Condition Monitoring Methods. Its purpose is to define very controlled procedures for performing CM techniques to ensure that work at all plants and labs will be interchangeable. It is highly recommended that these standards be used for CM work. The following five modules are either issued or in advanced development. Others are expected to be added in the future.

IEC/IEEE 62582-1; General [13.100]	(Published)
IEC/IEEE 62582-2; Indenter Modulus [13.101]	(Published)
IEC/IEEE 62582-3; Elongation at Break [13.103]	(due end 2012)
IEC/IEEE 62582-4; Oxidation Induction Techniques [13.102]	(Published)
IEC/IEEE 62582-5; Optical Time Domain Reflectometry [13.104]	(due 2013)

5.5 Industry Guides

The following plant engineering support guides for CAMP related topics have been issued by EPRI. These documents provide useful and detailed guidance for implementing a CAMP and are consistent with the needs as indicated by international CAMP regulations and research. The guidance is directed toward cable ageing as a result of long term degradation due to chronic adverse environments. It does not address random immediate degradation due to installation damage or manufacturing defects. EPRI 1022969 [13.61] was not available for review but is expected to provide a valuable guide for CM method selection based on specific cable type, etc.

EPRI 1020804-Ageing Management Program Development Guidance for AC and DC Low-Voltage Power Cable Systems for Nuclear Power Plants [13.65]

EPRI 1020805-Ageing Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plant [13.64]

EPRI 1008211- Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets[13.76]

EPRI 1003663 - Integrated Cable System Ageing Management Guidance: Low-Voltage Cable [13.79]

EPRI 1003317 - Cable System Ageing Management [13.80]

EPRI 1001391 - Training Aids for Visual/Tactile Inspection of Electrical Cables for Detection of Ageing [13.85]

EPRI 1022969 - Electrical Cable Test Applicability Matrix for Nuclear Power Plants [13.61]

In addition to the above EPRI CAMP guidance reports, EPRI is continuing to perform research on the subject and have plans to issue guidance on instrument and control cable and perform additional testing on low voltage wetted cables. A qualification program for MV quick disconnects is also underway to aide in CM testing of MV cables.

6.0 DARLINGTON NGS CABLE AGEING MANAGEMENT STATUS

6.1 Station Cable Ageing Management Programs

There is no current formal cable ageing management program in place at Darlington Nuclear Generating Station operating under formal Ontario Power Generation (OPG) governance [13.112]. This however does not mean that the condition of cables is being ignored. OPG has developed an OPG Cable Management Strategy N-REP-57100-10001 [13.108] which reviews internal and external operating experience and made cable ageing management recommendations. Subsequently OPG issued in September of 2011, N-PROC-MA-0099 Cable Surveillance Program [13.107]. This document establishes the corporate requirements for a CAMP, although this does not necessarily assure field implementation. The corporate level document sets overall requirements and establishes relative priorities. It is up to each OPG NPP to establish the budget and implementing procedures to establish a Cable Surveillance Program. OPG is currently working to establish the best technology to use with the testing of submerged cables.

Prior to this formal approach, CAMP activity has been undertaken at Darlington NGS to address the ageing of cables. These actions were not taken as part of a formal CAMP but as part of the plant's performance engineering actions. Cable Deposits were installed at Darlington as part of the original construction of the plant. The cables are installed in a high radiation and high temperature environments. The first harvesting of these samples was completed in 2005. DNGS stated that these removed samples were sent for review and no ageing related problems were identified [13.112]. The next harvesting of cables is planned for 2014.

In addition to the cable deposit activities, Darlington is monitoring the cables connected to the Pressurizer heater. DNGS stated that these cables have shown some visible signs of ageing, but based on laboratory testing these cables have demonstrated acceptable performance capabilities [13.112].

6.2 Cable Profile Summary

Darlington is of relatively recent construction (in-service 1990) and does not have the wide variety of cable insulation types found in plants of earlier construction. Many cable types were obsolete by the period of time that Darlington was under construction and this limits the number of cable types used. However, as a more modern design, Darlington has a very large number of cables in comparison to other Canadian NPPs. The Darlington cable list includes 121,117 cables. This is a manifestation of the higher level of sophistication and complexity in the plant control systems than those present in the earlier designs. In general the cable types selected for Darlington were types which offered superior fire retardancy properties and better electrical performance. At the time of Darlington construction cable requirements for nuclear service were better defined and an attempt was made to utilize only nuclear grade cables. There are very few cables at Darlington which run in trenches, etc., where submergence could be an issue.

Table 6.1 Installed Insulation Types at Darlington NGS

Insulation Type[1]	Percent (%) of cables installed
EPR*	14
Fibre Optic*	
Polyimide/Kapton*	3
LDPE*	
PEEK*	
PVC*	8
ETFE/Tefzel*	1
XLPE*	57
E-CTFE/Halar	1
Not readily identifiable	15

1. Types identified with an * were identified during the site interview, others were added from analysis of the cable list.

Table 6.1 is based on an analysis of a portion of the Darlington cable list. The analysis used the material type field. The XLPE insulation type includes TECK cables which make up approximately 8% of the cable list. Based on the codes used, 15% of the cables could not be readily classified. The cable list includes plant stock identification numbers and a more complete analysis could be completed using this approach. As with all plants it will be important to ensure that information on insulation formulation is addressed in assessing cable ageing. Not all cables carrying the same stock number will be of the same insulation formulation.

The primary power voltages in use at Darlington are 13.8kV, 4.16kV, 600/347V and 208/120V. The primary control voltages are 120VAC and 250VDC and 48VDC.

6.3 Cable Failure History and Analysis

During the site interview a review was requested of the site OPEX with regard to cable failures. This data was provided by the Darlington NPP representative via email dated 07/12/2011 [13.120]. Table 6.2 below is a summary of the information provided.

Table 6.2 Cable Failures and Resolutions Identified at Darlington NGS [13.120]

Plant Identifier	Description	Apparent Failure Cause/Mechanism	Resolution
D-2003-10150	FM knotted cable (600VAC, 20C#6)	No failure. Reason for knot was not stated. The cable knot was recognized as a potential adverse service condition which could result in early electrical failure.	Replaced section of cable.
D-2004-04859	Damaged Pwr/Ctl cables found in cable manway due to water/ice	No failure. Cable jackets found damaged due to water/ice. Identified to investigate potential conductor damage.	Not clear. Mods to eliminate submersion were recommended.
D-2005-00194	Numerous cables in U/G ducts to substation subject to periodic submergence	No failure. Issue recognized as adverse environment requiring attention. Opex from BNGS and Davis Besse was cited as basis for concern.	Not clear. Increased duct pumping frequency. Action to study duct design and assess cable condition.
D-2005-00653	F/M power track cable (85C#16) failure	Conductor fracture due to flex fatigue.	Not clear. Failed wires jumped to spare cable. Action to replace failed cable.
D-2006-04011	F/M power track cable failure	Open conductor. Reason not stated.	Not clear. Failed wire to spare. Cable to be replaced as failed wires accumulate.
D-2007-15047	Damaged ground cable	Damaged during excavation.	Repaired. Improved pre-job briefings recommended.
D-2009-14310	F/M power track cable conductor failure	Not stated.	Not clear.
D-2010-02494	F/M power track cable failed conductors	Not stated.	Not clear.
D-2010-07486	Sagging power track chain supports	Not stated. Correction of potential root cause to power track cables is cited reason for chain repairs.	Not clear.
D-2010-08740	Fuel handling computer unibus cable failure	Human error. Damaged cable during maintenance due to lack of training/experience.	Cable fixed. Recommended change of group assigned to work.
D-2010-08793	Fuel handling festoon cable failure	Damaged due to track condition.	Not clear. Action to repair track.
D-2010-09351	Defective moisture element cable	Not stated.	Not clear. Action to trend failures.
D-2011-04623	Cable to 1-63310-YE200#1 damaged	Brittle.	Cable replaced. Action to trend failures.
D-2011-04624	Cable to 1-63310-YE400#1 damaged	Brittle.	Cable replaced. Action to trend failures.

The Darlington OPEX does identify that there have been historical clusters of cable issues associated with submergence and cable flexing. While the resolution of these issues is not clear; the lack of similar OPEX in subsequent years suggests that effective corrective actions have been taken to correct these issues. The 2 OPEX items for 2011 are in themselves not of great concern, but they do indicate that issues due to cable embrittlement may be starting to appear.

It should be noted that Darlington has been operational for 21 years at the end of 2011. Due to a change in the processing of plant information, failure data is not available for the earlier years of plant operation. At the site interview it was identified that there had been an issue with ultra violet light attacking the wiring harnesses of cables going to some current alarm units. As these harnesses were supplied with the equipment they would be classified as equipment wiring and fall outside the scope of CAMP activities.

6.4 Assessment of Ageing Management Effectiveness

Darlington has taken specific reactive actions to address known concerns. The state of the fuel handling cables seemed to have been allowed to deteriorate to a very high level of degradation impacting both operating performance and potentially a heightened challenge to the safe operation of the plant. The concern with degradation of fuel handling cables is an issue of long standing. These events highlight the importance of effective CAMP activity to prevent the occurrence of this sort of situation.

As noted above, OPG has prepared and issued N-PROC-MA-0099 – Cable Surveillance Program [13.107]. This program will form the basis for future CAMP activities at OPG. This program identifies the key activities of a CAMP.

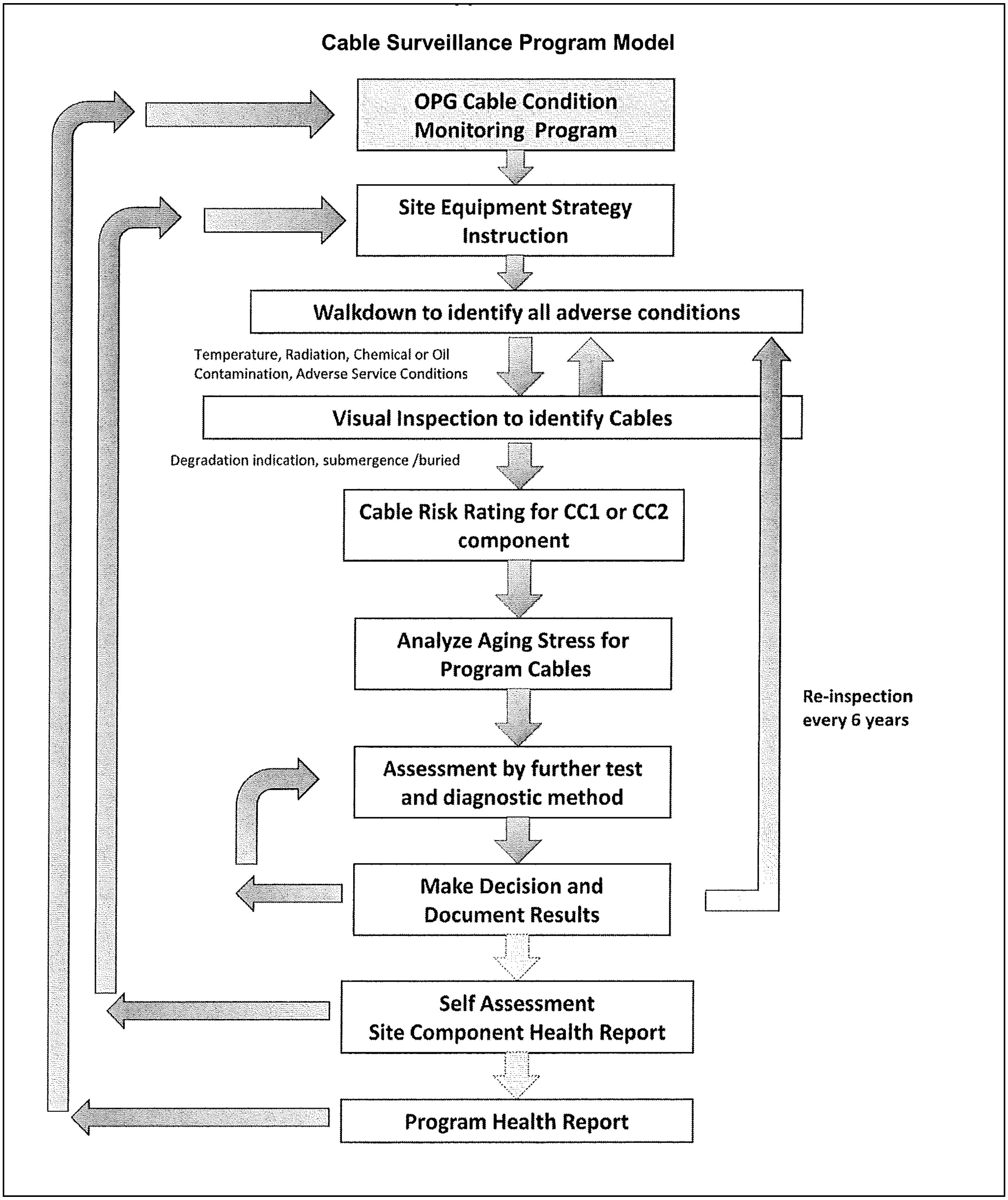


Figure 6.1 Appendix A of OPG N-PROC- MA-0099 – Cable Surveillance Program [13.107]

The following key activities are included in this program:

- Conditions which present high degrees of stress to cables are to be identified. This includes temperature, radiation etc.
- Site conditions are to be validated by walk downs.
- The selection of cables based on component criticality. The process identified utilizes the N-PROC-MA-0077 – "Critical Equipment Identification and Categorization Procedure" as a basis for identifying the required equipment. Once the equipment is identified the cables are derived from establishing those cables necessary to support the critical equipment. This process is adequate to meet the requirement of a CAMP and does follow international guidance in this area. It is noted that this process of cable identification is extremely onerous given the necessity to evaluate such a large amount of equipment.
- A risk ranking process is identified to prioritize downstream scrutiny of specific cables. This includes criticality, age, insulation material, voltage, load factor, and operating environment. The risk ranking process is a necessary process to limit the amount of resources required by the CAMP process. Given the large population of cables it is necessary to limit the scope of the program. The selected approach may result in certain cables being excluded but still critical to the plant operation.
- Testing and inspection to be performed on selected cables. The type and application of testing is not yet developed and is the responsibility of the individual plants to develop.
- The existing plant SCR process is used to document station condition and may be used to determine if corrective actions are required.
- Records are to be maintained of the activities undertaken
- The CAMP process is undertaken utilizing OPG Governance

To complete the requirements of the OPG Cable Surveillance Program, Darlington NPP must develop the necessary in plant procedures to achieve the programmatic requirements established in N-PROC-MA-0099 [13.107].

Currently Darlington has cable deposits installed in the plant. These samples will provide a valuable input on thermal and radiation ageing to a future CAMP program. Other than data gained from the cable deposit program no forward looking work appears to be in progress. The effectiveness of a CAMP increases the earlier it is implemented so that results are sufficiently mature to identify potential age-related failures far enough in advance to permit planning of corrective actions. Given that Darlington is entering a life extension program it would seem prudent that the capability of the cable to perform reliably for the extended life should be assessed (Section 12, element 10). There was no evidence provided that this has been done.

An assessment of current Darlington NGS cable ageing management practices, as identified in site interviews [13.112], against the recommended elements of a CAMP (Section 12) is provided in Table 6.3.

6.5 Safety Implications

Based on the available information, no safety implications could be confirmed with the current state of operation of Darlington. The past state of the fuelling machine cables could have been a safety or reliability concern. It appears that the issue of flooding has been ameliorated by frequent dewatering of the limited locations where flooding is a concern. It should be noted that degradation caused by flooding is not reversible and that the removal of the flooding slows the degradation of the cable but does not stop the degradation of the cable. Cables which have been exposed to flooding for a substantial period of time should be considered as prone to early failure [13.64].

Table 6.3 – DNGS CAMP Score Card

CAMP Element (Section 12) #	Description	Score*	Comments
1	Program Cable Scope	0	Discrete list of all safety-related and/or operationally significant cables could not be provided. Corporate direction for CAMP is provided in N-PROC-MA-0099. Station is to comply by 31 July 2013.
2	CAMP Database	0	No database for CAMP was provided.
3	Characterize and Monitor Service Conditions	0	No indication that cable service environments have been characterized.
4	Identify Stressors and Expected Ageing Mechanisms	0	No indication that stressors and expected ageing mechanisms for specific cables or cable types have been defined.
5	Select CM Techniques Suitable to Monitored Cables	0	No specific CM techniques were identified or justified re: cable condition monitoring. Recognize that some proactive testing to assess ageing has been implemented. Selection of CM techniques is in development. See element 8 for identified CM activities.
6	Establish Baseline Condition of Monitored Cables	0	See elements 5 and 8.
7	Identify Cable Characteristics & Ageing Effects Monitored by each CM Technique	0	See element 5.
8	Periodically Perform CM Tests and Inspections on Cables	1	Testing and monitoring of Pressurizer Heater cables, known to be in worst case environment. Samples have been removed for assessment. Further information is required to determine the scope of plant cables addressed by testing and if CM techniques are appropriate (element 5). Cable deposits have been installed and harvested once (2005) for condition assessment. No ageing problems identified. Next harvest scheduled 2014. Further information is required to determine the scope of plant cables addressed by testing and if CM techniques are appropriate (element 5).
9	Periodically Review and Incorporate OPEX	0	No process is in place to collect and compile cable related operating experience for review of composite information and revalation of ageing concerns. During the interview, no known age-related failures were known to have occurred. However, a follow-up search of plant SCR database revealed several age-related cable failures (see Section 5.3). It is acknowledged that some cables were replaced due to industry OPEX as a part of the EQ Program. However, it is also recognized that the basis for some of the cable replacements was to improve DBA performance and not due to ageing concerns.
10	Periodically Review and Trend the Condition of Monitored Cables	1	See element 8.
11	Identify Degraded Conditions and Define/Take Corrective Actions	0	See element 9 regarding EQ Program actions. Results of cable deposit and Pressurizer Heater CM activities indicated no action was required at this time. DNGS indicated that no acceptance criteria have been developed for CM activities yet. Therefore, there is no defined basis for acceptability of results of CM activities.
	Score (22 max)	2	

1. 0 = No practice indicated, 1 = Limited related practices, 2 = Complete compliance

7.0 PICKERING NGS CABLE AGEING MANAGEMENT STATUS

7.1 Station Cable Ageing Management Programs

Pickering NGS falls under the same corporate governance as Darlington. As such, the corporate program described in Section 6.1 also applies to Pickering NGS. For details of this program see Section 6.1. Pickering does not have a formal or informal CAMP in place [13.113].

7.2 Cable Profile Summary

Pickering, due to its age and long period of construction and operation, has a large number of cable types installed. Pickering was essentially under construction from the late 1960s to the early 1980s. There were significant changes in cable technology over this period of time. In the early 1960s many of the common cable insulation types such as XLPE and EPR were not commonly used. In addition the requirement for fire retardancy and low acid gas evolution were under development.

Table 7.1 Installed Insulation Types at Pickering NGS

Insulation Type1	Percent (%) of Installed Cables Pickering A	Percent (%) of installed cables Pickering B	Percent (%) of Length From Purchase History Pickering A&B
EPR*		Trace[2]	Trace
Paper&oil/PILC*	Trace	Trace	Not specified
SiR*		Trace	
PVC*	49	58	77
CTFE/Hypalon*			
XLPE*	16	9	12.6
ETFE/Tefzel*			
EVA			2.3
Butyl Rubber*			
PTFE/Teflon	Trace		
Fibre Optic		Trace	
MgO/MICC*	5	Trace	
PE*		Trace	
PEEK*	Trace		
Not readily identifiable	28	30	7

1. Types identified with an '*' were identified during the site interview [13.113]. Others were added from analysis of the cable list and the cable purchasing analysis provided by D. Johnson of OPG

2. Trace" is used to document that the type of cable insulation was found but the quantity is less than 1%.

The Pickering A Unit 1 cable list [13.121] was sorted by material type. The cable list identified 70 different types. Of these, most of the type designations were not familiar to the authors. The identifiable types are indicated in Table 7.1. Of the total of 17,368 cables identified, 28% of the cables could not be identified. Of these 4941 unidentified cables, 823 were noted as supplied by the manufacturer. This categorization identifies cable supplied by various equipment vendors and it is doubtful if there are significant technical records describing the construction of these cables.

A similar analysis was performed for Unit 8 of Pickering B cable list [13.122] of 14736 entries. The results of this analysis identified 42 types of cable. Many of the types were not readily identifiable (30% of entries).

While 49% of the cables are identified as PVC, investigation during the Environmental Qualification Program identified that ageing characteristics of PVC and other compounds are dependent on the formulation of the cable. At that time an investigation of the purchasing records available identified that there were many different formulations of PVC found at Pickering, with a less but significant diversity in XLPE, and EPR insulation compounds.

The purchasing history document identified EVA as an insulation type but none were identified in the cable list analysis. This can be explained by looking at the purchasing history of material code 71824781. This material code, while identifying one generic cable type, was supplied from 4 different companies and includes both EVA and XLPE insulation types. Other material codes have similar relationships. As the material code is the primary identifier for cable installation, this divergence of cable insulation types would not have been identified on the cable list. The differences in percentage between the purchase history and the installed cable percentage may be attributable to the purchase history percentages which are based on length purchased, while the number installed is simply a count of cables. Building services and security cables are generally not included in the cable list information.

The majority of cable at Pickering is routed indoors on cable tray and in conduit. There are, however, significant numbers of cables with the potential to have been exposed to submergence. These include cables routed to safety significant equipment such as the Emergency Core Cooling pump motors.

Substantial cable replacement was undertaken during the EQ program at Pickering A and B. PVC cable located inside the reactor building was replaced with fire rated qualified XLPE cable. In addition some ion chamber cables and flux detector cables were replaced. A substantial number of cables have been upgraded at Pickering as a result of other engineering driven activities. A sort of the Pickering Unit 1 cable list identifies that 7321 cables of the cables currently installed or planned to be installed at Pickering are from the period after 1990. This represents 41% of the Pickering Unit 1 listed cables. In the 6 operating units at Pickering there are 96,838 cables registered in the cable list. This does not include building services or security cables. Switchyard cables are included in this listing. It should be noted that Units 2 and 3 are not included. These units while out of service may very well have safety related cables associated with common services related to the remaining 6 operating units.

The main power voltages in use at Pickering NPP are 4.16kV, 600/347V and 120/208V. The control voltages are 120VAC and 250VDC and 48VDC.

Pickering is sponsoring a testing program to assess the radiation performance of Tefzel insulated conductors. It is assumed that Tefzel is present and forms part of the cables which cannot be readily identified from the cable list.

7.3 Cable Failure History and Analysis

Table 7.2 Cable Failures and Resolutions Identified at Pickering NGS

Plant Identifier	Description	Apparent Failure Cause/Mechanism	Resolution
P-1998-02158	Generic SCR to document issues with submerged cables	No failure.	Unknown
P-1998-04400	Cable exposed to oil	No failure. Cable insulation was softened.	Cable replaced
P-1999-02519	Documented near miss to critical cable installation	No failure. Potential error induced damage.	Unknown
P-1999-03913	Fibre Optic cable severed	Error induced damage.	Unknown
P-1999-07278	Wires severed	Error induced damage.	Unknown
P-2000-05282	Cable jacket “nicked”	Error induced damage.	Unknown
P-2001-04083	Cut grounding cable	Error induced damage.	Unknown
P-2002-08257	Broken cable	Error induced damage.	Unknown
P-2002-10636	Damaged cables in MER CDF	No failure. Error induced damage.	Unknown
P-2002-13004	O/H outside cable fallen	Support broken.	Unknown
P-2002-14130	Ground cable cut	Error induced damage.	Unknown
P-2003-06238	EQ cable sheath damaged	No failure. Error induced damage.	Damaged portion of cable removed
P-2003-06314	Cable supplied with join	No failure. Manufacturer QA.	Unknown
P-2003-13622	Cable broken at motor junction box	Not stated.	Unknown
P-2003-19243	Damaged cable jacket	Not stated.	Unknown
P-2004-00010	Failed cord on office equipment	Not applicable.	Unknown
P-2004-00810	LAN cable damaged by truck	Error induced damage.	Unknown
P-2004-01929	Damaged ground cable	Not stated.	Unknown
P-2004-07224	Cable installation issue	No failure. Error induced damage.	Unknown
P-2004-12689	Damaged (twisted) MI cable	Error induced damage.	Unknown
P-2004-12909	Cable installation damage	Not stated.	Unknown
P-2005-03716	Cable cut	Not stated. Probable error induced damage.	Unknown
P-2005-03892	Wire to shield short cable kinked	Not stated. Probable error induced damage.	Unknown
P-2005-05440	TE cable damaged, poor support	Error induced damage.	Unknown
P-2005-06806	Cable damaged, support issue	Error induced damage.	Unknown
P-2005-15261	B/R hoist cable (cabtire – mfr supplied) shows visible signs of degradation	Stated as probable “heat and radiation stress”	Unknown
P-2005-18780	Fire detection cable low IR to ground	Not stated.	Used spare wires

Plant Identifier	Description	Apparent Failure Cause/Mechanism	Resolution
P-2006-00401	Ion chamber cable jacket damaged	Error induced damage.	Unknown
P-2006-10235	Mfr ribbon cable failure	Not stated.	Cable replaced
P-2006-23420	Newly installed cable damaged	Error induced damage.	Unknown
P-2007-12633	Cable damaged during installation	Error induced damage.	Unknown
P-2007-15502	Generic Issue Cables routed in hot locations	No failure – preventative.	Unknown
P-2008-19542	Broken wire, physical damage	Not stated.	Unknown
P-2011-13701[1]	Moisture ingress into ion chamber MICC cable caused signal problem	Unknown.	Unknown

1. This SCR was not supplied by OPG but found in Bruce Power records.

The OPEX listing clearly identifies that the majority of cable related issues arise from ongoing work in the plant causing error-induced damage to cables. The other major cause of cable failure appears to arise from twisting or kinking of cables causing broken wires. Of the above OPEX only 5 items appear to have ageing related failures which do not reflect physical damage issues. Of these, two are raised as generic cable issues and 3 relate to potentially ageing related failure of the cable. The 3 selected ageing related failures are SCRs P-2006-10235, P-2005-15261 and P-2011-13701. All of these SCRs relate to cables supplied as part of manufactured assemblies and would fall outside the scope of a CAMP (Section 12, element 1).

Switchyard cables are not under the control of the NPP operator but under the grid operator. As such, OPEX associated with these cables may not be fully documented.

7.4 Assessment of Ageing Management Effectiveness

There are activities currently in progress at Pickering which provide some assessment of cable condition. Operator walk downs provide input based on visual inspection of cables; however, it is not clear what criteria are used to identify problems or what training is provided to the inspectors. Thermography is used to identify hot spots which are rectified on an ongoing basis. The provided OPEX identified the need to assess hot spots. Issues related to submerged cables at other plants were also identified for assessment of their applicability and required action at PNGS. No results of these initiatives were provided.

See Section 5.4 of this report for discussion on the developing OPG Cable Surveillance Program as documented in N-PROC-MA-0099 – Cable Surveillance Program [13.107].

The Pickering units are approaching the end of their planned life. It is important that efforts spent at this stage of the plant life are focussed where results can be implemented prior to the shutdown of the facility. The development of a CAMP program for the Pickering site should take into account the limited remaining plant operating lifetime. It would be reasonable to focus efforts at this stage of plant life on high risk cables and enhanced failure monitoring.

An assessment of current PNGS cable ageing management practices, as identified in site interviews [13.113], against the recommended elements of a CAMP (Section 12) is provided in Table 7.3.

7.5 Nuclear Safety Implications

Due to the low level of failures, there is no indication of an immediate safety problem due to the absence of a CAMP. Based on the OPEX provided; there is no trend evident of significant ageing related cable failures. Concerns relate to lack of predictability of future performance. Given the age of the plant, submerged medium voltage cables should be a priority and formally assessed for their capability to support the remaining station life [13.64].

Table 7.3 – PNGS CAMP Score Card			
CAMP Element (Section 12)		Score*	Comments
#	Description		
1	Program Cable Scope	0	Discrete list of all safety-related and/or operationally significant cables could not be provided. Corporate direction for CAMP is provided in N-PROC-MA-0099. Station is to comply by 31 July 2013.
2	CAMP Database	0	No database for CAMP was provided.
3	Characterize and Monitor Service Conditions	0	No indication that cable service environments have been characterized.
4	Identify Stressors and Expected Ageing Mechanisms	0	No indication that stressors and expected ageing mechanisms for specific cables or cable types have been defined.
5	Select CM Techniques Suitable to Monitored Cables	0	No specific CM techniques were identified or justified re: cable condition monitoring.
6	Establish Baseline Condition of Monitored Cables	0	See element 5.
7	Identify Cable Characteristics & Ageing Effects Monitored by each CM Technique	0	See element 5.
8	Periodically Perform CM Tests and Inspections on Cables	0	No indication that CM testing is being performed.
9	Periodically Review and Incorporate OPEX	1	No process is in place to collect and compile cable related operating experience for review of composite information and revelation of ageing concerns. However, it was recognized that OPEX had been used to proactively initiate investigation into potential related cable ageing issues.
10	Periodically Review and Trend the Condition of Monitored Cables	0	See element 8.
11	Identify Degraded Conditions and Define/Take Corrective Actions	1	There was no indication of a comprehensive process to identify and action degraded conditions. However, some recognition is given to actions as a result of operator walk downs, EQ program cable replacements, and an intent to define actions from generic OPEX issues (element 9).
	Score (22 max)	2	
1. 0 = No practice indicated, 1 = Limited related practices, 2 = Complete compliance			

8.0 POINT LEPREAU NGS CABLE AGEING MANAGEMENT STATUS

8.1 Station Cable Ageing Management Programs

A Cable Condition Monitoring (CCM) Program was established at Point Lepreau station in 1995 to manage ageing of EQ cables. This program is a living program and is an ongoing station activity. The program operates under the Point Lepreau NGS managed quality system. The original driver for the program was the need to establish cable capability for extended plant operation but is limited to Instrument and Control EQ cables inside Containment, although some non-EQ cables and one outside Containment test site are included to bound conditions [13.114].

The CCM activities undertaken in support of the EQ program have been integrated into a larger Cable Management Program intended to address plant cabling in general. Differing approaches are used to address the capability of cables - Figure 8.1 Cable Management Program at Point Lepreau NGS. As indicated in Figure 8.1, the program is structured using a series of internal reports and procedures subdivided into program elements used to: a) support EQ cable qualified life for the initial 30 year design life of the plant, b) support EQ cable qualified life for plant life extension to 60 years, and; c) general ongoing cable management/maintenance. The following discussion is based on a verbal description of these reports and program elements to the interviewers.

One of the key initial activities addressed by the program was a concern raised by AECL with regard to PVC cable used in EQ circuits. As a result, Point Lepreau undertook EQ testing of installed PVC cable types, the results of which demonstrated that the installed cables were found to be adequate for most applications. RTD circuits installed in trunk cables were found to be problematic. These RTD circuits, where required, have been modified to assure proper operation. In general most installed plant cables were found to be adequate for EQ applications. Successfully tested and qualified PVC cables (NT-PVC – OPG designation = PVC4) were retained and unknown PVC formulations were replaced in EQ applications (Figure 8.1).

Following the initial lot of testing, accelerated ageing simulation testing was undertaken of representative EQ cables to support 30 and 60 year qualified lives. The PVC/PVC and PVC/XLPE cable specimens were subjected to incremental ageing phases and subjected to indenter measurements to “fingerprint” the ageing characteristics of the cables. Details of this test program are documented in IR-60010-122. The cable ageing characteristics provided in the EQ test program are used to provide the condition indicators (indenter modulus) used to measure and trend cable degradation to ensure that the degraded cable condition existing prior to accident simulation is not exceeded. While this Cable Condition Monitoring program is currently confined to EQ cables, it may be extended to address similar cables outside the EQ program, particularly since the majority of PVC cables are from a common supplier and formulation [13.114]. A breakdown of cables used at Point Lepreau is documented in IR-121.

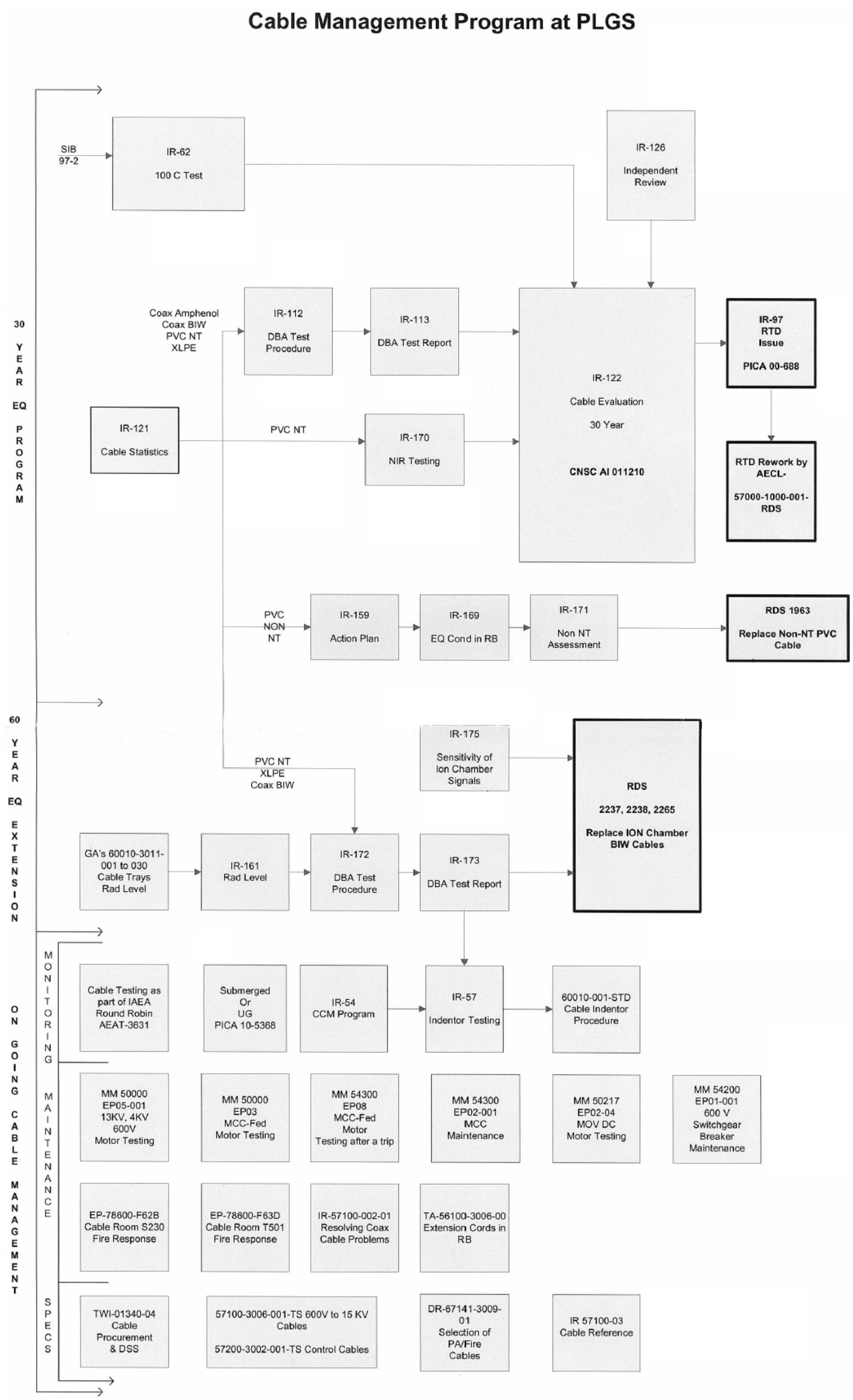


Figure 8.1 Cable Management Program at Point Lepreau NGS

The assessment of medium voltage cables while part of the plant Cable Management Program is an extension of the ongoing Monitoring and Maintenance Program. Medium voltage cables are assessed during the maintenance of their associated end device. The end device is subjected to a DC meggar test and polarization index. After reconnection of the cable to the end device, the assembly is subjected to another meggar and polarization test. Differences are attributable to the cable. The same basic process is used for larger 600 V loads. Smaller loads taken from MCCs do not have an ongoing testing program.

8.2 Cable Profile Summary

Point Lepreau Generating Station is a single unit NPP constructed between 1975 and 1983. In comparison to other facilities the plant has a relatively small diversity of cables when compared to the multi unit NPPs. There are $5x10^6$ feet of cable installed with $9.8x10^5$ feet in the reactor building. There are a limited number of cables subject to submergence at Point Lepreau NGS. There are no medium voltage direct buried cables [13.114]. Table 8.1 identifies the cable insulation types which are present in Point Lepreau NGS. In addition to the number of cable types being limited, the number of formulations of any one specific insulation type is also limited.

Table 8.1 - Insulation Types Installed at Point Lepreau NGS

Insulation Type[1]	Percent (%) Installed
PVC/FRPVC[2]	38
Polyarylene /Stilan*	
XLPE*	22
Polyimide/Kapton*	
MgO/MICC	trace
PEEK*	
Not readily identifiable	39

1. Types identified with an * were identified during the site interview [13.114], others were added from analysis of the cable list information provided by M. Debly of Pt Lepreau NGS .
2. The majority of PVC cable is from a single supplier and of a single compound –NT-PVC (PVC4) [13.114].

Types identified with an * were identified during the site interview, others were added from analysis of the cable list information provided by M. Debly of Pt Lepreau NGS . The percentage installed is based on a review of the cable list supplied to RCMT. The analysis of the cable list was done by sorting the cable list by part number and relating the part number to the list of part numbers provided. A significant number of the cables (39%) were not readily identifiable by this approach. Further review of the plant records would be required to establish the construction of these cables. The Point Lepreau cable list contains 6,676 cables, but does not include the switchyard, building services and security cables.

All power cables are XLPE insulation with PVC jacket. A large portion of the signal and control cables are PVC/PVC; however, there are smaller quantities of XLPE and other specialty cable insulations such as polyarylene (Stilan), polyimide (Kapton), and PEEK [13.114].

The power supply voltages at Point Lepreau are 13.8kV, 4.16kv, 600/347V and 120/208V. The control voltages are 250VDC, 120VAC and 48VDC.

8.3 Cable Failure History and Analysis

There have been a very limited number of cable failures reported at Point Lepreau generating station which is consistent with the plant size. The plant conditions are less severe than other operating nuclear plants with regard to normal operating temperature and radiation.

At the site visit a verbal report was given of the station OPEX with regard to cable related events. The plant OPEX system was searched for relevant events using key word searches. Eleven events were found having to do with cables. Of these, 8 had to do with cable damage caused during refurbishment and were not ageing related. One event was a review of submerged cables that identified no specific issues to be followed up. One had to do with premature ageing of an LDPE cable (Amphenol) which was not in compliance with that specified by Design and which was replaced as part of the EQ program. An additional event was recorded against the start up instrument cables which was addressed by replacing a small section of cable.

8.4 Assessment of Ageing Management Effectiveness

The portion of the cable management program explicitly addressing age-related cable condition monitoring (CCM) at Point Lepreau is limited to EQ cables although some non-EQ cables and one outside Containment test site are included to bound conditions [13.114]. Within the CCM program only instrument and control cables are addressed.

The current CCM program is intended to provide a reasonable level of assurance that the EQ control cable population will support an extended operating life for these cable types. This approach may be readily extended to the non-EQ control cable population, of similar cable type. The EPRI indenter is being used to track condition using indenter modulus (IM) as a condition indicator. This CM technique is effective in trending PVC degradation in relatively low radiation environments and provides leading indicator of insulation ageing degradation when applied to the jacket. It may not be an effective technique where PVC cables are subject to normal radiation doses over 15 Mrads and HCl evolution is a concern. Further information is necessary to determine if acceptance criteria and application of the method is effective in all circumstances. The EPRI indenter is also effective as a leading indicator of cable degradation for XPLE/PVC cables where it is demonstrated that the jacket will degrade more quickly (Section 4.4.1.3)

Power cables, while included in the overall cable management program, are not included in the CCM program or treated with the same degree of rigour as the EQ control cables. Given the external OPEX this appears to be a potential weakness of the Lepreau G.S. program.

In particular, the use of meggar (IR) tests and polarization index readings is not effective in monitoring progressive degradation of MV cables and will typically not detect degradation until it is very severe or failed, which is contrary to the concept of condition monitoring. Polarization testing is most frequently used to address the windings of electrical machines. Leakage currents are very small in cables and testing the cable with equipment may mask cable problems. IR readings may remain high until through cracking has occurred [13.13]. The Point Lepreau program could be greatly improved by the use of improved testing methodology where CCM is required. For MV cables that are within the scope of a CAMP and deemed to require condition monitoring (Section 12, elements 1 and 2), methods such as Tan-δ, partial discharge or LIRA are considered effective CM techniques [13.64].

General ambient temperature conditions are relatively benign at Point Lepreau. However, temperature monitoring and thermography are used to identify thermal hot spots [13.114]. These are recognized as effective tools in characterizing and monitoring cable environments to reveal adverse operating conditions (4.4.1.2). Further information is necessary to determine if the application of these methods is effective in addressing anticipated ageing concerns.

An assessment of current Point Lepreau cable ageing management practices, as provided in site interviews [13.114], against the recommended elements of a CAMP (Section 12) is provided in Table 8.2.

8.5 Safety Implications

Based on the information provided by the plant, the existence of safety concerns could not be confirmed nor suggested. There is a concern that the condition of medium voltage cable may be more degraded then believed due to the testing regime in use (Section 8.4).

9.0 GENTILLY-2 NGS CABLE AGEING MANAGEMENT STATUS

9.1 Station Cable Ageing Management Programs

No formal cable ageing management program is in place at Gentilly 2. Isolated individual actions have been completed for higher risk areas. Hydro Quebec completed a study [13.111] based on industry research, experience and engineering judgement, to assess the condition of installed cables and determine if any should be replaced during a plant refurbishment. The study identified the stressors and ageing mechanisms associated with the common plant cable types and concluded that the existing cables would be expected to continue to provide reliable service and support extended plant life. The cable condition assessment is not a cable ageing management program element and is therefore not within the scope of this report. However, development and implementation of a formal cable ageing management program has been considered should refurbishment of the plant proceed [13.115].

While no formal program has been implemented, steps have been taken to gather preliminary data which could, as a result of ongoing activities, form the basis of a program:

- NIR scanning
- Indenter measurements taken during EQ testing.

NIR cable scanning has been completed for a significant number of cables. The NIR scanning was performed primarily on EQ cables but some non-EQ cables were also scanned. If the measurements are re-taken at a later date, they could be compared to the previous values to determine the change in the amount of plasticizer within the insulation. The same measurement was completed on the cables during testing before/after thermal ageing, radiation ageing, etc., such that for PVC cable the minimum amount of acceptable plasticizer is known for cables that were environmentally qualified. This could be used at future dates to determine degradation.

Refurbishment is an opportunity to get samples of degraded cable that can be used for testing and further study of ageing affects.

A limited set of indenter data on test cables has been collected.

Table 8.2 – PLGS CAMP Score Card

CAMP Element (Section 12)		Score*	Comments
#	Description		
1	Program Cable Scope	1	The scope of a Cable Management Program was presented (Figure 8.1). However, the scope was limited to EQ and a limited number of large electrical machines. No discrete list of all safety-related and operationally important cables was available.
2	CAMP Database	0	No database for CAMP was provided or indicated.
3	Characterize and Monitor Service Conditions	1	Temperature monitoring and thermography are used to identify thermal hot spots. A review of submerged cables was performed [13.114]. Radiation conditions are defined for EQ cables. It is unclear if radiation hot spots are identified (Figure 8.1). Further info is required to determine if the scope of these is adequate. There is no explicit indication of processes to identify other adverse conditions such as ohmic heating, flexing, contamination, etc
4	Identify Stressors and Expected Ageing Mechanisms	1	Stressors and ageing mechanisms have been identified to support CCM subprogram. Further information is required to determine if this is complete and effective.
5	Select CM Techniques Suitable to Monitored Cables	1	EPRI indenter has been selected for PVC/PVC control cables. IR + polarization index has been used for major motors; however, this may not be effective as a lead indicator of cable degradation.
6	Establish Baseline Condition of Monitored Cables	1	Initial CM testing was performed to baseline cable condition in 1995 using procedural controls. Active environmental monitoring suggests a limited service condition baseline would have been provided. Further information is necessary to determine if all relevant design and installation inputs were considered.
7	Identify Cable Characteristics & Ageing Effects Monitored by each CM Technique	1	Ageing characteristics and IM condition indicators for CCM cables were defined by using incrementally-aged specimens during EQ testing. Further information is necessary to determine if this was fully adequate for all installations. The IR + polarization index test method used for major motor cables is not sensitive as an early indicator of age-related degradation.
8	Periodically Perform CM Tests and Inspections on Cables	1	The CCM program has performed regular testing for the past 17 years. Testing of major motor cables is performed as part of regular motor testing as part of the plant maintenance program. There is no indication of regular walk down/visual inspections of the larger cable population.
9	Periodically Review and Incorporate OPEX	1	No process is currently in place to collect all cable failure and issue OPEX for review. However, it was stated that there was a plant Problem Identification and Corrective Action (PICA) process in effect at the plant which may be readily adapted and applied to a CAMP by flagging cable issues as a topic to be readily collected for review and trending. The PICA process had been used to identify and address underground MV cable concerns (Figure 8.1).
10	Periodically Review and Trend the Condition of Monitored Cables	1	The review of CM data from CCM program currently indicates that no significant ageing of the relevant cables has occurred.
11	Identify Degraded Conditions and Define/Take Corrective Actions	1	No degraded monitored cables have been identified yet (element 10). Acceptance criteria are defined for CCM and IR/PI tests but further information is required to determine if these are adequate. Updated cable specifications addressing modern capability requirements have been produced and integrated into the Cable Management Program to provide a ready basis for cable procurement and replacement should it be necessary.
	Score (22 max)	10	

1. 0 = No practice indicated, 1 = Limited related practices, 2 = Complete compliance

9.2 Cable Profile Summary

Gentilly 2 Generating Station is a single unit NPP constructed between 1975 and 1983. Gentilly 1 is located adjacent to Gentilly 2 and is out of service. Cables associated with Gentilly 1 are not addressed in this report.

The insulation types of cables found at Gentilly 2 are identified in the Table 9.1 below:

Table 9.1 - Insulation Types Installed at Gentilly-2 NPP

Insulation Type[1]	% Installed
PVC/FRPVC	60
Polyarylene /Stilan*	2
XLPE*	23
Polyethylene	8
Polyimide/Kapton*	Trace
PTFE/Teflon	
MgO/MICC	Trace
PEEK*	Trace
Fibre Optic	Trace
CSPE	Trace
EPR/EPDM	Trace
Glass	Trace
Polypropylene	Trace
Rubber (cab tire)	Trace
SiR	Trace
Not readily identifiable	3

1. Types identified with an * were identified during the site interview [13.115], others were added from analysis of the cable list information provided.

The percentage installed is based on a review of the cable list supplied by to RCMT [13.117]. The analysis of the cable list was done by sorting the cable list by insulation type. A small number of the cables (3%) were not readily identifiable by this approach. In general, I&C cables are PVC/PVC and power cables are XLPE insulated [13.115]. The cable list includes work in progress which may further reduce the number of unidentified cables. The Gentilly 2 cable list provided the most detailed listing of any plant with the least number of cables that were not readily identifiable.

A list of the cable testing performed to support the Environmental Qualification Program was provided. This listing identifies that 10 distinct PVC formulations and 2 XLPE formulations as being required to establish environmental qualification of the plant legacy cables. It is believed that these cable types are similar to the bulk of the installed plant legacy cables. The testing date was taken during the qualification testing which can be applied to a condition monitoring program in the future [13.115].

The plant has a substantial amount of buried cable. Much of the buried cable is located in the switchyard. There are no buried cables associated with the Emergency Power

System. The Gentilly-2 cable list includes 24,266 cable entries. The cable list includes essentially all plant cables except those relating to the security systems.

The common operating voltages at Gentilly-2 are 8kV, 4.16kV, 600/347V and 208/120V. The common control voltages are 250VDC, 12VAC and 48VDC.

9.3 Cable Failure History and Analysis

No formal report was received with respect to cable OPEX at Gentilly-2. During the site interview it was noted that there had been multiple failures of the buried switchyard cables. These failures manifested themselves in low insulation resistance of buried cables such that the ground detector alarmed. Action is going forward during refurbishment based on the recommendations contained in G2-APR-5-57000-SSCC-01 [13.111]. Later correspondence identified two ageing-related cable failures, as follows:

One 1/C 250 MCM 8kV XLPE/PVC cable failed due to overheating. The cable is normally energized and missing conductor strands at the connector resulted in a high resistance termination and localized ohmic heating. Resolution is not stated.

Two wires of an 8C9 600V PVC/PVC cable failed due to heat ageing. The cable was connected to the generator CT and was subjected to continuous circulating currents. Connections were transferred to two other wires in the cable. Final actions are unknown.

Each of the above failures is associated with adverse service conditions as defined in Section 12, element 3. A CAMP which identified these cables as candidates for condition monitoring based on their adverse service conditions may have prevented their failure.

9.4 Assessment of Ageing Management Effectiveness

There is no ongoing CAMP in place. However, certain actions have been taken in preparation for a CAMP should refurbishment proceed [13.115]:

- A limited amount of cable condition data, primarily related to FT-NIR (to measure plasticizer content in PVC) and Indenter, have been collected during EQ cable test programs for potential use later.
- Some CM testing of field cables has been performed to be used as baseline CM data, if necessary.
- Some criteria have been defined for using visual inspection of cable jackets as a leading indicator of cable insulation ageing.
- Some sampling has indicated that cables are ageing more quickly at higher plant elevations. This may be useful in characterizing cable conditions and defining adverse conditions and/or bounding conditions.

All of the above actions are potentially suitable and even essential to developing a CAMP; however, further information is required to determine the effectiveness of the specific processes. An assessment of current Gentilly 2 cable ageing management practices, as provided in site interviews [13.115], against the recommended elements of a CAMP (Section 12) is provided in Table 9.2.

9.5 Safety Implications

Based on the information provided, the existence of safety concerns could not be confirmed nor suggested, dependent on the issue arising with direct buried switchyard cables having been fully resolved. Concern of the capability of the cable system to provide reliable operation in the future could be improved if a CAMP was in place. The application of CAMP methodology to submerged medium voltage cables should be a priority.

Table 9.2 – Gentilly 2 CAMP Score Card			
CAMP Element (Section 12)		Score*	Comments
#	Description		
1	Program Cable Scope	0	Discrete list of all safety-related and/or operationally significant cables could not be provided.
2	CAMP Database	0	No database for CAMP was provided.
3	Characterize and Monitor Service Conditions	0	No indication that cable service environments have been characterized.
4	Identify Stressors and Expected Ageing Mechanisms	1	An assessment of the anticipated stressors and ageing mechanisms associated with common cable types at Gentilly 2 was performed as a part of the cable condition assessment [13.111]. It is noted that this did not identify the actual stressors associated with identified specific hot spots and adverse conditions.
5	Select CM Techniques Suitable to Monitored Cables	1	While no specific CM techniques have been put into practice in the field, FT-NIR and Indenter techniques have been selected and used for “fingerprinting” cable ageing characteristics during EQ testing. Visual inspection has also been identified as appropriate to some cables.
6	Establish Baseline Condition of Monitored Cables	0	No formal baseline taken yet; however, it is recognized that limited field tests have been performed to potentially be used as a baseline data if refurbishment proceeds.
7	Identify Cable Characteristics & Ageing Effects Monitored by each CM Technique	1	See element 5.
8	Periodically Perform CM Tests and Inspections on Cables	0	Awaiting approval of refurbishment before proceeding.
9	Periodically Review and Incorporate OPEX	0	No process is in place to collect and compile cable-related operating experience for review of composite information and revelation of ageing concerns.
10	Periodically Review and Trend the Condition of Monitored Cables	0	See element 8.
11	Identify Degraded Conditions and Define/Take Corrective Actions	0	No evidence that proactive corrective actions have been taken on the basis of cable condition.
	Score (22 max)	3	
1. 0 = No practice indicated, 1 = Limited related practices, 2 = Complete compliance			

10.0 BRUCE A&B NGS CABLE AGEING MANAGEMENT STATUS

10.1 Station Cable Ageing Management Programs

There is currently no formal CAMP at Bruce. This does not mean that specific activities have not been performed to address cable ageing. Bruce Power staff is aware of the concerns with the ageing degradation of medium voltage cable. Testing of medium voltage cable is on-going using the partial discharge methodology. Bruce Power assigns the testing and interpretation of the test results to an external contractor.

10.2 Cable Profile Summary

Bruce Generating Station A Units 0, 1, 2, 3, 4 used PVC insulated and jacketed control cables extensively during the original construction for control and some 600V power applications. For the majority of 600V, 5kV, 8kV and 15kV applications PVC jacketed XLPE insulated cables were used. There are no power cables inside containment at Bruce A with voltages in excess of 600V. The original cables used in the supply of 600V power inside containment were Silicone Grease Filled Air Tight (SGAT) PVC cables. The analysis of the Bruce A unit 1 cable list identified 73 SGAT PVC cables. For EQ applications PVC insulated cable was replaced with XLPE or PEEK cable inside containment. In addition, some PVC insulated cable was replaced outside containment. Cables with PVC insulation may still be in service for containment cables with no specific EQ requirement [13.116]. MICC cables were used during the original plant construction for some services when armoured cable was required. These cables were used in particular for containment boundary functions for building electrical services. The general building service cable used during the original construction was a PVC covered aluminum sheathed XLPE insulated cable. For all applications in later plant modifications, cables similar to those used at Bruce B have been utilized. There are a wide variety of cable types installed to meet specific requirements or as supplied by manufacturers [13.116].

Bruce Generating Station B Units 0, 5, 6, 7, 8 have used a combination of XLPE insulated cables for general usage in control and 600V power applications. The cables installed as part of the original construction at Bruce B have superior fire retardancy to those installed at Bruce A. There are smaller quantities of EPR, Hypalon and silicone rubber cable installed. Special efforts were taken by Bruce B to improve fire retardancy and nuclear performance. For higher voltages EPR was used at the 15 kV/5kV level. Where armoured cables are required, including building services, TECK cables are generally installed. TECK cable is XLPE insulated with aluminum interlocking armour and a PVC jacket. There are specific special service cables, many types in limited applications, including EVA, EPR, Tefzel, Halar and Kapton. Where required by the EQ program, cables were replaced in a similar fashion to Bruce A [13.116].

The power voltages commonly used at Bruce A and Bruce B are 13.8kV, 8kV, 4.16kV, 600/347V and 120/208V. The primary control voltages are 120VAC and 250VDC and 48VDC. The Bruce A cable list contains 89,803 cables. The Bruce B cable list contains

83,124 cables. The cable lists do not include building service, security and fuel handling cables.

Table 10.1 is based on a review of the Bruce A Unit 1 cable list and the Bruce B Unit 8 cable list. [13.123]

Table 10.1 - Insulation Types Installed at Bruce A&B NGS

Insulation Type	Percent (%) Installed Bruce A	Percent (%) Installed Bruce B	Percent (%) Purchase History (Excludes Power Cable)
PVC	59	53	78
XLPE	11	18	12
EPR	Trace	1	2
ETFE		1	
EVA			1
MgO/MICC	Trace	Trace	
PEEK	Trace	Trace	
Rubber	Trace	Trace	
Fibre Optic	1%	Trace	
CTFE/Hypalon	Trace	Trace	
FEP/Teflon	1	Trace	
Not readily identifiable	26	27	

The differences between the purchase history and the cable list analysis are similar to those described in Section 7.2.

10.3 Cable Failure History and Analysis

A review of the station OPEX was completed by Bruce Power and is documented in Bruce Power Report NK21-CAR-57000-00001 [13.110]. A condensed version, deleting some material not applicable to the scope of this report, is reproduced in Table 10.2.

Table 10.2 - Cable Insulation Failure Descriptions and Resolutions

Plant Identifier	Description	Apparent Failure Cause/Mechanism	Resolution
SER B-97-142 and B-97	Failure of the buried 4.16kV cables (EPR insulated) to Bruce B switchyard	Not stated.	Cables Replaced
B-2000-02976	Cable in switchyard, outer insulation/sheath damaged, buried cable in area subject to submergence	No failure indicated.	Cable Replaced
B-2008-12742	Ground Cable detached	Not stated.	Repaired
B-2007-08889	U/G cable fault degraded splice	Not stated.	Replaced section
B-2007-13107	Cable failure to switchyard transformer	Not stated.	Unknown
AR#28148283	Degraded U/G cable for Standby Generator (SG8) 13.8kV cable was experiencing high PD values on one phase	Not stated.	Unknown

Plant Identifier	Description	Apparent Failure Cause/Mechanism	Resolution
B-2008-06303	Failure of a 120V TECK 90 cable inside unit 4 vault (supplying receptacles)	Stated as "due to prolonged exposure to heat and radiation"	Monitor deterioration and recommend changes as appropriate
B-2008-06589	During CCW pump motor isolation, motor leads found to have severe insulation damage	Not stated.	Note this is an equipment issue
B-2008-07837	Cables were found to have deteriorated outer jackets on containment side of penetration EP115527	Stated as "due to excessive heat in vicinity of EP"	Unknown
B-2001-05068	The insulation on the 120V cable to the fuel handling extension computer deteriorated	Not stated.	Cable replaced similar equipment inspected and found satisfactory
B-2002-00362	FH Power Track cables damaged	Wire insulation at connections melted due to overheating caused by missing conductor strands. Noted as a common occurrence.	Damaged part of cable removed
B-2002-01708	Cables submerged due to standing water in 4" conduits	No failure.	Unkown
B-2004-00142	Motor protection trip, failure of insulation bushing	Not stated.	Repaired
B-2004-03751	PHT PM termination hot	Not stated. No failure.	Repaired
B-2005-02591	One PHT PM HV cable found with elevated temperature while adjacent cables not hot	Probable phase imbalance due to bad termination.	Repaired termination
B-2006-00501 B-2005-05144 B-2005-05311 B-2005-02612 B-2005-05857	This series of events documents issues with cable supports in cable risers	No failure.	Install new supports
B-2005-04256	Visibly deteriorated insulation on 600V supply cable on transfer chamber cranes	No failure. Obvious visible deterioration judged to be age-related. IR readings did not indicate degradation.	"Refurbished" wiring
B-2005-04761	EQ scope issue		Not applicable
B-2005-07408	Ground fault on 1 of 2 1/C parallel red phase MV cables for U3 PHT Pump Motor. XLPE insulation/PVC jacket	Indeterminate. Probable electrical tree from insulation impurities. PD ad AC hipot previous year showed OK. No signs of thermal damage to insulation or PVC jacket.	Temporary repair followed by replacement of all 6 cables. Other PHT PMs tested
B-2006-00210	Control wiring termination issue	Not stated.	Unknown
B-2008-13279	Failure of 8kV PHT pump motor cables	Not stated.	Cable replaced

Plant Identifier	Description	Apparent Failure Cause/Mechanism	Resolution
B-2008-19740	U/G Standby Generator cable failure (13.8kV)	Water treeing.	Cable repaired
B-2009-00101	Water spraying on cables	Failure of Demin Tk3 Condensate return line.	Not applicable
B-2009-00328	Power cable insulation damaged/burned	Circuit overloading.	Replace damaged portion of cable
B-2009-02828	Degraded wiring in the Bruce A MPCC power distribution system as indicated by the oily feeling of the cables	Not stated.	Cables to be replaced
B-2009-05486	Frayed cable on transfer cart	Not stated.	Replace
B-2009-10794	Tie-wraps in the cable riser have broken with age and energized cables are loose	No failure.	Unknown
AR#28273047 * Nov.10, 2011	Poorly documented cable replacement cable list not updated	No failure.	Unknown
AR#28265729 * Sept.26, 2011	Cable kink CSA bridge	Unknown.	Unknown
AR#28166666 * Oct.03,2011	Cables to transfer bay have brittle and disintegrating insulation	Unknown.	Unknown
AR#28257462 * July7,2011	Fibre Optic cable damaged by installation work nearby	Unknown.	Replace cable
AR#28257843 * Jul. 08, 2011	Lighting cable damaged by support cable	Unknown.	Unknown
AR#28259902 * Aug. 01, 2011	Groundhog entering Emergency Power System cable trays	Unknown.	Unknown
AR#28260615 * Aug.15,2011	Cable hanging out of power track	Unknown.	Unknown

*items added by RCMT as a result of site visit

Since late 2005 Bruce A Units 1 and 2 have been undergoing extensive rehabilitation prior to restarting after several years of shut down. During the rehabilitation process plant conditions were recorded on a separate system to that used by the operating facility. Operating experience was gathered as part of this process. During the site interview a set of potentially applicable OPEX was provided. Table 10.3 is a summary of the applicable portion of this OPEX. Cable degradation associated with these events appears to be primarily error-induced damage during work activities.

Table 10.3 - Cable Insulation Failure Descriptions and Resolutions for Bruce A Units 1&2

Plant Identifier	Description	Resolution
10588	Conductors in 2 cables open circuit	
9739	Damage to lighting cables caused by work to floor	
9733	Damaged control cable found after field work	
9630	Short in ion chamber HV cable	
9354	Cables in flex conduit found damaged	
9337	Cables in flex conduit found damaged	
8795	Cable damaged during inspection	
8617	Damaged conduit	
8110	Damaged flex conduit	
7936	2 Instrument cables found stiff and cracked	
7662	Cables found wrapped around drive shaft	
7456	Ground cable caught by snow plough	
6817	Damaged control cable	
6708	Cables damaged by West Y drive platform	
6083	Kink found in cable	
6045	Damaged cable found	
5201	Cable found in riser exposed to bare conductor	
5185	Panel wire insulation damaged by sharp edge	
5009	Damaged wire in conduit	
4725	3 damaged cables found	
4397	Damaged co-axial cables	
3894	Worker damaged lighting cable	
3379	Damaged fire detection cable	
2510	Cable damaged by snow removal equipment	
2472	Truck damages cable trench	
2242	Crane cable failed	
843	Crane damages cable	
652	2 ground cables not properly supported	
575	Damaged Ground cable	
415	Excavation work damaged cable	

The Bruce Power OPEX is very similar to other stations with one major exception. Bruce Power has encountered a significant number of issues with medium voltage power cables. The failures have occurred in cables with high load factors or subject to submergence.

10.4 Assessment of Ageing Management Effectiveness

Bruce Power is in the process of developing a formal CAMP(s) but none has yet been fully defined or implemented [13.116]. In 2010, Bruce Power issued BP-PLAN-00044, *Cable Life Cycle Management Plan* [13.109] which acknowledges the need for a cable ageing management program and provides a review of the industry knowledge and practices at that time. The document indicates that two future Condition Assessment (CA) documents are to be completed, one for Medium Voltage cables and the other for Low Voltage cables. The stated intent is for these CAs to include the detailed requirements for cable ageing monitoring and mitigation tasks, including replacement and spare parts strategies, for all cables critical to safe and reliable plant operation. These documents have not yet been completed.

Bruce Power issued NK21-CAR-57000-00001, Rev.1, “Condition Assessment Report, Cable, Conduit and Cable Tray” [13.110] in November 2011. This document is focused on defining the condition of general cabling in units 0, 3 and 4 and its supporting infrastructure, with a view to defining what actions are recommended during refurbishment of these units to support life extension. The document acknowledges that development and implementation of a separate Cable Life Management Program is still required. A similar report is planned for Bruce B but not yet completed. Based on the documentation provided work has commenced on a CAMP but no information was provided with respect to this planned CAMP. Bruce Power, as with other utilities, will be able to leverage the work done as part of their EQ cable program to address many of the plant cables. This will be possible as the original plant construction did not differentiate between EQ cables and non-EQ cables.

Medium voltage cable testing at Bruce does include methods recognized by international organizations as acceptable for CAMP activities dependant on the concerns. The Partial Discharge Testing methodology is recognized as an acceptable approach for dry MV cables; however, recent reports from EPRI [13.64] indicate that the tan-δ or LIRA may be more appropriate depending on the circumstances. In addition, partial discharge has the disadvantage of having the potential to further damage an already weak cable. Partial discharge testing is unlikely to be suitable for wet MV cables and tan-δ combined with VLF withstand testing is recommended as it will identify degradation of medium voltage cables at an earlier stage. There are unshielded 5kV cables at Bruce. The currently available testing methodology does not provide good results when applied to unshielded cables. A separate approach will be required for these cables. Further guidance on condition assessment of shielded and non-shielded MV cables is provided in EPRI 1020805 [13.64].

The development of a CAMP for Bruce Power is strongly recommended as the Bruce A NPP has challenging environmental conditions combined with the longest planned operating life in the CANDU NPPs.

An assessment of current Bruce Power cable ageing management practices, as provided in site interviews [13.116], against the recommended elements of a CAMP (Section 12) is provided in Table 10.4.

10.5 Safety Implications

The issues around the cables to the standby generators are of particular concern given their importance to safety. These cables have experienced failure B-2008-19740 or test concerns AR#28148283. These cables are continuously energized. The testing method selected (Partial Discharge) does not identify the development of water trees but does identify the further degradation which occurs when water trees develop into electrical trees. As such, if these cables are wet, water-related degradation may not be detected in time to anticipate and prevent further failures of the remaining cables. The other concern relates to the other medium voltage cables. In addition to the submerged cables there have been failures of heavily loaded medium voltage power cables. The bulk of the plant medium voltage cables are of similar age and construction to the failed cables. Bruce power has initiated a test regime using a partial discharge testing. This methodology is considered to be one suitable method to identify degraded dry MV cables but should be reviewed to determine if other methods may be more effective (Section 8.4). As with other plants there are no significant reports of insulation failures in the 600V and control cables.

Table 10.4 – BNGS CAMP Score Card

CAMP Element (Section 12) #	Description	Score*	Comments
1	Program Cable Scope	0	Discrete list of all safety-related and/or operationally significant cables could not be provided. BNGS acknowledges the need for a CAMP and has indicated an intent to implement one [13.116][13.109].
2	CAMP Database	0	No database for CAMP was provided.
3	Characterize and Monitor Service Conditions	0	No indication that cable service environments have been characterized.
4	Identify Stressors and Expected Ageing Mechanisms	0	Stressors and expected ageing mechanisms are not generally identified for cables or cable types; however, some have been identified for MV cables and heavily loaded cables [13.110].
5	Select CM Techniques Suitable to Monitored Cables	0	Few specific CM techniques were identified or justified re: cable condition monitoring. However, it is recognized that PD is used for some MV cables which is accepted as a suitable method for dry MV cables, depending on the circumstances. Further information is required to confirm suitability in its specified applications.
6	Establish Baseline Condition of Monitored Cables	0	See element 5.
7	Identify Cable Characteristics & Ageing Effects Monitored by each CM Technique	0	See element 5.
8	Periodically Perform CM Tests and Inspections on Cables	0	See element 5.
9	Periodically Review and Incorporate OPEX	0	No process is in place to collect and compile cable-related operating experience for review of composite information and revelation of ageing concerns.
10	Periodically Review and Trend the Condition of Monitored Cables	0	See element 8.
11	Identify Degraded Conditions and Define/Take Corrective Actions	1	Some degraded cables have been replaced [13.110].
	Score (22 max)	2	
1. 0 = No practice indicated, 1 = Limited related practices, 2 = Complete compliance			

11.0 ANALYSIS AND CONCLUSIONS

Available OPEX from Canadian NPPs (Sections 6-10) is consistent with the international experience (Section 5.2). The majority of failures are related to random installation/maintenance damage or age-induced degradation due to adverse service conditions. There was no indication that cables in low stress environments are prematurely failing due to ageing, which is also consistent with international experience. While the number of ageing related events is small it is interesting to note that, once the medium voltage cable failures are removed, the insulation ageing events are dominated by cables which were not purchased using utility specifications for the purchase of the cable. Table 11.1 suggests that, based on a total cable population in excess of 420,000 individual cables, cable failure is a low probability event.

Table 11.1 - Summary of Repetitive Type Cable Failures

Plant	Ageing	Submergence	Physical	Flexing	Other
Darlington	3	2	4	6	0
Pickering	6	1	19	3	4
Lepreau	1	1	8	0	1
Bruce	10	5	31	3	18
Gentilly 2	0	1	0	0	0
Total	20	10	62	12	23

There were 4 clearly identifiable event categories of note in the provided OPEX.

- Submergence as a precursor/accelerant to ageing failure
- Medium voltage cable insulation failure
- Flexing as a cause of cable failure
- Activities relating to human performance as it impacts cable condition

As with the international experience, the main area of concern is medium voltage (MV) cables in wet/submerged environments. The continued presence of water leads to accelerated degradation and premature cable failure, typically in MV cables. Many of the Bruce NGS failures are failures of medium voltage cables which run in underground ducts or trenches. Although the number of submerged cables in a plant would be an extremely small fraction of the hundreds of thousands of cables installed, submergence-related failures represent 8% of the failures in Table 11.1. If the non-ageing related failure categories of “physical (damage)” and “other” are removed, then this represents 24% of the cable failures that may have been anticipated and prevented by a CAMP. This suggests that, when implementing a CAMP, prioritizing efforts to address the limited population of potentially submerged cables would have the most immediate positive effect on overall cable system reliability. There are two other events which relate to low insulation resistance in cables potentially subject to submergence. These events are the Gentilly 2 switchyard cable events and Pickering SCR 2005-18780. Therefore, potentially submerged cables must be included in a cable ageing management program.

Aside from submerged MV cables, it is noteworthy that two MV cable failures were related to Bruce Primary Heat Transport pump motors which are supplied with 3 sets of 2 conductors in parallel. It is possible that age related degradation of the conductor terminations may be causing an imbalance in the parallel conductors causing increased ohmic heating resulting in accelerated thermal degradation of these cables. However, a root cause has not been confirmed. A significant number of cable failures were also noted due to flexing, primarily in the fuel handling system.

The single largest category of OPEX event is related to cables damaged by operations and maintenance activities or by refurbishment installation and inspection activities. This type of error induced event is common to all reporting NPP's. These types of events result in immediate and acute cable damage/degradation and, by definition, are not directly related to a progressive increase in cable failure rates due to the chronic effects of ageing. By their nature, these events tend to be isolated, localized and randomly distributed. Therefore, defence against these types of events adversely affecting continued plant safety and reliability is provided by probabilistic reliability based barriers, such as redundancy and separation (Section 1.3). Prevention of these types of cable failures is not an explicit CAMP objective or expectation. The primary barriers to the occurrence of these types of events are plant Design, Maintenance, Operations and Procurement controls and quality assurance.

There are issues that may affect the above OPEX analysis. No plants, with the exception of Point Lepreau, were able to provide OPEX extending back to plant start up. Most utilities have updated their computer systems without moving old information forward into the newer systems. All OPEX received was reviewed and revealed concerns that the OPEX data may not be complete. OPEX data at all plants is typed into a database and key word searches are performed on that information. This methodology is problematic in that it requires the searcher to speculate on appropriate key words. Typically, plant personnel performed keyword searches based on the word "cable" with further modifiers such as "failure" and "defective". This has gathered a considerable amount of material but searches on other keywords may identify additional items. There is also a concern that not all items are being entered into the system in a retrievable manner. The plants operate their work management system based on equipment code where work is initiated and reported based on a specific equipment tag. Cable failures could be effectively misrepresented as failures of the end device. Two OPEX items (Darlington SCR 2005-00653 and Bruce SCR 2002-00362) were found that refer to multiple additional related events but no OPEX for the additional events was provided. These SCRs imply that failures of cables are being treated as a normal breakdown event and may not all be recorded in the OPEX system. The quality of records was also brought into question since the have been cables replaced without updating cable list information. Nevertheless a substantial amount of OPEX has been gathered. It is doubtful if additional OPEX would substantially change in the identified trends and analysis.

Internal and external OPEX has proved to be a potentially valuable tool in identifying specific cable failure trends that may expose unanticipated cable ageing problems. A cable ageing management program should include improvement and integration of the cable OPEX collection process. Each cable failure should be assessed to determine if it is are-related and if the ageing/failure mechanism is applicable to other cables. Conclusions should be documented.

Based on the OPEX provided in the plant interviews, no immediate safety concerns were confirmed or suggested, with the possible exception of Fuelling Machine and Standby Generator cable failures. There was no indication of a poor safety culture. Some of the NPPs had limited cable ageing management programs focused on EQ cables and/or had elements of CM programs that could be integrated into a more comprehensive program. All had some form of cable testing and surveillance of EQ and/or non-EQ cables but none had a fully coordinated and comprehensive CAMP.

Cable lists were provided by the NPPs. In some cases the list of EQ cables was discernable but none of the plants appears to have defined a complete list of safety related cables and/or operationally important cables. NPP cable lists each include thousands of cables totalling thousands of kilometres. Any cable ageing management program must first define the scope of cables important to plant safety and reliability and characterize their construction and environments. Alternatively, it may be more practical to exclude cable groups that are not safety related or operationally significant and manage cable ageing based on the remainder. Efforts should then be focused on those areas where specific cables are exposed to adverse condition and bulk cables may be represented by similar cables in bounding conditions.

International guidance has tended to focus on cable constructions common to the plants in the individual countries. The Canadian NPPs have many cables that are of similar generic construction but types vary more widely. In particular, PVC is more common and its ageing characteristics tend to vary much more between formulations than the other common insulations such as XLPE, EPR, etc. The cable lists provided did not clearly identify specific formulation types but the program will need to address the unique ageing characteristics between insulation formulations. This type of data should already exist for EQ cables. During construction of most Canadian NPPs, there was no major distinction made between cables purchased for safety related applications and general cabling; therefore, data collected during cable EQ test programs may be applied to ageing management of non-EQ applications, where EQ data is relevant.

One key differentiation made between EQ and non-EQ cable ageing management is the selection of acceptance criteria and related condition indicators (Section 4.3). Unlike mild environment cables, EQ cables must retain sufficient material properties to survive the harsh DBA conditions and the condition indicator must be relevant to the cable's ability to preclude the potential failure modes introduced by the DBA stressors. Also, the plant EQ program demands much more rigour than a general ageing management program and the "end-condition" acceptance criterion should be defined by the condition measured following accelerated thermal and radiation ageing representing normal service, just prior to application of accident radiation dose and DBA simulation.

For mild environment cables, qualification for the service conditions may be demonstrated by certification to the design/purchase specifications and an end of life condition, relevant to the required service conditions, defined by engineering judgement. Alternatively, if the mild environment cable is an EQ type, the EQ acceptance criteria may be conservatively applied or modified to the condition measured during the post-DBA simulation. Acceptance criteria should incorporate an administrative margin on absolute end-of-life condition to provide time to plan and implement mitigating or corrective actions (Figure 4.1).

Caution must be used when selecting CM techniques and acceptance criteria in that the condition indicator must be linked to a cable property relevant to its capability of continued performance in its expected service conditions. Electrical properties are the ultimate concern, and these may be adequate indicators of reliable service in typical environments of low severity; however, they are not typically indicative of a cable's ability to survive harsh or severe environments. In wet environments, loss of mechanical properties is the precursor to failure for low voltage cables. Therefore, for EQ cables, 50% absolute elongation-at-break has been generally accepted as a point where the insulation retains sufficient ability to flex without cracking. However, this is not always the case. PVC cables are known to produce HCl and production of conductive salts under high temperature and or high radiation dose environments which may result in failure when exposed to steam. This failure mode would need to be addressed by an EQ test program and the CM method and acceptance criteria chosen based on EQ test data. It is unlikely a concern where for PVC cable in low temperature, low radiation, dry environments where elongation, or electrical properties, would continue to be the relevant indicator of continued performance.

Selection of the correct CM method and test location is essential to an effective CM program (Section 4.4). EPRI 1022969 - Electrical Cable Test Applicability Matrix for Nuclear Power Plants [13.61] has recently been issued with the intent of providing thorough and up-to-date guidance on effective selection and application of cable CM methods. This document was not available for review but is expected to provide an excellent basis for implementing CM into a cable ageing management program. New in-situ CM methods, FT-NIR and Deformation Recovery Time (AECL Portable Polymer Tester), are currently under development at COG and may provide improved effectiveness for some ageing characteristics of specific cable types (Sections 4.4.1.4 and 4.4.1.5).

It is also important that CM methods are repeatable from lab to field and from lab to lab. Industry research indicated that, unless CM test procedures are adequately controlled the results may be different due to changes in the test environment or due to small differences in the specific procedures used to perform a test. IEC/IEEE 62582 - Electrical Equipment Condition Monitoring Methods [13.100,13.101,13.102,13.103,13.104] was issued to provide the necessary controls to ensure that CM test data accurately represents ageing trends throughout the entire process. In addition, selection of test methods should avoid technologies that depend on uncommon or proprietary tools/data or single providers where future obsolescence or absence of these may defeat the long term objectives of the program.

Cable deposits are a logical and popular bulk cable ageing monitoring method for new NPPs, since the deposits and service cables have a common baseline. The ability to coupon deposit samples for destructive testing reduces uncertainty in correlating condition indicators with the more pertinent cable property (e.g. Elongation at Break). Retrofitting a cable deposit to an operating NPP is a larger challenge; however, it may be possible if abandoned cables in bounding service conditions can be located or if new cable are installed to create sacrificial specimens.

None of the NPPs have implemented a comprehensive systematic cable ageing management program that assures all safety and operationally important cables in adverse environments are addressed, although some are closer than others. For example, Point Lepreau has been conducting an EQ cable condition monitoring program for the past 17 years and has a well defined cable management program. However, documentation of cable surveillance programs and procedures, insufficient program details were provided to verify complete adequacy or optimization. OPG corporate has recently issued procedure N-PROC-MA-0099 - "Cable Surveillance Program" [13.107] to provide direction regarding the requirements for inspection, testing, surveillance and technical assessment of low and medium voltage cables at OPG NPPs; however, there was no evidence that this procedure has been implemented at the NPPs yet. The OPG procedure addresses the essential requirements for a cable ageing management program, consistent with international guidance and CNSC governance (RD 334 [13.150]); however, the high level guidance will require the individual NPPs to ensure implementation is effective in addressing ageing concerns. The cable risk rating process [13.107] requires further review to determine its effectiveness in addressing cable safety and reliability risks.

Assessment of Canadian NPP configurations and cable failure experience against international research, experience and regulation guidance indicates that the current international guidance on cable ageing management is generally appropriate and recommended for Canadian NPPs. Recommendations for regulatory guidance are developed on this basis (Section 12). The following are references considered valuable to developing the core basis of a cable condition monitoring program.

Valuable References

IEEE 1205-2000: "IEEE Guide for Assessing, Monitoring, and Mitigating Aging Effects on Class 1E Equipment Used in Nuclear Power Generating Stations", The Institute of Electrical and Electronics Engineers, March 2000 (note: major revision due mid-2014 that would significantly improved CAMP guidance) [13.95,13.96]

EPRI 1021629 – Aging Management Program Development Guidance for Instrument and Control Cable Systems for Nuclear Power Plants (unavailable for review) [13.63]

EPRI 1020804-Aging Management Program Development Guidance for AC and DC Low-Voltage Power Cable Systems for Nuclear Power Plants [13.65]

EPRI 1020805-Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plant [13.64]

EPRI 1008211- Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets [13.76]

EPRI 1003663 - Integrated Cable System Aging Management Guidance: Low-Voltage Cable [13.79]

EPRI 1003317 - Cable System Aging Management [13.80]

EPRI 1001391 - Training Aids for Visual/Tactile Inspection of Electrical Cables for Detection of Aging [13.85]

EPRI 1022969 - Electrical Cable Test Applicability Matrix for Nuclear Power Plants (*unavailable for review*) [13.61]

EPRI TR-109619 – Guideline for the Management of Adverse Localized Equipment Environments [13.89]

IEC/IEEE 62582; *Electrical Equipment Condition Monitoring Methods*

IEC/IEEE 62582-1; General [13.100]	(Published)
IEC/IEEE 62582-2; Indenter Modulus [13.101]	(Published)
IEC/IEEE 62582-3; Elongation at Break [13.103]	(due end 2012)
IEC/IEEE 62582-4; Oxidation Induction Techniques [13.102]	(Published)
IEC/IEEE 62582-5; Optical Time Domain Reflectometry [13.104]	(due 2013)

12.0 RECOMMENDATIONS

A coordinated and systematic program should be implemented in Canadian NPPs to provide reasonable assurance that cable degradation due to ageing will not lead to increased cable failure rates that would challenge the safety and reliability of the plant. The following elements should be included within the framework of a comprehensive, coordinated cable ageing management program, consistent with domestic plant experience, international experience and guidance, and existing CNSC requirements (RD 334 [13.150]).

1. Definition of Scope of Cables to be Addressed by Program

The purpose of scoping is to consider the extent of cables that would require condition monitoring if subjected to adverse service conditions or otherwise suspected as being vulnerable to premature age-related failure. It is not the intent of the cable ageing management program to assess and monitor the condition of every cable within its scope (Figure 12.1). Rather, the majority of cables within the program, in typically benign plant environments and operating conditions, may be addressed by representative cables in bounding conditions [13.35]. The objectives of a cable AMP are best realized by focusing effort and resources on cables of concern [13.7]. By focusing on cables in worst-case environments, confidence is provided that other similar cables in less severe conditions are in satisfactory condition. Other cables may have sufficient available ageing information to demonstrate that, under relevant plant service conditions, the margin-to-failure is adequate to negate the need for CM altogether. Condition monitoring of selected cables within the scope of the program should be augmented where:

a) there is an adverse service environment (element 3),

b) failure of cables connected to critical equipment has been experienced (element 9),

c) operational history indicates failure of cables (element 9),

d) industry operating experience indicates a need to for augmented monitoring for the similar, or less severe, conditions and equipment configuration (element 9),

e) ageing of EQ cables is managed or supplemented using qualified condition.

The overall program scope should include cables supporting nuclear safety-related functions or whose failure, as a result of ageing, may prevent a safety-related function from being fulfilled. As well, cables whose failure may result in a plant trip or transient, or are required to mitigate a transient should be included. Cables essential to precluding station blackout should also be included.

Cables on the plant EQ list are, by definition, a subgroup of the cables to be enveloped by the cable ageing management program. The plant EQ program may adopt CM methods to extend, support or replace the qualified lives of cables based on a qualified condition. Due to the unique considerations and expertise associated with EQ cables, it may be convenient to address these cables under a separate CM sub-program that is integrated into the overall CAMP.

The program should address control and instrument/signal cables and power cables up to 15 kVAC and 250VDC. The complete list of cables included in the overall program scope may be discretely defined based on applicability of the program criteria or, alternatively, based on the complete cable list modified by justified exclusion of cable groups that do not meet the scoping criteria. The basis for inclusion or exclusion should be documented.

The inclusion of fibre optic cables with the plant cable ageing management program should be considered, as appropriate. A detailed discussion of fibre optic cable ageing considerations is provided in Appendix A of NUREG/CR-7000 [13.17]. Optical time domain reflectometry (OTDR) is one condition monitoring method effective for fibre optic cable. IEC/IEEE is currently developing a standard for the application of OTDR [13.104].

Internal equipment wiring and connections need not be included in the program and should be addressed by equipment inspection and maintenance programs. Field cables that enter equipment are not considered internal equipment wiring. Cable accessories, such as connectors, terminal blocks, splices etc, are outside the scope of this report; however, many CM techniques will inherently address some of these items.

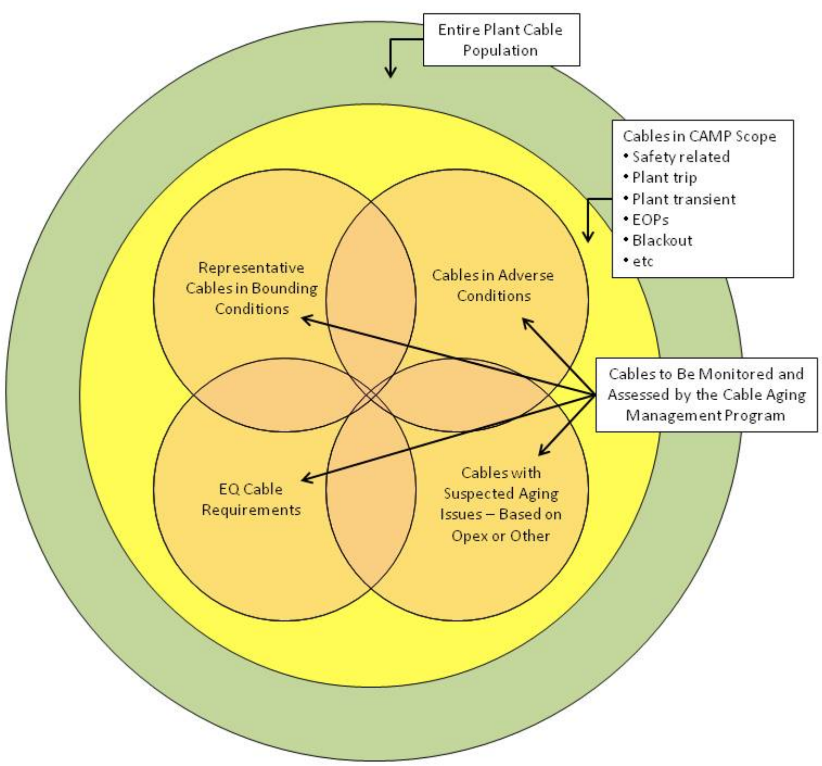


Figure 12.1 – CAMP Scoping Process

2. Develop and Maintain a Database of All Cables to be Monitored

A centralized database should be developed and maintained to include all cables within the scope of the program. The database must incorporate all data necessary to access, analyze and evaluate documentation and data to determine cable condition and guide decisions. The database should include all relevant information pertaining to the physical characteristics of the cables, application data, installation, service environment (ambient and operational), OPEX, inspection and CM test data, condition evaluation and assessment. The database will provide the primary resource necessary to define the subset of cables that require CM activities and to control and evaluate cable operating environment conditions and trends and initiate corrective actions. The following information should be included for cables in adverse (or bounding) conditions or otherwise require ageing management [13.65][13.64]:

a. Nature and location of adverse environment or service conditions

b. Cable circuits affected

c. Associated load of affected circuits (e.g. tag# - specific motor, bus, transformer, etc)

d. Degradation mechanism(s) of concern (thermal damage, voltage/water damage, etc)

e. Method(s) of assessing or monitoring the effect and frequency of assessment (e.g. one-time assessment, periodic visual inspection, periodic test, etc)

f. Methodology of assessment and tests

g. Results of assessments and tests

h. Repair and replacement descriptions

i. Details of barriers or procedures credited for mitigating environmental conditions (e.g. vaults, manholes, automatic drainage systems, heat shields, etc).

j. Related OPEX

It is not essential that all of the above data be specifically defined for each and every cable within the program. The critical objective is to include sufficient information to provide reasonable assurance that cables within the scope of the program are not becoming vulnerable to increasing failure rates as a result of age-related degradation. Where lightly/moderately loaded low voltage power cable and I&C cables are located in mild, dry, indoor, above grade environments it may only be necessary to ensure that there is sufficient information to demonstrate that the cables are enveloped by testing and/or analysis used to bound bulk installations. Particular emphasis should be applied to collecting more extensive data on cables in potentially adverse service conditions.

Internal and external cable OPEX should also be reviewed to identify any cable ageing trends that require specific attention. Although ageing effects are already required to be managed under the more rigorous EQ program, EQ cable ageing test data should also be reviewed to identify any if there may be any specific cable insulation formulations that include service limitations, or a large uncertainty or lack of margin when considering extension of qualified life. Many non-EQ cables are of similar construction to those on the EQL and these data may be used to define potential long term ageing concerns in non EQ applications as well.

3. Characterize and Monitor Service Conditions

This element includes three sub-elements; initial characterization of service conditions, periodic monitoring of conditions and management of conditions. The service conditions of the cable systems within scope must be characterized to identify ambient environmental stressors and operational stressors. Service condition information should be adequate to identify where cables are exposed to physically localized or circuit-specific adverse service conditions and global conditions that may be used to bound bulk cable installations. Following initial characterization the service conditions should be monitored on a regular basis to determine if conditions have changed. An unanticipated change in service conditions may require adjustments to the type and frequency of CM testing and assessment and/or actions to mitigate the effects of the change.

Plant documentation, such EQ Room Conditions Manuals, Heath Physics records, system design information and other environmental monitoring records may be used to help define the general cable service environments. This should be supplemented with OPEX review, interviews with plant maintenance personnel and cabling walk downs to identify unexpected localized adverse conditions. It is advisable that initial walk downs be conducted in conjunction with CM screening methods such as visual inspection of cables for indication of ageing damage or contamination and IR thermography to identify localized radiation heat sources. Special attention should be given to inaccessible locations, particularly those that may be vulnerable to flooding or significant wetting. Locations of cable deposits used to represent bounding cable environments should be defined in detail. Plant locations known to not include any cables, or only cables outside the program scope, may be flagged and excluded from further consideration.

The identification of adverse service conditions is central to defining the subset of cables to be subjected to CM and assessment. Service conditions can be subdivided into environmental conditions and operational conditions. The degree to which an elevated stressor may be considered adverse may depend on the type of cable and its operating conditions. Adverse conditions include those occurring only under normal and abnormal plant operation and do not include the harsh conditions associated with a DBA. Adverse service conditions of common concern include the following [13.17][13.64][13.65]:

- High temperature (ambient and ohmic heating)
- High radiation (type and dose rate)
- Voltage/submergence (MV cables)
- Submergence (LV cables)
- Flexing (e.g. fuelling machines, cranes, etc)

- Chemical/Oil contamination

High Temperature

The service temperature of a cable is comprised of the ambient temperature plus the heat rise due to current loading (ohmic heating). The design life of non-EQ commercial grade cables is based upon a continuous maximum temperature rating which includes both elements. Ampacity ratings define the maximum current permitted, for a given wire gauge, to limit the heat rise to within the maximum temperature rating. The thermal qualified life of EQ cables is based on the accelerated ageing parameters used during EQ testing. These parameters typically use assumptions of bounding ambient service temperatures and a heat rise that may, or may not, include the maximum allowable heat rise associated with continuous service at the maximum cable temperature rating.

Characterization of plant thermal environments should begin with a review of existing plant documentation. The EQ programs at Canadian NPPs have devoted much effort to documenting the conservative normal bulk environmental conditions for rooms that are exposed to harsh DBA environments and provide a convenient resource that represents a substantial portion of the NPP cable location. Other environmental monitoring programs at the plant may be used to provide temperature information in rooms not addressed by EQ room condition manuals. These sources of bulk room temperature should be supplemented with interview of plant maintenance personnel and walk down with a focus of determining if the identified maximum temperatures may be approached or exceeded in other plant locations.

The ambient temperature of cables in heavily loaded cable trays, or conduits, may be slightly higher than that of the bulk room temperature due to heat dissipated from adjacent energized cables and a lack of air circulation. Some Canadian NPP EQ programs have documented analyses used to support these heat rise assumption for EQ cable test programs. These should be reviewed for applicability for non-EQ cables as well. Cabling design procedures may also provide related information.

Typical bulk ambient temperatures, and cableway temperatures, alone are not considered adverse, and cables subjected only to these temperatures are expected to provide long and reliable service [13.64][13.65]. However, where the thermal qualified life of EQ cables is based on an assumption of service temperatures without significant heat rise, it may be necessary to identify worst case bulk temperature locations to support life extension based on qualified condition.

Adverse temperature conditions leading to premature degradation may exist when cable heat rise is significant due to localized radiant heat sources and/or ohmic heating due to current loading. Therefore, efforts to characterize temperature conditions should emphasize identification and location of these thermal “hot spots”. While NPP cabling designers make every effort to route cableways and field run cables away from known radiant heat sources, isolated situations may exist where cables are exposed to radiation heat from hot piping, hot electrical or mechanical equipment, or steam leaks, etc.

Heat rise due to ohmic heating is not a concern for I&C cables or power cables that are normally de-energized or lightly loaded. The focus should be to identify power cables within the program that are continuously heavily loaded. A review of power circuit design information, and electrical power load operating duties, should be conducted to determine if specific cables may be vulnerable to significant ohmic heat rise. Consideration of the ambient temperatures in the various location though which the cable passes must be also considered in conjunction with ohmic heat rise.

It is recognized that some Canadian NPPs incorporated conservatisms into plant cabling design through the application of ampacity deratings to limit heat rise. Since conductor heat rise is proportional to the square of the current, a limitation of 80% of ampacity would result in a limitation of 64% of allowable heat rise. For a 90°C rated cable in a 40°C ambient temperature, the bounding heat rise would be limited to approximately 32°C and a conductor temperature of 72°C [13.65]. Actual operating currents will be lower in most cases and the effects would be further mitigated by the operating duty of the end device. Most electrical power devices, such as motors and heaters, etc do not operate at 100% duty. However, it is also recognized that the above analysis example represents the heat rise along the entire cable length based on conductor resistance. Local heat rise due to ohmic heating may be exacerbated at high resistance connections. Also, if multiple individual conductors are used per phase for large loads, such as Main PHT Pump motors or station transformers, load imbalance may occur which could result in overload of individual cables. Load balance should be verified through IR thermography or current measurements for these types of circuits [13.64].

In addition to documentation review and analysis, walk downs should incorporate steps to identify thermal hot spots. The use of infrared thermography during walk downs provides a valuable tool for easily identifying radiant heat sources, steam leaks and elevated cable and connection temperatures. To be meaningful, the walk downs must be coordinated and scheduled to coincide with plant and equipment operating conditions where thermal stress limits would be evident. Thermographic surveys for radiant heat sources should be performed when the adjacent piping systems are hot or when adjacent equipment is energized and hot. Surveys for ohmic heating should be performed when the electrical load has been energized and operating at normal operating load for sufficient time to ensure thermal stabilization. Credit may be taken for periodic or post-maintenance IR thermographic surveys performed as a part of plant maintenance programs. Consideration should be given to bulk room temperature differences due to plant operational state and seasons.

The following plant areas and components are examples of potential sites for adverse temperature conditions to exist:

- PHT System piping and valves (radiant heat)
- PHT System Pressurizer and heater (radiant and ohmic heating)
- Feeder cabinets (radiant heat)

- Electric cabinets - MCCs, DCCs, etc
- Main Steam lines and valves (radiant heat)
- Boiler blow down lines (radiant heat)
- High power incandescent lighting (radiant heat)
- Upper elevations of Turbine Hall
- Continuously operated motors, particularly connections - e.g. Main PHT pump, Moderator pump, LACs, D_2O Feed Pump, CCW pump, RCW pump, etc (ohmic & radiant heating)
- Transformers (ohmic heating)
- Main Buses (ohmic heating)

High Radiation

Total integrated radiation doses under 5 Mrads should produce no observable physical effects in cables. Consequently, locations that are not expected to exceed 5 Mrads are not considered adverse except where cables of known sensitivity to low radiation exist (e.g. Teflon, fibre optic, etc). Another exception is where the cable is also operating at a very high temperature, above 50^{o}C and heavily loaded, which could produce a synergistic effect and more appreciable damage [13.64][13.65]. Areas that may exceed 15 Mrads should be identified where PVC cables are located. Above 15 Mrads, PVC cables may become vulnerable to the unique ageing mechanism of HCl generation which could affect the selection of CM techniques [13.60].

Cable system designers typically route cableways to avoid radiation hot spots. However, some cables may be routed through locations where accumulated dose may become appreciable. It is expected that only a small fraction of plant cables would be exposed to more than 5 Mrads radiation, under normal operation, over the life of the plant; those that are would be limited to isolated locations within the Containment Building. EQ room condition manuals will provide radiation information for rooms and more specific locations where EQ equipment are located in high radiation. Radiation doses shown in the EQ room condition manual are typically conservative for a specific location within the room. Data may be supplemented with more detailed information from radiation zone maps and reports. Dose estimates must include expected neutron radiation doses as well as gamma, where applicable. This information should be reviewed to identify high radiation areas exist to determine if program cables are located in these areas. The review should determine if further radiation information needs to be gathered.

The degree to which radiation exists in typical plant locations will vary between plants. The following locations and equipment are examples of areas that may have cables in adverse radiation conditions:

- Moderator Pump Room

- Moderator Heat Exchanger
- Vaults
- Fuelling Machines
- Near Feeder Cabinets/catwalks
- In proximity to PHTS and Moderator System Piping/valves
- PHT System Pre-Heater and Pressurizer

Submergence/Prolonged Wetting

Special attention should be applied to identifying where cables are routed through areas that are, may be, or may have been flooded or wet. International experience indicates that operation of medium voltage cables in submerged or wetted conditions has resulted in premature cable failures related to water induced degradation [13.32]. There is less evidence that long term wetting has resulted in premature failure of low voltage cables, however, it is prudent to include potential submerged or wetted cable locations for low voltage cables until evidence is provided to demonstrate that wet conditions are not adverse for low voltage cables [13.65].

Water permeation into extruded polymer cable insulation takes time to occur. For the purpose of defining adverse wet/submerged conditions, a cable must sit in or be covered by water for months or more. A conservative approach for medium voltage cables is to assume that all underground cable locations are wet until proven otherwise. Direct buried cables must be assumed to be always wetted since observation cannot demonstrate that they are always above the water table and free of subterranean water pockets. Locations that may be temporarily flooded or wetted for short periods and automatically drained are not considered adverse with respect to cable ageing and may be considered dry. However, water degradation in cable insulation is not reversible and removal of the wet conditions may only slow the rate of degradation. Therefore, cable locations that may have been flooded or wet for extended periods in the past must be considered to be adverse environments, regardless of the current service condition. Where the cable specialist intends to take credit for water barriers and/or draining or pumping to consider the cables dry, inspections must be performed to confirm that barriers remain effective and draining/pumping frequencies preclude long term wetting [13.64].

The following are examples of areas that may be subject to flooding or long term wet conditions:

- Direct buried cables
- Cable trenches
- Cable ducts
- Cable vaults

- Sump pits
- Undrained conduits in areas exposed to moisture

Chemical/Oil Contamination

Cables are not expected to be subjected to chemical or oil contamination. If contamination has occurred, it would be related to a separate failure or event, such as a spill or leak. The effect of contamination depends on the chemical and its compatibility with the specific cable material(s). The effects of specific chemicals and oils on specific cables insulations can be obtained through literature searches.

Locations of cables in proximity to, areas and equipment where chemicals or oils are stored or transported should be identified, if the leak/spill could result in contact with the cable. Cables should be visually inspected during walk downs to determine if contamination has occurred. Once a cable has been contaminated a determination must be made as to whether it has had a permanent effect on the cable condition and if further action is required.

The following locations are examples of potential sites for chemical and oil contamination:

- Hydraulic tanks and cylinders
- Fuel systems and storage tanks (e.g. Emergency Generators, Standby Generators, etc)
- Lube oil systems (e.g. major motors, generators, etc)

Cable Flexing

Frequent flexing of cables can introduce significant mechanical stress on cable conductors and insulation. Over time, the conductor or insulation may crack or break. This may be promoted by embrittlement due to thermal and radiation stressors working in synergy. Significant flexing may occur in cables on mobile equipment, bridging of moving parts or subject to frequent handling due to maintenance.

Locations where cables are subjected to significant flexing should be identified. Examples of locations and equipment that experience significant flexing are:

- Fuelling machines
- Cranes
- Electrical devices on hinged doors
- Frequently connected/disconnected devices

The service conditions should be monitored periodically to identify changes due to plant design and operational changes. Environmental information must remain relevant to reveal conditions that may require prompt attention and action to remove or mitigate the environmental stressors and prevent cable failure.

Emphasis should be placed on monitoring of inaccessible and underground cable locations since they are not readily visible and because of the unpredictability of moisture entry and accumulation. Barriers that may have prevented moisture accumulation prior to initial condition assessment may be breached or conditions may change due to heavy rainstorms or seasonal thaws and underground flooding.

The results of initial condition characterization and periodic monitoring are used as inputs to condition management decision making. Periodic monitoring data may be compared to baseline condition information to determine if conditions are changing or if new, or previously undetected, adverse conditions have emerged. The cable specialist will use these data in conjunction with cable CM data to determine if actions are required to mitigate the effects of the service conditions on cable condition. Cable service conditions may be modified through pumping, draining, thermal or radiation barriers, removal of root causes, etc. Plant safety and/or reliability risks, in conjunction with environment severity, may be used to determine the frequency and locations for future walk downs or a need for more continual monitoring methods.

Further valuable guidance related to the characterization, monitoring and management of adverse cable conditions is provided in IEEE Std 1205 [13.95,13.96], EPRI TR-109619 [13.89], EPRI 1020804 [13.65], EPRI 1020805 [13.64], IAEA NP-T-3.6 [13.4] and NUREG/CR-7000 [13.17].

4. Identify Stressors and Expected Ageing Mechanisms

Stressors, and their severity, should be identified from the environmental characterization and monitoring process. Stressors are either environmental, typically ambient conditions, or operational, resulting from system operation or maintenance activities. They may be global or localized. These stressors should be assessed against the known ageing mechanisms for the specific cable types exposed to bounding or adverse service environments to determine if there is any concern for potential failure modes affecting safe and reliable cable operation. A discussion of stressors, ageing mechanisms and their influence on cable failure modes is provided in section 3.2.

The cable specialist should establish the anticipated normal environmental and operational stressors acting on specific cables and locations from the data collected during condition characterization (element 3). The ageing mechanisms associated with these stressors for specific cable types and constructions can then be determined and evaluated to support selection of appropriate CM methods sensitive to detecting and trending cable degradation [13.17][13.148]. Cable degradation mechanisms are largely different between low and high voltage cables and wet and dry conditions [13.36]. PVC cables have unique degradation mechanisms in high radiation environments.

Valuable guidance on relevant stressors and ageing mechanisms may be found in IAEA-TECDOC-1188 [13.7,13.8] and NUREG/CR-7000 [13.17].

5. Select CM Techniques Suitable to Monitored Cables

The cable specialist must select CM techniques to monitor cables at risk of significant age-related degradation or used to represent bounding ageing conditions for bulk cable installations. The chosen CM technique must be sensitive to the ageing mechanisms of concern and correlated with specific cable materials and properties related to continued reliable performance (element 4). Section 4 provides a discussion of CM considerations and CM techniques in use, or in development, in the nuclear power industry and considered most applicable and effective with respect to the cable types identified in Canadian NPPs. Further techniques and detailed guidance on effective selection of CM techniques is provided in EPRI 1022969 [13.61]

It has been broadly recognized that no single CM technique is capable of addressing all cable materials and issues, when used alone. Instead, multiple methods must be integrated into an overall program. A suite of CM methods should be selected to address all aspects of cable ageing. Non destructive and non intrusive techniques that are easily implemented may be broadly applied for screening and bulk cable assessment while methods that address full cable length may be used to identify unexpected hot spot degradation for further investigation. As specific concerns are identified more sensitive, and possible intrusive or destructive, methods may be used to provide more confidence in the condition of the cable. Cable deposits, potentially including abandoned cables, may be used to limit intrusive/destructive testing to non-service cables.

The currently available CM methods may be divided into 4 categories; visual, electrical, mechanical and chemical, each having its strengths and weaknesses. The desirable CM attributes to be factored into selection are as follows:

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

The general approach to selecting techniques and implementing them into an overall program should be to use inexpensive, easily implemented screening techniques to identify early indicators of ageing on a large population of the cables within the program. This may be supplemented with increasingly intrusive and expensive techniques to provide improved ageing trend resolution to validate the conclusion of broad based testing or where cable ageing is evident or expected. The primary factors affecting ageing mechanisms and CM selections are low and high voltage and dry and wet service.

Dry Low Voltage Cables

For dry LV cables, the first, and most broadly applied, CM technique should be visual/tactile inspection, wherever cables are visible and accessible. This method may be integrated into the initial and periodic walk downs. Visual/tactile examination can be effective in identifying the signs of ageing, particularly with yellow PVC jacket cables, but its qualitative nature limits it effectiveness in tracking and trending degradation to an end condition. Where results indicate that significant ageing degradation has occurred, more sensitive diagnostic techniques should be chosen.

Where cables are not easily accessible, and there is potential for adverse service conditions, global diagnostic techniques such a LIRA may be used to detect if and where degradation has occurred. Once a site of degradation has been located, additional effort, such as ladders or scaffolding, etc, may be used to implement more sensitive local test methods to monitor the cable. EQ cables notwithstanding, I&C cables typically carry low voltage low current signals and would not be subject to significantly more severe operational service during abnormal plant operating conditions. For I&C cables not required to operate in harsh DBA conditions, normal surveillance and reliability testing of the systems would be adequate to demonstrate continued functionality if the cables are included in the test method [13.14].

Where more sophisticated CM techniques have been deemed necessary to track and trend cable degradation the selected techniques(s) should consider that generally only the cable jacket is easily accessible. Insulation may be exposed inside junction boxes and equipment but access may require special permit and maintenance support. Non-destructive and non-intrusive techniques such as the EPRI Indenter, FT-NIR Spectroscopy and AECL PPT are relatively cost effective and easily applied methods to monitor age-related degradation in cable jackets. The jacket condition is then used to imply insulation condition and a leading indicator of significant degradation which may require further action. Each technique has its advantages and disadvantages.

The EPRI Indenter is one CM method that has been used internationally for many years to cost effectively monitor large numbers of cables in NPPs and has been proven effective on most common cable jacket materials. Notable exceptions are PVC jackets in high radiation and XLPE (which is not a common jacket material in Canadian NPPs). An international standard is available for EPRI Indenter procedural control to ensure accuracy and repeatability of data [13.101]. The necessary equipment may be purchased for testing by plant personnel or is available from multiple external service providers. The AECL PPT is physically similar to the EPRI Indenter and is also effective on XLPE and irradiated PVC, but not sensitive to HCl evolution in PVC. The AECL PPT is still in development and the timing and breadth of availability is unclear. FT-NIR is another alternative. Its primary disadvantage is that it is not effective on black material, a common jacket colour. However, it is effective on yellow cable jackets, which are common in some Canadian NPPs. It has the advantages of requiring less cable manipulation and should be sensitive to HCl in PVC where colour coded insulation is exposed. Although its use as a CM tool is still in development, it has been used in

Canadian NPPs for many years to identify EQ cable insulation formulations and is available from multiple service providers.

Where sacrificial cables are available, destructive test methods, such as EaB and OIT/OITP may be used directly on cable insulation to provide further accuracy and resolution to cable ageing information. This may be adopted where the CM results of less direct techniques are not anticipated to remain within conservative acceptance criteria to the end of plant life. Sacrificial cables may also provide representative destructive test specimens to bound all, or large groups, of similar cable types operating within the envelope of their service conditions, thereby reducing, or potentially eliminating, the scope of CM testing on in-service cables.

Sacrificial cables may be provided in cable deposits deliberately installed in bounding NPP environments at the start of plant operation for the purpose of providing destructive CM test specimens [13.1]. Cable deposits may also be made available in operating NPPs through the identification of previously abandoned cables, the replacement and abandonment of selected in-service cables, or pre-ageing cables for creation of a deposit. In either case, the cable deposits and their service conditions must be accurately or conservatively recorded in the cable database to provide the set of bounding service conditions that the deposit represents. Since cable deposits are not energized, their environment will not directly address ohmic heating in LV power cables or worst-case heat rise from cable tray overloading. However, the margin between the ambient cable deposit and ambient temperature of in-service cables may be used to address heat rise. A conservative heat rise for cable tray loading may be defined and ohmic heating of individual power circuits may be estimated using current heat rise calculations or thermography (see element 3). Where the service conditions of individual, or groups of, in-service cables are not enveloped by the cable deposit, they will require separate CM. Cable deposits will not typically represent age-degradation from non thermal/radiation stressors such as flexing or chemical contamination.

Further guidance on CM for dry LV cables is provided in EPRI 1020804 [13.65].

Wet Low Voltage Cables

Low voltage cables in wet environments should be subjected to regular CM testing to trend degradation. Insulation resistance remains the only effective method of monitoring moisture-induced degradation of insulation in low voltage, wet environments. Care must be taken to ensure that the influence of varying temperature and moisture conditions at the time of testing is considered when assessing results. Further guidance on the use of IR testing of wet LV cables is provided in EPRI 1020804 [13.65].

Wet Medium Voltage Cables

The most effective CM approach to wetted shielded MV cables is Tan-δ complemented by VLF withstand testing where required (see section 4.4.1.7). Since Tan-δ is sensitive to water related damage, it is effective as a leading indicator of condition and provides ample lead time to take action prior to failure. Tan-δ can be performed off line and requires disconnection. Where periodic testing is planned, the installation of separable connectors should be considered. Tan-δ is not recommended for non-shielded MV cables [13.64].

Partial discharge (PD) testing is not likely to be suitable for CM of most wet MV cables since it is not sensitive to water damage. Water trees must be converted to electrical trees before PD will sense damage and degradation may become rapid once this occurs. Also, corrosion of tape shield may interfere with measurements [13.64].

CM of non-shielded MV cables is problematic due to the absence of a uniform ground plane. Available off line CM alternatives are limited to forensic analysis of failed cables, operating experience from similar cables, and testing of abandoned or removed cables [13.64]. Although these alternatives do not provide optimal insight into cable degradation, they are likely the best CM techniques currently available for non-shielded cables.

EPRI 1020805 [13.64] provides detailed guidance for the application of Tan-δ and VLF withstand testing of wetted MV cables.

Dry Medium Voltage Cables

Selection of CM techniques for dry MV cables will depend on various factors, including insulation/jacket materials, cable/circuit configuration, cable vintage, etc. Depending on the circumstances, suitable CM methods for dry rubber insulated MV cables include visual examination, LIRA, Tan-δ or PD testing. EPRI 1020805 [13.64] provides guidance for CM selection for dry common rubber insulated MV cables.

Valuable guidance regarding the availability and selection of CM techniques is provided in EPRI 1022969 [13.62], EPRI 1020804 [13.65], and EPRI 1020805 [13.64]. Further useful information is provided in IAEA NP-T-3.6 [13.4]. CM should incorporate incorporate adequate procedural controls to ensure reproducibility/repeatability of test results throughout the entire process of modelling cable insulation ageing characteristics in the laboratory to ultimate field measurements. IEC/IEEE 62582 should be used where applicable to the chosen CM method.

6. Establish Baseline Condition of Monitored Cables

Baseline condition data must be collected for those cables monitored within the program. Ideally, this data should represent the condition of the cables at time of installation; however, for operating plants retrofitting a program it is recognized that this may need to be the condition established at the time of program initiation. The CM techniques used to monitor cable condition are selected in program element 5. Baseline condition data is used as a benchmark against which to compare future CM inspection and test data (element 10) to determine serviceability and ageing degradation trends.

Baseline visual CM inspection should record all relevant physical attributes of the cables, such as colour, damage, contamination, etc, as well as all important installation and operational information such as design/specification data, proximity to adverse condition(s), thermographic survey data, sharp bends, etc. Detailed procedures should be developed to standardize how inspections are conducted and what information is collected to make subsequent inspection information more useful for comparison. It is recommended that this work be coordinated with environmental characterization walk downs (element 3).

Using the CM techniques selected in program element 5, initial testing of cables must be performed to provide a basis for comparison of subsequent tests (element 8). Adequate procedural controls should be maintained to ensure that CM data derived in laboratory testing is repeatable and reproducible in the field and at other laboratories [13.7].

The performance of baseline condition assessments should be prioritized and scheduled based on evaluation of safety significance and risk of failure. For instance, increasing failure rates of wetted MV cables have been recognized as a problem in some plants and EPRI 1020805 [13.64] Section 4 provides an evaluation of relative susceptibility to water induced degradation and failure based on cable type. Operating experience may also indicate a history of recurring failures in specific cable groups or locations in the plant. By prioritizing known or suspected problem cables, early baseline condition information may provide the necessary information to trigger actions to pre-empt incipient in-service cable failures (element 10).

Further guidance regarding the establishment of baseline cable conditions is provided in NUREG/CR-7000 [13.17].

7. Identify Cable Characteristics/Ageing Effects Monitored by each CM Technique

Program element 4 identifies the stressors acting on the cables and related ageing mechanisms. These data are then used to select a suitable CM technique to measure and track ageing degradation in the cables (element 5).

The specific CM techniques are designed to measure changes in specific cable characteristics which are used as a condition indicator. These condition indicators are correlated with cable properties essential to continued reliable serviceability. For example, Indenter Modulus (IM) measures hardness which is correlated with EaB for a given material, an indicator of embrittlement and potential cracking of the material. If the measurements are taken on a cable jacket, they may require correlation with the EaB of the underlying insulation. When demanded by the CM method, testing of representative cable samples must be used to baseline the ageing characteristics of the cable and correlate condition indicators from CM techniques to critical cable properties relevant to its continued serviceability under expected service conditions (Section 4). Tan-δ measures the ratio of resistive leakage current through the insulation divided by the capacitive current which may be used to indicate water damage, or other degradation, in MV cables [13.64].

The cable characteristics and related ageing effects being monitored by the selected CM technique must be established and recorded for each specific cable type to facilitate review and assessment of regular CM testing (elements 8 and 10).

8. Periodically Perform CM Tests and Inspections on Cables

Condition monitoring inspection and testing must be periodically and routinely performed to collect data for inclusion in the cable database [13.17]. The scope and intervals for the CM tests are initially determined by the cable specialist based on environmental baseline inspections (element 3) and baseline condition information (element 6). CM testing should be integrated with existing planned preventative maintenance programs, either as new activities or as an expanded part of existing activities.

The CM test data is to be progressively compared to baseline and prior incremental data to determine current cable condition and establish ageing trends. The result of regular CM inspection and test data are intended for review and assessment by the cable engineer to determine if action is required, including potential changes to scope and/or frequencies of inspections and CM tests (elements 10 and 11).

9. Periodically Review and Incorporate Plant and Industry OPEX

Industry and plant operating experience can be a very valuable resource in revealing unanticipated cable ageing problems [13.17]. OPEX-related cable failures, research, and other issues related to cable ageing management, such as changes to service environments, new research information, etc should be collected and reviewed on a regular basis to determine if adjustments to the cable ageing program are warranted.

Regular review and analysis of cable-related problems within the plant may reveal adverse performance trends and problem areas that demand further scrutiny and correction before the problems become more severe or widespread. External operating experience can also identify issues with cables and their operating environments that illuminate concerns. A system of identifying problems, causes of failures, solutions and corrective actions can provide a powerful tool for identifying unanticipated and emerging ageing concerns and facilitating corrective actions before plant reliability is significantly challenged.

The following are examples of sources for internal and external cable-related operating experience:

- Internal SCRs, event reports, work reports, maintenance personnel interviews, shift logs, condition assessments, plant reliability records
- CANDU event reports, COG research projects, EQ cable test reports
- USNRC Opex – information notices, generic letters, circulars, bulletins, LERs, 10CFR Part21 reports, NUREG reports, etc – available on NRC website www.nrc.gov
- IAEA research reports, EPRI research reports, INPO, etc

Further guidance regarding the value of OPEX is provided in NUREG/CR-7000 [13.17]

10. Periodically Review, Assess and Trend Condition of Monitored Cables

A formal periodic review and assessment of the CM test data (elements 6 and 8) must be performed. This review considers all inspection and CM results, environmental and condition monitoring information, systems surveillance test results, and OPEX to identify degradation trends and provide an assessment of cable condition [13.17]. By regular review and assessment of all of these factors, the responsible cable specialist is able to determine the condition and continued reliability of cables at the time of analysis and estimate the remaining service life. As a result of the analyses, the cable specialist may determine that actions are required to mitigate the effects of cable ageing or to implement additional CM techniques that provide better resolution and insight into cable condition (element 11).

Further guidance on the review and assessment of cable condition is provided in NUREG/CR-7000 [13.17].

11. Identify Degraded Conditions and Define/Take Corrective Actions

During the review and assessment of program cable condition and service condition data (element 10), the responsible cable specialist must determine if the long term condition and reliability of cables is challenged and define and implement actions to preclude in-service cable failure. The cable specialist must consider many contributing factors when determining if the remaining reliable cable service life is less than, or approximately the same as, the remaining plant design life and defining a course of action to mitigate the ageing effects. Further discussion regarding corrective action considerations is provided in NUREG/CR-7000 [13.17].

The results of initial environmental characterization and baseline condition assessments (elements 3 and 6) provide an early basis for the cable specialist to identify areas of concern and determine strategies to support reliable cable performance to the end of plant life. Upcoming major plant refurbishment projects may also provide a window of opportunity to test, replace, and/or reroute suspect cables and/or implement design changes to mitigate or remove adverse service conditions. The cable specialist may consider the benefits of solutions that negate or reduce the cost, risk and maintenance burden of relying on long term regular CM tests and analyses. Other issues, such as circuit design improvements, fire retardancy, device termination improvements, operational problems, EQ, etc. should be factored into the solution strategies.

The results of CM inspection and testing should be reviewed regularly to determine the current condition of cables and identify any ageing related trends. Condition indicators and trends should be compared to acceptance criteria to predict remaining cable life and determine if there are any potential challenges to long term acceptable performance of the cables. Acceptance criteria should include administrative limits/margins to trigger corrective actions to manage the effects of age degradation in sufficient time to avoid failure in service (Section 4). Administrative limits and acceptance criteria to define cable functionality can be application specific and therefore judgements must be made by experienced personnel considering all CM data and design inputs [13.17].

Valuable guidance on defining action strategies for mitigation and correction of adverse environments and degraded cable is provided in EPRI TR-109619 [13.89], EPRI 1020804 [13.65] and EPRI 1020805 [13.64].

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APPENDIX A. IN-SITU CONDITION MONITORING METHODS

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Ageing Mechanisms Detected	Advantages	Limitations
Visual Inspection (potentially supported with borescope, mirrors, etc.)	Screening	• All accessible cables • All insulation and jacket materials	• Elevated Temperature • Radiation exposure • Mechanical stress • Voltage stress & Moisture exposure • Submergence • Exposure to chemicals and other surface contaminants	• Thermally induced embrittlement and cracking • Radiation induced embrittlement and cracking • Mechanical damage and wear • Potential for water treeing • Potential for moisture intrusion • Surface Contamination	• Simple to perform • Inexpensive equipment • Provides useful qualitative information on cable condition • Can detect localized degradation	• Requires access to cable under test • Does not provide quantitative data on cable condition • Knowledge and experience produce best results
Compressive Modulus (Indenter)	Diagnostic	• Low-voltage cables • Most effective for Ethylene-Propylene Rubber, Polyvinyl Chloride, Chlorosulfonated Polyethylene,	• Elevated Temperature • Radiation exposure	• Thermally induced embrittlement • Radiation induced embrittlement (except PVC)	• Relatively easy to perform • Provides trendable data on commonly used cable insulation materials	• Requires access to cable under test • Location of test specimen may not be in area of concern • Difficult to obtain direct

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Ageing Mechanisms Detected	Advantages	Limitations
		Silicone Rubber, and Neoprene® materials			• Results can be correlated to known measures of cable condition	access to insulation in problem areas
Force Recovery Time (AECL Portable Polymer Tester)	Diagnostic	• Low-voltage cables • Effective for Ethylene-Propylene Rubber, Polyvinyl Chloride, Chlorosulfonated Polyethylene, Crosslinked Polyethylene, materials	• Elevated Temperature • Radiation exposure	• Thermally induced embrittlement • Radiation induced embrittlement	• Relatively easy to perform • Provides trendable data on commonly used cable insulation materials • Results can be correlated to known measures of cable condition	• Requires access to cable under test • Location of test specimen may not be in area of concern • Difficult to obtain direct access to insulation in problem areas • In development
Fourier Transform Near Infrared Spectroscopy (FT-NIR)	Diagnostic	• Low- and Medium-voltage cables • All non-black insulation and jacket materials	• Elevated Temperature • Radiation exposure	• Thermally induced embrittlement • Radiation induced embrittlement • Radiation	• Relatively easy to perform • Provides trendable data on commonly used cable	• Requires access to cable under test • Location of test specimen may not be in area of concern

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Ageing Mechanisms Detected	Advantages	Limitations
				induced HCl elimination (PVC)	insulation materials • Results can be correlated to known measures of cable condition	• Requires formal training to perform and interpret results • Not effective with black materials • In development
Dielectric Loss -Dissipation Factor/ Power Factor (AC Voltage @ varying frequencies) Also known as Tan-δ	Diagnostic	• Low- and Medium-voltage cables • Best results on shielded cables • All insulation and jacket materials	• Elevated Temperature • Radiation exposure • Mechanical stress • Voltage stress & Moisture exposure • Submergence • Exposure to chemicals and other surface contaminants	• Thermally induced cracking • Radiation induced cracking • Mechanical damage • Water treeing • Moisture intrusion • Surface Contamination	• Relatively easy to perform • Provides trendable data on commonly used cable insulation materials • Access to entire cable not required • Can be correlated to known measures of cable condition	• Cable must be de-terminated to perform test • Best results obtained on shielded cables
Insulation Resistance	Pass/Fail	• Low- and Medium-voltage	• Elevated Temperature	• Thermally induced cracking	• Relatively easy to	• Cable must be de-terminated to

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Ageing Mechanisms Detected	Advantages	Limitations
(DC Low Voltage)		cables • All insulation and jacket materials	• Radiation exposure • Moisture exposure • Submergence	in the presence of moisture • Radiation induced cracking in the presence of moisture • Moisture intrusion	perform • Access to entire cable not required • Can be corrected for environmental effects	perform test • Typically considered a go/no-go test with little trendable data • May not detect severe insulation degradation under dry conditions • Insulation resistance can be difficult to measure accurately under certain conditions
Infrared Thermography	Screening	• Low- and Medium-voltage cables • All insulation and jacket materials	• Elevated Temperature • Ohmic heating	• not applicable (detects thermal stressors only)	• Relatively easy to perform • Identifies temperature and location of hot spots • Measurements made when	• Requires training and experience for best results • Measurements made when circuit is operating at full load can be a

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Ageing Mechanisms Detected	Advantages	Limitations
					circuit is operating at full load • Data may be stored and trended with appropriate software • Non-destructive, non-intrusive, does not required contact with cable, does not require cable to be de-terminated	safety concern • High end imagers and analysis software are expensive • Area to be monitored must be visually accessible • Does not provide quantitative data on cable condition
Line Resonance Analysis	Diagnostic	• Low- and Medium-voltage cables • All insulation and jacket materials	• Elevated Temperature • Radiation exposure • Mechanical stress	• Thermally induced embrittlement and cracking • Radiation induced embrittlement and cracking • Severe mechanical	• Can be performed in situ without de-terminating the cable • The effects of loads attached to the cable can be	• It is not a simple test to perform or interpret • Training and experience are needed to obtain meaningful results

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Ageing Mechanisms Detected	Advantages	Limitations
				damage	accounted for in the analysis of results • Can locate localized degradation	

APPENDIX B. LABORATORY CONDITION MONITORING METHODS

Laboratory CM Techniques (Adapted from Table 3.1 of USNRC NUREG/CR-7000 (BNL-NUREG-90318-2009) “Essential Elements of an Electric Cable Condition Monitoring Program”)

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Ageing Mechanisms Detected	Advantages	Limitations
Elongation-at-Break	Diagnostic	• Low- and Medium-voltage cables • All insulation and jacket materials	• Elevated Temperature • Radiation exposure	• Thermally induced embrittlement • Radiation induced embrittlement	• Provides information on insulation condition that can be correlated with electrical performance • Proven technique for monitoring material condition • Data is trendable	• Destructive test • Requires relatively expensive equipment and training to perform
Oxidation Induction Time Oxidation Induction Temperature	Diagnostic	• Low- and Medium-voltage cables • Most effective for Ethylene Propylene Rubber, Polyethylene,	• Elevated Temperature • Radiation exposure	• Thermally induced embrittlement • Radiation induced embrittlement	• Provides information on insulation condition that can be correlated with electrical performance	• Requires access to cable to obtain a small sample of insulation or jacket material • Requires formal training to

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Ageing Mechanisms Detected	Advantages	Limitations
		and Cross-Linked Polyethylene materials			• Considered non-destructive since only a small sample of insulation material is required	perform and interpret results • Location of test specimen may not be in area of concern
Fourier Transform Infrared Spectroscopy	Diagnostic	• Low- and Medium-voltage cables • Most effective for Ethylene Propylene Rubber, Polyethylene, and Cross-Linked Polyethylene materials	• Elevated Temperature • Radiation exposure	• Thermally induced embrittlement • Radiation induced embrittlement	• Provides information on insulation condition that can be correlated with electrical performance • Considered non-destructive since only a small sample of insulation material is required	• Requires access to cable to obtain a small sample of insulation or jacket material • Requires formal training to perform and interpret results • Location of test specimen may not be in area of concern
Density	Diagnostic	• Low- and Medium voltage cables • Most effective for Ethylene-Propylene	• Elevated temperature • Radiation exposure	• Thermally induced embrittlement • Radiation induced embrittlement	• Provides information on insulation condition that can be correlated with	• Requires access to cable to obtain a small sample of insulation or jacket material

CM Technique	Test Type	Applicable Cable Categories and Materials	Applicable Stressors	Ageing Mechanisms Detected	Advantages	Limitations
		Rubber, Polyethylene, Polyvinyl Chloride, Chlorosulfonated Polyethylene, and Neoprene® materials			electrical performance • Considered non-destructive since only a small sample of insulation material is required	• Requires formal training to perform and interpret results • Location of test specimen may not be in area of concern