

Long-term radiation ageing in polymers —

Part 3: Procedures for in-service monitoring of low-voltage cable materials

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, the CEI IEC title page, pages ii to iv, pages 1 to 30 and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

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Procédés pour le contrôle en service
des matériaux des câbles basse tension**

Long-term radiation ageing in polymers –

**Part 3:
Procedures for in-service monitoring
of low-voltage cable materials**



Commission Electrotechnique Internationale
International Electrotechnical Commission
Международная Электротехническая Комиссия

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Introduction

Polymers are widely used as electrical insulating materials (e.g. in cables for control, instrumentation and power) in environments in which they are exposed to radiation. In such applications, these materials may well be required to survive the full working life of the plant, which may be more than 40 years, and accident conditions at the end of working life. Although considerable data are available on the behaviour of polymeric insulating materials under irradiation, there is still some uncertainty on the effects of long-term low dose rate irradiation, such as would be experienced by cables. There is therefore a requirement for techniques for monitoring the state of degradation of cable materials *in situ* throughout the lifetime of the plant. Suitable cable monitoring techniques would also be important to surveillance programmes in support of plant life extension and licence renewal. Although this report is primarily aimed at cable condition monitoring in nuclear power plants, it can also be applied to other polymeric components. Many of the techniques are equally applicable to thermal-only ageing of polymeric components in conventional power plants.

1 Scope

This technical report summarizes the main cable monitoring techniques which are currently being assessed worldwide. These techniques are primarily aimed at monitoring degradation of low-voltage cables. Most of the methods are at the development stage and require in-plant evaluation before they could be recommended as standard techniques. The advantages and disadvantages of each method, and its current state of development, are outlined in the following sections. There are two aspects of cable monitoring that need to be taken into account — techniques suitable for ageing evaluation and techniques suitable for monitoring faults in cables. The methods discussed may, in some cases, be more suitable for monitoring faults than for evaluating the degree of degradation of the cable materials.

2 Requirements of a monitoring technique

There is a range of requirements which the ideal cable monitoring technique would need to satisfy. In practice, no one technique will satisfy all of the requirements and a range of techniques is likely to be needed. In each case, baseline data (i.e. data on unaged material of the same formulation and manufacturer) are needed to make full use of the techniques.

The ideal monitoring technique would have the following attributes:

- non-destructive;
- capable of use during normal operation;
- not require disconnection of equipment;
- related to an identifiable degradation criterion;
- applicable to a wide range of cable materials and configuration;
- applicable at accessible locations;
- capable of identifying hot-spots;
- reproducible and capable of compensating for environmental conditions (temperature, humidity);
- less expensive to implement than periodic cable replacement;
- readily available reference data.

3 Techniques available

There is a wide range of possible techniques being considered for cable monitoring. A few are already in use in-plant, others are only at the laboratory evaluation stage. The methods can be grouped together under generic types, as follows.

Local tests without sampling

- indenter
- sonic velocity
- near infrared reflectance
- torque testing

Local tests with micro-sampling

- infrared
- oxidation induction time (OIT)
- plasticizer content
- density

Global tests with spatial resolution

- time domain reflectometry (TDR)
- partial discharge

Global tests without spatial resolution

- dielectric loss
- time domain spectrometry (TDS)
- pass/fail tests — dielectric strength, insulation resistance

Paced tests — elongation at break

Each of these types of test is described in more detail in the following subclauses.

3.1 Local tests without sampling

The term “local” refers to techniques which give information on the state of the cable at the measuring point only and are thus likely to miss defective spots. These methods can only be applied in man-accessible areas and are generally limited to tests of the cable jacket material except at terminations where the insulation is exposed. Where the techniques have been cross-correlated with changes in elongation at break, these methods have a predictive capability. This type of test will provide immediate data in-plant on the state of the cable. Where the cable jacket is more likely to degrade than the insulation (which is often true) the methods provide early warning of cable failure. Local bend tests by manipulation of the cable by hand can give qualitative information when carried out by experienced personnel.

3.1.1 Indenter

The indenter is a portable device developed by the Franklin Institute which measures a property related to the modulus of elasticity of cable jacket and insulation materials [1] [2]¹⁾. A schematic diagram of the indenter is shown in Figure 1. An instrumented probe of known shape is driven against the outside of the cable at a fixed velocity (12,7 mm/min) and the slope of the force versus distance is obtained over a force range of 2 N to 9 N. The probe shape used is the same as that used in the ASTM standard for hardness testing [3], i.e. a truncated cone, but with an end area equal to half that of the ASTM cone.

The indenter modulus values measured with the portable indenter have to be corrected for temperature to obtain comparable data sets when used in-plant. The amount of temperature compensation required varies with the ageing of the cable material [4], see Figure 2. Practical tests of the unit in nuclear power plants have shown that the indenter can be successfully used *in situ* to test cables in trays, panels and junction boxes, provided that about 7,5 cm of exposed cable are accessible [4]. In accelerated ageing tests, good correlation has been obtained between modulus measurements and elongation at break for polyvinyl chloride (PVC) jacketed cables, chlorosulphonated polyethylene (CSPE) and a range of elastomers [4] [5] [6]. Examples are shown in Figure 3 and Figure 4 for an ethylene propylene (EPR)/CSPE cable and for an EPR based cable (kerite FR) respectively. The indenter does not appear to be suitable for use with polyolefins and radiation aged PVC because their modulus changes very little with ageing. More recent indenter data indicates that the method may be usable with these materials with a modified technique [7].

Limitations:

By its very nature, the indenter can only measure the properties of the cable material over a limited area in the vicinity of the probe. The indenter modulus values obtained can show a marked variation if the jacket thickness is variable, increasing as the thickness decreases. The construction of the cable, for example the presence of armouring or shielding, is also likely to affect the modulus value. Because of this, extensive baseline data would be required to cover the range of cable materials and construction types used in a typical power plant. The indenter is limited to those materials which harden or soften significantly during ageing; this includes many of the types of cables used in older plants.

In most of the cable areas which are accessible to the indenter, only the properties of the jacket material can be measured. Since the jacket materials in most cable constructions tend to degrade more rapidly than the insulation materials, indenter measurements can still give early warning of cable degradation.

¹⁾ Figures in square brackets refer to the bibliography given in Annex A.

3.1.2 Sonic velocity

This technique is at an early stage of development and at present has only been tested on PVC based cables [6]. Sonic velocity testing is based on the fact that the velocity of sound in a solid medium is dependent on both the density and the modulus and is given by:

$$C^2 = \frac{E}{\rho}$$

where

- C is the sonic velocity;
- E is the elastic modulus;
- ρ is the polymer density.

Since both modulus and density can change during ageing of cable materials, changes in sonic velocity would be expected to occur on ageing.

The tester uses piezoelectric transducers to transmit and receive a series of 20 kHz pulses, as shown schematically in Figure 5. The signal transit times are plotted as a function of transducer separation distance (up to a few centimetres) to obtain the slope which represents velocity [6]. Sonic velocity measurements have been made on a series of PVC jacketed cables and on strips of jacket material cut from the cables. Comparison between the data obtained on the test strips and the complete cables has shown that the technique is dependent on the cable geometry and adjacent shielding and insulation components, see for example Figure 6. The magnitude of the sonic velocity also varies considerably with different formulations of PVC, therefore baseline data would be required for each type of cable used in a plant if the technique was to be of practical use.

Limitations

The sonic velocity tester measures properties of the cable jacket over a small volume between the transducer probes. The measurements obtained are strongly dependent on the cable construction and the specific formulation of the jacket material. Therefore, extensive baseline data would be required. The technique is at an early stage of development and has so far only been tested on PVC jacketed cables, but it is still under active development. At present the technique is more suited to laboratory evaluation than field use, but its high sensitivity to ageing degradation indicate that it may well be worth further development.

3.1.3 Near infrared reflectance

Changes in the infrared spectrum of polymers are known to occur with ageing, primarily in functional groups such as carbonyl (C=O), hydroxyl (O-H) and carboxyl (COOH). These functional groups are normally observed in the infrared spectrum in transmission, but for use in-plant a portable unit based on near-IR reflectance (NIR) using a fibre optic probe would be more suitable.

NIR reflectance measurements have been carried out on PVC jacketed cables in the wavelength range 1 300 nm to 2 100 nm [6] using a fibre optic probe pressed against the cable jacket. Baseline shifts arising from small changes in optical path length are often seen in the absorbance spectra. These small baseline shifts can be eliminated by using the first derivative of the absorbance spectra (Figure 7), since the first derivative is the slope of the absorbance spectrum at each wavelength. Various regions of the IR spectrum were found to correlate well with changes in the elongation at break of the PVC material tested; for example, changes in the spectrum at 1 640 nm to 1 650 nm are shown in Figure 8 for thermal ageing of PVC. This technique using fibre optic probes for reflectance measurements is at an early stage of development.

Limitations

The NIR reflectance spectrum obtained is only from a thin surface layer of the cable material being tested. This surface may not be representative of the state of degradation of the bulk of the material. As in the other techniques in this category, data are limited to the immediate area of the probe. Care must also be taken in interpreting the data as some stabilizing additives in polymers have peaks in the same range of wavelengths. The technique is not likely to be sensitive to the cable geometry or construction but calibration curves would be required for each cable material. This technique is not currently under active development.

3.1.4 Torque tester

The degradation of cable jacket materials can also be determined using a torque-strain response method [8]. A pair of chucks are used to grip the outside of the cable and a small angle torque, in the range 5° to 10° , is applied to one of the chucks at up to 2 Hz. A prototype apparatus for such measurements is shown in Figure 9. Preliminary data on the behaviour of PVC cables have been used to optimize the test conditions for the torque method. The effect of torsion frequency on the torque values obtained is small in the frequency range 0 Hz to 2 Hz; for PVC the optimum frequency is 0,8 Hz. In both as-received and aged cables the torque values measured increase linearly with the applied torque angle up to 10° . At higher torque angles, components other than the jacket material will significantly contribute to the values obtained. For a non-destructive technique, a maximum torque angle of 10° is recommended.

The effect of the length of cable between the chucks has also been investigated. At shorter cable lengths, the measured response will be strongly dependent on the insulation, conductors and any shielding components, whereas as the cable length increases, the sensitivity of the torque-strain response will decrease. The optimum cable length between chucks is 50 mm for PVC cables.

There is a strong correlation between the torque values measured using the prototype tester and elongation at break, both for thermally aged material and for cables subjected to sequential radiation and thermal chemical ageing (Figure 10 and Figure 11). A linear relationship between elongation and torque is found over a wide range of elongation values. Deviations from this linear relationship are only observed when heterogeneous oxidation has occurred in the accelerated tests (Figure 12). The torsion test is a measure of the bulk properties of the jacket material whereas elongation at break is determined by crack initiation in the more highly oxidized surface layer in this material. In most cable applications in nuclear plants, homogeneous oxidation is likely to occur.

A portable version of the torsion tester which could be clamped onto sections of cable in-plant has been developed. This enables data to be taken non-destructively on accessible lengths of cable *in situ*.

Limitations

As in all local tests, measurements are limited to man-accessible areas and jacket materials. Since torque values will be significantly affected by differences in cable construction and geometry, baseline data for a wide range of cable types would be needed in practice. If there are environmental conditions in-plant which give rise to heterogeneous oxidation, the technique would tend to underestimate the degree of degradation of the jacket material.

3.2 Local tests with microsampling

These methods are also limited to man-accessible areas and mainly provide information on the jacket materials. Where they are cross-correlated with baseline data on changes in elongation at break they have a predictive capability. All of these techniques are laboratory based with a varying degree of complexity of equipment required.

3.2.1 Infrared spectroscopy (IR)

Changes in the infrared spectrum of polymers are known to occur with ageing, primarily in functional groups such as carbonyl (C=O), hydroxyl (O-H) and carboxyl (COOH). An alternative to reflectance measurements in-plant is to take samples from the cable material and measure the IR spectrum in the laboratory. Such samples would usually be in the form of scrapings or slivers of material cut from the surface, but sufficiently small to not affect the operation of the cable. Changes in the carbonyl peak at about $1\,720\text{ nm}$ are most frequently used for monitoring changes in the state of degradation of the material [9] [10] [11]. Figure 13 shows the change in carbonyl absorbance for radiation aged XLPE and Figure 14 shows the change for thermal chemical ageing of XLPE. This functional group is sensitive to the early stages of oxidative degradation but may not be sufficiently sensitive in the later stages when mechanical properties are significantly degraded.

Limitations

IR spectra taken from samples are limited to the surface layers of the cable jacket unless exposed insulation is accessible. The depth of material sampled is greater than for the in-plant IR reflectance measurements, but may still not be representative of the bulk material. The technique is limited to those parts of the cables that are man-accessible for sampling and is not very sensitive to the later stages of degradation.