LIFE PERFORMANCE OF AN EPR-INSULATED POWER CABLE EXPOSED IN SERVICE BEYOND 3 MGy IN A HIGH-LEVEL RADIATION AREA

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Mechanical and electrical test results are reported for a power cable that has been installed for three and a half years in a high-level radiation area at the European Organization for Nuclear Research (CERN). The degradation of selected mechanical properties as a function of absorbed dose is compared with results of a short-term irradiation in a nuclear reactor. The tensile test specimens have been taken from the ethylene propylene rubber insulation and the polyvinyl chloride sheath material of the cable after exposure in service. For the measurement of breakdown voltage, short portions of insulated cable have been used. The aim of this work was to verify that the combined functional and environmental stress factors did not lead to more damage of the cable than was expected from the value of absorbed dose, and eventually to predict more precisely the service life of similar cables. The ratios of doses after service and short-term irradiation at 50% reduction of elongation at break were about 0.5 for the insulation and 1.0 for the sheath material at a dose of about 1 MGy. However, the breakdown voltage did not show any significant variation in the dose range covered up to 3.6 MGy. Therefore, a safe lower dose limit may readily be derived from accelerated tests, but the margin until failure in service remains to be determined.

1. Introduction

A service life exceeding forty years is a current requirement for power cables conforming to IEC standards [1,2] operating under normal functional and environmental conditions in industrial and commercial power installations. A shorter life or a higher risk of failure has to be taken into account when cables with organic insulation are exposed to ionizing radiation exceeding certain levels. Therefore, early replacement is sometimes preferred in order to prevent the risk of breakdown of weakened parts. Guidelines for determining the performance characteristics of insulating materials for service under ionizing radiation are defined in IEC Standard 544 and in other standards [3,4].

A considerable amount of test data has been produced on mechanical properties of individual materials measured after accelerated radiation exposures of small samples. In particular, such data, covering a wide range of cable insulating materials, are given in ref. 5. However, there is a lack of data from tests of complete full-size cables after long-term exposure under conditions representative of actual service conditions. Such data are not easily available because of the lengthy process involved in obtaining irradiated specimens of real cables and of the lack of information on the absorbed dose.

Accelerated life testing of various materials is necessary for comparing the quality in terms of selected

properties. However, it is difficult to predict cable life in service from accelerated life test data of the individual materials. Accuracy depends on uncertainties about the extrapolation relationships involved, which may be grouped as follows:

- a) extrapolation from accelerated radiation exposure to service dose-rate exposure (with corrections for temperature, reactive gases, humidity, etc.);
- b) extrapolation from mechanical and electrical test stress levels to service stress levels;
- c) extrapolation from selected reference properties of constituent materials to over-all life characteristics of the full-size cables.

At CERN, the usual procedure for determining the relative stability against radiation of cable insulation materials consists of mechanical tests at several dose values accumulated in a few days in a nuclear reactor [5]. Based on these data, an extrapolation is made using end-point criteria for the most sensitive mechanical properties, including certain safety factors, in order to arrive at the dose that can be withstood during a service life of at least ten years. Since it is known that the dependence of radiation damage on dose rate [3,6] is not the same for all materials, and that there is a strong synergistic effect of the irradiation temperature [7], supplementary long-term tests have been performed at the CERN accelerators in some typical zones with a variety of materials [8]. However, the results are not homogeneous for any given class of insulation materials, but

depend on details of composition and manufacture. There will always remain some uncertainty in the prediction of operational life, which has to be accounted for by a suitable safety factor. Also, the long-term irradiation tests of materials performed so far could closely reproduce service conditions such as temperature and dose-rate history or the presence of reactive gases for only a few typical cases.

The replacement of the power cables in the CERN Super Proton Synchrotron (SPS) neutrino beam tunnel offered the possibility to compare the effects found in the insulation of an actual typical cable, after service in a high-level radiation environment, with the results of the extrapolation procedure described above.

2. Description of the cable and the service conditions

2.1. Cable construction

The cable examined is an ethylene propylene rubber (EPR)-insulated, polyvinyl chloride (PVC)-sheathed 3.6/6 kV, $4 \times 95 \text{ mm}^2$ Al power cable conforming to IEC Standard 502 [1]. It consists of four aluminium conductors, each insulated with 3 mm EPR. These four conductors are held together by a wrapping of fabric, the space between them being filled with soft plastic, and then by an outer sheath made from 2.5 mm flame-retardant PVC. Both the EPR and PVC materials are filled with calcinated clay and contain Sb_2O_3 ; the EPR also contains Al_2O_3 . The technical data on the cable are summarized in table 1.

Table 1
Characteristics of 3.6/6 kV EPR-insulated power cable

Manufacturing year	1975
Type designation	ARG 50 R/11
Standard applicable	IEC 502
Rated voltage	$U_0/U = 3.6/6 \text{ kV}$
Routine test voltage	11 kV a.c.
Conductors	$4 \times 95 \text{ mm}^2$ Al, IEC 228 class 2
Insulation	EPR terpolymer compound (Vistalon 2504 and 3708); charged with calcinated clay and aluminium trioxide (Al_2O_3), plasticized with paraffin, to which was added antimony trioxide (Sb_2O_3). Thickness 3.0 mm.
Sheath	PVC polymer compound charged with calcinated clay, plasticized with polymeric plasticizer to which was added chlorinated paraffin; stabilized with antimony trioxide (Sb_2O_3) and lead salts. Oxygen index > 30. Thickness 2.5 mm.

Table 2

Functional and environmental service conditions (For irradiation conditions, see section 3).

<i>Functional service conditions</i>	
Oscillatory discharge voltage	< 7 kV peak-to-peak
Discharge current per cable core	< 1 kA peak, 100 A r.m.s.
Current density	< 10 A/mm ² peak, 1 A/mm ² r.m.s.
Pulse repetition frequency	≈ 0.1 Hz
Duty factor	≈ 0.01
Operation time/total time	≈ 30%
Installation and mounting	fixed installation (open tray)
Bending radius	> $0.5 \times 15(D + d) = 480 \text{ mm}$
Corresponding elongation	≈ 2% for insulation ≈ 6% for sheath
<i>Environmental conditions</i>	
Ambient air temperature	< 30°C
Relative humidity	< 50%
Ozone concentration	< 0.1 ppm by volume
Ionizing radiation	< 1 MGy/year (see section 3)
Other agents	reactive gases and corrosive contamination produced by radiation

2.2. Service conditions

This cable was manufactured in 1975, and a number of sections were installed in 1976. They remained in service up to the middle of 1980, and were used to feed the pulsed magnets of the CERN SPS neutrino facility. In this service the cables carried pulsed current discharged from capacitor banks located some 150 m outside the radiation area. The total length of the 28 cable sections actually located inside the high-level radiation area amounted to about 2 km.

The cables inside the radiation area are exposed to the combined effect of the cyclic electric, mechanical, and thermal transient stresses under pulsed operation (summarized in table 2) and the environmental stresses specific to service in high-level radiation areas.

3. Irradiation history of service exposure and of accelerated tests

3.1. Irradiation history of exposure of cables in service

The configuration of the radiation sources and the location of the cables in the neutrino beam tunnel are outlined in fig. 1. This simplified layout of the neutrino beam tunnel shows the magnets fed by the cables tested, together with the position numbers.

Fig. 1. Identification of the positions in the SPS neutrino tunnel where samples of cable-insulating materials have been taken. The magnets after target T11 and the collimator are labelled with the position numbers used here.

When these cables were exchanged in the autumn of 1980, samples were taken from each of the first ten magnets downstream of the neutrino target in order to determine the radiation effects. Two positions in the cable were selected for each magnet: one position, near the connection to the magnet, called "top"; the other, "bottom", where the cable descending from the magnet reached the floor.

The radiation source is primarily the neutrino target, where a 200 to 400 GeV primary proton beam produces a wide spectrum of secondary particles, out of which mainly pions and kaons are guided into the neutrino decay tunnel by the above-mentioned magnets. Added to the radiation from the target is the secondary radiation from a collimator and other loss points to which the cable has been exposed. During the total time of service (i.e. three and a half years), the cables were irradiated 40.3% of the time (or about 12400 h). The number of protons incident on the neutrino targets was 2.2×10^{19} , the multiplicity of the targets being about 10.

The distance of position "top" to the two particle beams is 0.6 m and 1.1 m; for position "bottom" it is 1.3 m and 1.9 m. Between these beams and the cables there is a shielding by the magnets themselves of 15–20 cm of iron. Also, for the top position there is some shielding by the magnets and for the bottom position there is some shielding (difficult to assess) by the iron support structure for the magnet tables.

The dose estimated for the different positions was deduced from glass dosimeters distributed in this area, which were read approximately every six months [9]. There were dosimeters on top of each magnet, and at certain intervals on the magnet table (= position "top") and on the floor. To obtain the dose value at the desired positions where the cable samples were taken, the trend along the beam line was joined through the measured nearby positions, smoothing out some occasionally deviating points. This cited dose is an approximation of the true mean dose in this position within a factor of 2. However, some samples may have received smaller do-

ses because of additional shielding. This is especially the case for position "bottom", where structure elements may add up in screening the direction of the target.

3.2. Accelerated radiation life tests of individual component materials

For the short-term tests, the samples were taken from a piece of non-irradiated cable in the autumn of 1980 and sent to a nuclear reactor, where they were irradiated according to our routine procedure [10,11] at a dose rate of 10^3 Gy/h in air at about 35°C. This represents an acceleration factor of $1-5 \times 10^3$ with respect to the actual service conditions. The neutron flux present at this reactor position is known to add less than 3% to the received dose and falls within the stated error of $\pm 15\%$.

4. Testing methods and results

4.1. Mechanical tests

At CERN, mechanical tensile tests and Shore hardness tests are used as a routine method to measure the radiation damage in flexible, organic, cable-insulating materials. The most sensitive mechanical property is the elongation at break or elongation at maximum load. This selection of mechanical tests is in accordance with IEC Standard 544 [3], and it allows to follow up the degradation of the polymer well before its destruction. Of course, electrical breakdown may be expected after serious mechanical degradation of the insulation and sheath material especially in an accelerator environment.

4.1.1. Test methods and test samples

The standard mechanical test methods used are described elsewhere [11]. However, for comparison with other test results, it should be noted that the tensile test

Fig. 2. Mechanical test results for the EPR insulation material: Elongation at break (E), tensile strength (R), and Shore C hardness (H) are plotted over absorbed dose for reactor irradiation (squares) and service exposure (triangles and circles, see inset in fig. 3).

specimens had to be cut from a manufactured cable, whereas normally we use moulded plates of the insulating material to obtain better accuracy. Therefore the test results for the EPR insulation, which had an outer radius of curvature of 10 mm and an irregular inner surface, may be somewhat dependent on this geometry. Also, the hardness measurements normally require a certain flatness of the specimen. The elongations at break measurements are more accurate, since small variations in sample dimensions have less influence on the results.

4.1.2. Results

The mechanical test results are summarized in table 3 and are illustrated in fig. 2 for the EPR insulation and in fig. 3 for the PVC sheath. In these figures, the elongation at break (E), tensile strength (R), and Shore hardness (H) are plotted as a function of dose, where circles represent the position "bottom", triangles the position "top", and the squares are the short-term reactor irradiation results for comparison. One notes that the tensile strength remains nearly constant and the hardness increases slightly, reaching the end-point criterion [3] of a change of 10 degrees Shore at 2.5 MGy in both cases.

Compared to these small effects, the elongation at

Fig. 3. Mechanical test results for the PVC sheath material. Note that hardness is given here in different units (Shore D). Symbols are explained in the inset.

break develops a clearly visible degradation of more than 75%. In the dose range of 0.5 to 4 MGy, the measured values for elongation at break after service exposure are nearly linearly dependent on dose and seem to follow some natural decay law, which is approximated by the dashed line in this range. In both cases, and for the sheath as well as for the insulation samples, the values for positions 8 and 9 bottom are probably outliers and are marked by a cross inside the open circle in figs. 2–4. This may be due to additional shielding, as mentioned in section 3. Using the dashed guide lines for interpolation, the end-point criteria of 50% of the initial value were reached at 1.0 and 1.2 MGy, for insulation and sheath, respectively.

4.1.3. Comparison of service exposure and accelerated tests

Comparing the reactor irradiation with the service exposure data, a clearly visible difference is found, at least for the sheath material. For this PVC compound there is initially less damage as measured in tensile tests, whereas at dose levels above 2 MGy, the reduction of elongation at break is stronger than in service exposure. For the the EPR insulation, there is a less pronounced difference in hardness and no difference in tensile strength up to this dose; instead there is a slightly earlier degradation of elongation at break as compared to service exposure.

Table 3

Results of mechanical tests before irradiation, after reactor irradiation, and after service exposure during three and a half years in the SPS neutrino beam tunnel

Identification			Measured values PVC sheath			Measured values EPR insulation		
No.	Position ^{a)}	Dose (MGy)	Tensile strength <i>R</i> (MPa)	Elongation at break <i>E</i> (%)	Hardness Shore <i>D</i>	Tensile strength <i>R</i> (MPa)	Elongation at break <i>E</i> (%)	Hardness Shore <i>C</i>
NR20	Reference	0.0	18.3 ± 1.0	260.0 ± 20.0	34.6	6.4 ± 0.4	264.0 ± 11.0	21.0
NR21	Reactor	0.50	15.9 ± 0.9	279.0 ± 11.0	41.0	6.0 ± 0.3	135.0 ± 7.0	31.5
NR22	Reactor	1.0	16.3 ± 1.5	216.0 ± 28.4	42.4	5.4 ± 0.6	96.0 ± 6.5	32.1
NR23	Reactor	5.0	15.5 ± 1.0	12.0 ± 2.5	56.3	3.3 ± 0.6	21.5 ± 3.8	48.8
NL02	Bottom	0.63	10.8 ± 0.5	140.0 ± 10.0	38.0	6.0 ± 0.4	166.0 ± 18.0	27.0
NL02	Top	0.75	10.0 ± 0.5	135.0 ± 30.0	36.4	6.6 ± 0.3	175.0 ± 12.0	29.0
NL03	Bottom	0.70	11.6 ± 1.4	166.0 ± 24.0	37.2	–	–	–
NL03	Top	0.95	10.7 ± 0.6	156.0 ± 24.0	37.2	6.2 ± 0.4	151.0 ± 11.0	26.1
NL04	Bottom	0.80	12.8 ± 1.6	168.0 ± 44.0	38.4	6.4 ± 0.4	188.1 ± 9.0	24.6
NL04	Top	1.2	10.4 ± 1.2	147.0 ± 24.0	35.4	5.7 ± 0.4	132.3 ± 9.0	29.0
NL05	Bottom	0.90	11.0 ± 0.5	114.0 ± 27.0	47.2	6.1 ± 0.3	128.0 ± 11.0	28.0
NL05	Top	1.2	12.6 ± 1.6	99.0 ± 27.0	47.4	6.1 ± 0.9	101.0 ± 13.0	30.4
NL06	Bottom	1.0	11.8 ± 2.0	141.0 ± 27.0	39.3	5.7 ± 0.3	121.8 ± 7.7	28.8
NL06	Top	1.3	11.7 ± 1.5	136.0 ± 16.0	40.8	6.0 ± 0.7	118.0 ± 5.0	29.4
NL07	Bottom	1.1	10.7 ± 0.5	136.0 ± 20.0	38.7	5.9 ± 0.6	120.6 ± 6.6	27.4
NL07	Top	1.5	12.7 ± 0.9	117.0 ± 30.0	39.0	5.2 ± 0.6	90.0 ± 12.0	30.0
NL08	Bottom	1.3	14.7 ± 0.9	224.0 ± 40.0	36.2	6.7 ± 0.2	222.0 ± 18.0	24.1
NL08	Top	1.7	10.8 ± 1.6	104.0 ± 16.0	39.6	6.0 ± 0.8	93.9 ± 3.3	32.8
NL09	Bottom	1.6	14.9 ± 1.0	242.0 ± 20.0	50.1	6.3 ± 0.3	250.0 ± 16.0	23.0
NL09	Top	2.1	12.0 ± 2.4	96.0 ± 36.0	40.6	5.5 ± 0.6	81.6 ± 8.0	33.0
NL10	Bottom	2.0	9.8 ± 0.6	136.0 ± 20.0	44.0	5.6 ± 0.3	121.1 ± 7.0	27.8
NL10	Top	2.5	10.6 ± 0.7	88.0 ± 40.0	49.6	6.6 ± 0.9	97.2 ± 6.0	33.0
NL11	Bottom	2.4	13.4 ± 2.0	102.0 ± 20.0	47.0	6.0 ± 0.8	114.0 ± 10.0	31.0
NL11	Top	3.0	13.2 ± 2.4	62.0 ± 18.0	46.0	5.3 ± 0.6	7.3 ± 3.0	34.0
NL12	Bottom	3.0	13.2 ± 2.2	110.0 ± 10.0	46.0	5.3 ± 0.4	94.5 ± 2.7	30.6
NL12	Top	3.6	11.8 ± 1.8	60.0 ± 20.0	51.9	5.1 ± 0.8	57.6 ± 7.2	37.0

^{a)} For explanation of irradiation positions, see Section 3.

This indicates for the PVC sheath material a typical dose-rate effect of a factor of 2 to 3 between accelerated irradiation (10⁵ Gy/h) and service irradiation (≈ 130 Gy/h) below about 1 MGy. For these dose rates, recently available data [7] predict a factor of 4.5 less dose needed at the low dose rate and at an ambient temperature of 43°C to produce the same effect as at the high dose rate. The difference between these factors may be accounted for, by the fact that neither the temperature nor the PVC-type were the same.

No such data were available for the EPR insulation material, but it is known also from our long-term irradiation program that in EPR the dose-rate effect must be very small [8]. The data presented indicate even less damage for long-term irradiation; this may be due to a

protection of the EPR insulation against the influence of oxygen by the surrounding gum filler and the stabilized PVC sheath. For the accelerated irradiation, the tensile samples were exposed to air. However, taking into account measurement errors and spread of data, the dose-rate effect is not very significant for this material.

4.1.4. Comparison of EPR insulation and PVC sheath

The difference in the behaviour of the two materials (EPR insulation and PVC sheath) can be demonstrated more clearly by eliminating the influence of the error in the dose assigned to the samples. Therefore, the cross-correlations of the mechanical data are plotted in fig. 4, using the same symbols as in figs. 2 and 3. For the

elongation at break, a significant distinction is seen between reactor irradiation and service exposure. Also, this graph clearly shows that the deviation from the mean of points 8 and 9 bottom in figs. 2 and 3 is due to an erroneous dose only. The result, that both materials show the same degradation as indicated by slope 1 of the correlation line, depends not only on the initial value – which happened to be the same – but also on the degradation as a function of dose. For different materials, a non-linear correlation would be expected, as is the case for the reactor irradiations.

For hardness and tensile strength results, the correlation between insulation and sheath materials is less obvious. This may be due to loss in accuracy because of the need to cut the specimens from a manufactured cable after irradiation.

4.2. Electrical tests on short specimens of full-size cable

The most important property which determines the life of a cable in service is the long-term voltage endurance of its insulating system under the functional and environmental stresses of the actual service conditions. The most direct way to measure the progressive deterioration of the insulating properties and the life characteristics of the cable is, however, to test the breakdown voltage as a function of exposure.

A longer life test closer to operating voltage, for example at two, three, or four times the rated voltage, would be preferable but will usually be excluded because of prohibitive time. However, short-time breakdown voltage tests do not necessarily reflect very well the voltage endurance characteristics of interest for long life in service. Therefore, they ought to be accompanied by other post-exposure measurements, including those of resistivity, dissipation factor ($\tan \delta$), and partial discharge, which, although less conclusive, may yield extremely useful data on the insulation quality. These methods are non-destructive and may therefore be more easily repeated at various stages of exposure.

It is desirable to perform the breakdown voltage measurements on specimens of the manufactured cable because it is recognized that the voltage endurance characteristics of a dielectric system are not easily predictable by extrapolation from simple tests on specimens of the individual materials.

Finally, if one extrapolates from the short-term irradiation test data on materials to the life of cables in service, still more uncertainties have to be taken into account.

4.2.1. Aim of the electrical test

The specific aim of the electrical test reported here was to measure the breakdown voltage and the time to breakdown of the cable as a function of the ionizing radiation dose, and to compare the measured values

Fig. 4. Cross-correlation of mechanical test results on EPR insulation and PVC sheath. Elongation at break (a) and Shore hardness (b) are plotted for reactor irradiation, service exposure, and before irradiation. For symbols see (b).

with recognized reference values; in particular:

- comparison with the standard voltage test requirements for unaged cables specified in IEC Standard 502, namely $2.5U_0 + 2 = 11$ kV;
- comparison with the end-point criteria defined for electric strength in IEC Standard 544-3, namely 75% and 50% retention of initial value;
- comparison of the electrical performance of the cable

Table 4

Breakdown voltages and failure times measured in step voltage test on short specimens of insulated cores of the full-size cable

Cable and test identification				Radiation dose (MGy)	Breakdown voltage (kV r.m.s.)	Time to breakdown at final voltage	
Position	Core no.	Sample no.	Electrode no.			(cycles)	(s)
–	1	1	1	0	32.4	1450	29
–	1	1	2		28.8	2850	57
–	1	1	3		32.4	850	17
1	2	5	1	0.70	32.4	850	17
1	2	5	2		28.8	2650	53
1	2	5	3		32.4	1450	29
1	1	1	1	0.75	32.4	600	12
1	1	1	2		32.4	2350	47
1	1	1	3		32.4	900	18
2	4	7	1	0.63	32.4	500	10
2	4	7	2		28.8	2100	42
2	4	7	3		28.8	850	17
2	1	2	1	0.73	32.4	1750	35
2	1	2	2		32.4	200	4
2	1	2	3		32.4	1800	36
2	1	1	1	0.75	32.4	450	9
2	1	1	2		28.8	2750	55
2	1	1	3		28.8	2300	46
6	1	6	1	1.1	28.8	2550	51
6	1	6	2		32.4	2100	42
6	1	6	3		36.0	< 50	< 1
6	1	1	1	1.3	32.4	2850	57
6	1	1	2		32.4	900	18
6	1	1	3		28.8	2150	43
8	1	6	1	1.4	32.4	750	15
8	1	6	2		32.4	750	15
8	1	6	3		32.4	600	12
8	3	5	1	1.4	32.4	1600	32
8	3	5	2		32.4	2800	56
8	3	5	3		32.4	2400	48
8	1	4	1	1.5	28.8	2000	40
8	1	4	2		32.4	2100	42
8	1	4	3		32.4	1850	37
8	1	3	1	1.6	36.0	< 50	< 1
8	1	3	2		32.4	1800	36
8	1	3	3		32.4	2500	50
12	1	1	1	3.6	32.4	1450	29
12	1	1	2		32.4	2850	57
12	1	1	3		32.4	850	17

with the performance one might predict by extrapolation from mechanical test data on individual materials.

4.2.2. Test samples

Samples of insulated cores, 250 mm in length, were

cut from the part of each cable which had been exposed to the highest radiation dose. For comparison, similar samples were taken from unirradiated lengths of cable coming from the same manufacturing batch.

After storage for several weeks in an assembling hall, where the relative humidity was about 50%, the cables

Fig. 5. Breakdown voltage versus absorbed dose, measured on EPR insulated conductors of a 3.6/6 kV power cable after three and a half years' service in a high-level radiation environment. Voltage was increased in steps of 3.6 kV every minute after an initial step of 5 min at $3U_0 = 10.8$ kV.

were not dried or heat-treated prior to the voltage test. It should be noted that these cable samples had been subjected to a certain amount of bending and unbending during installation and service and during removal from the installation after exposure.

Each sample was fitted with three equally spaced

single-turn ring electrodes of 2.0 mm copper wire wrapped around the EPR core insulation.

4.2.3. Test procedure

The 50 Hz a.c. test voltage was applied successively between each of the three ring electrodes and the core

Fig. 6. Time to breakdown at $9U_0$ versus absorbed dose, measured during the step voltage test on EPR insulated conductors of a 3.6/6 kV power cable after three and a half years' service in a high-level radiation environment. Voltage was increased in steps of 3.6 kV every minute. Breakdown times at different voltages have been converted to equivalent breakdown times at $9U_0 = 32.4$ kV using the inverse power rule with a life exponent value of 12.

conductor. Corona was suppressed by immersing the test sample in oil (relative permittivity $\epsilon_r = 2.5$). The

accuracy of the test voltage was better than $\pm 2.5\%$.

The test voltage was first held at $3U_0$ for 5 min as an

Fig. 7. Demonstration of surface effects by tensile tests on PVC sheath material. An unirradiated sample (a) and a sample irradiated during service exposure (b) are shown under the same load of 200 N at an elongation of 66% and 110%, respectively. In (c), the narrow region is enlarged to show the numerous cracks which open at the outer surface of the cable.

initial stage, and then progressively increased in steps of $1U_0 = 3.6$ kV every 60 s until the core insulation broke down.

4.2.4. Test data and results

A record of the breakdown voltages and the failure times measured is given in table 4. The ambient temper-

ature during the measurements was $20 \pm 2^\circ\text{C}$. A graph of the measured values of breakdown voltage, plotted as a function of radiation dose, is shown in fig. 5. The times to breakdown versus dose are shown in fig. 6, where the inverse power rule with a life exponent value of 12 has been taken for converting breakdown times at different voltages to equivalent breakdown times at $9U_0 = 32.4$ kV.

The voltage tests did not reveal any change in the breakdown voltage nor in the time to breakdown up to the maximum irradiation dose under service conditions. Therefore, no correlation between mechanical and electrical degradation could be established. However, it can be concluded from these tests that the margin between the dose at which the mechanical end-point criterion would be reached and the beginning of electrical degradation of the EPR insulation of this power cable is larger by a factor of 3.6 and 7 for extrapolation from long-term exposure and accelerated life exposure, respectively.

It was also noticed that the breakdown path through the EPR core insulation was usually not along a straight radial line but along a zigzag path at an average angle of typically more than 60° with respect to the radial direction. Furthermore, this oblique path was always pointing in the same direction along the cable. This indicates a systematic inhomogeneity in the insulation, presumably due to the manufacturing process.

4.3. Examination of the sheath surface

Apart from mechanical and electrical tests, some other results, mainly concerning the structure of the external surface of the cable after service exposure, have been obtained. Visual inspection already gave some evidence of surface effects, e.g. an increased roughness and colour change from glossy black to light grey, which could be changed back to black by rubbing with a piece of metal. Since the surface exposed to air would be attacked more readily during irradiation because of the accelerating action of oxygen, this was checked during tensile testing and by scanning electron microscope analysis.

During tensile testing, numerous cracks are seen on the surface exposed to air during the long-term irradiation, contrary to the inner surface. This is shown in fig. 7, where a tensile test specimen of the sheath material before and after irradiation is seen under the same load of 200 N and elongation of 66% and 110%, respectively.

The cracks already exist before testing, as can be seen from the scanning electron micrographs in fig. 8. No cracks are present in the unirradiated surface sample, but scratches can be seen which are due to the manufacturing process (fig. 8a). In the irradiated sample, cracks are seen both on the surface (fig. 8b) and in the bulk (fig. 8c). The surface contains a lot of small

Fig. 8. Scanning electron micrographs of PVC sheath surface before irradiation (a), after 2.4×10^6 Gy service exposure (b) at position 11b, and a section through this about 1 mm below the surface (c), all at a magnification of about $300\times$. In (d), an example is given for the EPR insulation material at the same position at a magnification of about $1200\times$.

cracks, as does the bulk sample, but they are partly screened out by a lot of flakes that are present after irradiation. X-ray analysis shows a high content of filler in the flakes, which are probably the remnants after destruction of the surface layer of the polymer by oxygen or ozone attack during irradiation. This would also explain why the scratches from processing are no longer seen, but instead an isotropic granulated surface, which resembles the fracture surface of the bulk specimen (fig. 8c). No cracks were seen in any specimen of the EPR insulation (see, for example, fig. 8d).

5. Conclusions

These tests on a typical power cable after service exposure in a high-level radiation area have provided the rare opportunity to check the usual extrapolation procedure used to determine the lifetime and maximum

admissible dose from short-term irradiation tests. From the results obtained we can draw the following conclusions:

- i). From the mechanical tests after service exposure the dose at 50% reduction of elongation at break is found to be ≈ 1.0 MGy for the EPR insulating compound and ≈ 1.2 MGy for the PVC sheath material.
- ii) For the accelerated exposure the dose at 50% degradation of elongation at break is ≈ 0.5 MGy for the EPR insulating compound and ≈ 1.3 MGy for the PVC sheath.
- iii) Accordingly, for 50% degradation of elongation at break, the ratio between accelerated exposure dose and service exposure dose is about 0.5 for the EPR insulation and about 1.0 for the PVC sheath. These results indicate that the correction factor to be applied to the dose when extrapolating from accelerated exposure to service exposure is relatively

small in comparison with other uncertainties entering into the prediction of cable life in service.

- iv) The results of the voltage tests on the cables did not show any significant variation of breakdown voltage over the range of radiation dose up to 3.6 MGy covered by the present measurements. In particular, the dose at 25% reduction in breakdown voltage, the end-point specified in IEC Standard 544, was not reached in the service exposure.
- v) The present results confirm that elongation at break is a property which is particularly sensitive to radiation. However, the recommended end-point criterion for this parameter shows a considerable margin between the lower limit and the actual service life. From the present limited amount of data it is not possible to establish how much this margin is, nor a correlation between elongation at break of the materials and the breakdown voltage of the cable.

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