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**ABSORBED DOSES AND RADIATION DAMAGE DURING  
THE 11 YEARS OF LEP OPERATION**

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**Abstract**

During the 11 years of operation of the Large Electron Positron Collider (LEP), synchrotron radiation was emitted in the tunnel. This ionizing radiation induced degradation in organic insulators and structural materials, as well as in electronics. Annual dosimetric measurements have shown that the level of radiation increased with the ninth power of the beam energy.

During the machine shut-downs and at the end of the operation, samples of rigid and flexible polymeric insulators (magnet-coil resins and cable insulations) were taken out and checked for their integrity. The test results are compared with the results obtained during the qualification of the materials, 12 to 15 years ago. At that time, lifetime predictions were done; they are now compared with the real time aged materials.

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## 1. Introduction

At the European Organization for Nuclear Research (CERN) several large particle accelerators are used for the purpose of high-energy physics research. Today's accelerators are mainly colliders which produce head-on collisions between hadrons (proton-proton or proton-antiproton) or between leptons (electron-positron). From these collisions, new short-lived particles are produced and are studied in large physics detectors installed on the circumference of the accelerator.

The Large Electron-Positron Collider (LEP) was build in the 1980s [1], and came into operation in 1989. With its 27 km in circumference, it was the largest particle accelerator in the world. The circumference was not a perfect circle: it was divided into eight straight sections (on each side of the eight access pits), and eight bending sections equipped with the dipole magnets. The four physics experiments were located in the middle of the four even-numbered straight sections.

LEP was the most powerful lepton accelerator: it produced head-on collisions of electrons and positrons with a 200 GeV energy in the centre of mass. The leptons were brought to these high energies by means of superconducting high-frequency cavities (located in the straight sections), but the more numerous components of the collider were the electromagnets to keep the beams on their tracks and for the focusing. The particle beams circulated in a single metallic vacuum chamber surrounded by the guiding magnets and the control equipment. Organic insulators were mainly used for the insulation of the magnet coils and of the electrical cables, as well as for small electrical equipment. Organic materials were also sometimes used for small mechanical structures.

## 2. Radiation doses in LEP

In LEP, the ionizing radiation was mainly produced by synchrotron radiation during the deviation of the lepton beams with X-rays of a wide energy spectrum up to several MeV [2, 3]. The leptons lost in the elements of the machine interact by 'bremsstrahlung', also producing high-energy X-rays. At the highest energies, the X-ray could interact with the nuclei by photonuclear interactions and produce neutrons. The production rate is, however, low, and the dose absorbed by the organic materials due to the neutrons accounted for less than 1% of the total ionizing dose.

From the beginning of operation in 1989, the absorbed doses in the LEP tunnel were measured by means of polymer-alanine dosimeters (PADs) [4, 5], as well as by hydrogen-pressure dosimeters (HPDs) [6, 7] during the last two years when the dose levels were very high on magnet coils. Several hundred points were under dosimetric control, and the results have been published every year [8].

The evolution of radiation levels over the years (following the beam-energy increase, from 45 GeV to 100 GeV) was mainly followed in 'standard positions': in half of octant 1 between the injection point in pit 1 and the end of octant 1 towards octant 2, the dosimeters were placed on the dipole and quadrupole coils, on the power cables of the quadrupoles (at the foot of the magnet), and on the control cables on the side cable trays.

Table 1 shows the dose-measurement results on selected components of the machine. The given values are averages calculated on about 30 to 50 positions along octant 1, for each of the cited components. The Table also shows the energy increase, the integrated current, and the operation time over the years. Usually, several energy levels were exploited during the year. Only the maximum energy reached during the year concerned is given. In this Table, the seven first years are grouped, because the absorbed doses were comparatively very low at low energy.

Over the years, the results also show that the normalized radiation levels (dose/integrated current) in the curved sections increased up to the ninth power of the lepton energy. This comes from the fact that the energy released (by synchrotron radiation) from the lepton beams increases with the fourth power of their energy; furthermore the X-rays have a higher energy, making the shieldings less effective.

This is demonstrated in Table 2 (adapted from Ref. [8]), which gives, in its upper part, the calculated multiplication factors [3] and in its lower part the normalized dose rate (in kGy/Ah) on some significant components of the machine at the various energies (see also Fig. 1). It is to be noted that if several energies were exploited during a given year (which was usually the case), then the following calculation was applied to assess the normalized dose rate:

$$\begin{aligned} \text{Yearly absorbed dose} &= \text{Normalized dose rate at energy A} \times \text{Ah at energy A} \\ &+ \text{Normalized dose rate at energy B} \times \text{Ah at energy B.} \end{aligned}$$

Table 3 shows the calculated approximate dose rates on the components; the values are simply obtained by dividing the yearly absorbed doses by the operation times (from Table 1). This leads to average dose rates, but they were essentially variable along the year. Also shown in this table are the measured multiplication factors (in brackets) which in comparison with the values given in the upper part of Table 2 are in best agreement with the calculations for the coaxial cable position. For the other positions the values are in general lower, which can be explained by multiple scattering and shielding effects. Figure 1 shows the evolution of the dose rate in kGy/Ah as a function of the beam energy. As there were numerous measuring points for each cited component, e.g. dipole coil, vacuum chamber etc., the values given are averages. At some places the dose rates and dose levels may be ten times higher (right-end symbols on Fig. 1).

Figure 2 shows a typical example of the integrated doses distributed at the dipole coils along the curved section of octant 1, from the start-up in 1989 to the end of operation in November 2000. In contrast with proton accelerators [9] the longitudinal dose distribution is much more uniform over the curved sections. At this position the total integrated dose over the lifetime of LEP was of the order of  $10^7$  Gy, a factor 5 below the dose where severe radiation damage of the coil insulation would have been expected. The dose distribution across the tunnel was also measured; Figure 3 shows an example between two dipoles at a beam energy of 98.6 GeV normalized to Gy/Ah. This clearly shows the distance factor and the effect of shielding of the magnet yoke. Also shown in Fig. 3 are the normalized predicted dose values from 1984 [3], which are in remarkably good agreement with the calculations.

In addition to 'standard positions' and dose-distribution measurements as described above, numerous dosimeters were also placed on specific equipment such as control electronics, lighting, wiggler magnets, control and instrumentation cables which came closer to the beam line where they were connected to the equipment, as well as in specific places such as the injection lines and in some places where the shielding was weaker than in 'standard positions'. The results of these dosimeters allow a good estimation of the absorbed dose to all significant components of the tunnel; they can be consulted in Ref. [8].

### 3. Qualification of materials – tests methods – radiation index

For several decades, radiation tests have been performed at CERN for the selection of polymer-based materials to be used in radiation environments. Many results have been published in the form of catalogues [10]. Since the main variations of the electrical properties

are transient during the irradiation, and since at high doses the degradation of the electrical properties results from mechanical damage [11], standard IEC 60544 of the International Electrotechnical Commission recommends that mechanical tests be carried out on insulating and structural materials [12].

The qualification tests of the organic materials were therefore based on the recommendations of this standard:

- Flexible plastics (mainly thermoplastics and rubbers used for cable insulation) undergo tensile tests (ISO 37), the dumbbell samples are tested at a speed of 50 mm/min. The elongation at break is usually the most sensitive parameter and recommended as the critical property; it decreases significantly with the irradiation dose. The ultimate tensile strength and the Shore hardness are also measured.

- Rigid polymer-based materials (structural plastics, high-performance thermoplastics and composites) undergo flexural tests, and their critical property can be either their ultimate flexural strength or their limit of deformation. The three-point flexural test is based on the ISO 178 standard: the distance between the two external supports of the flexural jig is 67 mm. The cross-head speed is 2 mm/min. Any apparent defect of the sample is recorded to check its influence on the testing results.

Standard IEC 60544 - Part 4 defines a Radiation Index (RI) as the logarithm (base 10) of the absorbed dose (in Gy) at which the end-point criterion is reached. This dose is often called dose-to-equivalent damage (DED) in the literature;  $RI = \log DED$ . At CERN, we also adopted the recommended end-point criterion: it is reached when the critical property is reduced to 50% of its initial value. The Radiation Index must be determined at a given dose rate (usually above 1 Gy/s during qualification).

Several authors also use the Oxidation Induction Time (OIT) to check the ageing of some thermoplastics. The measurements are done in specific conditions of air-flow rate and temperature, by the standard thermal analysis method, Differential Scanning Calorimetry (DSC). A non-aged plastic contains a given amount of unused antioxidant, and will take some time to be oxidized. After ageing, some of the antioxidant is consumed, and the onset time of oxidation will be shorter. The reduction of OIT values can be correlated with the ageing of the plastic (see Ref. [12], Part 5).

At the time of material selection for LEP, the radiation qualification tests were carried out after accelerated irradiation either in a nuclear reactor (at a dose rate of the order of  $2 \times 10^5$  Gy/h) or in a  $Co^{60}$  source (at dose rates of the order of 4–6 kGy/h).

#### **4. Dose-rate effect – expected lifetime**

During long-term irradiation, oxygen and moisture diffuse into the materials and induce more severe degradation than accelerated irradiation; this phenomenon is known as the ‘dose-rate effect’, which is more pronounced in thermoplastics than in thermosets [11, 13–16]. Because of this effect, standard IEC 60544 also recommends the carrying out of tests after irradiation at dose rates as close as possible to the expected dose rate in situ. It is to be noted that if the materials are irradiated in an inert atmosphere, such as, for example, a cryogenic gas, the degradation is less pronounced [17].

In 1991, a study was conducted at CERN to estimate the lifetime of cables in the radiation environment of LEP [18]. At that time, irradiations were performed in a nuclear reactor (dose rate  $\approx 2 \times 10^5$  Gy/h) and with a  $Co^{60}$  source, at dose rates of 6 kGy/h, sometimes 13 kGy/h, 1 kGy/h and 100 Gy/h. Figure 4 shows a typical example of the decrease of the elongation at break as a function of the absorbed dose, with the dose rate as a parameter.

As recommended by an IEC Technical Report (see Ref. [19], Part. 2), the level of degradation given by the RI can be plotted as a function of the dose rate, and the curves can be extrapolated to the expected dose rate in LEP. Prior to this, an appropriate Radiation Index had to be defined for each material. It is indeed sometimes unrealistic to base the end-point criterion on a reduction by 50% of the elongation at break. A material which presents an initial value of its elongation at break above 500% absolute cannot be considered as unusable if this property is reduced to 250% absolute. In Table 4, the percentage of reduction was chosen for each material such as the remaining elongation at break ( $E_{\text{limit}}$ ) after ageing to be between 50 and 130% absolute.

From the extrapolation, it should be possible to determine the expected lifetime for the given criterion, at a chosen dose rate:

$$\text{DED} = 10^{\text{exp}} (\text{RI, at the expected life dose rate})$$

$$\text{Lifetime} = \text{DED} / \text{life dose rate}$$

In 1991 the life dose rate for LEP was assumed to be 15 Gy/h.

Figure 5 illustrates the extrapolation method for the material of Fig. 4; Radiation Indices for two end-point criteria are plotted as a function of the dose rate, one for the usual  $E/E_0 = 0.5$ , the other for the more realistic  $E/E_0 = 0.2$  ( $E_{\text{limit}} = 98\%$  absolute). Extrapolating this case for LEP life conditions, the calculation leads to

$$\text{DED} = 10^{\text{exp}} 5.55 = 355 \text{ kGy}$$

$$\text{Lifetime} = 355 \text{ kGy} / 15 \text{ Gy/h} = 23\,654 \text{ h} (\sim 8 \text{ years of operation}).$$

For some materials, the extrapolation method was not applicable in case of no or very low dose rate effects or because an 'inverted dose rate' was observed: the degradation was less pronounced after irradiation in a cobalt source, at a few kGy/h, than in the reactor at 200 kGy/h. This will be illustrated later.

Table 4 gives the list of some cable insulating materials which were included in the 1991 study, and which were tested after the LEP dismantling. The Table sometimes gives two different TIS Nos. (one for 1991, one for 2000), the type of compound, and the expected lifetime for each qualified material. Today, it is possible to check these extrapolations: real cables and insulating samples were irradiated for several years, at low dose rates, in LEP. It must be noted that the dose rate in LEP was essentially variable: it increased over the years with the beam energy; there was no radiation during the winter shutdown months; and the radiation level varied from one place to another. Table 4 reproduces the TED estimated in 1991 on the basis of a 15 Gy/h dose rate, and gives new values of the RI based on the 1991 extrapolation at the estimated dose rate in LEP where samples were taken in 2000. The results of some of the mechanical tests are presented here and, when possible, are compared to the calculated degradation and lifetime predictions made in 1991.

Although for resin-based composites, used as magnet-coil insulation, no dose-rate effect was usually observed within the explored qualification dose-range, it cannot be neglected in the case of long-term operation in the radiation environment of LEP, where doses as high as 22 MGy were reached (even up to 100 MGy for the dipole of cell 161 at injection).

## 5. Tests results and discussion

### 5.1. Cable insulating materials

For the survey of radiation ageing of cables in the LEP tunnel, some samples were pre-cut (dumbbell) from real cables prior to their installation. They were positioned in an open metal box and irradiated in situ in cell 170, on the side cable tray. For the record of the absorbed dose, alanine dosimeters were also placed in the box, together with the samples. Some of them were tested in 1998, when the absorbed dose was  $3.8 \times 10^4$  Gy. At that time, the degradation was negligible [16]. The rest of the samples were tested after the end of operation of LEP, at an integrated dose of  $7 \times 10^5$  Gy. This time the degradation was sometimes so severe that no tensile tests were possible. In addition, some more samples were also irradiated in these boxes from 1999 onwards. Some of the results are presented in Ref. [20].

In order to check the radiation ageing of real cables which have been in operation for 11 years, samples were taken just before the LEP dismantling. The difference between the two sets of samples is that in the former ones the oxidation could take place from both sides of the samples during irradiation, while for the real cables, oxygen could come only from the outside. It is, however, to be noted that the oxidation could also take place from the inside at cable ends next to the connectors.

Some specific and representative tensile test results from cable insulating materials are presented below. The discussion is based on the variation of the elongation at break as the critical property.

#### 5.1.1. EPR and EPR/VAC rubbers

Usually, little dose-rate effect is observed on this type of cross-linked copolymer, and the prediction of the amount of degradation (residual elongation at break) can be very good. Figure 5 shows that for a VAC material, according to the chosen end-point criterion, the extrapolation was either slightly too optimistic, or slightly too pessimistic compared to the LEP dose rate. Choosing an end-point criterion at  $E/E_0 = 0.3$  leads to a perfect estimation (not illustrated on Fig. 5).

#### 5.1.2. Cross-linked polyolefins

For this class of materials, many different types of behaviour were observed.

The mechanical properties of the EVA-based Sioplas sheath C951 (Fig. 6) of the 18 kV cable are reduced to 80% of their initial values after an absorbed dose of 40 kGy in LEP. This material is based on the same cross-linked EVA as material C545 (Ref. [10], Part 1, 2<sup>nd</sup> ed. not in Table 4). The degradation in LEP was more pronounced by a factor two as would have been expected for extrapolation at high dose rate.

The cross-linked coloured polyethylene used for the insulation of the multi-conductor power cable made by AEG (C769) presented a significant high dose-rate effect. The decrease of elongation in LEP was about the same as at 100 Gy/h, (Fig. 7).

The cross-linked black polyethylene used for the sheathing of power cable made by Nuova Fulgor Cavi (C759) presented a significant dose-rate effect between reactor and  $\text{Co}^{60}$  irradiation, whereas at LEP dose rates it is impossible to relate the degradation to the absorbed dose: between 40 kGy and 500 kGy, the elongation remains around 80% absolute; and hence, it is impossible to evaluate the Radiation Index (Fig. 8).

The EVA developed by Lynenwerk (C959) presented an 'inverse dose-rate effect' between the cobalt and the reactor irradiations; the properties were better after the 100 Gy/h

irradiation than after the reactor irradiation. The rate of degradation of the properties in LEP is similar to that due to the reactor irradiation. This effect remains unexplained (Fig. 9).

### **5.1.3. Other polyolefins**

Again many different types of behaviour were observed for this class of materials.

The Rheyhalon polyolefin (C994) developed by AEG for the sheathing of the power cables, as well as the Exalon (by Cablerie Seneffoise C935) presents a very good radiation behaviour and almost no dose-rate effect. The Rheyhalon C868 on the contrary shows a significant dose-rate effect with, however, a very good extrapolation to service conditions, (Figs. 10 and 11).

The Cogegum polyolefin was proposed by Norsk-Kabel (C914) for instrumentation and control (I&C) cables. Despite its rather good radiation behaviour, it was not used; the Unifos 5040 was chosen instead. Figure 12 shows that the extrapolation method is very unreliable for this material.

The case of the two remaining compounds has to be discussed more extensively. Most of the (I&C) cables in LEP are sheathed either with the BP D2383 FR or with the Unifos 5040 polyolefins, both based on EVA. The radiation behaviour of the BP material has been extensively studied in Ref. [15]. An example is given in Fig. 13 where all the samples were taken from the same cable. This material presents poor mechanical properties, and the spread in the results is very large; up to 60% (one sigma) for the example given. Moreover, from one cable to another, the difference from one average value to another can be as high as 40%. It is therefore impossible to make any assumption on the lifetime of a specific cable sheathed with this material.

It was later decided to replace the BP compound by the Unifos 5040 compound. We had a good experience with this material used by Dätwyler for SPS cables (C862 Ref. [10] Part 1, 2nd ed. and Ref. [16]). At the time, the initial elongation at break of this compound was around 140%. In 1988, Norsk-Kabel, the main manufacturer of LEP control cables, made a prototype with the same compound, but this time, the initial elongation at break of this compound was around 540% (see C960 Fig. 14). The radiation-test results allowed an extrapolation with  $E/E_0 = 0.2$ , and the material was approved (Fig. 15). Other cable manufacturers also decided to use this compound, and we were surprised to measure different initial properties ( $E_0$  varied between 280% and 545%). With this compound, the spread of the results, from one manufacturer to another, ranges within a factor 2, even within a factor of 4 if we consider the first material C862 (Fig. 16). The results obtained from LEP samples show that the radiation behaviour of this material is as poor as that of the BP compound.

### **5.1.4. Experience with installed cables**

In 1998, a red cable, of the type SVB 11, made by Intercond in 1986, was removed from cell 171 because of severe radiation damage. At its extremity towards the vacuum pump, the cable was very close to the beam pipe and presented important cracks on its outer sheath, while the inner insulations was brittle and fell apart. The maximum dose absorbed by this cable was of the order of 400 kGy [16].

During the 1999/2000 shut down, a campaign took place to cut the extremities of the control cables which came close to the beam pipe. This was decided because the degradation of the cables was severe at their connectors: the combination of radiation and mechanical stress damaged the sheath, while the open end of the cable allowed more radiation-oxidation of the

inner insulations. Some 20 to 40 cm of cable extremities were cut, and the connectors were re-mounted on the less-damaged part of the cables.

At the decommissioning in 2001, some control cables were found severely damaged at places where absorbed doses exceeded some 300 kGy. The inner insulations of these cables were also heavily damaged; Fig. 17 shows a picture of some of these cables.

The multi-conductor cables (sheathed with polyolefins, made by Nokia and Pirelli) which were used as K-modulation coils on the quadrupole magnets were also found to be severely damaged. The levels of radiation absorbed by these cables are similar to those measured on quadrupole magnet coils, i.e., close to 1 MGy.

A special case concerns the high-voltage, high-frequency coaxial cables used for the kicker magnets. Some lengths of this cable will be re-used for the ejection system of the Large Hadron Collider (LHC). This cable, made by P.K.I. uses a low-density polyethylene (LDPE) made since more than 30 years by BASF, namely Lupolen 1812 (first results published in Part 1 of the catalogue [10] in 1979). The same LDPE was also used in this type of cable in the former ISR (Intersecting Storage Rings) at CERN, where its mechanical properties were degraded only by some 20% after an absorbed dose of 10 kGy (see Ref. [10], Part 1, 2<sup>nd</sup> ed., 1989). Some samples were also taken from a spare LEP cable. The initial values of these different batches of materials are not the same (by almost a factor 2), a precise comparison is therefore not possible. Radiation test results of the spare LDPE are shown in Fig. 18. It clearly shows that the variation of the Oxidation Induced Time (OIT) or of the gel fraction (cross-linked part, induced by radiation) are better parameters than the elongation at break for the assessment of the degradation of a polyethylene [19, 20]. The sheath of these HV-HF cables is also made from Unifos 5040. The results obtained from this sheath are well in line with expectations, even somewhat better.

## **5.2. *Insulating resins of the magnet coils***

Samples of pure insulating resins were moulded or cut into rectangular strips of 10 mm x 80 mm, of thickness between 2 mm and 4 mm. They were prepared by the magnet manufacturers from the same resin and at the same time during the production of the magnet coils. Several samples from different resin types have been irradiated in the LEP machine since 1993. They were placed in open grid metallic boxes, on the vacuum chamber at the end of dipole and quadrupole magnets; they were positioned in such a way that the beam-sample distance was about the same as the beam-magnet-coil distance. This allows the control of the ageing of these reference samples, and hence of the magnet-coil insulation.

Some samples were already taken out from the most exposed positions, and tested in 1998 [16]. From these tests, an unexpected dose-rate effect was observed on the glass-fibre reinforced, epoxy-based, prepreg (R468). Further tests from samples taken after the end of LEP operation confirmed, however, that the unexpected results presented in Ref. [16] were actually obtained from badly prepared samples; the curing conditions affect the mechanical properties. The results presented here confirm that the degradation of proper samples irradiated in LEP for 8 years stayed within the expected level, i.e. almost no degradation (Fig. 19). It is to be noted that this material always delaminates at failure, i.e. breaks into several layers, which is the usual behaviour of prepreg composites.

The 1998 test results showed an important degradation of the pure Araldite CY 205 (R483) irradiated in LEP at 3 MGy. Further tests (after 12 MGy) do not present any further significant degradation: the mechanical properties of this resin have been reduced to about 50% of their initial value, which was the expected level of degradation (Fig. 20).

The comparison between the results of resin R483 prepared by Ansaldo and of resin R484 prepared by ABB, which have exactly the same composition (they are both Araldite CY



205, from Ciba-Geigy<sup>1</sup>), but processed by two different magnet manufacturers, shows that the two resins do not behave in the same way. The resin R484 was better after irradiation in the reactor at high dose rate, but tended to degrade faster in LEP. The dose-rate effect is slightly more pronounced for this second resin (Fig. 21). This also tends to show that the resin processing has an influence on its radiation resistance.

It is to be noted that the darkening (important for pure resins) of all irradiated samples cannot be brought into direct correlation with the degradation of the mechanical properties, especially in the case of life irradiations where this darkening from oxidation and natural ageing is in competition with the bleaching from temperature annihilation.

### **5.3. *Miscellaneous materials and components***

#### **5.3.1. *Optical cables***

Standard optical fibre cables were installed in the tunnel on the side cable trays from the beginning. Loss of signal intensity, due to fibre darkening, was observed immediately at the start-up even at 45 GeV when the beam intensity was at low energy. The cables could no longer be used after only a few weeks. After this bad experience, more radiation-hard multi-mode and single-mode glass fibre cables were installed in the main drains below 40 cm of concrete. These cables accumulated a radiation dose of less than 100 Gy except at some places below the access plates and where they came close to the equipment, they stayed operational until the end of the run in 2000.

#### **5.3.2. *Fire detectors, fire extinguishers***

Fire detectors based on the ionization of the molecules in air were installed in the side alveoli which contained electronic equipment. After a few years, and with integrated doses of less than 100 Gy, some of the detectors gave no signal anymore. The reason for this was the radiation damage of a MOS-FET transistor in the amplifier. As it is known that MOS technology is mainly sensitive to ionizing dose (from synchrotron radiation), while the bipolar-technology components are mainly sensitive to displacement damage due to particle irradiation [21], the MOS-FETs were replaced by bipolar transistors, and the detectors could be operated until the decommissioning.

The composition of the various components of powder fire-extinguishers had not been checked prior to their installation in the tunnel. After a few years of ageing, and radiation doses of the order of some tens of kGy, their hoses and connectors were damaged. The connectors were found to be made of Delrin (polyacetal resin) which is known to be very radiation sensitive (see Ref. [10] Part 2, 2nd ed.) The hoses were made of a rubber reinforced by natural fibres.

#### **5.3.3. *Lighting, telephones, electronic locks, electrical junction boxes***

The main lighting in the tunnel was based on fluorescent tubes. These tubes had to be changed regularly because of normal ageing, and did not suffer from radiation damage up to doses of the order of some kGy. On the other hand, the 'starter' of the lighting devices broke down at places where the absorbed doses were higher. The emergency lighting was properly qualified before commissioning, and fulfilled its mission until the end of LEP operation.

The separating gates in the tunnel were controlled by electronic locks from the control room. Some of these locks had to be replaced during the lifetime of the machine.

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<sup>1</sup> Today *Vantico*

After qualification the emergency telephones remained operational during the lifetime of LEP.

The covers of electrical junction boxes installed on cable trays were made of translucent Makrolon (polycarbonate). They darkened with doses comparable to the ones absorbed by control cables, i.e., a few tens of kGy; they became brittle at a dose of about 500 kGy (see Ref. [10], Part 2, 2<sup>nd</sup> ed.).

## 6. Conclusions

The present study offered a unique opportunity to compare the radiation degradation of electrical insulating materials measured during accelerated tests with the real-life degradation observed after 11 years of LEP operation. This allows a number of interesting conclusions to be drawn:

1. The so-called dose-rate effect is more pronounced in cable insulating materials than in epoxy-based magnet coil insulations.
2. Also within the cable materials some do not show any dose-rate effect, in particular cross-linked ones.
3. The extrapolation method to estimate the time to equivalent damage to service dose rates works well for a number of materials as shown in Table 4, where the RI estimated in 1991 agrees with the one measured in 2000. There are, however, materials where this method does not work at all.
4. Materials which are fabricated under the same trade name can give very different results both in initial value and in radiation degradation of the critical property.
5. In order to make meaningful estimates of lifetime under irradiation, the end-point criterion has to be adapted to the initial value of the critical property.
6. The results obtained confirm that the radiation dose limit for a large number of cable insulating materials is 0.2–0.5 MGy and for pure epoxy resins 2–5 MGy. This is in perfect agreement with earlier experience.
7. The results also confirm that standard optical fibre cables cannot be used in radiation areas and that auxiliary equipment has also to be qualified for use in radiation areas.
8. The radiation dose estimates made in 1984 agree very well with the values measured in LEP normalized to beam energy and current.
9. On account of the uniform dose distribution in LEP, the measured values can be used for the design of future electron accelerators.

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Table 1: Measured yearly absorbed doses (average, in Gy) on selected components of LEP

Year of operation	1989-1995	1996	1997	1998	1999	2000	Total
Max. beam energy (GeV)	45–68	80–86	92	94.5	98.6	103	
Integrated current (Ah)	36.5	1.9	3.0	12	12	10	75
Operation time (h)	9880	670	1470	1500	1530	1350	16400
Dipole coils	7.5E+4	2.9E+5	7.0E+5	2.0E+6	3.5E+6	4.3E+6	1.1E+07
Coax. cables for pick-ups	5.5E+3	3.2E+4	9.5E+4	2.0E+5	4.1E+5	4.9E+5	1.2E+06
Magnet power cables	1.9E+2	4.0E+2	2.0E+3	6.0E+3	1.1E+4	2.0E+4	4.0E+04
Control cables	1.2E+2	2.1E+2	1.0E+3	4.0E+3	5.2E+3	6.0E+3	1.7E+04

Table 2: Calculated multiplication factors and evolution of the normalized dose rates (kGy/Ah) on selected components (shielding has been improved over the years)

Beam energy (GeV)	45	68	80	86	91.5	94.5	98.6	103
Energy factor (power 4)	1	5.2	10.2	13.3	17.1	19.4	23.0	28.5
Shielding factor	1	17	24	27	32	42	39	44
Total multiplication factor	1	90	245	360	545	696	911	1270
Dipole coils	1.1	64	130	185	230	290	495	510
Coax. cables for pick-ups	0.065	5.1	12	24	31	37	60	67
Magnet power cables	0.001	0.06	0.18	0.22	0.63	0.71	1.80	3.00
Control cables	0.003	0.08	0.12	0.21	0.40	0.52	0.90	1.80

Table 3: Approximate dose rates (Gy/h) on some components, evolution with the beam energy (multiplication factors to be compared with Table 2)

Beam energy (GeV)	45	68	80.5	86	94.5	98.6	103
Dipole coils	2.5	200 (80)	400 (160)	600 (240)	1330 (532)	2250 (900)	3200 (1280)
Coax. cables for pick-ups	0.2	20 (100)	40 (200)	60 (300)	133 (670)	270 (1350)	360 (1800)
Magnet power cables	0.004	0.20 (50)	0.6 (150)	1.0 (250)	4.0 (900)	7.2 (1800)	14.8 (3700)
Control cables	0.004	0.15 (38)	0.3 (75)	0.6 (150)	2.7 (675)	3.4 (850)	4.4 (1100)

Table 4: Estimate of lifetime of cable insulating materials in LEP

Materials		Type of compound	E0 (%)	E_limit (%)	Estimated in 1991		At dose-rate (1991)	RI (estim. 2000)	RI (meas. 2000)	Result in Fig.
1991 No.	2000 No.				RI (15 Gy/h)	TED (/year)				
862		PO, 5040	141	70	5.30	4.3	n.a. (see Ref. 14)			
933	1199	PO, 5040	490	98	5.58	7.2	20	5.60	5.34 *	14, 15
960	960	PO, 5040	545	109	5.20	3	15	5.20	5.30	
860	944	PO, D 2983 FR	465	70	4.96	1.8	25	5.02	5.64 *	
868	1208	PO, Reyhalon	202	60	5.35	4.3	50	5.43	5.44	10, 11
994	905	PO, Reyhalon	216	65	5.32	4	15	5.32	5.36	
935	935	PO, Exalon	187	93	5.60	7.4	70	5.68	5.71	12
914	914	PO, Cogegum	277	92	5.49	6	15	5.49	5.42	
812	959	EVA, 4G 269	185	92	5.57	7.1				
951	951	EVA, Sioplas	118	59	5.71	11.4	15	5.71	5.60	6
759	1209	XLPE balck	142	71	5.48	5.7	15	5.48	5.53	8
906	769	XLPE coloured	304	91	5.63	8.1	15	5.63	5.61	7
995	995	VAC	489	98	5.55	6.8	15	5.55	5.60	4, 5
871	871'	EPR-VAC	663	133	5.52	6.3	15	5.52	5.52	
952		EPR, G5	110	55	5.84	13.5	70	5.82	5.80	

Lifetime with (RI = 5.34) = 10 939 hours

PO = unknown polyolefin, EVA = ethylene-vinyl acetate copolymer, VAC = vinyl-acetate copolymer.

XLPE = cross-linked polyethylene, EPR = ethylene-propylene rubber.

E\_limit is the value of the elongation at break at which the Radiation Index has been calculated. It was chosen between 50% and 130% absolute.

RI In 1991, it was extrapolated down to 15 Gy/h, the estimated dose-rate in the LEP tunnel.

In 2000, higher dose rates were found and the estimate of 1991 was adjusted accordingly.

Moreover, it is important to note that only a few points were available for the LEP measurements, and all of them were at different dose rates. Hence, there are large errors on both the assumed dose rate (which moreover was variable with time, see Table 3) and on the measured (estimated) RI.

TED Time to Equivalent Damage (in hours and in years of operation)

= calculated time needed to reach the limit value of the elongation at break.

\* In these cases, it is important to note that not exactly the same materials were tested in 2000 compared to 1991.

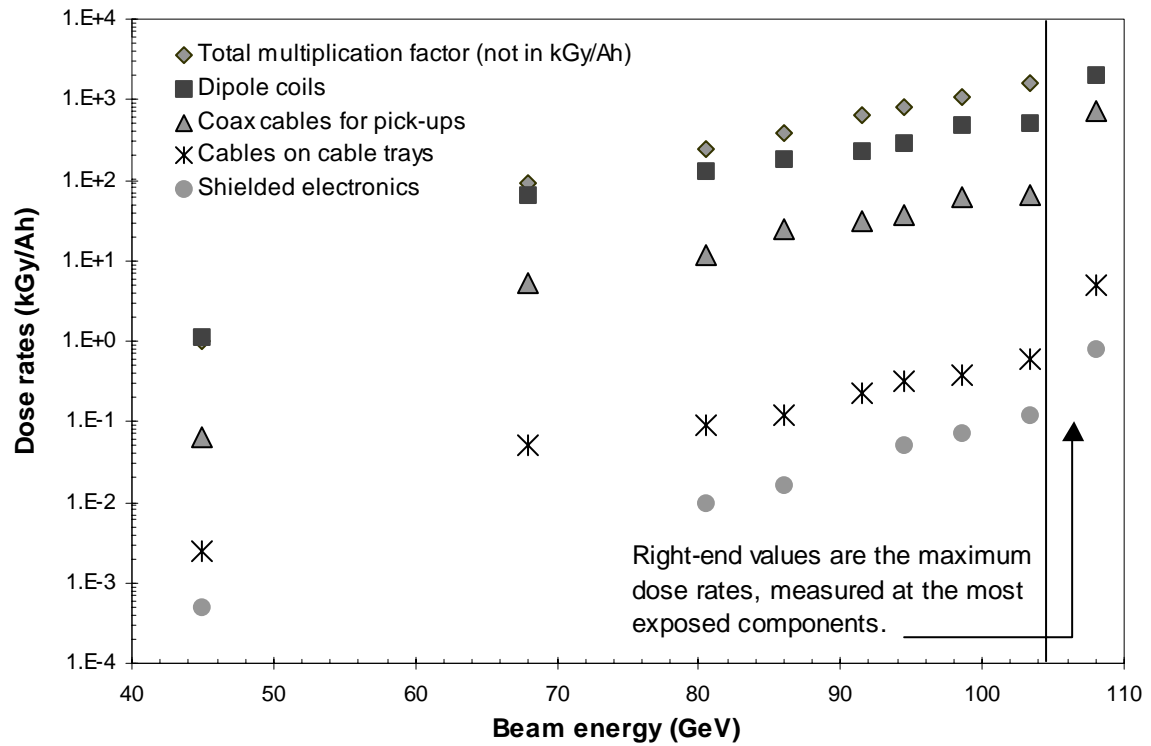


Fig. 1: Evolution of the dose rates (in kGy/Ah) in the curved section of the LEP tunnel, as a function of the beam energy (GeV), which increased over the years of operation (see Tables 1 and 2).

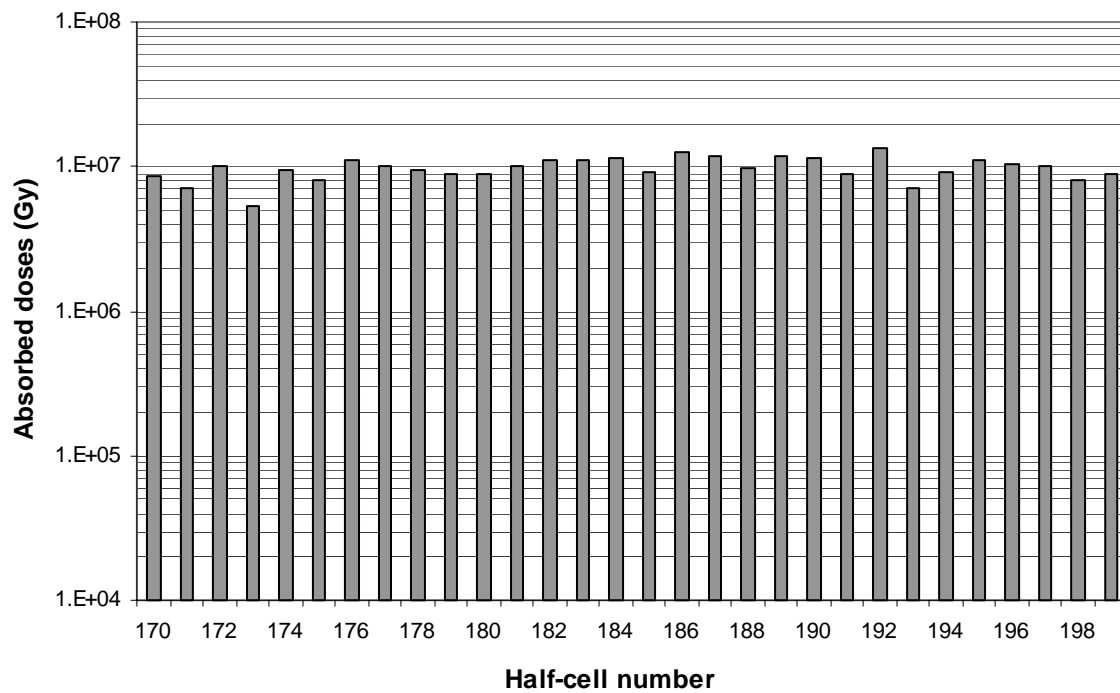


Fig. 2: Integrated doses at the dipole coils from 1989 to 2000.

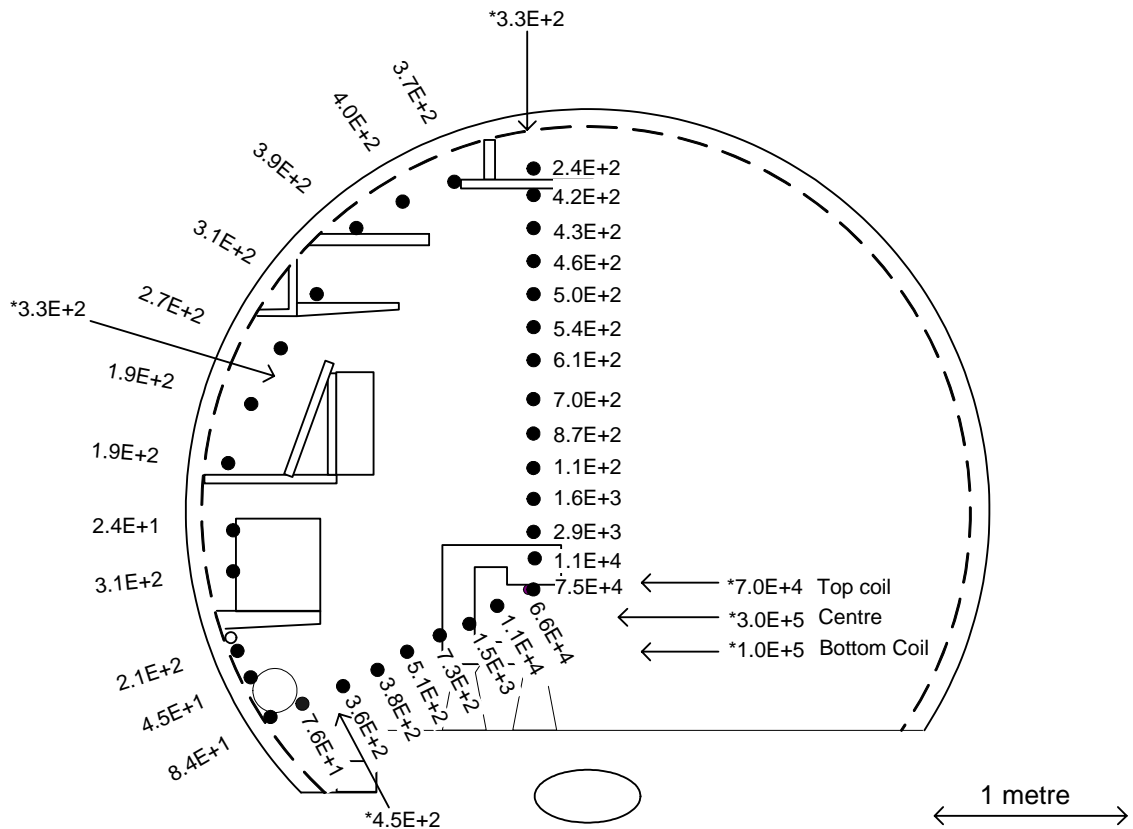


Fig. 3: Dose distribution in Gy/Ah at 98.6 GeV in a dipole section (HC 216)  
 Values with \* show the normalized predicted doses in Ref [3].

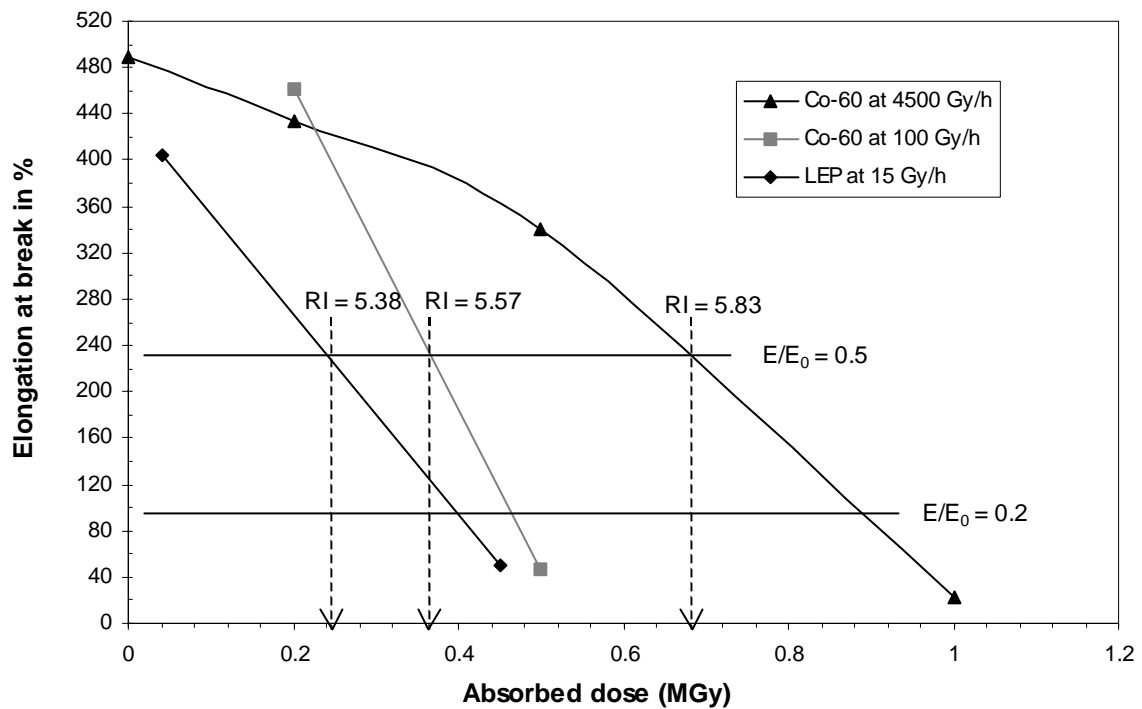


Fig. 4: Decrease of elongation at break of a cable sheathing VAC material C 995, as a function of the absorbed dose, at different dose rates.



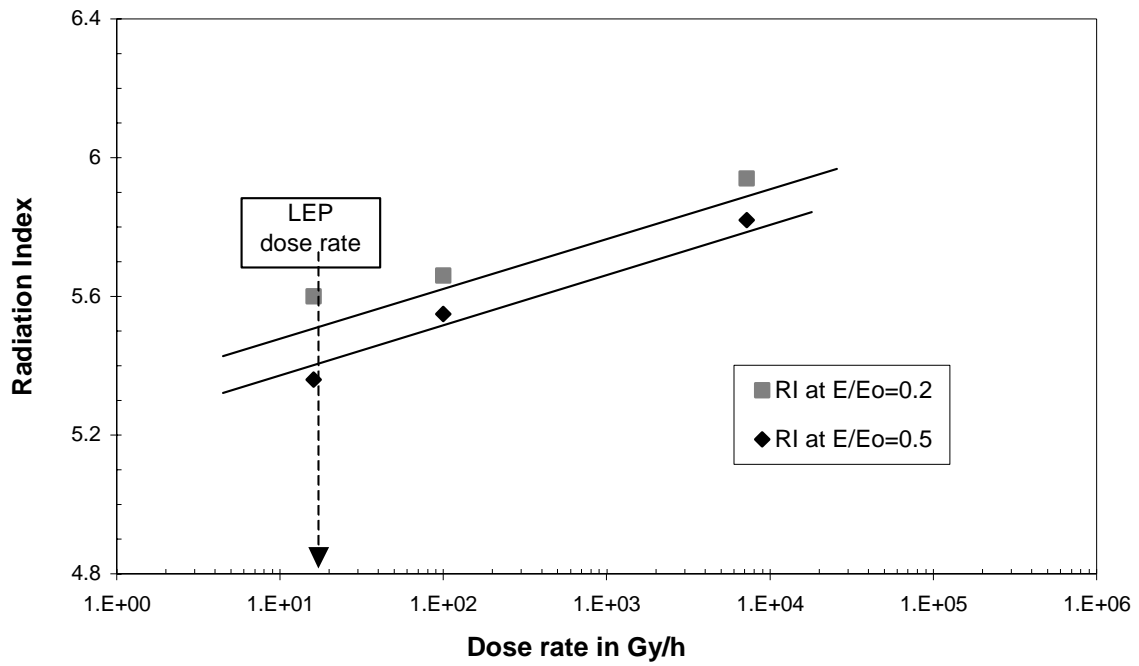


Fig. 5: Radiation indices (obtained from Fig. 4) vs dose rate for cable sheathing VAC material C 995, and extrapolation to the LEP dose rate (15 Gy/h).

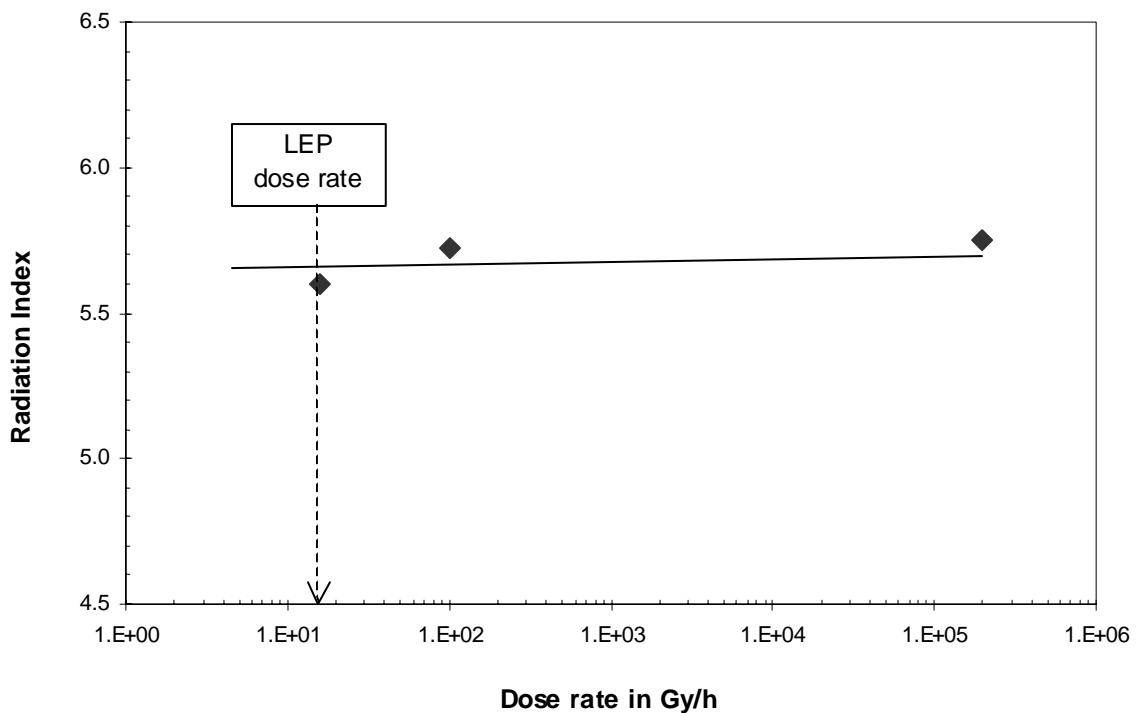


Fig. 6: Radiation Index vs dose rate for cable sheathing materials Sioplas C 951.

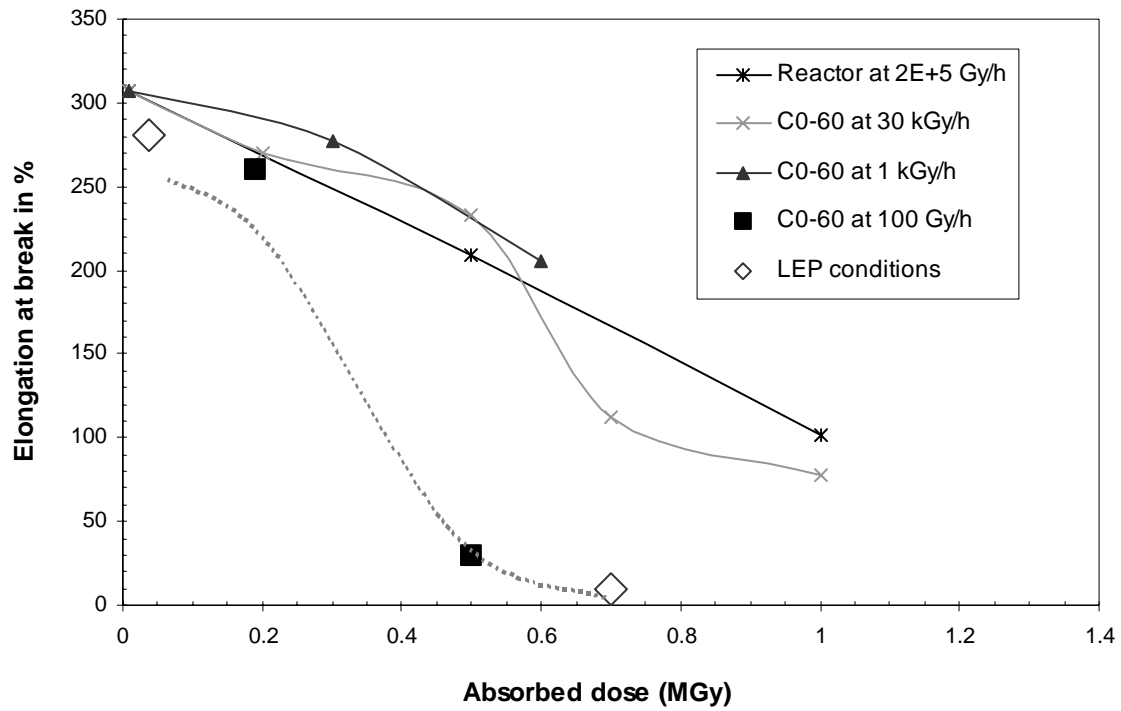


Fig. 7: Decrease of elongation at break of cable insulating XPLE – C 769 as a function of absorbed dose at different dose rates.

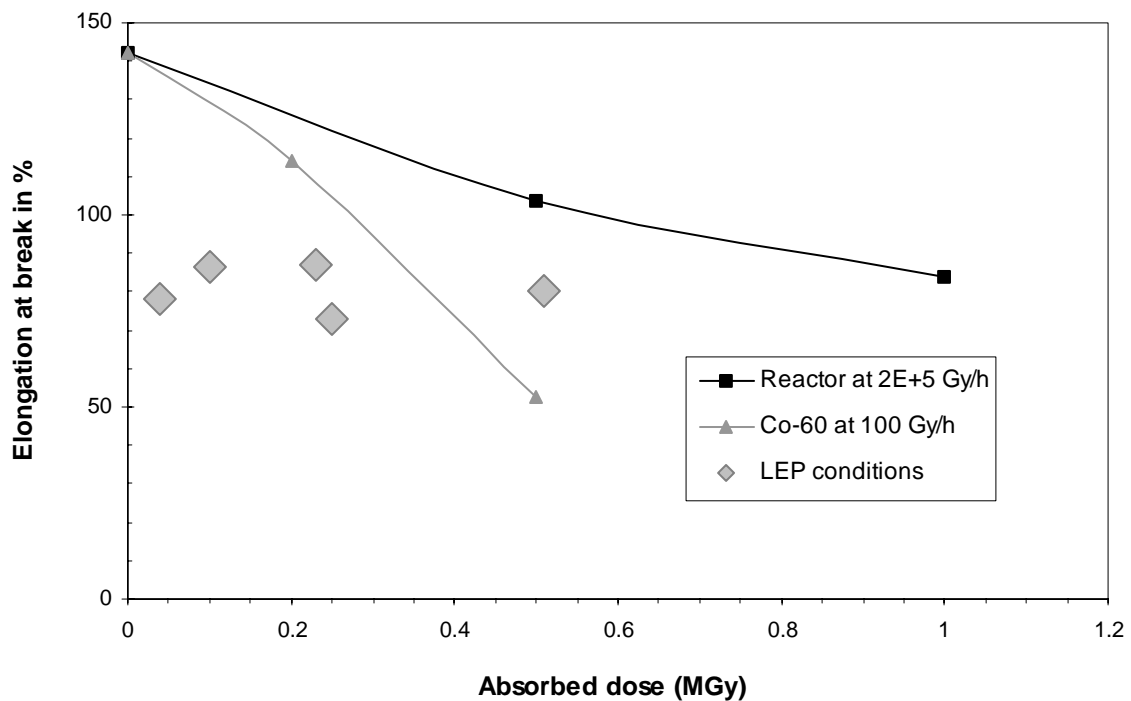


Fig. 8: Decrease of elongation at break of cable sheathing XLPE C 759 = C 1209 as a function of absorbed dose at different dose rates.

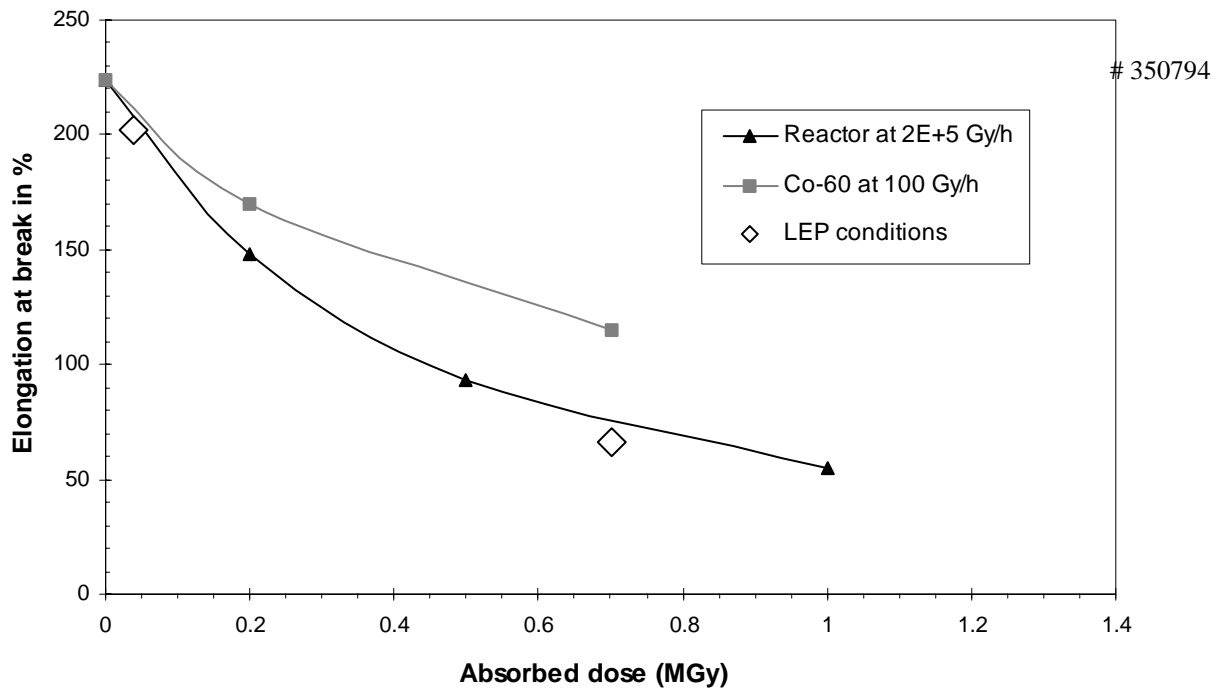


Fig. 9: Decrease of elongation at break of cable material EVA – C 959 as a function of absorbed dose at different dose rates.

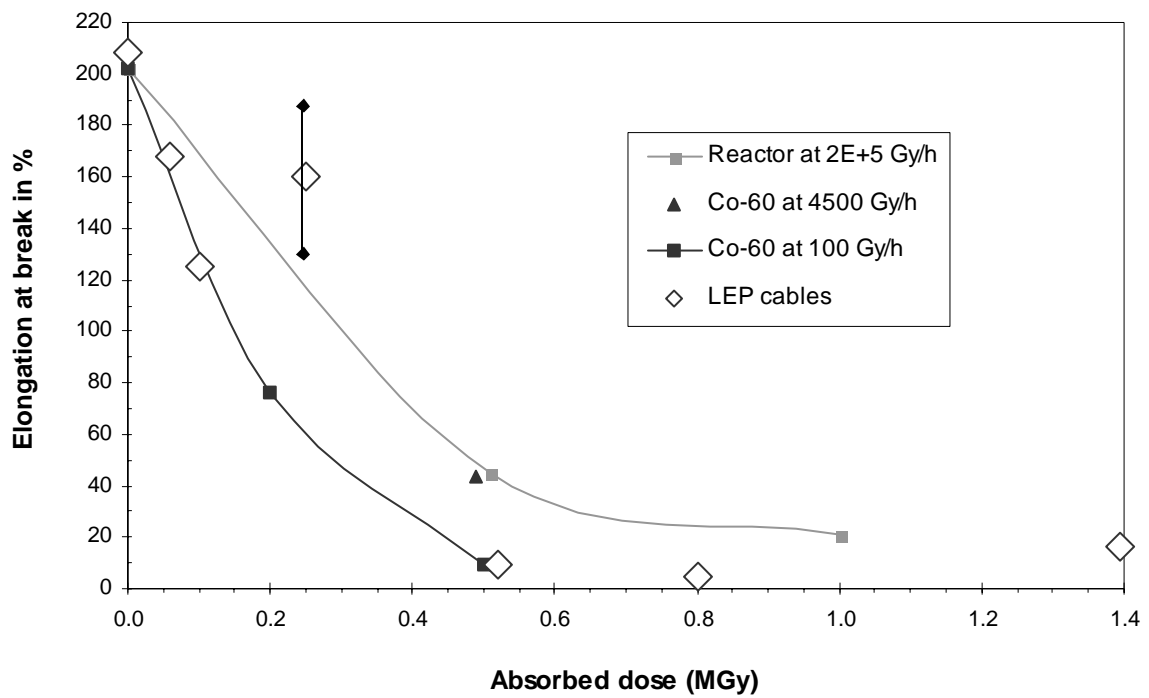


Fig. 10: Decrease of elongation at break of cable material C 868 = C 1208 as a function of absorbed dose at different dose rates.

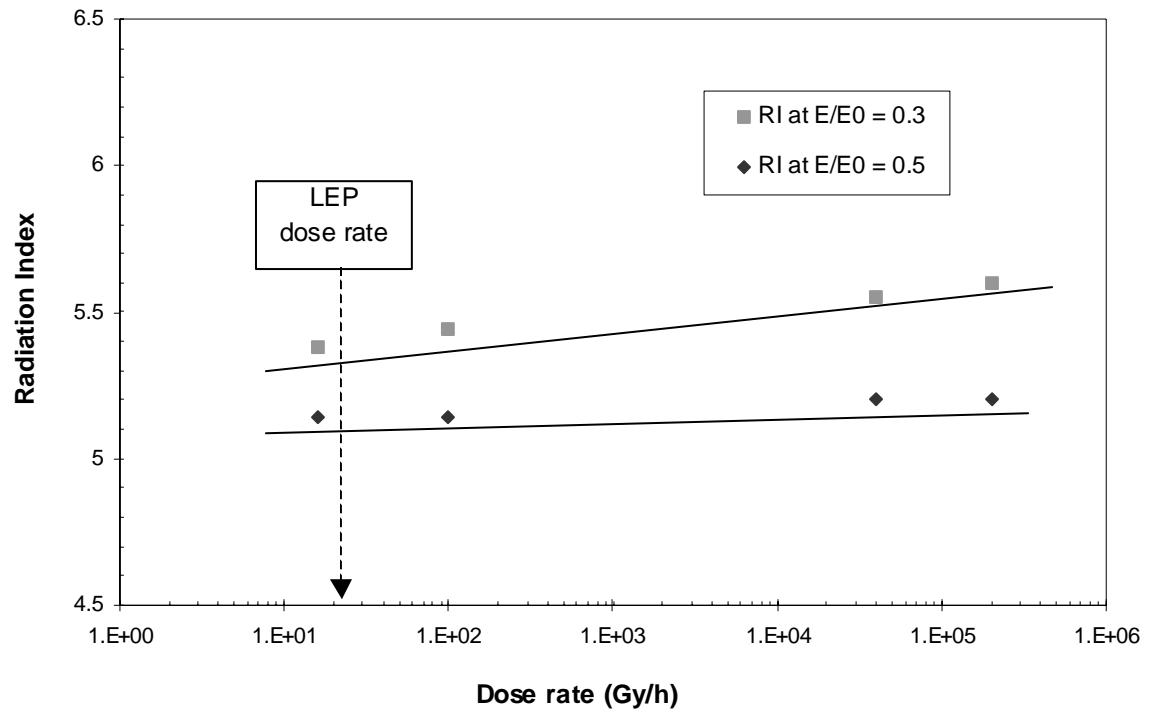


Fig. 11: Radiation Index vs dose rate for cable sheathing materials Rheyhalon C 868 = C 1208.

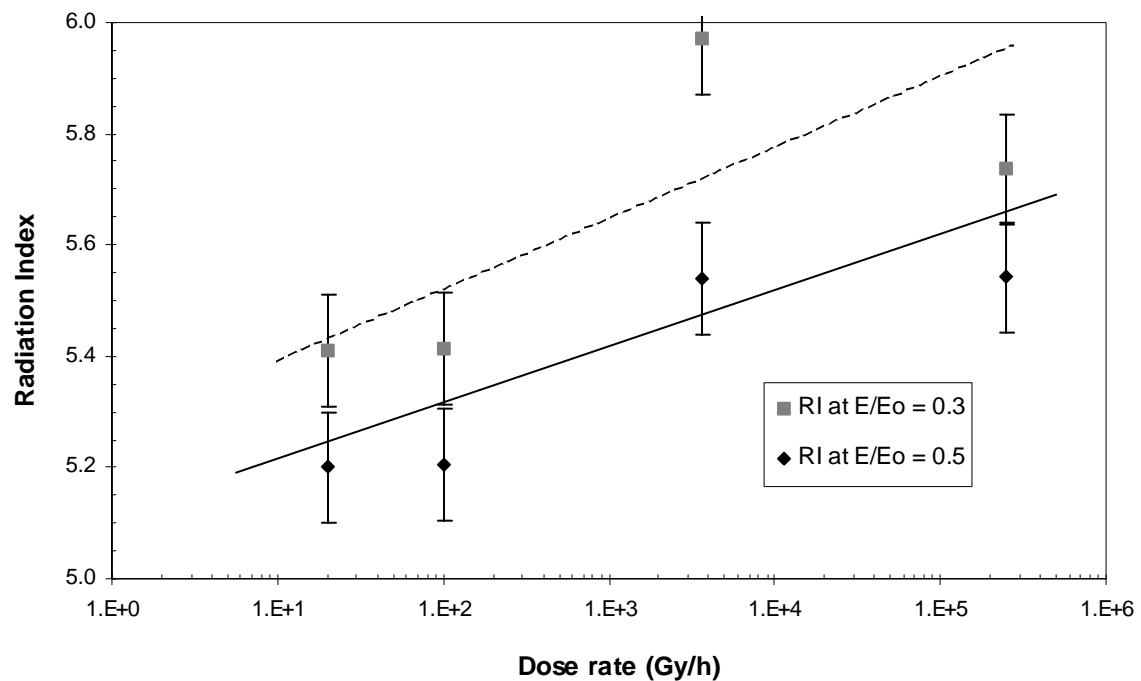


Fig. 12: Radiation Index vs dose rate for cable sheathing materials Unifos 5040 (C 914) (a case where extrapolation is not possible).

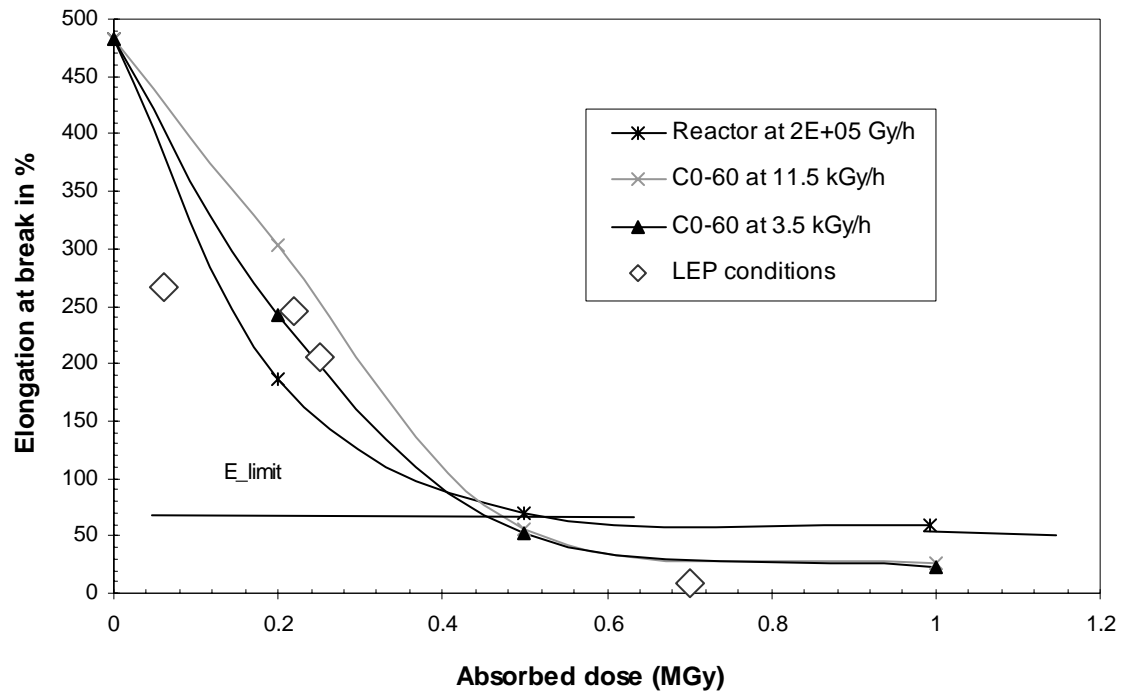


Fig. 13: Decrease of elongation at break of the cable-sheathing polyolefin BP 2383 FR (C 944), as a function of the absorbed dose, at different dose rates.

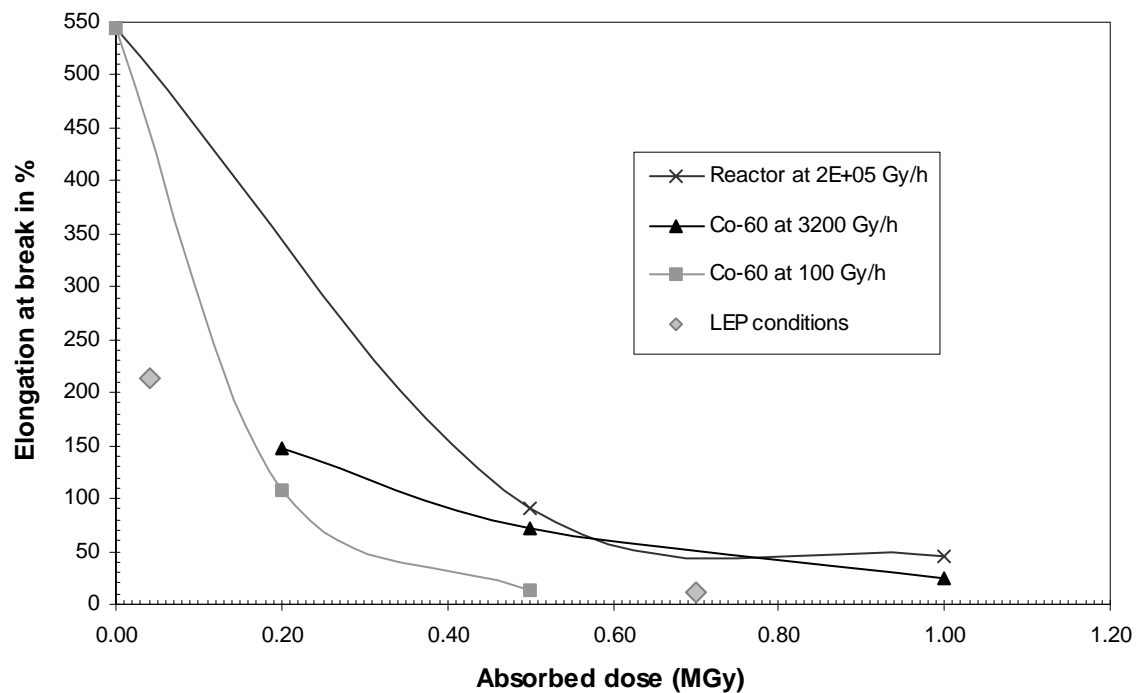


Fig. 14: Decrease of elongation at break of cable sheathing Unifos 5040 (C 960) as a function of absorbed dose at different dose rates.

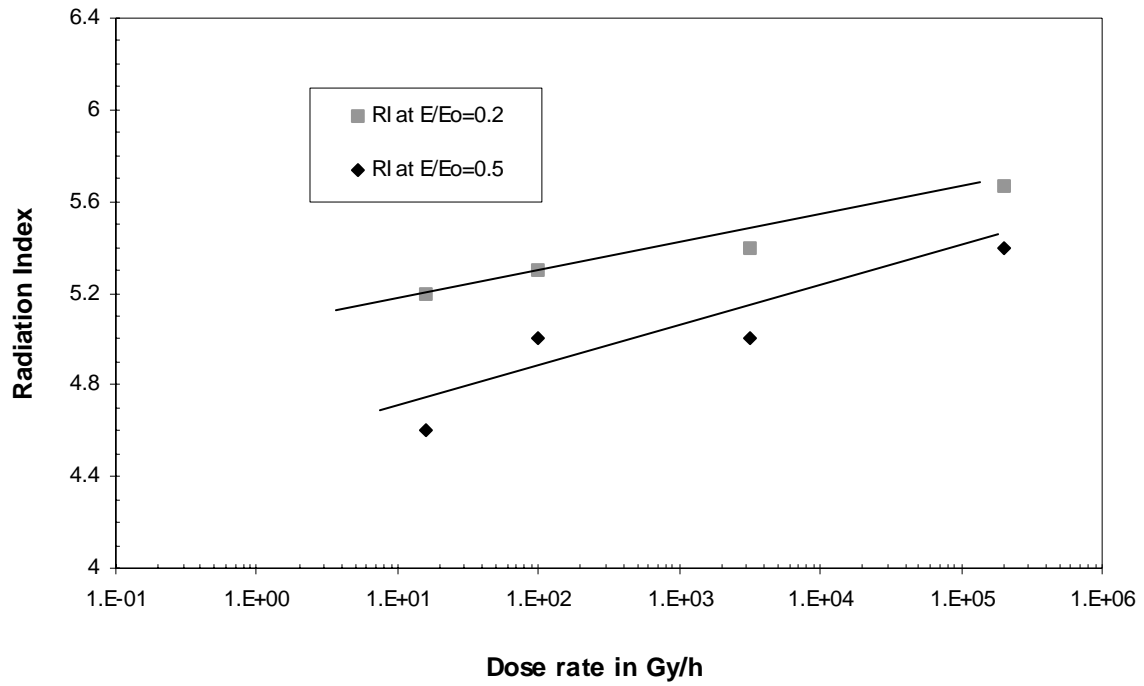


Fig. 15: Radiation Index vs dose rate for cable sheathing materials Unifos 5040 (C 960).

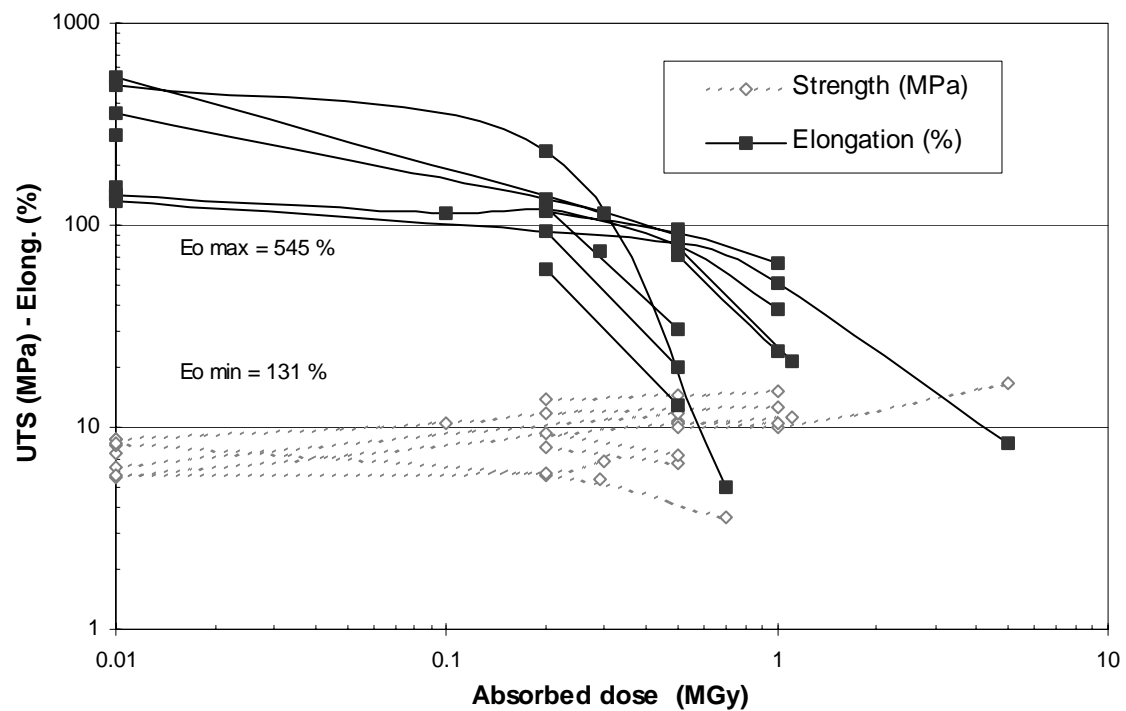


Fig. 16: Mechanical properties of Unifos 5040 cable sheath material obtained by different suppliers.



Fig. 17: some coaxial and control cables damaged by the radiation in LEP. Also seen on the picture is a metallic box containing samples of magnet insulating resins and dosimeters.

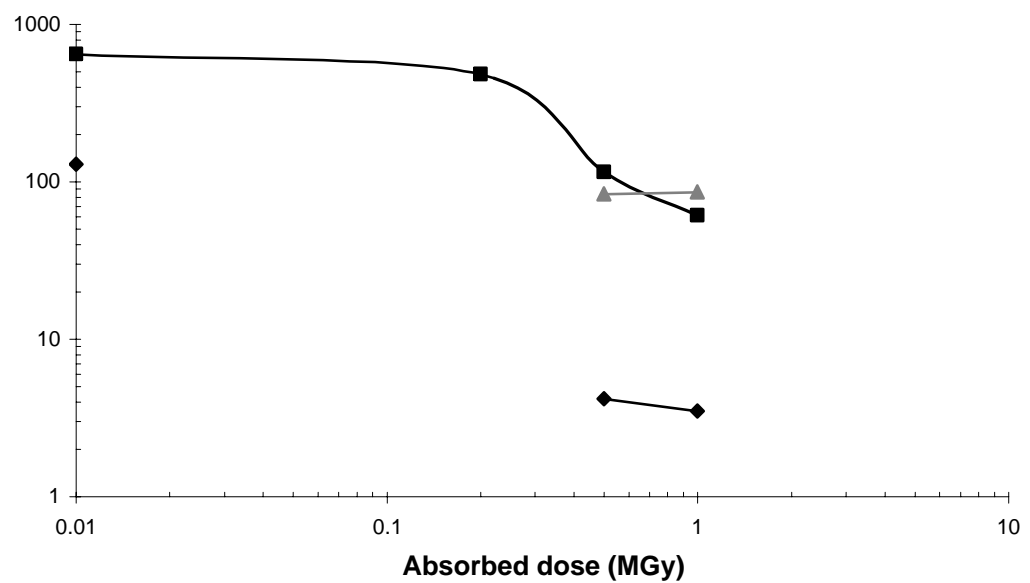


Fig. 18: Radiation effect on the mechanical and chemical properties of a LDPE (Lupolen 1812).

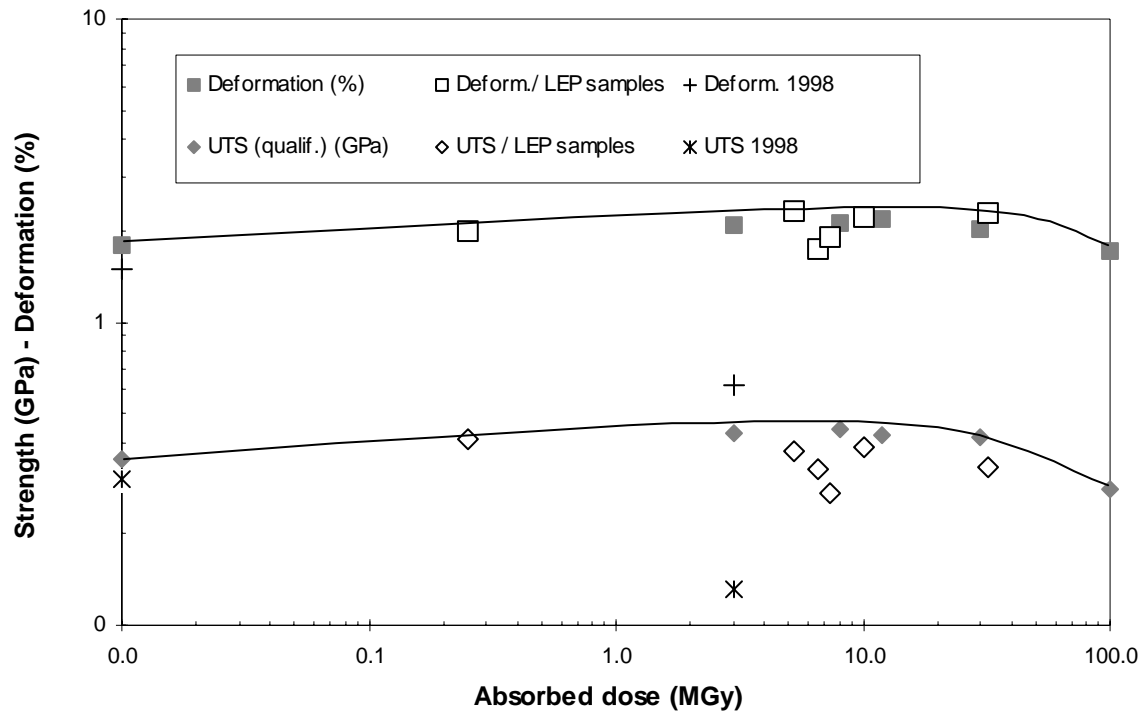


Fig. 19: Radiation effect on a glass-fibre-epoxy laminate (R 468).

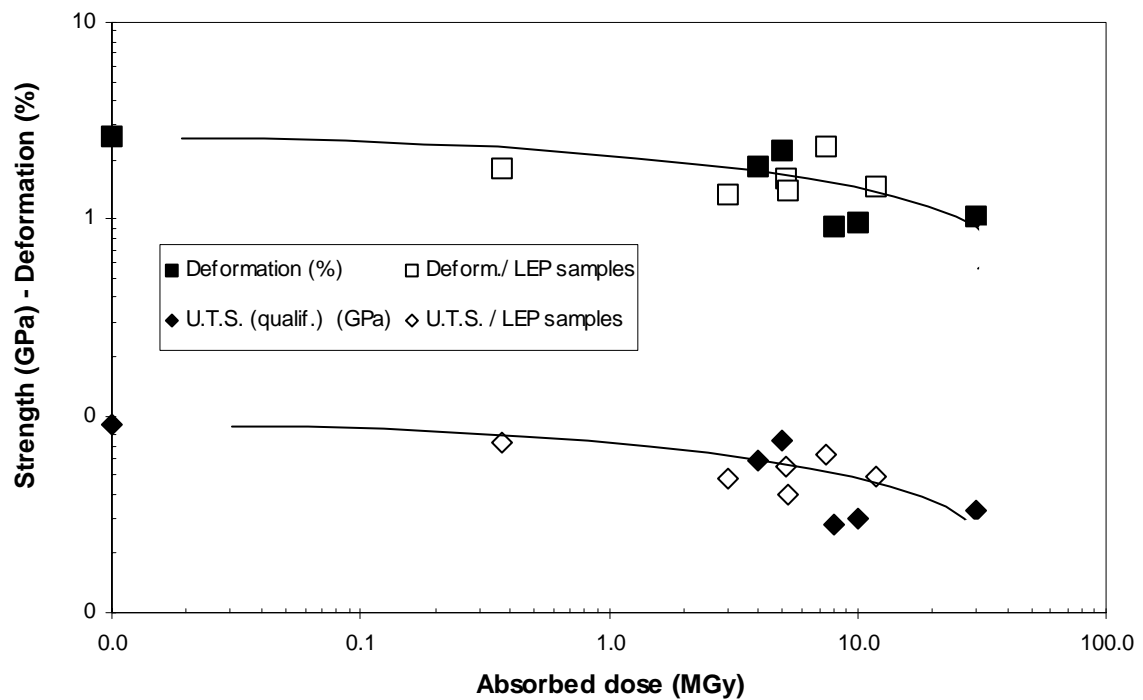


Fig. 20: Radiation effect on pure Araldite F (CY 205) prepared by Ansaldo (R 483).



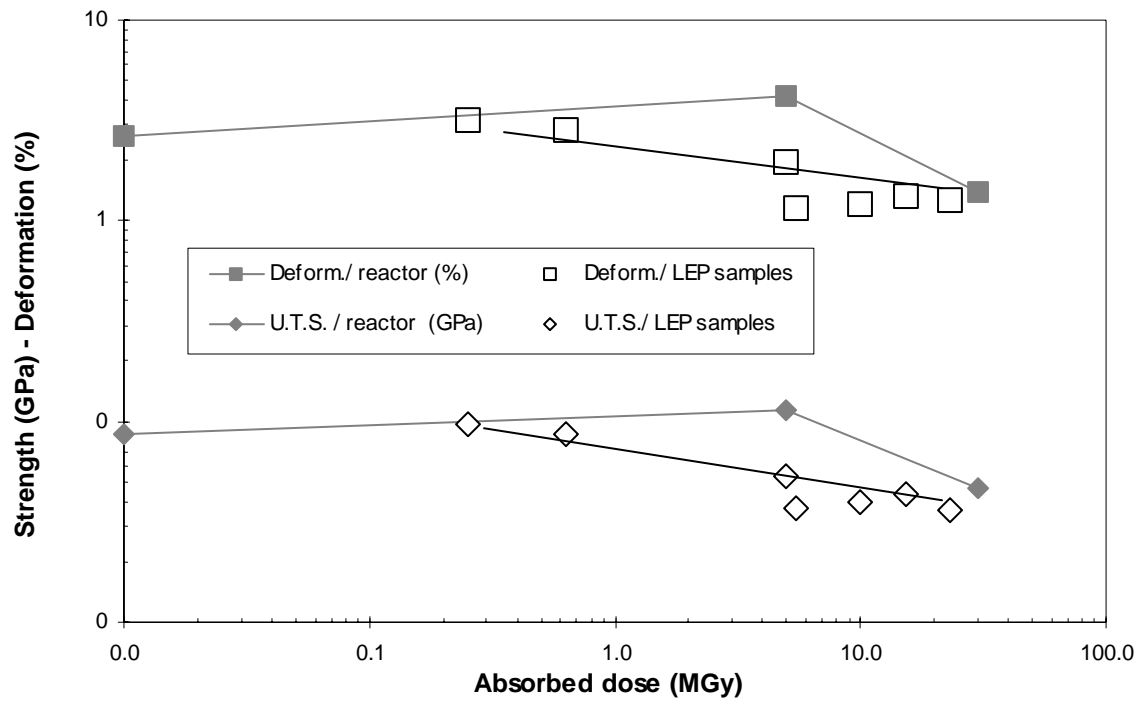


Fig. 21: Radiation effect on pure Araldite F (CY 205) prepared by ABB (R 484).