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LONG-TERM RADIATION EFFECTS  
ON COMMERCIAL CABLE-INSULATING MATERIALS  
IRRADIATED AT CERN

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## ABSTRACT

Long-term irradiation damage tests have been carried out on a variety of flexible cable-insulating materials offered to CERN by different European cable manufacturers. Tensile test specimens were exposed for a maximum of three years in high-level radiation areas of the Super Proton Synchrotron (SPS) and for comparison at high dose rates in a nuclear reactor.

The degradation of mechanical properties after irradiation in air depends not only on the total absorbed dose, but also on the dose rate for most of these polymer compounds. These dose-rate effects vary between material types and for different compounds.

The results presented here illustrate the difference in radiation damage between short-term and long-term irradiation conditions in a typical service application for the various materials tested. They also allow safety factors to be estimated for the extrapolation of the limiting exposure in service from accelerated material tests in the range of dose rates covered.

A discussion of the available models of the dose-rate effects results in a conservative estimate for extrapolation to low dose rates from measured values at intermediate dose rates of the order of 0.1 Gy/s. Based on short-term irradiation tests only, the safety factors to be applied depend on the end-point criterion used, and may vary between 1 and 10 for the range of dose rates and materials considered here.

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## 1. INTRODUCTION

In the planning and construction phase of the CERN Super Proton Synchrotron (SPS) accelerator project, a programme for radiation testing of organic materials was initiated so as to provide data for the selection of materials according to their degree of resistance to radiation. This was not only to assure a reasonable lifetime of the machine components, but also to avoid the necessity of human intervention when repairs had to be effected after the machine had become radioactive during service, in order to keep the radiation exposure to personnel as low as is reasonably achievable. The most radiation-sensitive components, apart from semiconductors and optical fibres, are flexible organic cable-insulating materials and thermoplastic and thermosetting resins for magnet-coil insulation. A large number of materials from these classes were irradiated at a nuclear reactor, and the test results of standard mechanical properties were used for material selection and were later published<sup>1-3</sup>).

After the start of the SPS operation in 1976, test samples of selected materials were exposed in the vicinity of loss points in the accelerator in order to detect possible radiation damage prior to component failure. In the present case of cable-insulating materials, this method soon proved to be useful, and already the first results gave an indication of the magnitude of deviations to be expected from short-term irradiation data<sup>4,5</sup>). Temperature, electrical stress, humidity, and atmospheric oxygen, which can lead to ageing even without radiation, may influence the radiation resistance, and the various radicals and corrosive gases produced by radiation in the material itself and in the surrounding medium may react differently under conditions of service and accelerated tests.

A number of results of long-term radiation effects for typical polymer types<sup>6-10</sup>) and for cable-insulating materials<sup>11-13</sup>) are available. Differences in the compounding of materials, e.g. different amounts of stabilizers and fillers, can change the radiation resistance of a given material in a significant way. Also, in nuclear reactor environments elevated temperatures can lead to synergistic effects, which are usually not of importance in high-energy accelerator technology.

Therefore, the aim of the tests reported here was to make a comparison between the radiation resistance under long-term irradiation conditions and that under short-term irradiation in a nuclear reactor for materials actually installed at the CERN accelerators.

Because of commercial availability the compositions were not known in detail, and this has restricted the interpretation of our results and their extension to similar materials. For a more basic understanding of dose-rate effects and for results on newly developed materials, especially halogen-free fire-resistant ones, another series of tests<sup>14,15</sup>) are now being carried out, the results of which will be published.

## 2. EXPERIMENTAL METHODS

### 2.1 Material selection

When the samples for this study were selected in 1977, the cable-insulating and cable-sheathing materials commonly used were low-density polyethylene (PE) and plasticized polyvinyl chloride (PVC) compounds. Small numbers of compounds for special applications, based on cross-linked polyethylene (XLPE), ethylene-propylene rubber (EPR), polyurethane rubber (PUR), silicone rubber (SIR), and chlorosulfonated polyethylene (CSP), are also represented in the present work. The different materials from which samples have been taken are listed in Table 1, where each material is identified by the abbreviation of the base polymer name and by a material number. A key indicating the application is given, as far as this is known. According to whether the samples have been cut from moulded plates or from the manufactured cable, a coding has been chosen which also identifies the type of tensile samples. The material thickness is given in the last column.

### 2.2 Test methods

The methods used for testing the radiation resistance of insulating materials are listed in IEC Standard 544, Part III<sup>16</sup>), from which tests of mechanical properties [tensile strength and elongation at break in tensile tests on dumbbell-shaped specimens<sup>17</sup>), and the hardness Shore test<sup>18</sup>)] have been selected. Electrical properties have not been tested, since, according to our experience and the discussion in the cited Standard, many electrical properties of typical insulation compounds will only begin to degrade permanently at radiation doses where the elastic properties of the material are already degraded. This was recently observed for an EPR-insulated power cable with PVC sheath, irradiated during service at CERN<sup>19</sup>).

For the determination of permanent damage in cable-insulating materials, the measurement of elongation at break is very convenient because the numerical value does not depend on small variations in sample thickness and the property is very sensitive to radiation damage; it usually shows large variations over several orders of magnitude in irradiation dose. The end-point criterion for the appreciation of radiation resistance can either be defined as a chosen percentage (e.g. 50%) of the initial value<sup>16</sup>), or as the acceptable value of the property in view of an application [e.g. 100% elongation at break<sup>1</sup>)].

**Table 1**  
Characterization of materials

Polymer base	Mat. No.	Application key <sup>a)</sup>	Sample type <sup>b)</sup>	Thickness (mm)
PE	78	IC	P1	2.0
PE	82	IC	P1,2	2.0
PE	212	IC	P1	2.0
PE	233	MP	P1	2.5
PE	234	MP	P1	2.5
PE	236	MP	P1	2.2
PE	402	IP	P1	2.0
PVC	140	D	P1	2.0
PVC	262	-	P1	2.0
PVC	321	SP,FR	P1	1.6
PVC	322	SP,FR	P1,2	2.2
PVC	331	SP,FR	P1	2.2
PVC	366	SP	P1	2.2
PVC	TA	SC (NDY 26)	C2	0.9
PVC	TB	SC (NDY 48)	C2	1.0
PVC	TE	SC (TAA 3)	C2	0.9
PVC	TO	SC (RG 214)	C2	1.3
PVC	TS	SC (NDX 48)	C2	1.5
PVC	TU	SC (CB 50)	C2,3	1.0
PVC	TW	SC (CB 75)	C2	1.4
PVC	TX	SC (CC 50)	C2	1.4
XLPE	320	IP	P1,2	1.4
XLPE	324	IP	P1,2	2.5
XLPE	455	I	P1	2.1
EPR	126	-	P1,2	3.8
EPR	375	S	P1	2.8
EPR	453	S	P1	2.8
EPDM	395	-	P1	2.3
EPDM	399	S	P1	2.5
CSP	135	D	P1	1.4
SIR	109	IC	P1	2.4
PUR	11	D	P1	2.0
PUR	12	D	P1	2.1

a) I = insulation; S = sheath; M = intermediate layer; D = development compound; C = control cable; P = power cable; FR = flame-retardant additive; code in brackets = internal identification.

b) P = cut from moulded plate; C = cut from cable; 1, 2, 3 = sample types S1, S2, and S3 (DIN 53504); S1 = ISO/R 527 Type 2, S2 = ISO/R 37 Type 2.

Remark: In Fig. 2 the results of 20 other PVC and PE materials from Ref. 4 have been used to generate the shaded area.

The samples were cut from moulded plates or from manufactured cables prior to radiation exposure, using cutting dies of standard dimensions. Five specimens were tested under the same conditions, and the result reported is the mean value with standard deviation. Further details about our test and data-evaluation procedures may be found elsewhere<sup>20)</sup>.

## 2.3 Irradiation procedure

### 2.3.1 Radiation sources and dosimetry

The radiation spectrum is not well known at the parasitic irradiation positions in the accelerator. We have measured doses with two types of integrating solid-state dosimeters calibrated at cobalt radiation sources, and have used spallation detectors to measure the fluence of high-energy particles<sup>9)</sup>. The doses produced by the various high-energy particle radiations in organic materials are due to the cascades of secondary particles and to secondary gamma radiation. The cited dose rates are the means over the total operation time of the accelerator for the period of sample exposure, during which radiation pulses of a few milliseconds down to  $10^{-5}$  s width (according to the mode of operation) were delivered at a repetition rate of about 12 s. The instantaneous dose rate may be of the order of  $10^4$  Gy/s. For the maximum dose rate used here, 2.4 Gy are distributed per pulse, corresponding to 1 meV per 2900 CH<sub>2</sub> groups. These irradiation conditions should not lead to any difference, as compared to continuous irradiation. Also, the time interval of 12 s between pulses is too short to permit equilibrium conditions to be re-established by diffusion of gases and stabilizer molecules, which justifies the consideration of mean dose rates only.

Table 2

Irradiation positions, doses and dose rates for long-term irradiation

Dose (MGy)	Dose rate (mGy/s)	Description of irradiation positions (contribution to total dose is in brackets)	Date installed	Total time (years)
0.050	5.0	On cable tray passage way neutrino target	11/79	0.60
0.052	5.2	On cable tray passage way neutrino target	11/79	0.60
0.17	10	On cable tray neutrino target	6/77	1.3
0.20	8.9	On top of dump LSS4	6/77	2.0
0.27	8.4	On top of dump LSS4 (74%) and cable tray LSS4 (26%)	6/77	2.6
1.0	60	On cable tray neutrino target	6/77	1.3
1.0	60	On cable tray neutrino target	6/77	1.3
1.7	170	On cable tray neutrino target	11/79	0.60
2.0	200	On cable tray neutrino target	11/79	0.60
2.7	160	Under dump (26%) and on cable tray neutrino target (74%)	6/77	1.9
2.7	160	On top of dump (26%) and on cable tray neutrino target (74%)	6/77	1.9
2.7	160	On top of dump (26%) and on cable tray neutrino target (74%)	6/77	1.9

Remark: 1 mGy/s = 360 rad/h = 3.15 Mrad/y.

At the reactor, the doses are determined with reference to calorimeter measurements and are mainly due to gamma radiation<sup>21</sup>. Neutrons add less than 3% to the dose in (CH<sub>2</sub>) materials; also, nuclear reactions initiated by thermal neutrons (e.g. in Cl) are usually negligible in relation to the total dose. The main difference in the irradiation positions in the CERN accelerators, in view of the radiation degradation of cable-insulating materials, is the dose rate, which is about 50 Gy/s in the reactor position E1. In the accelerator irradiation positions the dose rates are about 3 orders of magnitude lower, with the highest values being about 0.2 Gy/s. According to IEC 544, dose rates of less than 30 mGy/s are considered as low, so that the dose rates available at the accelerator are situated within a factor of 6 on either side of this limit.

A short description of the irradiation positions is given in Table 2, where dose rates and the doses absorbed by the samples are listed together with other details of the irradiation programme. The dose values measured for the long-term irradiations ought to be correct within a factor of 2, and for short-term irradiations at the reactor the doses are known within ± 15%.

### 2.3.2 Sample positioning and exposure

For each irradiation position and material, five tensile samples were stacked to a package, with Mylar spacers and metal-face plates for stability and identification. They were then installed at one of the positions listed in Table 2, in a container which allowed free exposure to air. A typical layout plan of long-term irradiation positions is sketched in Fig. 1. The first lot was installed in 1977, and some containers were taken out in October 1978, May 1979, and August 1979. Some samples were tested and others reinstalled at different locations in November 1979, which were finally tested during the long shutdown of the accelerator in June 1980. The relative importance of the second period for the

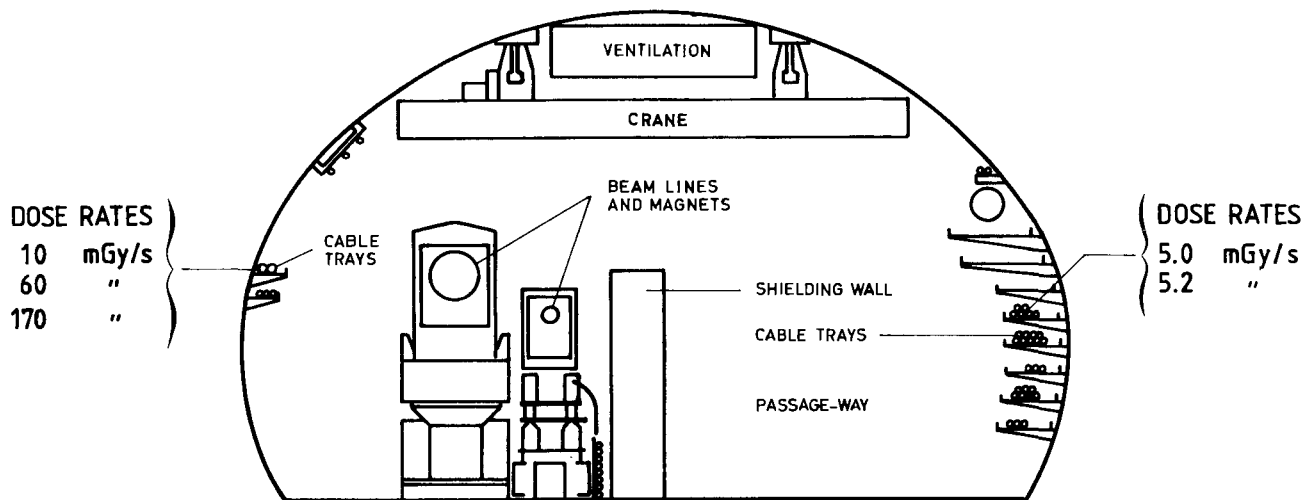


Fig. 1 Layout of long-term irradiation positions in the Super Proton Synchrotron. A typical cross-section of the tunnel behind the neutrino target (T9/T11) is shown, some irradiation positions being identified by their respective dose rate (see Table 2).

total dose of the samples in the container has been used as a weighting factor in the calculation of the mean dose rate, and is listed in Table 2 together with the description of locations. Also given is the total time of installation in the accelerator, which may be of importance for judging environmental influences, whereas for the calculation of dose rates, only the operation time of the accelerator has been used.

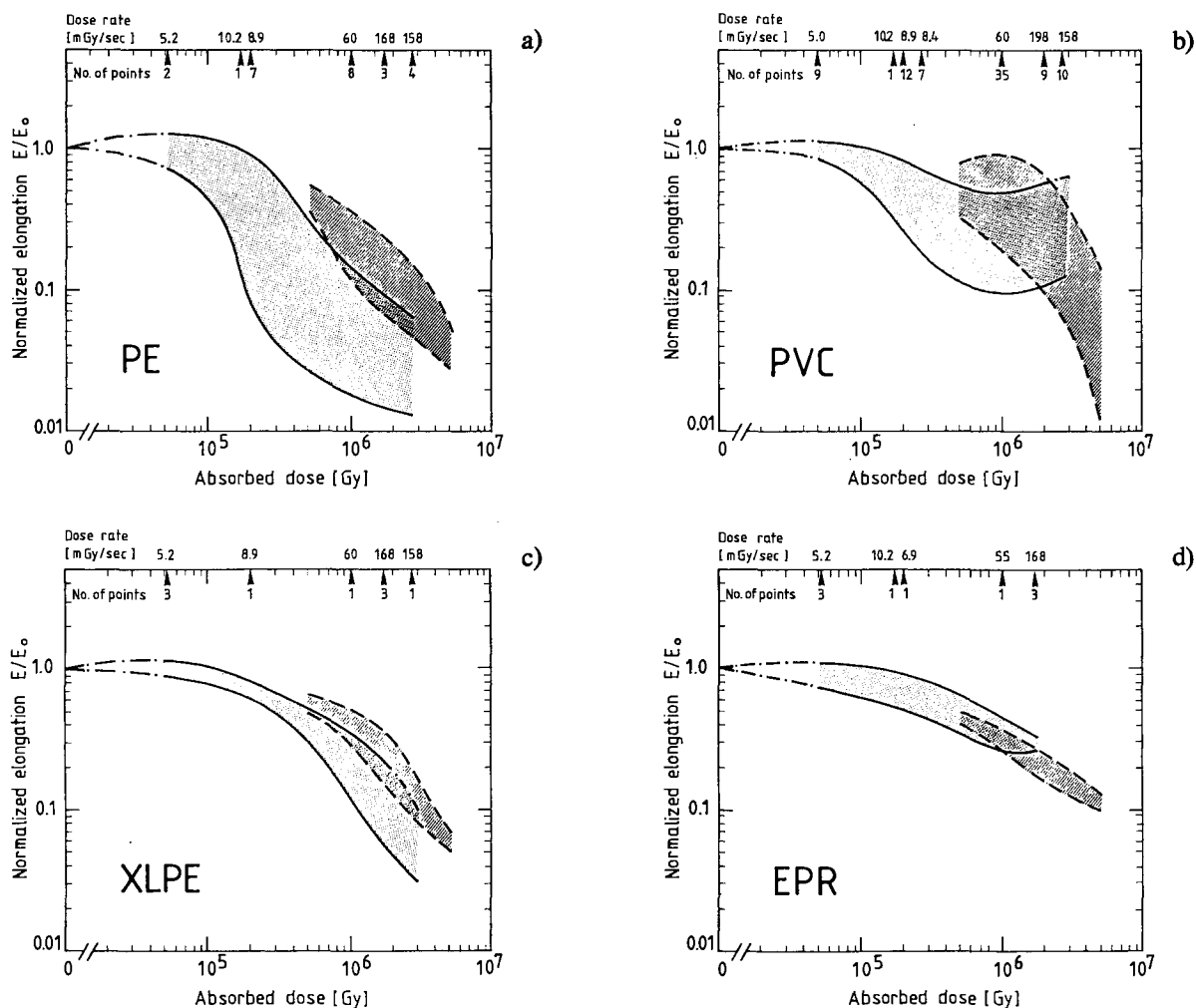
All samples were exposed to air at ambient temperature (20–23 °C) during long-term irradiation, as well as during short-term irradiations in the reactor at 30–40 °C. Thus gaseous radiolysis products, e.g. HCl in the case of PVC, were prevented from accumulating in the vicinity of the samples. For long-term irradiation, however, the air circulates in the accelerator tunnel for periods of up to several weeks with only partial filtering, which leads to a certain concentration of noxious gases of radiochemical origin, such as ozone and nitrous oxides. These may in turn attack the samples at the surface; for example, ozone leads to embrittlement of the surface and to formation of characteristic cracks. The concentration of ozone has been estimated to be below 1 ppm<sup>19</sup>. No clear correlation between environmental conditions and degradation effects has been found, apart from the influence of oxygen during irradiation.

### 3. RESULTS OF MEASUREMENTS

For each set of five tensile samples the mean values of elongation at break ( $E$ ), tensile strength ( $R$ ), and Shore hardness ( $H$ ) are given, together with dose and dose rate, in the table in the Appendix. For  $E$  and  $R$ , the standard deviation for the five samples is also given. A graphic representation of these basic data is also available<sup>22</sup>.

#### 3.1 Range of radiation effects for typical cable-insulating materials

As one would expect, different radiation resistance of materials belonging to different classes of base polymers is observed. We show the range of radiation effects on elongation at break (Fig. 2) and tensile strength (Fig. 3) for low-



**Fig. 2** Elongation at break normalized to the value before irradiation for four classes of base materials: a) polyethylene, b) polyvinyl chloride, c) cross-linked polyethylene, and d) ethylene-propylene rubber, as a function of absorbed dose (bottom scale) and dose rate (top scale). The measured values fall within the two shaded regions, with line shading for short-term and dotted shading for long-term irradiations. For the latter, the number of measured points at each dose is also indicated (see top of drawing).



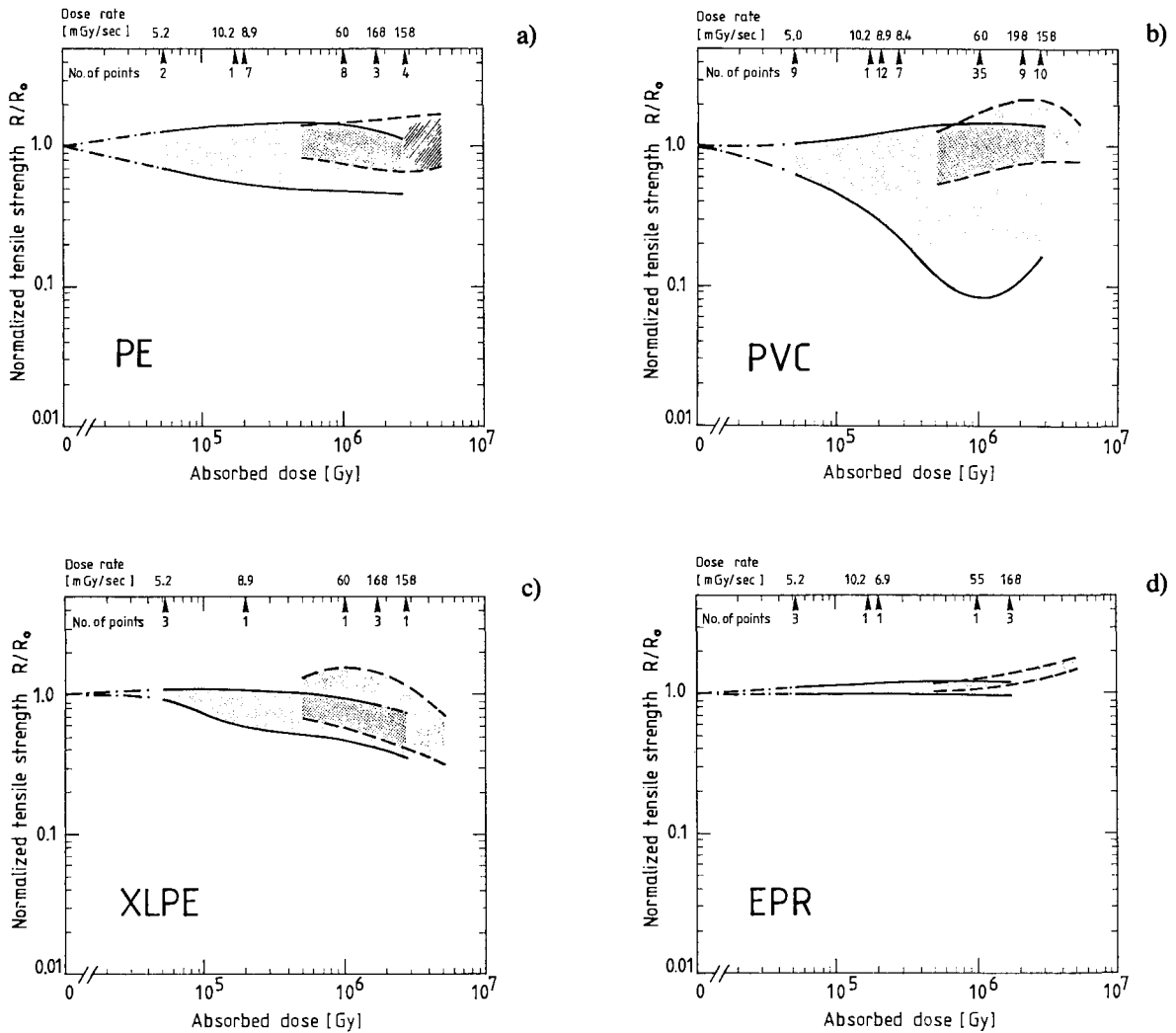


Fig. 3 Same presentation as for Fig. 2, but here the tested property is the tensile strength.

density polyethylene (PE), polyvinyl chloride compounds (PVC), cross-linked polyethylene (XLPE), and ethylene-propylene rubber compounds (EPR/EPDM). The measured values, normalized to the initial value, fall within two shaded regions for long-term irradiation (dotted shading) and short-term irradiation (line shading). The border lines reflect also an impression of the general sequence of measured values for each material. It should be noted that this sequence is not only a function of dose but also of dose rate, both varying between measured points as indicated by the two horizontal scales. This correlation of dose and dose rate is typical for practical applications in which the service life of an installation has to be estimated.

The dash-dotted portion of border lines is not supported by measured points, and for this reason it has been omitted for the short-term irradiation. For the dotted region, the number of measured long-term values is noted on the upper horizontal scale. Within the overlapping region of the two shaded areas, either the difference between long-term and short-term irradiations was small, or the overlapping values belonged to materials from different suppliers. This ambiguity will be resolved by the corresponding graph in subsection 3.2.

Comparing the radiation effects on elongation at break (Fig. 2) for the most common materials, PE and PVC, these summary graphs show a clear difference in the dependence on dose and dose rate. For PE the short-term irradiation effects show a more narrow distribution than for PVC, and the upper border decreases more steeply for doses below 1 MGy.

The difference is more pronounced in long-term irradiations, where above 0.3 MGy and 10 mGy/s the PE samples are less resistant than the PVC ones. This superior performance of PVC with regard to elongation at break is in contrast with the results for tensile strength in long-term irradiations (see Fig. 3), which decreased by a factor of 10 at 1 MGy for the worst cases, whereas the long-term values for PE and the short-term results for both materials stay within 50% of the initial values.

The corresponding summary graphs for the three XLPE samples show a behaviour similar to that of PE, but are significantly better than PE in long-term tests above 1 MGy. For tensile strength, the results of XLPE are within the range for PE after long-term irradiation and slightly below in short-term tests.

For EPR materials the values for relative elongation at break are higher than for XLPE and fall within the upper region of PVC; the same is true for tensile strength, which remains nearly unchanged by irradiation.

For the few remaining materials (EPDM, PUR, SIR, and CSP), we refer to the table in the Appendix. They are not represented in Figs. 2 to 5, and serve only as examples for comparison, because the results of a few materials may not be typical for the polymer compounds they represent.

For the interpretation of all these results, it should be borne in mind that they refer to the specific materials as received from the cable manufacturer, and that for practical applications the absolute values of a property may be of a greater importance than the changes relative to the unirradiated value.

### 3.2 Ratio of long-term to short-term irradiation results

For the comparison of long-term irradiation results obtained in high-level radiation areas at CERN with the routine short-term tests carried out at the reactor, the ratio of the long-term results to the approximated short-term values at the same dose are shown in Figs. 4 and 5. If this ratio were less than 1, a safety factor would be needed for the extrapolation from short-term measurements to service conditions which accounts for the dose-rate effect. The lines in these graphs are only meant as a visual aid to distinguish the different materials, and are not expected to represent an approximation to the functional dependence of the property on dose, since the dose rate also changes.

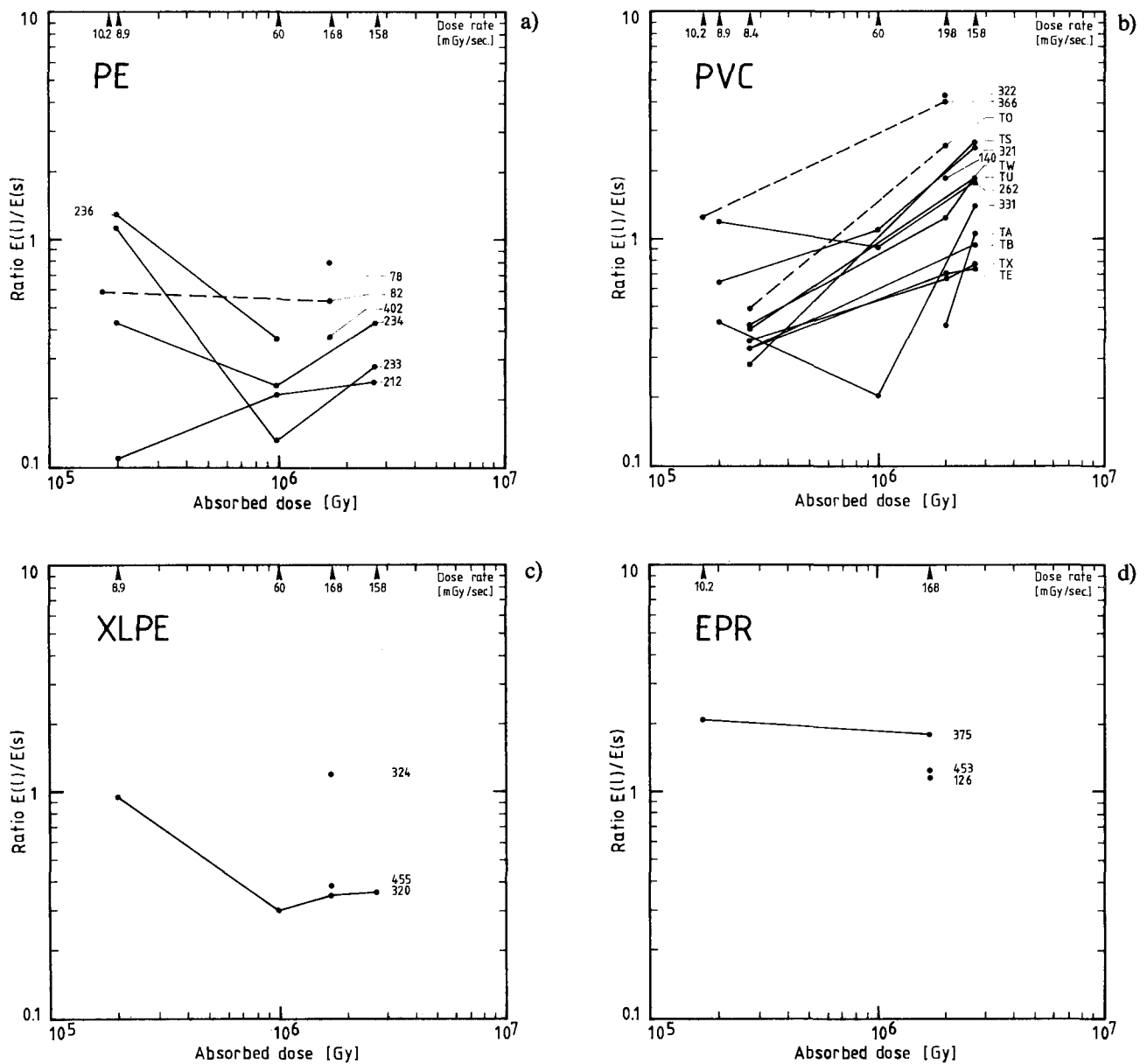


Fig. 4 Ratio of long-term to short-term irradiation results for elongation at break as a function of dose (bottom scale) and dose rate (top scale), for four types of compounds: a) polyethylene, b) polyvinyl chloride, c) cross-linked polyethylene, and d) ethylene-propylene rubber. The lines connect measured points for same materials and are marked with the material number. If there are only two points, the lines are dashed, and points at less than 0.1 MGy are not shown.

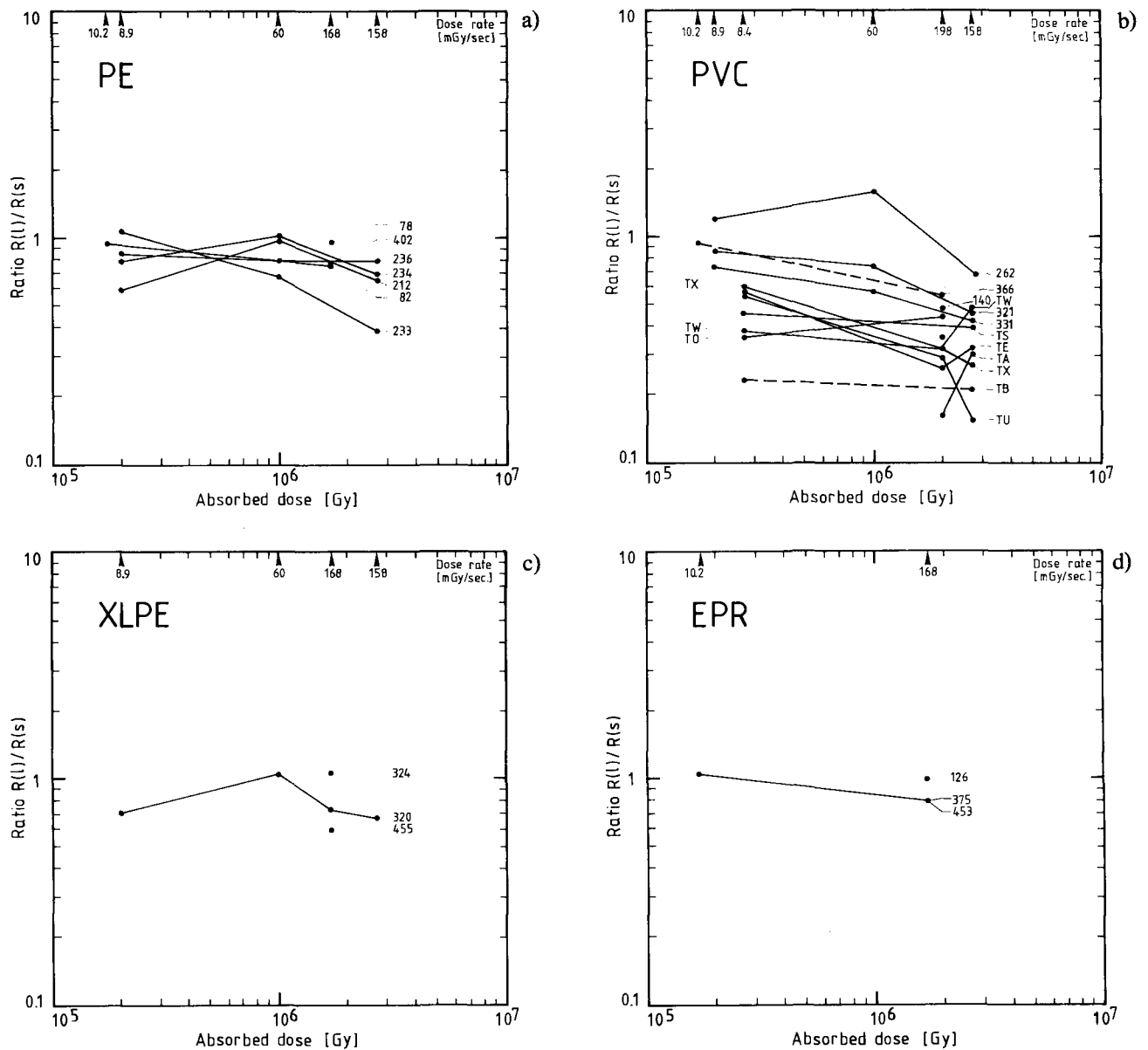


Fig. 5 Same presentation as for Fig. 4, but here the tested property is the tensile strength.

As before, a summary for four material classes is given for elongation at break and tensile strength, and again the most pronounced difference is found between the PE and PVC compounds. For PE (Fig. 4a) nearly all ratios for elongation at break are below 1 and even reach 0.1, which indicates greater damage for long-term irradiations up to a factor of 10. A general tendency of this dose-rate effect for different values of dose and dose rate is difficult to detect in this figure, but there seems to be a smaller spread between different materials at higher doses and dose rates. For tensile strength, however, most values lie within 50% of unity.

For PVC the dose-rate effect for elongation at break is smaller than for PE up to a dose of 1 MGy (dose rate 60 mGy/s). At higher doses and dose rates, the ratios range between 0.4 and 4, the majority being larger than 1. This indicates less damage at 160–200 mGy/s than at 50 Gy/s at the same dose of 2 to 3 MGy. The tensile strength ratio, however, does not follow this dependence, but for nearly all materials it remains below unity and decreases with increasing dose and dose rate up to 3 MGy.

For the other materials, the description for the ratios of long-term and short-term irradiation results follows the one given in subsection 3.1. Again the dose-rate effect for XLPE is comparable to that of PE for tensile strength and falls within the upper half of PE for elongation at break. The EPR and EPDM are not much different, and are ranging between 1 and 2 for elongation at break and between 0.7 and 1 for tensile strength, which again is comparable to the upper values for PVC.

## 4. DISCUSSION OF THE RESULTS

In the preceding section we tried to show, as clearly as possible, the spread of values within one material class and differences with respect to other materials, using our experimental data and with emphasis on any differences in short-term results. In fact, this was the aim when the experiment was designed, since, at that time, possible long-term irradiation effects were only known from literature for reactor and gamma-source irradiations, which did not include high-energy accelerator environments<sup>6-13</sup>). However, as the spread of results even within a given class of materials was unexpectedly large, some caution has to be taken in making or using general statements for those materials.

On the one hand, various measurement errors could be suspected of producing an increased scatter of data. For the mechanical properties, the standard deviation of the five tensile samples is given in the Appendix; this deviation is normally small compared with the irradiation effect, but in some cases it is not negligible. More important are the measurement errors for dose and dose rate in the long-term irradiations. Since the doses have been accumulated over long periods of time, the stated error of a factor of 2 seems to be a realistic estimate for comparing doses obtained at different irradiation positions. Also, the dose rate could have changed during the whole irradiation period owing to machine schedule and fluctuations in beam alignment. Thus, when determining the dose rates, we only took the operation time into consideration.

Nevertheless we believe that the differences found within a given material class are real, and that they are due to a different composition of the materials, especially the degree of stabilization against normal ageing. Another subsequent experiment where the amounts and types of stabilizers were deliberately varied<sup>15</sup>) already provided evidence for this.

### 4.1 Radiation effects in organic cable insulations

For convenience, some basic radiation effects are recalled here as a background for the discussion in subsections 4.2 and 4.3. The description is not specific for a special type of cable-insulating material, and disregards details of the composition, which in practice determine the properties of materials.

#### 4.1.1 Primary radiation effects

When ionizing radiation passes through an organic polymer material, energy is transferred to the molecules mainly by electronic excitation. In irradiations with neutral particles and with small probability in charged-particle irradiations, also a nucleus of the constituent atoms may be hit, which then, in turn, will lose its energy by ionization and eventually by nuclear transformation. The energy absorbed by the electrons may lead to excitation of the molecule, to the breaking of chemical bonds, and to ionization of atoms. As a result, more or less unstable radicals are formed. The simplest and most common case is the liberation of a hydrogen atom, leaving behind it a reactive site in the polymer chain. This primary effect is virtually independent of the type of radiation, because the energy transferred in a single process is very small compared to the primary energy of the radiation, and in most cases is transmitted by secondary electrons. Therefore, the number of radiation-induced radicals is proportional to the total absorbed dose. Exceptions may be found at very high dose rates (e.g. in a particle beam or near a strong radiation source) and for irradiation with heavy charged particles, but these cases are not normally of any concern for cable insulations.

#### 4.1.2 Secondary reactions in the polymer

The transformation of the radiation-induced radicals into more stable ones or into stable reaction products depends not only on the chemical composition of the polymer but also on additives and gases present, on the temperature, on the local concentration of radicals and free electrons, and on the accumulated dose. These conditions give rise to dose-rate effects since they depend on time, e.g. the concentration of small molecules may depend on diffusion constants and that of radicals on dose rate.

The chemical reactions occurring in a polymer under irradiation are complicated, and a large variety of different irradiation products have been detected.

The most common gaseous products found are usually hydrogen and halogen acids if halogens are present, and carbon dioxide if oxygen is present. The composition of the non-volatile part depends on whether gaseous oxygen is available inside the material. In Table 3 some typical reactions are listed for irradiation with and without oxygen. While some polymers are also degraded in the absence of oxygen, the typical effect is the cross-linking of adjacent polymer chains, which may improve technical properties at moderate doses. Chain scission and degradation into low molecular weight products, which is the cause of mechanical failure, is the predominant effect in the presence of oxygen for all polymers.

The important difference between the two situations is the formation of metastable peroxy radicals in the presence of oxygen and their capability to catalyse further degradation. In the vicinity of a peroxy radical and in presence of oxygen, the degradation may continue, especially at elevated temperatures and even without irradiation<sup>23</sup>). An example of a degradative chain-process is shown in Table 3 — reactions 4 and 5, which consume oxygen and reconstitute a propagating active site under favourable conditions. Similar reactions involving hydroperoxides are also possible. Since such a degradation may already be initiated by ultraviolet light, especially at the surface, commercial cable

**Table 3**

Example for radiation-induced reactions in polymers

Irradiation conditions	Qualitative chemical reaction <sup>a)</sup>			Stability of products	Effect
	No.	Radiation-induced radicals; ligands	Intermediate and final products		
Oxygen not available	1	$R\cdot, H\cdot$	$R-CH=CH-R'$	Stable	Unsaturation
	2	$R\cdot, H\cdot$	$R'\cdot, R''\cdot$	Unstable	Chain scission
	3	$R\cdot, H\cdot; R'HR''$	$R'-R-R''$	Stable	Cross-linking
Oxygen is available	4	$R\cdot; O_2$	$R-O-O\cdot$	Metastable	Peroxy radical formation
	5	$RO_2\cdot; R'H$	$RO_2H, R'\cdot$	Unstable	Propagation
	6	$RO_2H$	$R'CHO, HOR''$	Stable	Chain scission
	7	$RO_2\cdot, R'O_2\cdot; R''$	Oxidation products	Stable	Addition (termination of reaction chain)

a) R, R', R'' represent polymer chains, e.g. an alkane chain in PE.

R· and RO· are the typical radicals: alkyl radicals (R-CH-R') and peroxy radicals (R-O-O·)

insulations are protected against this type of ageing by suitable antioxidants and other additives. Whether or not a strong dose-rate effect will be found, depends not only on the type of polymer but also on the concentration of oxygen and antioxidants, which may change at elevated total doses even for constant dose rates. Therefore, the dependence of material properties on dose and dose rate is not expected to be separable for the whole range of irradiation conditions of interest, and extrapolation of rules outside the range covered by experimental results must be treated with caution.

#### 4.1.3 Influences of composition

The stabilizers and antioxidants often consist of organic molecules containing several substituted aromatic groups. They terminate degradative chain-reactions and can neutralize excited sites on the polymer chain. Typical concentrations are much less than 1% in the polymer. However, the addition of so-called antirads<sup>24)</sup> has often not proved to be useful in practice, as they affect the technical properties of the material. The mechanisms of stabilization are partly understood, and know-how is available in industry.

Long-term irradiation experiments can help to determine the optimum stabilization against radiation degradation under service conditions, and such experiments are also in progress at CERN<sup>15)</sup>. The radiation resistance of a practical cable-insulating or cable-sheathing material may also depend on the type of filler. It often consists of an inorganic powder and is much more radiation resistant than the polymer, but the bond between the two materials may be influenced.

Other additives provided as fire protection may also modify the radiation resistance of the compound, although it has been found that the fire protection itself will rarely be modified under irradiation<sup>24,25)</sup>. However, the requirements of good mechanical and electrical properties and a high radiation resistance of these compounds on the one hand, and that of fire protection and exemption of halogens on the other, can only be satisfied by a compromise in the degree of filling.

#### 4.1.4 Effects due to the environment

Typical aggressive agents present in a high-level radiation area are ozone and various nitrous oxide gases produced by radiation in air, and hydrogenated halogens or other halogen-containing volatile compounds produced by irradiation of halogen-containing materials such as PVC and certain fire-resistant materials. Of these, ozone may attack the polymer surface of the sheath and lead to typical cracks, especially if the polymer is under mechanical stress. The others also readily react with radicals, as does gaseous oxygen, but because of their low concentration should only produce surface effects.

The damage to the cable sheath and to the insulation itself may be negligible, but if cracks develop because the surface is being attacked, these environmental conditions may increase the rate of oxygen-assisted radiation degradation of the polymer, and reduce the safety margin for operation of the cable in critical places.

## 4.2 Models for the description of long-term irradiation test results

### 4.2.1 Oxygen concentration as a function of dose rate

Gaseous oxygen is available in the polymer, with a saturation concentration  $C_0$  depending on the solubility and the atmospheric pressure, and is consumed during irradiation by the formation of peroxy radicals with the

radiation-induced polymer radicals (see Table 3, line 4). The rate  $dS/dt$  at which oxygen is bound to radicals depends on the concentration of the radiation-induced radicals  $[R \cdot]$  and the oxygen concentration  $C$  with a rate constant  $k_1$ , and the oxygen concentration further depends on the diffusion constant  $\Theta$ :

$$\partial S/\partial t = k_1[R \cdot]C, \quad (8)$$

$$dC/dt = \Theta \nabla^2 C - \partial S/\partial t. \quad (9)$$

The time dependence of the concentration may be neglected in the region of mechanical damage for our sample types, as the saturation concentration starting from  $C = 0$  is reached in a few days, and at high dose rates all initially dissolved oxygen is used up at doses below 0.1 MGy.

Under steady-state conditions and for dose rates below a certain material-dependent limit (to be defined below), the oxygen concentration within the sample cross-section can be obtained, in analogy to the one-dimensional case, in a simple form for elliptic cross-sections with the radii  $p$  and  $q$  of the ellipse, as an approximation of the rectangular cross-section of the narrow region of the tensile test samples. With the dose rate  $\dot{D}$  and the generation constant for radicals  $g$ , the concentration relative to the saturation concentration becomes

$$C/C_0 = 1 - (g\dot{D}p^2/2\Theta C_0)(1/4 - x^2/p^2 - y^2/q^2)/(1 + p^2/q^2).$$

The difference between this two-dimensional solution and the one-dimensional form, obtained from the former in the limit of  $q$  infinite, is not very pronounced apart from cases near the limit of its validity, where the concentration in the centre of the sample approaches zero.

At intermediate dose rates, the concentration of gaseous oxygen becomes zero in the inner regions of the sample under steady-state conditions, and a numerical solution method must be used. In this case, the chemical reactions in this inner region correspond to high dose-rate conditions, whereas in the outer regions the formation of peroxy radicals that are typical for low dose rates continues. The transition to zero oxygen concentration somewhere in the sample will be used to define the upper limit of the region of low dose rates.

In the present experiment the dose rates varied between 5 and 200 mGy/s, and the sample thicknesses were 1 to 3 mm at a width of 4 and 6 mm in the narrow region. Using data on oxidation layer thicknesses<sup>26)</sup> for PE and EPR cable-insulating materials, the limiting dose rate below which our samples are fully penetrated by oxygen is about 30 mGy/s. At the dose rate of 60 mGy/s, about 70% of the sample volume is penetrated, and at 200 mG/s about 40%. For the PVC compounds, the oxygen penetration may be more varied according to material composition, but as our samples were rather thin in this case (see Table 1), we expect a considerable fraction of the volume to be penetrated by oxygen.

According to these considerations we suppose that for the measured values at dose rates of 60 mGy/s and more, corresponding to doses of 1 MGy and above in our case, an inner region of the sample is free of oxygen and is therefore damaged at a slower rate than the outer one. The consequences of such inhomogeneous damage on the measured mechanical properties will depend on the difference between the two regions and on the degree of damage. At small elongations, the modulus should be an average of the oxygen-free and oxygen-penetrated values according to the respective cross-sections. However, for tensile strength and elongation at break, the composite value may depend on details of the load curve, and whether cracks develop in the outer region or not. For large contributions to damage from the oxygen-penetrated region, the contribution of the inner region can be masked and the test results will be similar to the oxygen-saturated case.

These arguments could be used to explain some of the details found in the data shown qualitatively in Figs. 2 to 5, especially the apparent extrema in the ratio of long-term and short-term irradiation results for PE and PVC. However, without detailed knowledge of material composition and of oxygen permeation data, a conclusive interpretation will be difficult to obtain.

#### 4.2.2 Dose-rate dependence of end-point doses under oxygen-saturation conditions

In an application of a cable-insulating or cable-sheathing material in radiation areas, it is necessary to know the dose at which a given end-point criterion will be reached in order to determine the service lifetime. The end-point criterion may depend on the application; here we consider 100% of residual elongation at break and 50% of the initial elongation at break value.

From measurements of elongation at break with a separate variation of dose and dose rate, the required end-point dose can be obtained as a function of the service dose rate. For low dose rates, extrapolation will be necessary.

Depending on dose rate and reaction rate constants, different functional relations between the end-point dose and the dose rate can be found. The reaction chemistry treatments concern only concentrations of chemical species; the way in which these affect the measured mechanical damage is a problem on its own. However, at constant dose rates, one would expect the concentration of chain scissions or the inverse of the molecular weight to be proportional to dose. It has been found that mechanical properties of polyethylene at various low dose rates follow a master curve when

plotted as a function of molecular weight<sup>7)</sup>. Even if this master curve were not known, a specified end-point value of a mechanical property would correspond to a certain molecular weight and to a certain amount of chain scissions for comparable materials in the absence of cross-linking. As the number of chain scissions is in some way related to the amount  $S$  of oxygen bound to the polymer (see Table 3, reactions 6 and 7), the dose-rate dependence of the dose necessary to reach a specified concentration of bound oxygen should reproduce the dose-rate dependence of the end-point dose derived from mechanical tests.

If there were no propagation of radicals and each initially created peroxy radical would produce a chain scission with stable end products according to reactions 4 and 7 in Table 3, there would be no dependence of end-point dose on dose rate:

$$d[R\cdot]/dt = g\dot{D} - k_1C[R\cdot] = 0 \quad (\text{steady state})$$

$$S = g\dot{D}t = gD.$$

If there is a propagation of radicals (i.e. apart from the radicals produced by irradiation, others are continuously produced by reactions of the type 5 in Table 3 or by similar ones involving the hydroperoxides), a dose-rate dependence of the end-point dose is expected. The type of relation depends on the reaction involved and the reaction rate constants. For example, considering the processes 4, 5, and 7 in Table 3, and assuming the simple termination reaction  $2[RO_2\cdot] \xrightarrow{k_3}$  (stable products), the following rate equations hold<sup>11)</sup>:

$$d[R\cdot]/dt = g\dot{D} - k_1C[R\cdot] + k_2[R][RO_2\cdot], \quad (10)$$

$$d[RO_2\cdot]/dt = k_1C[R\cdot] - k_2[R][RO_2\cdot] - k_3[RO_2\cdot]^2. \quad (11)$$

Under steady-state conditions ( $d[R\cdot]/dt = 0$ ), ( $d[RO_2\cdot]/dt = 0$ ), we obtain:

$$dS/dt = g\dot{D} + k_2[R][RO_2\cdot], \quad (\text{from 8, 10})$$

$$[RO_2\cdot] = (g\dot{D}/k_3)^{1/2}, \quad (\text{from 10, 11})$$

$$S = gD\{1 + k_2[R]/(k_3g\dot{D})^{1/2}\}.$$

The dependence of end-point dose  $D_e$  on dose rate is, in this case,

$$D_e \sim (k_3g\dot{D})^{1/2}/\{k_2[R] + (k_3g\dot{D})^{1/2}\}. \quad (12)$$

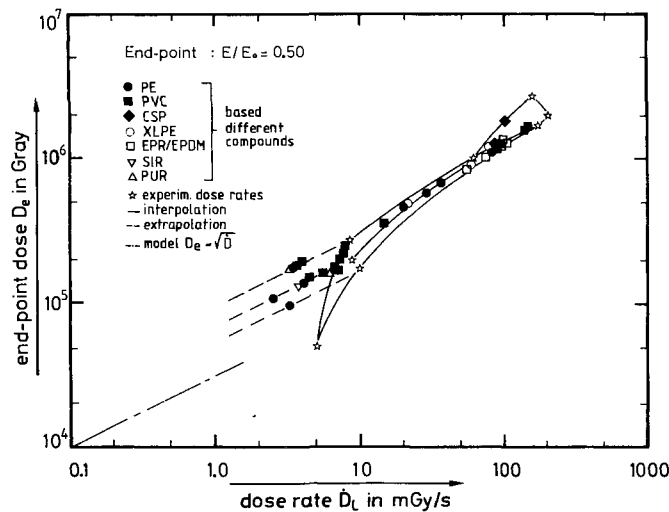
Depending on the rate constants  $k_2$  for peroxy-induced radical production and  $k_3$  for termination of this chain reaction into stable products, the end-point dose is proportional to a power  $n$  of dose rate between  $n = 1/2$  and 0.

Because the rate constant  $k_3$  is temperature-dependent and the probability for termination of the chain reaction process is influenced by the stabilization and antioxidants, the observed behaviour cannot be easily predicted for our samples.

In the present experiment, strong dose-rate effects have been detected (see Figs. 2-5), but the dependence of the end-point dose on  $\dot{D}$  cannot be extracted from these data. As dose and dose rate have not been varied independently for each material, we can determine the end-point dose only by interpolating, at the same time,  $D$  and  $\dot{D}$  at the end-point value. For each material this defines one point of the end-point dose to dose-rate relation, and can be used to find the offset between these curves if a relation of type (12) discussed above, e.g.  $D_e \sim \sqrt{\dot{D}}$ , is assumed.

In Fig. 6 the doses were determined by linear interpolation at the end-point value  $E/E_0 = 0.5$ , and the dose rates by interpolation according to the above square-root relation. Each material is represented by a symbol for the base polymer in the compound. The doses and dose rates for the measured values (see Appendix) are indicated by a star symbol, and the interpolation path used to reach the end point is shown by the continuous lines. The broken line of slope 0.5 indicates the end-point dose to dose-rate relation predicted by Eq. (12) for each material separately, in the case of the domination of peroxy-radical production over their neutralization, e.g. for weak stabilization. If the materials were highly stabilized or would favour a neutralization of peroxy radicals without chain scission (e.g. EPR), the appropriate relation could have a smaller slope, including zero.

Comparing the spread of end-point doses in Fig. 6 with that in Fig. 2 for  $E/E_0 = 0.5$ , the variation of a factor of 10 for all materials and a factor of 4 for PE alone in Fig. 2 is smaller by about a factor of 2 than the interpolated points in Fig. 6. Whilst this difference may be due to the few values at low dose rates available in our data, one is cautioned to extrapolate not too far from measured values, if the dose to dose-rate relation for the type of material in question has not been previously established.



**Fig. 6** End-point doses over dose rate for 33 different cable-insulating compounds (for symbols, see inset), for an end-point criterion of 50% reduction of elongation at break. The points have been obtained by interpolation along the thin lines between measured values at the doses and dose rates indicated by the star symbols (for details, see text). The supposed functional dependence of end-point dose on dose rate for each material separately is indicated by the slope of the dash-dotted line.

#### 4.2.3 Dose-rate dependence of end-point doses under diffusion-limited conditions and at high dose rates

As already noted in subsection 4.2.1, increasing the dose rate from the region of oxygen saturation leads to a gradient in the oxygen concentration inside the sample. When the concentration of free oxygen under steady-state conditions becomes zero in the centre of the sample, damage mechanisms typical of high dose rates or oxygen-free irradiation replace the peroxy-radical formation discussed above in that part of the sample. The cross-section of this inner region then increases with increasing dose rate, until nearly the whole sample is free of gaseous oxygen owing to oxygen consumption in a thin outer layer. We estimated that, in our case, up to a dose rate of 60 mGy/s the samples are fully penetrated by oxygen, which is of course dependent on sample dimensions and material constants. Comparing a relevant standard<sup>16)</sup>, the limit of low dose-rate irradiation is set to 30 mGy/s, and the region recommended for high dose-rate irradiations is 1 to 100 Gy/s.

We will not attempt a discussion of this whole range of dose rates in a way comparable to that for low dose rates, because our data are limited to only a small range of dose rates, and also the possible effects become more complicated with increasing dose rate. For example, in the oxygen-penetrated part of the sample, the increasing density of primary radicals can lead to reaction types that are negligible in the low dose-rate region, which renders the reaction-kinetic treatment too complex. Already the solution of the diffusion equation requires numerical methods.

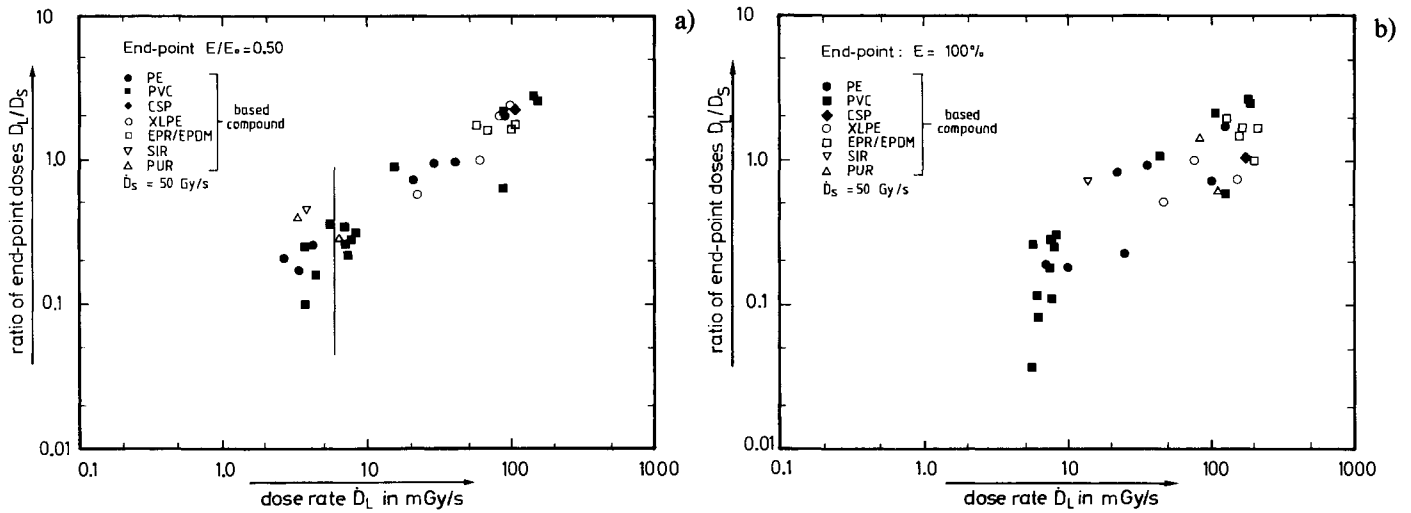
However, it can be expected that at higher dose rates the cross-linking and formation of low molecular weight products in the oxygen-free region become more and more effective with increasing dose rates, leading to a reduction in the total dose necessary to reach a given damage level. Therefore, at dose rates above those of full oxygen penetration, the exponent of the relation  $D_e \sim \dot{D}^n$  between end-point doses and dose rates should gradually change from the value  $n = 0.5$  to  $n \approx 0$ , and at very high dose rates with intense cross-linking,  $n$  could even become negative. At least, such a change of slope would be necessary in order to explain our results of having less damage during long-term irradiation than in short-term irradiation tests for some EPR- and PVC-based compounds (see Fig. 4).

The ratio of end-point doses at dose rates below 0.2 Gy/s and at 50 Gy/s is discussed in the next subsection. Whilst in the present work we did not obtain data in the intermediate region of dose rates, the first results of a subsequent irradiation experiment<sup>15)</sup> indicate that there is no marked difference for the dose rates 60 Gy/s and 8 Gy/s. Between 60 Gy/s and 0.5 Gy/s, however, the end-point doses at high damage levels were already lower by more than a factor of 2 for the lower dose rate, corresponding to  $n \approx 0.15$ . The influence of stabilizer type and concentration, however, becomes obvious only at dose rates below 0.5 Gy/s. So, whereas the dose-rate effects seem to be small for dose rates above this value — a range which is not of interest for practical application owing to the short lifetime — it is necessary to know, for each material, the typical behaviour of the end-point dose to dose-rate relation from experiment, or at least the ratio of end-point doses over this gap, in order to extrapolate from short-term tests to life exposure.

#### 4.3 Comparison of long-term and short-term irradiation results

In this subsection the ratio of end-point doses, as determined in long-term ( $D_L$ ) and short-term ( $D_S$ ) irradiations, is used to show the variation of dose-rate effects in different materials with a view to extrapolating from relatively short irradiation tests to life exposure. As stated earlier, two end-point criteria have been selected at CERN: either 50% of the initial value of elongation at break, or 100% residual elongation at break. The latter corresponds typically to less than 20% of the initial value for polyethylene cable-insulating materials, and about 40% of the initial value for polyvinyl chloride sheath compounds. For these two end-point criteria the ratio of end-point doses is plotted over the





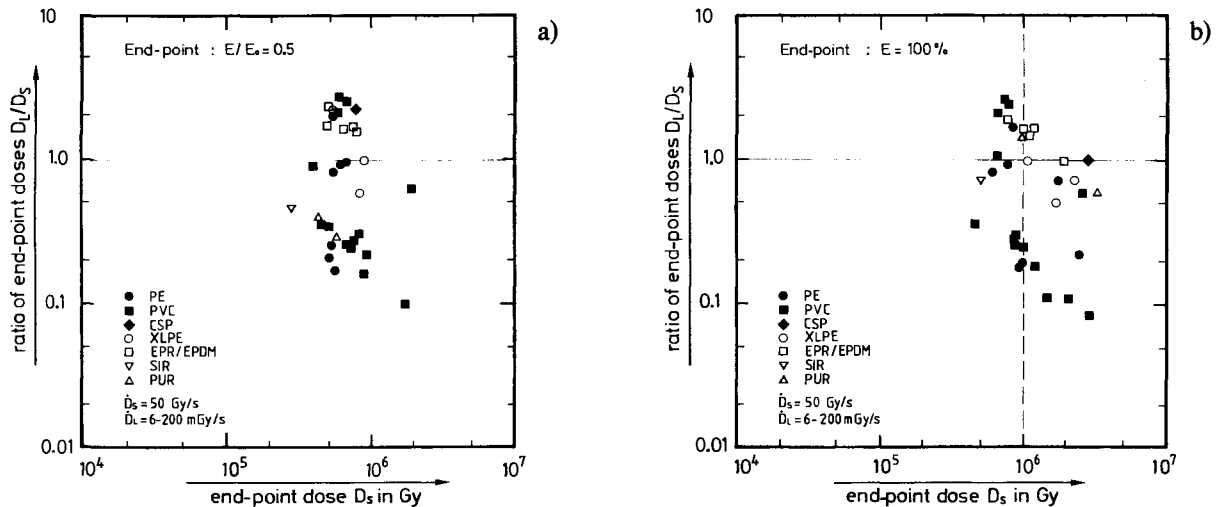
**Fig. 7** Ratio of end-point doses in long-term  $D_L$  and in short-term  $D_S$  irradiations over dose rate  $\dot{D}_L$ , for the end-point criteria  $E/E_0 = 0.5$  in (a) and  $E = 100\%$  in (b). The region of extrapolation is indicated by the shaded border line, but also several other points were obtained by extrapolation (for symbols, see inset).

corresponding dose rate of the long-term irradiation in Figs. 7a and 7b. Again, doses have been interpolated linearly at the end-point, and dose rates according to  $D_e \sim \sqrt{\dot{D}}$  as in Fig. 6. The region where extrapolation was necessary is indicated by shading. For both end-point criteria the majority of the materials have a ratio  $D_L/D_S$  less than 1, with EPR and a few others above. Most values range between 0.1 and 1, and this is the order of the factor which has to be applied to end-point doses in short-term irradiations to obtain the end-point dose for the given dose rate in long-term irradiations under the conditions of our case.

In the shaded region and for some other points, extrapolations from measured values had to be made to arrive at the end-point value. These are included to demonstrate the degree of scattering to be expected in such a case. Comparing Figs. 7a and 7b, it seems that by selecting the end-point at a higher damage level, the differences between materials are more pronounced. This depends not only on the design of the experiment, but also on the rate of change of the property with dose at the selected end-point.

Depending on the end-point criterion, the ratios of end-point doses in long-term irradiations and short-term tests are about 1 or above for dose rates above 30 mGy/s. Therefore, only for dose rates below this value have corrections to be applied in an extrapolation from short-term tests at 50 Gy/s for these materials. However, for other materials, this limit was found at about 500 mGy/s (see previous subsection). In a practical case, measurements at dose rates of the order of 0.1 Gy/s are recommended in order to support an extrapolation to lower dose rates, if the behaviour of the given material type is not known.

A simpler approach to the practical problem of estimating the probable end-point dose of a material from short-term irradiation tests is the application of safety factors to the end-point doses found in the accelerated test, or the choice of a very restrictive end-point criterion. To determine the necessary safety margin, measured values for representative materials and dose rates should be used. In Figs. 8a and 8b,  $D_L/D_S$  is shown as a function of the



**Fig. 8** Ratio of end-point doses in long-term  $D_L$  and in short-term  $D_S$  irradiation tests plotted over the end-point dose  $D_S$ , for the end-point criteria  $E/E_0 = 0.5$  in (a) and  $E = 100\%$  in (b). The limit used normally for material selection ( $10^6$  Gy in short-term tests for  $E = 100\%$ ) is indicated by the dashed line in (b).

end-point doses of the short-term test, for dose rates in the same range as in Fig. 7 and for the same end-point criteria. Up to now, an end-point dose of  $10^6$  Gy had usually been considered sufficient for the criterion at 100% residual elongation, and for 50% of the initial value a lower limit should be used. The safety factor necessary is about 0.1 in this case, as was already apparent in Fig. 7. However, it could be expected that materials with low radiation resistance at high dose rates would also show large dose-rate effects, resulting in a positive correlation of  $D_L/D_S$  with the end-point doses  $D_S$  in Fig. 8. This is clearly not the case. Instead, one may note that the variation of the safety factor due to the dose-rate effect is more than twice as important as the differences found between most materials in short-term irradiations. To compare the safety factors for different material compositions it is therefore necessary to obtain the end-point dose for a dose rate of the order of 0.1 Gy/s (which stays the same for all materials), in addition to the short-term tests. Otherwise, the material selection will be more conservative than is really necessary with respect to radiation resistance, and competing requirements such as fire resistance or electrical qualities have to be reduced.

## 5. CONCLUSIONS

To check the validity of lifetime predictions for cable-insulating and cable-sheathing materials installed at CERN accelerators, results of long-term irradiations of test samples have been obtained for a series of commercial compounds, and these have been compared with the usual short-term irradiation tests.

The present results have shown that for some types of polyethylene the reduction of elongation at break at the same dose may be up to a factor of 10 higher when irradiated at the CERN accelerator at low dose rates ( $\dot{D} \approx 10$  mGy/s), compared with the irradiation at high dose rates (50 Gy/s). The same applies for the tensile strength of PVC. For other types of PE and PVC, and also for EPR, the difference in measured values at the same dose was considerably smaller or even negligible.

A correlation of doses and dose rates, as chosen in this study, is typical for cables actually installed at CERN, where a cable passes through zones of different dose rates. Experience has shown that the degradation of mechanical properties of the polymer compounds is most pronounced in zones of high doses and proportionally high dose rates. However, these dose rates are still low enough to permit the observation of dose-rate effects due to oxygen-assisted degradation. A model description has been discussed which predicts a dependence of the time to reach the end-point criterion as the inverse of dose rate to a power between 0.5 and 1, depending on materials and stabilization. This relation could be applied to obtain an estimate of the end-point doses, in particular if some measured data that are representative of the above condition of low dose rates were available.

Another approach to the extrapolation to low dose rates is the application of safety factors to short-term irradiation test results—which has been employed at CERN up to now—or the equivalent formulation of a rather restrictive end-point criterion. The present work permits the necessary safety margin to be estimated realistically. However, in the case of power-cables with thick sheathing and an insulation thus protected against air access, the short-term test results may be perfectly representative for the insulation, which is the most critical component of a cable.

In general, there will always be the need to bridge the gap between simulation and application dose rates. Therefore, irradiation tests at low dose rates will be carried out in future on a routine basis on new compounds of cable-insulating materials, as a complement to the usual short-term tests.

## Acknowledgements

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The experimental set-up and the tests were to a large extent carried out by P. Beynel. His efficient and reliable work was an important contribution to the realization of this study.

No.	Material	Dose	Dose rate	Tensile strength	Elongation at break	Hardness Shore D		
		(MGy)	(mGy/s)	R(MPa)	E (%)	(degree)		
236	PE	0.0	---	11.5 ± 0.6	262.0 ± 3.6	48.0		
		0.50	50 000	15.6 ± 0.9	155.1 ± 3.0	49.6		
		1.0	50 000	15.0 ± 0.8	54.0 ± 1.8	51.0		
		0.20	8.9	13.4 ± 0.7	239.0 ± 10.0	44.0		
		1.0	60	12.0 ± 0.6	20.0 ± 0.8	48.0		
		2.7	160	10.3 ± 0.5	14.0 ± 5.0	48.0		
402	PE	0.0	---	18.6 ± 1.1	744.0 ± 20.0	49.0		
		1.1	50 000	18.3 ± 0.9	146.0 ± 14.0	56.1		
		2.0	50 000	18.6 ± 0.9	81.6 ± 6.0	54.6		
		0.052	5.2	15.4 ± 0.8	568.0 ± 40.0	47.0		
		1.7	170	14.8 ± 0.8	35.0 ± 1.6	51.0		
		140	PVC	0.0	---	13.5 ± 0.7	218.0 ± 3.3	34.0
0.50	50 000	11.3 ± 0.6		120.0 ± 2.7	---			
1.0	50 000	15.8 ± 0.8		52.0 ± 1.8	42.2			
5.0	50 000	16.1 ± 0.8		10.0 ± 0.4	50.4			
0.050	5.0	11.0 ± 0.7		201.0 ± 27.0	33.6			
2.0	200	7.6 ± 0.4		48.8 ± 4.0	33.0			
262	PVC	0.0	---	16.8 ± 0.9	362.0 ± 4.0	28.0		
		0.50	50 000	16.8 ± 0.9	129.9 ± 2.7	44.0		
		1.0	50 000	15.0 ± 0.7	70.8 ± 2.0	48.8		
		3.0	50 000	35.8 ± 1.8	25.5 ± 3.3	77.6		
		5.0	50 000	17.1 ± 0.9	7.5 ± 0.4	---		
		0.20	8.9	20.4 ± 1.0	208.8 ± 4.4	38.0		
		1.0	60	23.5 ± 1.2	65.0 ± 10.0	57.9		
		2.7	160	23.2 ± 1.4	51.1 ± 7.0	62.1		
		321	PVC	0.0	---	16.2 ± 0.8	198.0 ± 27.0	45.0
				0.50	50 000	13.9 ± 0.7	89.0 ± 5.0	49.0
1.0	50 000			19.4 ± 1.0	38.5 ± 4.5	57.0		
3.0	50 000			27.0 ± 1.4	17.1 ± 3.3	74.4		
5.0	50 000			20.7 ± 1.4	2.4 ± 0.9	75.2		
0.20	8.9			11.9 ± 0.6	75.2 ± 8.0	39.0		
1.0	60			14.4 ± 0.7	41.6 ± 3.6	47.0		
2.7	160			11.8 ± 0.6	46.2 ± 6.0	57.0		
322	PVC			0.0	---	16.9 ± 0.9	236.0 ± 16.0	34.0
				0.50	50 000	13.3 ± 0.8	144.8 ± 8.0	36.0
		1.0	50 000	19.0 ± 1.3	65.0 ± 2.0	---		
		5.0	50 000	17.2 ± 1.8	4.4 ± 0.9	69.0		
		0.050	5.0	14.8 ± 0.8	243.0 ± 14.0	37.0		
		2.0	200	6.5 ± 0.3	94.0 ± 11.0	39.0		

No.	Material	Dose	Dose rate	Tensile strength	Elongation at break	Hardness Shore D		
		(MGy)	(mGy/s)	R (MPa)	E (%)	(degree)		
331	PVC	0.0	---	14.1 ± 0.7	250.0 ± 14.0	33.0		
		0.50	50 000	13.4 ± 0.7	142.2 ± 6.0	37.0		
		1.0	50 000	15.4 ± 0.8	120.0 ± 11.0	38.0		
		3.0	50 000	17.7 ± 0.9	30.8 ± 1.5	61.5		
		5.0	50 000	17.3 ± 0.9	4.0 ± 0.2	69.9		
		0.20	8.9	9.4 ± 0.4	68.6 ± 7.0	39.0		
		1.0	60	8.8 ± 0.4	24.0 ± 5.4	39.0		
		2.7	160	7.1 ± 0.4	49.6 ± 4.4	42.0		
		366	PVC	0.0	---	15.2 ± 0.8	228.0 ± 15.0	35.6
				0.50	50 000	13.2 ± 0.6	124.6 ± 7.0	31.6
1.0	50 000			15.8 ± 0.8	68.0 ± 8.8	37.6		
5.0	50 000			12.0 ± 0.8	5.4 ± 2.2	63.0		
0.050	5.0			14.3 ± 0.7	236.0 ± 4.0	40.0		
0.17	10			12.5 ± 0.6	188.0 ± 11.0	42.0		
2.0	200			7.7 ± 0.4	94.5 ± 3.0	37.0		
T.A	PVC			0.0	---	13.0 ± 0.7	270.0 ± 14.0	33.0
				1.0	50 000	17.3 ± 1.2	189.7 ± 7.0	25.0
				3.0	50 000	14.2 ± 2.0	77.4 ± 9.0	35.0
		5.0	50 000	17.4 ± 2.0	32.4 ± 2.4	38.0		
		0.050	5.0	12.4 ± 0.7	272.0 ± 4.5	24.0		
		2.0	200	2.5 ± 0.3	46.2 ± 2.0	16.0		
		2.7	160	4.5 ± 0.8	90.3 ± 7.0	30.0		
		T.B	PVC	0.0	---	16.4 ± 0.8	293.0 ± 10.0	26.0
1.0	50 000			16.6 ± 0.8	181.6 ± 4.4	25.0		
3.0	50 000			13.9 ± 0.7	91.0 ± 2.4	31.0		
5.0	50 000			14.0 ± 0.9	39.0 ± 6.0	31.0		
0.27	8.4			3.8 ± 0.2	70.0 ± 2.0	22.0		
2.7	160			3.0 ± 0.2	90.3 ± 7.0	15.0		
T.E.	PVC			0.0	---	18.3 ± 0.9	298.0 ± 4.4	47.0
		0.50	50 000	10.1 ± 0.7	149.4 ± 6.0	39.6		
		1.0	50 000	18.0 ± 0.9	128.1 ± 3.0	36.0		
		3.0	50 000	15.6 ± 1.0	73.5 ± 5.0	43.0		
		0.050	5.0	16.6 ± 0.9	296.0 ± 16.0	31.0		
		0.27	8.4	5.9 ± 0.3	56.0 ± 5.0	29.0		
		2.0	200	4.2 ± 0.3	62.0 ± 4.4	26.0		
		2.7	160	4.9 ± 0.6	57.6 ± 6.6	30.0		

No.	Material	Dose	Dose rate	Tensile strength	Elongation at break	Hardness Shore D
		(MGy)	(mGy/s)	R(MPa)	E (%)	(degree)
T.O	PVC	0.0	---	17.0 ± 1.2	226.0 ± 10.0	24.0
		0.50	50 000	20.8 ± 3.6	170.0 ± 24.0	41.6
		1.0	50 000	29.5 ± 4.5	77.4 ± 9.0	51.6
		3.0	50 000	32.5 ± 5.5	40.8 ± 8.0	69.0
		0.050	5.0	13.5 ± 3.0	244.0 ± 22.0	27.0
		0.27	8.4	7.0 ± 0.4	97.2 ± 9.0	24.0
		2.0	200	13.8 ± 3.6	135.9 ± 9.0	21.0
T.S	PVC	0.0	---	17.5 ± 1.0	272.0 ± 22.0	27.0
		0.50	50 000	16.0 ± 2.2	198.0 ± 18.0	34.0
		1.0	50 000	21.3 ± 3.0	66.0 ± 12.0	43.6
		3.0	50 000	23.5 ± 1.3	19.0 ± 2.2	59.4
		0.27	8.4	6.9 ± 0.4	63.7 ± 7.7	29.0
		2.7	160	9.4 ± 1.2	58.8 ± 6.0	45.0
T.U	PVC	0.0	---	14.1 ± 1.0	288.0 ± 24.0	21.0
		0.50	50 000	9.7 ± 0.5	172.4 ± 3.6	33.0
		1.0	50 000	14.2 ± 0.8	98.0 ± 11.0	33.6
		3.0	50 000	19.0 ± 2.2	35.7 ± 6.3	36.6
		0.050	5.0	11.8 ± 0.8	239.2 ± 8.0	19.0
		0.27	8.4	5.4 ± 0.3	82.0 ± 5.0	19.0
		2.0	200	5.0 ± 1.0	63.0 ± 13.0	23.0
		2.7	160	9.1 ± 1.0	75.0 ± 6.0	29.0
T.W	PVC	0.0	---	17.3 ± 0.9	225.0 ± 3.6	20.0
		0.50	50 000	14.0 ± 1.8	172.2 ± 7.0	29.5
		1.0	50 000	17.0 ± 0.8	69.9 ± 2.7	28.5
		3.0	50 000	15.0 ± 2.2	30.0 ± 5.0	40.6
		0.050	5.0	12.4 ± 1.3	226.0 ± 16.0	23.0
		0.27	8.4	5.2 ± 0.3	80.0 ± 2.2	23.0
		2.0	200	4.8 ± 1.3	64.0 ± 5.5	22.0
		2.7	160	6.8 ± 0.8	61.0 ± 5.0	24.0
T.X	PVC	0.0	---	14.2 ± 1.6	219.0 ± 12.0	20.0
		0.50	50 000	8.9 ± 0.4	126.6 ± 3.0	33.0
		1.0	50 000	12.0 ± 0.7	106.5 ± 2.7	35.0
		3.0	50 000	13.4 ± 0.7	39.9 ± 3.0	51.0
		0.050	5.0	9.3 ± 0.5	238.0 ± 13.0	22.0
		0.27	8.4	5.3 ± 0.3	48.8 ± 2.0	21.0
		2.0	200	4.1 ± 0.2	39.0 ± 1.8	25.0
		2.7	160	3.5 ± 0.5	33.5 ± 5.0	22.0

No.	Material	Dose	Dose rate	Tensile strength	Elongation at break	Hardness Shore D
		(MGy)	(mGy/s)	R(MPa)	E (%)	(degree)
320	XLPE	0.0	---	21.2 ± 2.2	450.0 ± 22.0	39.0
		0.50	50 000	15.6 ± 2.0	296.0 ± 22.0	41.0
		1.0	50 000	12.7 ± 0.7	187.0 ± 15.0	44.0
		2.0	50 000	12.5 ± 0.7	64.5 ± 2.7	44.6
		3.0	50 000	10.6 ± 0.5	37.2 ± 1.8	46.6
		5.0	50 000	7.0 ± 0.4	24.8 ± 1.0	40.0
		0.052	5.2	22.1 ± 1.1	530.0 ± 11.0	41.6
		0.20	8.9	12.6 ± 0.9	314.0 ± 18.0	36.6
		1.0	60	13.4 ± 0.7	56.8 ± 4.4	43.0
		1.7	170	9.3 ± 0.4	28.7 ± 6.3	39.0
		2.7	160	7.4 ± 0.4	15.6 ± 3.0	43.0
324	XLPE	0.0	---	20.0 ± 1.0	417.0 ± 5.0	45.0
		0.50	50 000	16.8 ± 2.7	215.0 ± 45.0	43.0
		1.0	50 000	15.0 ± 1.6	134.0 ± 20.0	---
		5.0	50 000	6.5 ± 0.7	25.0 ± 5.0	38.0
		0.052	5.2	21.2 ± 1.1	422.0 ± 11.0	38.0
		1.7	170	12.3 ± 0.7	93.8 ± 7.0	46.0
455	XLPE	0.0	---	15.9 ± 0.8	239.0 ± 14.0	50.1
		1.0	50 000	25.3 ± 1.3	103.6 ± 6.3	54.9
		2.0	50 000	22.2 ± 1.1	47.6 ± 1.8	54.9
		0.052	5.2	16.3 ± 0.8	220.0 ± 16.0	49.0
		1.7	170	13.4 ± 0.7	21.6 ± 2.2	54.9
126	EPR	0.0	---	7.5 ± 0.4	256.0 ± 3.6	26.0
		0.50	50 000	8.8 ± 0.4	127.2 ± 2.7	30.0
		1.0	50 000	8.8 ± 0.4	75.2 ± 2.2	32.0
		2.0	50 000	9.0 ± 0.4	56.8 ± 4.0	30.0
		5.0	50 000	11.6 ± 1.6	27.2 ± 1.1	---
		0.052	5.2	8.0 ± 0.4	268.0 ± 22.0	29.0
		1.7	170	8.8 ± 0.5	70.2 ± 6.0	35.0
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375	EPR	0.0	---	5.5 ± 0.3	406.0 ± 70.0	13.5
		1.1	50 000	6.4 ± 0.3	102.0 ± 27.0	20.0
		2.0	50 000	6.9 ± 0.3	66.0 ± 11.0	22.0
		0.052	5.2	5.7 ± 0.3	385.0 ± 50.0	16.0
		0.17	10	6.4 ± 0.3	375.0 ± 10.0	16.0
		1.7	170	5.5 ± 0.8	133.7 ± 7.0	19.0
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453	EPR	0.0	---	6.1 ± 0.3	339.0 ± 27.0	15.0
		0.50	50 000	7.0 ± 0.4	165.0 ± 10.0	19.0
		1.0	50 000	7.8 ± 0.4	99.2 ± 8.0	21.0
		2.0	50 000	8.2 ± 0.5	70.0 ± 18.0	23.5
		5.0	50 000	10.4 ± 0.6	41.6 ± 4.0	29.0
		0.052	5.2	6.1 ± 0.3	240.0 ± 20.0	17.0
		1.7	170	6.5 ± 0.3	96.0 ± 14.0	20.0
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No.	Material	Dose (MGy)	Dose rate (mGy/s)	Tensile strength R (MPa)	Elongation at break E (%)	Hardness Shore D (degree)
395	EPDM	0.0	---	9.3 ± 1.4	284.0 ± 22.0	14.0
		1.0	50 000	6.7 ± 1.0	103.6 ± 6.3	14.0
		2.0	50 000	6.4 ± 0.9	68.4 ± 2.7	27.5
		0.052	5.2	7.9 ± 0.4	270.0 ± 16.0	13.0
		1.7	170	6.1 ± 0.3	92.1 ± 2.7	16.0
		399	EPDM	0.0	---	7.9 ± 0.5
		0.50	50 000	6.6 ± 0.4	312.0 ± 16.0	17.0
		1.0	50 000	6.7 ± 0.3	194.0 ± 14.0	17.0
		2.0	50 000	8.4 ± 0.4	91.0 ± 6.3	23.5
		5.0	50 000	9.9 ± 0.5	53.4 ± 6.0	28.5
		0.052	5.2	6.9 ± 0.3	498.0 ± 30.0	14.0
		1.7	170	6.1 ± 0.4	137.6 ± 8.0	19.0
11	PUR	0.0	---	54.6 ± 2.7	756.0 ± 4.4	48.8
		0.50	50 000	21.3 ± 1.4	416.0 ± 4.0	43.8
		1.0	50 000	13.7 ± 0.7	181.2 ± 3.3	42.6
		5.0	50 000	15.3 ± 1.0	37.2 ± 1.4	52.8
		0.20	8.9	9.9 ± 0.5	312.0 ± 20.0	29.0
		1.0	60	8.4 ± 0.4	152.0 ± 11.0	31.0
		2.7	160	7.3 ± 0.4	62.5 ± 4.5	31.0
		12	PUR	0.0	---	43.8 ± 2.2
		0.50	50 000	14.8 ± 0.8	220.8 ± 3.3	44.4
		1.0	50 000	12.5 ± 0.6	98.0 ± 2.4	43.2
		5.0	50 000	16.2 ± 1.6	20.4 ± 0.9	59.1
		0.27	8.4	9.4 ± 0.4	106.0 ± 10.0	30.0
		1.0	60	10.0 ± 0.6	118.0 ± 15.0	35.0
		2.7	160	9.2 ± 0.4	53.6 ± 2.0	33.0
109	SIR	0.0	---	7.8 ± 0.4	548.0 ± 4.4	10.0
		0.50	50 000	4.8 ± 1.8	54.4 ± 1.8	28.5
		1.0	50 000	3.3 ± 1.3	15.2 ± 0.6	41.6
		0.20	8.9	6.8 ± 0.3	113.7 ± 3.6	16.0
		1.0	60	5.9 ± 0.6	27.0 ± 12.0	19.0
		2.7	160	4.3 ± 1.2	11.2 ± 4.4	29.0
135	CSP	0.0	---	16.0 ± 2.0	440.0 ± 4.0	11.0
		0.50	50 000	15.6 ± 1.8	284.0 ± 3.6	---
		1.0	50 000	14.4 ± 0.9	171.9 ± 3.3	---
		5.0	50 000	13.8 ± 1.6	10.0 ± 0.4	---
		0.20	8.9	15.4 ± 1.8	393.0 ± 27.0	13.0
		1.0	60	17.6 ± 1.0	312.0 ± 18.0	19.0
		2.7	160	12.8 ± 1.8	121.0 ± 11.0	29.0