CERN 96-05
4 July 1996

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

RESULTS OF RADIATION TESTS AT CRYOGENIC TEMPERATURE ON SOME SELECTED ORGANIC MATERIALS FOR THE LHC

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GENEVA
1996

CERN–Service d'information scientifique–RD/965–2500–juillet 1996

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ISSN 0007-8328
ISBN 92-9083-086-7

ABSTRACT

Future multi-TeV particle accelerators like the CERN Large Hadron Collider (LHC) will use superconducting magnets where organic materials will be exposed to high radiation levels at temperatures as low as 2 K. A representative selection of organic materials comprising insulating films, cable insulations, and epoxy-type impregnated resins were exposed to neutron and gamma radiation of a nuclear reactor. Depending on the type of materials, the integrated radiation doses varied between 180 kGy and 155 MGy. During irradiation, the samples were kept close to the boiling temperature of liquid nitrogen i.e. ~ 80 K and thereafter stored in liquid nitrogen and transferred at the same temperature into the testing device for measurement of tensile and flexural strength. Tests were carried out on the same materials at similar dose rates at room temperature, and the results were compared with those obtained at cryogenic temperature. They show that, within the selected dose range, a number of organic materials are suitable for use in the radiation field of the LHC at cryogenic temperature.

CONTENTS

1. INTRODUCTION

For the selection of polymer-based materials to be used in radiation environments, radiation-resistance tests are performed at CERN on a routine basis in accordance with the IEC 544 standard [1]; flexural tests are performed on rigid plastics, resins and composites, and tensile tests are performed on flexible plastics and rubbers, and the results are published [2]. With one exception [3], the irradiations and the mechanical tests have always been carried out at room temperature. In Ref. [4], the materials have been tested at 77 K prior to and after irradiation at room temperature up to a dose of 1.7×10^7 Gy.

With the next generation of high-energy particle accelerators and detectors, many materials will have to be used at temperatures as low as 2 K [5]. It is well known that thermal and mechanical properties of polymers are temperature sensitive; for example, the specific heat generally falls by more than two orders of magnitude between 300 K and 4 K, and the ultimate deformation is reduced to a few percent [3, 4]. It is therefore necessary to check whether the mechanical radiation tests performed at room temperature are still representative of the degradation at cryogenic temperature.

For many years, various types of (fibre-reinforced) plastics have been tested after electron, gamma, and reactor irradiations at the Atomic Institute of the Austrian Universities (ATI) in Vienna. Materials are tested in tension as well as intralaminar fracture modes I and II. Fracture mechanical tests in the intralaminar (crack-opening) mode I (splitting tests) and the intralaminar (shear) mode II ('punch-through-shear tests') were developed and proposed. In addition, three-point-bending and short-beam-shear tests are also performed on various laminates, in order to investigate the flexural and interlaminar shear behaviour of selected material compositions. After ambient or low-temperature (5 or 80 K) irradiation, the composites are tested at room temperature and/or at 77 K with and without warm-up to room temperature prior to testing. The influence of the irradiation environment, the irradiation and testing temperature, as well as of the annealing cycle and the type of the fibre reinforcement on the (fracture mechanical) properties of the materials is investigated [6].

The radiation behaviour of the silicon diodes for the quench protection of the Large Hadron Collider (LHC) magnets is also under investigation at CERN [7]. The response of the dosimeters used to record the absorbed doses has been assessed [8].

In the USA, a selection of materials foreseen for the Superconducting Super Collider project have been irradiated at 4 K with an electron beam, and tested at 77 K after intermediate warm-up to room temperature [9].

This paper presents the results of a test programme carried out in a collaboration between CERN and the ATI to irradiate and test, at liquid-nitrogen temperature, a selection of organic materials to be used as insulations in the LHC. A summary of these results was also presented at the International Cryogenic Materials Conference in Columbus, Ohio in July 1995 [10].

2. EXPECTED DOSES IN THE LHC

To prevent resistive transition of the superconducting state of the LHC magnets, the dose rate deposition due to beam losses will have to be limited to very low values. The alarm threshold of the beam-loss monitors will be set to a loss of the order of 10^6 protons per second and per metre. It is expected that the loss in most of the dipole magnets will be one-tenth of this value. The corresponding dose rates are deduced from energy-deposition and transport calculations taking into account the geometry and the density of the materials. The calculations have shown that the proton energy is fully deposited in the magnet volume [11]. The lost high-energy protons will induce nuclear cascades in the components which will lead to neutron (or neutron-equivalent) exposures.

Assuming the beam conditions given in Table 1, the corresponding dose and fluence levels will be of the order of 7 kGy and 2×10^{13} n cm^{-2} per year for most of the dipole magnets (Fig. 1). The most exposed dipoles could be subjected to doses 10 times higher than these figures, and the quadrupole magnets to even higher values, reaching the megagray range (MGy) or more.

At this level of radiation, it is not expected that resin-based insulating materials will suffer significantly from mechanical radiation damage. Common cable insulating materials and rigid thermoplastics usually show mild to severe degradation at these dose levels. In order to check the behaviour of the resin-based insulations and to be able to make the best choice for the cable and film materials, it was decided to carry out this radiation test programme in a cryogenic environment.

Table 1

Expected beam parameters in the LHC

Proton beam energy	2 x 7 TeV
Beam intensity	2 x 540 mA
Annual protons loss	1.65×10^{11} protons per metre

3. THE SELECTED MATERIALS

The materials selected for this programme are being considered for the LHC machine and experimental detectors, they are described below and listed in Table 2.

It should be noted that all the selected materials are halogen-free. The cable insulations have satisfactory oxygen and temperature indices, and the rigid materials present a UL–94 rating of V–0 (sometimes V–1), complying with the CERN Safety Instruction No. 41. This does not automatically imply that the final components made with these materials will fulfil all safety aspects, for instance cables will have to pass the IEC 332 fire test [12].

The film materials range from the most common PETP (polyethylene-terephtalate, Mylar) to the most expensive PEEK (polyether-ether-ketone, Litrex), as well as PI (polyimide, Kapton). They are being proposed for the thermal superinsulation (thickness of a few micrometres) or for the primary electrical insulation of the magnet coils (thickness of the order of 100 μm).

Among the selected cable insulations, some are known to be sensitive to oxygen degradation; their degradation in a cryogenic fluid could be less pronounced. The rubber insulations have been selected because they usually offer a better long-term radiation resistance. These materials are also known to be very sensitive to temperature.

The epoxy resins without filler R 422 and R 423 have been selected because their radiation behaviour is already well known, and for comparison with the tests carried out by M. Van de Voorde et al. 20 years ago on very similar epoxy resins [2, 3].

The pure epoxy moulding compounds XB 3183 and XB 3192, and the rigid high-performance thermoplastics PEI (polyether-imide), PES (polyether-sulfone) and PSU (polysulfone) have been selected for their interesting properties and their promising radiation behaviour at room temperature [13, 14].

The prepregs have been proposed by suppliers for the secondary electrical insulation of the LHC magnet coils [15], and the carbon/epoxy composites for the ‘cold feet’ of the cryostat.

Table 2

List of selected materials

Ref. No.	Material	Type
M 701	Mylar sheet (250 µm)	Polyethylene terephtalate
M 702	Kapton H film (125 µm)	Polymide, pure, amorphous
M 702′	Kapton AH film (125 µm)	Polyimide + $Al_2(OH)_3$
M 703	Litrex a film (125 µm)	Polyether-etherketone (amorphous)
C 763	Cable insulation	EPR + acetate copolymer 85–2/179
C 764	Cable sheath	Vinyl Acetate Copolymer thermoplastic 85–4/20
C 1011	Wire insulation	Olisafe (= Siltem) (PEI + silicone)
C 1027	Cable insulation	Polyethylene DFDM 6005
C 1028	Cable sheath	Polyolefin EVA BPD 537
C 1047	Cable sheath	EPR = ethylene-propylene rubber
C 1048	Cable sheath	EVA = ethylene-vinyl acetate
R 422	Epoxy resin	Araldite EPN1138/MY745/CY221/HY905/DY73
R 423	Epoxy resin	Araldite MY 745/HY 906/DY 073 (100/90/1.5)
R 453	Epoxy moulding compound	XB 3183
R 455	Epoxy moulding compound	XB 3192
R 533	Thermoplastic resin	PEI = polyether-imide
R 534	Thermoplastic resin	PES = polyether-sulfone
R 535	Thermoplastic resin	PSU = polysulfone
R 538	Epoxy laminate (prepreg)	Vetronite epoxy G 11 (epoxy + glass)
R 545	Epoxy laminate (prepreg)	Epoxy + glass fibres
R 546	Epoxy laminate (prepreg)	Vetronite (epoxy + glass)
R 547	Epoxy laminate (prepreg)	Epoxy + E glass fibres
R 548	Epoxy laminate (prepreg)	Epoxy + E glass fibres + Kevlar
R 549	Composite	Epoxy + carbon fibres
R 550	Composite	Epoxy + carbon fibres

4. IRRADIATION CONDITIONS AND DOSIMETRY

4.1 Irradiations at Room Temperature (RT)

CERN uses the following two irradiation sources for room-temperature (RT) tests:

1) In the ASTRA 7 MW pool reactor in Seibersdorf (Austria), the 'Ebene 1' position is in the pool, 26 cm away from the reactor core. The irradiation container is ventilated by air and the temperature is kept below 60°C. The doses are measured by means of an ionizing chamber for

CH_2-equivalent materials. Figure 2 shows the reactor configuration, the irradiation container, and the gamma and neutron doses distributions. The dose rate is in the order of 200 kGy/h, and the contribution of thermal and fast-neutron flux density to the total dose is less than 5%. Therefore, no correction has to be calculated for material-specific compositions.

2) The industrial cobalt source Ionisos in Dagneux (France) is a panoramic 2×10^{15} Bq source delivering a dose rate of the order of 4 kGy/h. The irradiations are made in air at ambient temperature. This source is used for total absorbed doses up to 1 MGy.

4.2 Irradiations at 77 K

The irradiations at liquid-nitrogen temperature (77 K) were carried out in the nuclear research reactor IVV-2M (15 MW) in Zarechny of the Institute of Metal Physics in Ekaterinburg (Russia). Figure 3 shows the low-temperature irradiation facility located in one of the 60 mm holes and consisting of a cryostat which is supplied with ultra-pure liquid nitrogen in order to minimize air (oxygen) contaminations, which are known to lead to ozone and NOx production under irradiation. In this position, the samples have been irradiated in an ultra-pure aluminium container.

Neutron flux densities were measured by several nuclear reactions, and the neutron flux density distribution was assessed by a computer code. The total neutron flux density is 3.76×10^{14} cm^{-2} s^{-1}. The flux density of the neutrons with an energy above 0.1 MeV is 1.6×10^{14} cm^{-2} s^{-1}. These high neutron flux densities lead to a neutron-dose contribution of about 75% of the total dose, this percentage depending on the exact composition of the material.

The total dose rate was measured by calorimetry methods at full power. The results are the following: 1.3×10^7 Gy/h in graphite and 2.3×10^7 Gy/h in polyethylene.

These data refer to the total dose deposited in the materials by the entire gamma and neutron spectrum. In the following, all the doses are quoted in terms of the above-given experimental polyethylene dose rate of 2.3×10^7 Gy/h.

These measurements were compared with damage calculations according to the computer code SPECTER for two materials of a current research programme for which the composition is well known. These materials were ISOVAL 10/S from Isovolta AG, Wiener Neudorf, Austria, and ZI-003 from Shikibo Ltd., Osaka, Japan. The compositions of the resins, as well as the doses deposited in them by the neutrons and by pure gamma radiation are listed in Table 3 and compared with 'polyethylene dosimetry'. It will be noted immediately that the relative contributions of both kinds of radiation depend to a major extent on the hydrogen content of the material. Hence, for low-H materials, polyethylene dosimetry will result in dose errors of the order of 5%, whereas this error increases to ~ 45% in the case of a material with higher hydrogen content.

Table 3

Damage calculations according to SPECTER for Isoval 10/S and ZI-003:
Fast neutron fluence: 1×10^{22} m^{-2} (E > 0.1 MeV). Total neutron fluence: 2.35×10^{22} m^{-2}.
Irradiation time: 1.74 h. Gamma dose: 1.88×10^7 Gy (1.08×10^7 Gy h^{-1})

Material	H (wt %/Gy)	C (wt %/Gy)	O (wt %/Gy)	Total neutrons (Gy)	Total gamma rays (Gy)	Total neutrons and gamma rays (Gy)	Polyethylene dosimetry (Exp.: 2.3×10^7 Gy/h) (Gy)
Isoval 10/S	7 1.65×10^7	76 2.86×10^6	17 3.85×10^5	1.97×10^7	1.88×10^7	3.85×10^7	4.00×10^7
ZI-003	15 3.52×10^7	75 2.82×10^6	10 3.82×10^5	3.84×10^7	1.88×10^7	5.72×10^7	4.00×10^7

Based on these considerations, the reactor power and the irradiation times required for the present irradiation programme were estimated. For the low-dose irradiations (Mylar films, cable insulation and resins 533–535) a reduced reactor power of 0.25 and 2.5 MW, respectively, was chosen and the irradiation time fixed to 35 minutes. All the other irradiations were made at full reactor power for times between 55 and 550 minutes. The actual dose rates are shown in Table 4.

Table 4

Container	Dose	Dose-rate	Material
A1	**184 kGy**	**88 Gy/s**	Mylar Cable insulation 763 Cable insulation 764 Cable insulation 1011 Cable insulation 1027 Cable insulation 1028 Cable insulation 1047 Cable insulation 1048
C1	**2.03 MGy**	**967 Gy/s**	Cable insulation 763 Cable insulation 764 Cable insulation. 1011 Cable insulation. 1027 Cable insulation 1028 Cable insulation. 1047 Cable insulation 1048
C2	**1.66 MGy**	**790 Gy/s**	Mylar Resin 533 Resin 534 Resin 535
E1	**14.38 MGy**	**4.4 kGy/s**	Cable insulation 1011 PEEK a PEEK c Kapton a Resin 422 Resin 423
E2	**13.68 MGy**	**4.2 kGy/s**	Resin 453 Resin 455 Prepreg 538 Prepreg 545 Prepreg 546
E4	**19.46 MGy**	**5.9 kGy/s**	Prepreg 547 Prepreg 548
E5	**19.46 MGy**	**5.9 kGy/s**	Epoxy/Carbon 549 Epoxy/Carbon 550
F1	**35.2 MGy**	**3.7 kGy/s**	PEEK a PEEK c Kapton H Kapton a Resin 422 Resin 423
F2	**37.33 MGy**	**3.9 kGy/s**	Resin 455 Resin 534 Prepreg 538 Prepreg 545 Prepreg 546
G1	**119.1 MGy**	**3.6 kGy/s**	PEEK a PEEK c Kapton H Kapton a Resin 422 Resin 423
G3	**155.7 MGy**	**4.7 kGy/s**	Prepreg 547 Prepreg 548
G4	**155.7 MGy**	**4.7 kGy/s**	Epoxy/Carbon 549 Epoxy/Carbon 550

Not all the runs went completely smoothly. In one case, a container filled with prepregs R 547 and R 548 and composites R 549 and R 550 showed a sudden temperature excursion within the irradiation facility (6 minutes up to a temperature of 270 K) at a dose level of about 12 MGy, although the second thermocouple mounted inside the container still indicated regular temperature conditions (77 K), i.e. no loss of coolant had occurred in the cryostat. Since later runs with the same kind of samples did not lead to comparable problems, it was not possible to explain the incident. Table 5 lists the missing samples after irradiation.

Table 5

List of missing samples

Ref. No.	Material	Dose	Missing
C 764	Cable insulation	0.184 MGy	2 samples
C 764	Cable insulation	2 MGy	1 sample
C 1028	Cable insulation	0	1 sample
M 702	Kapton H film (125 μm)	14.4 MGy	lost
R 533	PEI resin	119 MGy	lost
R 453	Epoxy resin	119 MGy	lost
R 538	Vetronite laminate	156 MGy	lost
R 545	Epoxy laminate	156 MGy	lost
R 546	Vetronite laminate	156 MGy	lost
R 547	Epoxy laminate	37 MGy	temperature rise
R 548	Epoxy laminate	37 MGy	temperature rise
R 549	Carbon/epoxy composite	37 MGy	temperature rise
R 550	Carbon/epoxy composite	37 MGy	temperature rise

After completion of the mechanical tests, severe gas release was noted from resins R 422 and R 423. During their warm-up to RT, they suddenly started to burn partially ('char'), emitting thick brown smoke.

Two further sets of samples did not completely survive the irradiation programme. Some of the samples of cable insulation 763 and 764 embrittled so heavily that they desintegrated during mounting onto the grips. In addition, several films of M 702 could not be found in the irradiation container upon opening after irradiation.

5. MECHANICAL TESTS

Mechanical tests were performed according to the recommendations of the IEC 544 standard [1]. The rigid materials were submitted to three-point flexural tests carried out in accordance with the ISO 178 standard. The flexible materials were submitted to tensile tests carried out in accordance with the ISO R527 standard (dumbbell samples).

The tests at 77 K (prior to and after irradiation) have been carried out at Ekaterinburg without warm-up between the irradiation and the test. Some authors claim that the test procedure is more severe if the samples are allowed to warm up between the irradiation and the mechanical tests [16]. Most of the materials have been fully tested at CERN at RT, four were only tested at zero dose (prior to irradiation).

For the flexural tests carried out at CERN at RT, the speed of the crosshead was 2 mm/min for the more rigid and more brittle materials, and 5 mm/min for the semi-rigid materials. The span is 67 mm for all thicknesses of samples between 2 and 5 mm. For each measuring point five samples were tested.

At Ekaterinburg, the flexural tests at 77 K were carried out at a speed of 3 mm/min, the span is 50 mm. For each measuring point three samples were tested. Some zero-dose tests have also been carried out on this geometry at RT for comparison with the CERN results; they agree very well as expected.

The tensile tests were carried out at a speed of 50 mm/min at CERN, at 30 mm/min at Ekaterinburg for the ambient-temperature (zero-dose) tests, and at 3 mm/min for the zero-dose and irradiated samples at 77 K. The thickness of the samples ranges between a few tens of micrometres for the films and 1.5 mm for the cable sheaths.

6. RESULTS AND DISCUSSION

The results are presented and discussed separately for each type of material. For the assessment of the radiation degradation of a material, the IEC 544 standard defines a radiation index (RI) as being the logarithm (base 10) of the absorbed dose (in Gray) at which the critical property is reduced to 50% of its initial value. For flexible materials, the elongation at break is recommended as being the critical property. The ultimate flexural strength (UFS) is recommended for rigid plastics, but our experience has shown that the deformation is sometimes more sensitive to radiation than the strength [17]. In this experiment under cryogenic conditions, this also applies to the flexural modulus.

6.1 Films

Figures 4–7 present the mechanical test results of the PETP (Mylar), PI (Kapton) and PEEK (Litrex) films tested at RT and at 77 K. As expected, the initial value of the ultimate tensile strength (UTS) is higher at 77 K than at RT, while the elongation is considerably reduced.

At both temperatures, the tensile strength remains almost constant up to the highest dose, which was 1.7 MGy for the Mylar film and 119 MGy for the Kapton and Litrex films. The important difference between the two irradiation conditions appears in the evolution of the ultimate elongation: when the samples are irradiated in air at RT, they are degraded by radiation and oxidation, while if they are irradiated in liquid nitrogen, their ultimate elongation stays almost constant, therefore $RI_{77K} > RI_{RT}$ (see Figs. 4–7).

Some Kapton H films (dose 14 MGy) could not be found in the irradiation container upon opening after irradiation.

6.2 Cable insulations

Figures 8–14 present the evolution of the mechanical properties with dose. Again, the initial value of the UTS is higher at 77 K than at RT, while the elongation at 77 K is dramatically reduced to a few percent. Because of this drastic reduction of the elongation at break, and although the UTS remains in most cases constant up to 14 MGy, the most common cable insulations such as polyolefins and rubbers cannot be used at cryogenic temperature. For example, some cable insulations became so brittle that they disintegrated during mounting on the test grips (e.g. C 763 and C 764).

6.3 High-performance thermoplastics

In the case of these high-performance thermoplastics, PEI (533), PES (534) and PSU (535), the change of the initial mechanical properties with temperature is much less pronounced than in the case of the flexible thermoplastics (see Figs. 15–17). The initial value of the UFS is about doubled and the initial deformation is reduced to about one-half.

With irradiation in liquid nitrogen, the ultimate deformation stays almost constant up to 1 MGy (leading again to $RI_{77K} > RI_{RT}$). Unfortunately, the samples at higher doses charred during irradiation, and it is difficult to draw conclusions from the results obtained. It appears that the flexural modulus, which usually increases slightly with irradiation, shows a slight decrease in the case of cryogenic irradiations.

6.4 Thermosets

Epoxy resins R 422 and R 423 have been extensively used at CERN and some radiation tests at 77 K up to 10 MGy are reported in Ref. [3]. The results presented in Figs. 18 and 19 show that these materials fulfil specification requirements at cryogenic temperatures from 20 MGy to 50 MGy (RI = 7.3 and 7.7, respectively).

Figures 20 and 21 show that, for the most recent epoxy moulding compounds R 453 and R 455, each initial, tested, mechanical property is slightly higher at 77 K than at RT, and that they stay almost constant up to 14 and 34 MGy, respectively, then they decrease slightly with irradiation. The data at higher doses are unavailable, because the samples were lost. From the results at RT, however, (RI > 8) it can be expected that these compounds are usable beyond 100 MGy.

6.5 Laminates and carbon-epoxy composites

From the results presented in Figs. 22–28 of these composite materials, there is less evidence of differences between irradiations at RT or at cryogenic temperature. For some materials, not enough samples have been supplied for 77 K and RT tests; the RT results of laminates R 545 (by Isola, on Fig. 21) and R 547 (by Isovolta, on Fig. 23) and of carbon–epoxy composite (R 549, on Fig. 25) appear only at zero dose. For comparison with the 77 K results of Vetronite (R 546, on Fig. 22), the values given for the RT results are mean values of other comparable Vetronite tested at CERN over the years (these explain the sigma of about 20% in the results).

With regard to the radiation behaviour, commonly used materials such as Vetronite (R 538, Fig. 22, and R 546, Fig. 24) show, as expected, good resistance between 20 MGy and 50 MGy. Some more recently developed composites, with Kevlar or carbon-fibre reinforcements (R 548, R 549 and R 550, Figs. 26 to 28) have excellent radiation resistance up to the highest dose obtained in this experiment, i.e. 156 MGy.

7. CONCLUSION

This paper presents results of radiation tests at RT and at 77 K of a representative selection of organic materials comprising polyolefin and rubber cable insulations, thermoplastic films and resins, as well as thermosets and composites. Figure 29 presents an overview and appreciation of the radiation resistance of all materials tested. From this figure, it becomes evident that significant differences exist between material types and to a lesser extent within the same material type depending on the irradiation temperature. The main conclusions can be summarized as follows:

Despite the fact that the RI values given on the figures are higher at 77 K than at RT, common rubber and polyolefin cable-insulating materials are not suitable for low-temperature applications. Even without irradiation their elongation at break is reduced to less than 3%.

The radiation degradation of thermoplastic materials is less pronounced at low temperature. This could be related to the absence of oxygen during irradiation. The effect is very pronounced with thin films and makes most of the high-performance thermoplastics (including Litrex and Kapton films) suitable for the LHC environment. For the super isolation at 40 cm from the beam also common polyester films (Mylar) can be used.

No significant influence of the irradiation temperature is observed on the radiation degradation of thermosets and composites. Therefore, good indications for the radiation response of these types of materials for an application in a cryogenic environment can be assessed from RT tests after the initial properties have been measured at low temperature.

ACKNOWLEDGEMENTS

This work became only possible thanks to the support of G. Brianti at CERN and the obligingness of the Atomic Institute of the Austrian Universities to take part in a test programme carried out for the European Fusion Reactor Project.

We would like to thank Prof. B.N. Goshchitskii (Institute of Metal Physics, Russian Academy of Sciences, Ekaterinburg, GSP-170, 620219 Russia) for irradiations of the test materials which were carried out under a grant issued by the Atomic Institute. One of us (K. Humer) wishes to thank also the Russian Academy of Sciences for the hospitality during a two-week stay at Ekaterinburg and Zarechny. The cooperation of Dr. V.V. Bobrovskii, Dr. Y.I. Filippov, Dr. V.D. Parkhomenko and Prof. V.V. Sagaradze (Ekaterinburg and Zarechny), is also acknowledged.

We also thank the CERN technical students P. Suva from University of West Bohemia (Pilsen), for the preparation of the irradiations, and A.-S. Boullin from Institut Universitaire Professionnalisé (Poitiers) for the data handling.

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TABLE CAPTIONS

FIGURE CAPTIONS

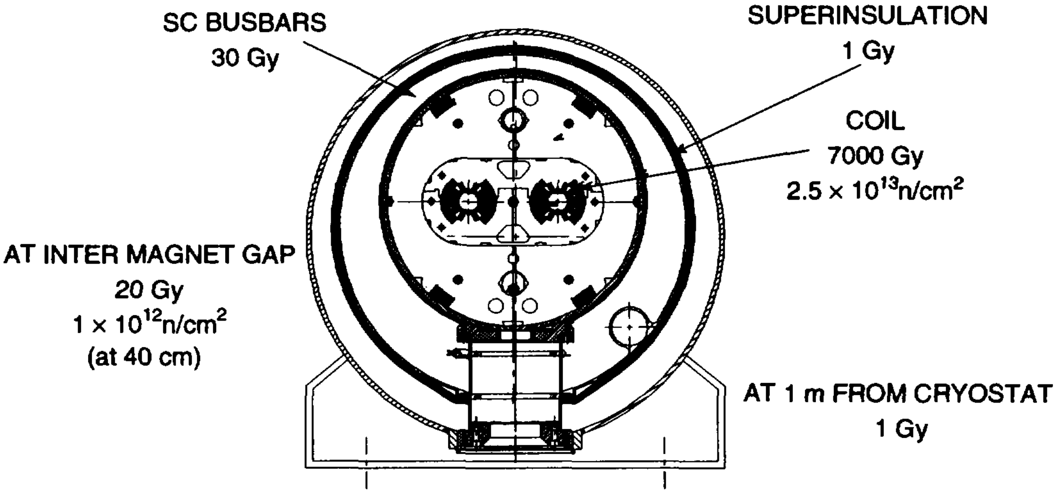
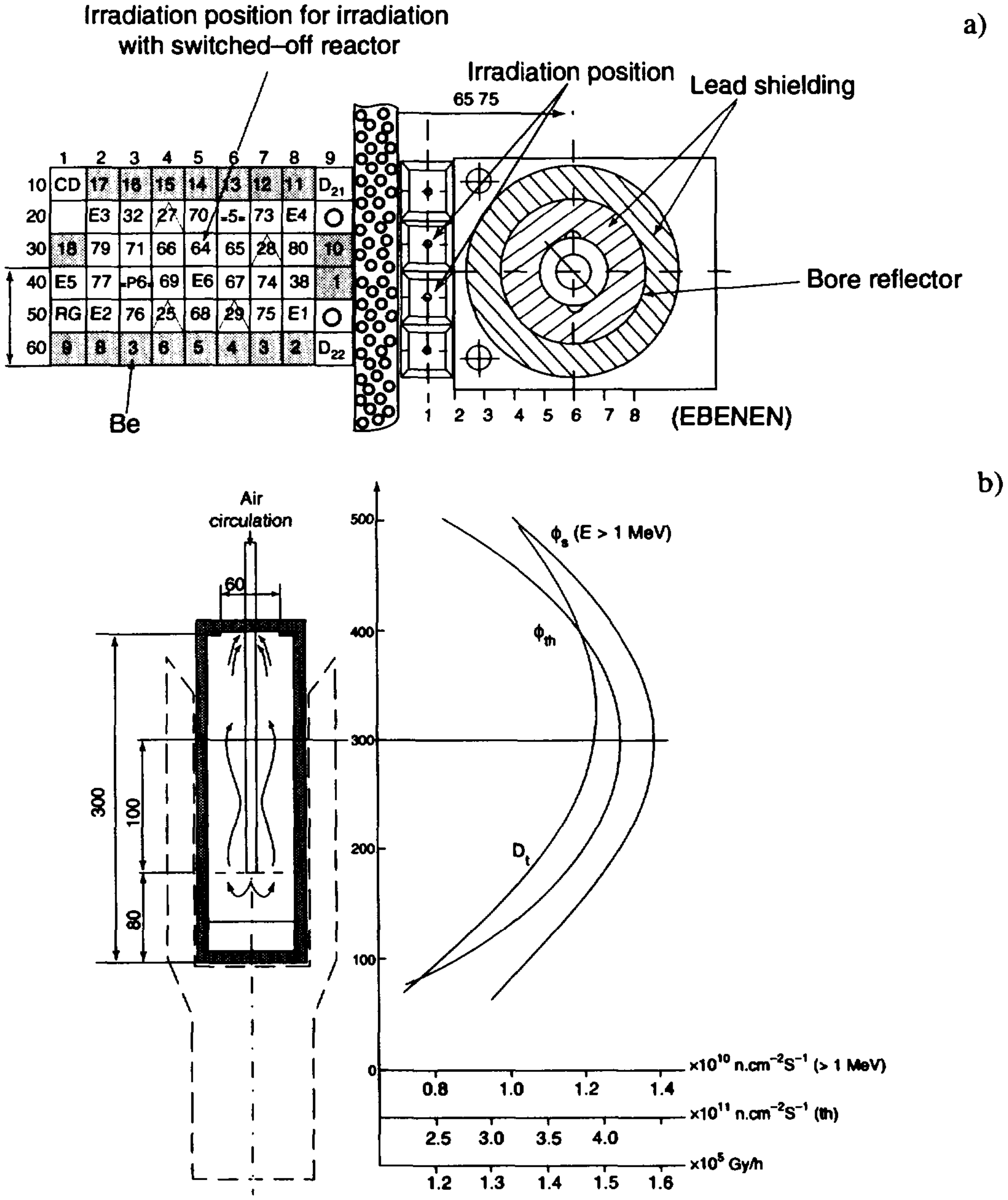


Fig. 1:Yearly doses and fluences in LHC dipoles



	1	2	3	4	5	6	7	8	9
10	CD	17	16	15	14	13	12	11	D_{21}
20		E3	32	27	70	5	73	E4	O
30	18	79	71	66	64	65	28	80	10
40	E5	77	P6	69	E6	67	74	38	1
50	RG	E2	76	25	68	29	75	E1	O
60	9	8	3	6	5	4	3	2	D_{22}

Fig. 2: (a) Core configuration with irradiation positions. (b) Irradiation container in position Ebene 1, with neutron flux densities and dose rate.

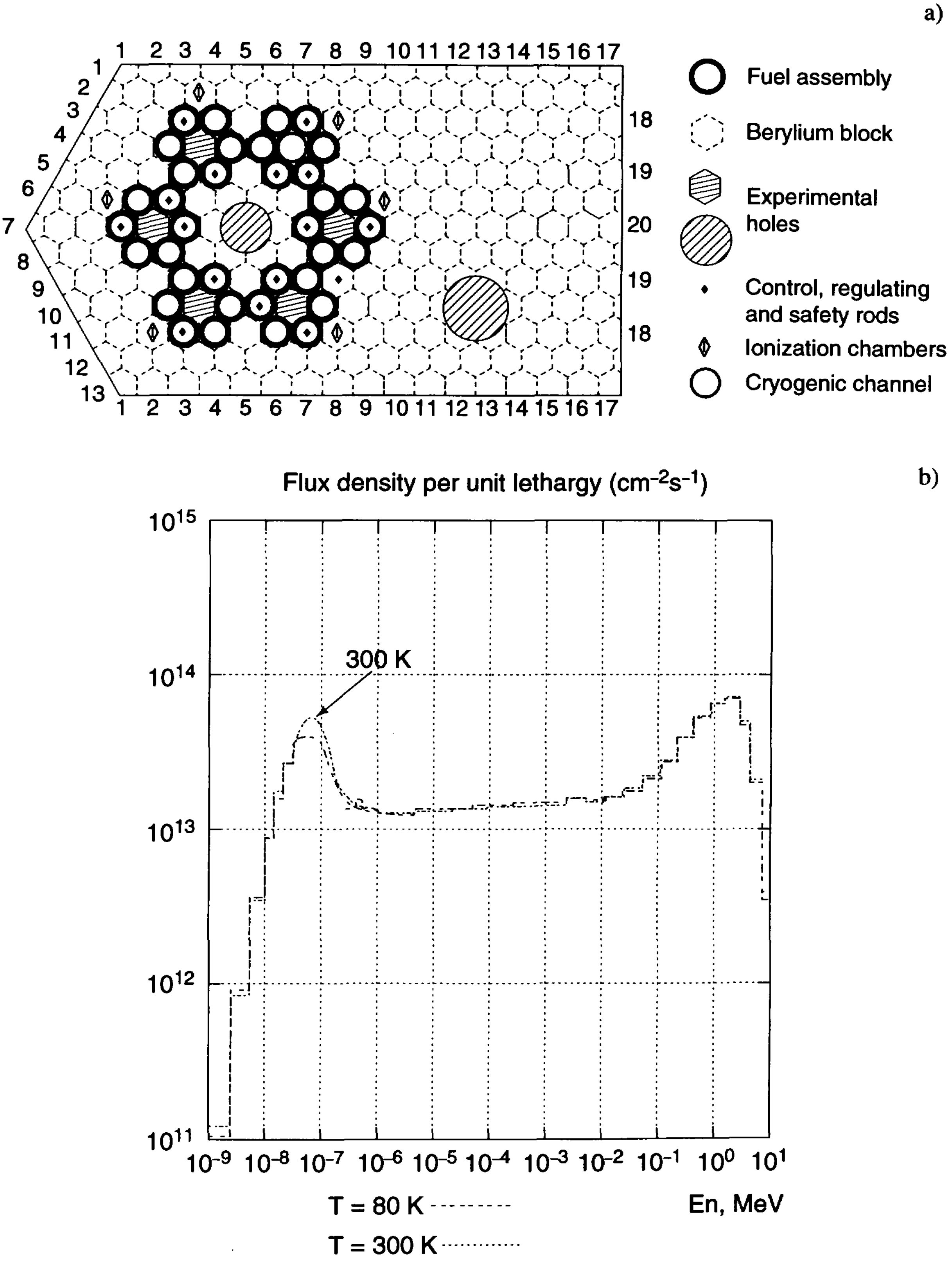


Fig. 3: (a) Core assembly of the IVV-2M reactor in Zarechny. (b) Flux density distribution in the low temperature ('80 K') and in the ambient temperature irradiation facility of the IVV-2M reactor, versus neutron energy.

Material: **PETP** TIS No. **M 701**
Type **Mylar**

Supplier: **CERN stores** UL 94:
Remarks: 250 micron film LOI: n.m.

Radiation test results according to IEC Standard 544

Dose (MGy)	Mechanical test results at RT			Mechanical test results at 77 K	
	Strength (MPa)	Elongation ε (%)	Hardness (Shore D)	Strength (MPa)	Elongation ε (%)
0	**116.7** ± 11.0	**62.1** ± 18.0	71	**314** ± 7.5	**5.5** ± 0.1
0.18				**296** ± 4.9	**6.7** ± 0.1
0.20	**111.5** ± 6.1	**57.5** ± 7.4	63		
0.5	**106.4** ± 8.1	**48.8** ± 13	65		
1.0	**92.5** ± 6.5	**13.3** ± 11	67		
1.7				**260** ± 5.6	**5.4** ± 0.1
RI =	**> 6**	**5.8**		**> 6.2**	**> 6.2**

Radiation effect on Mylar film M 701

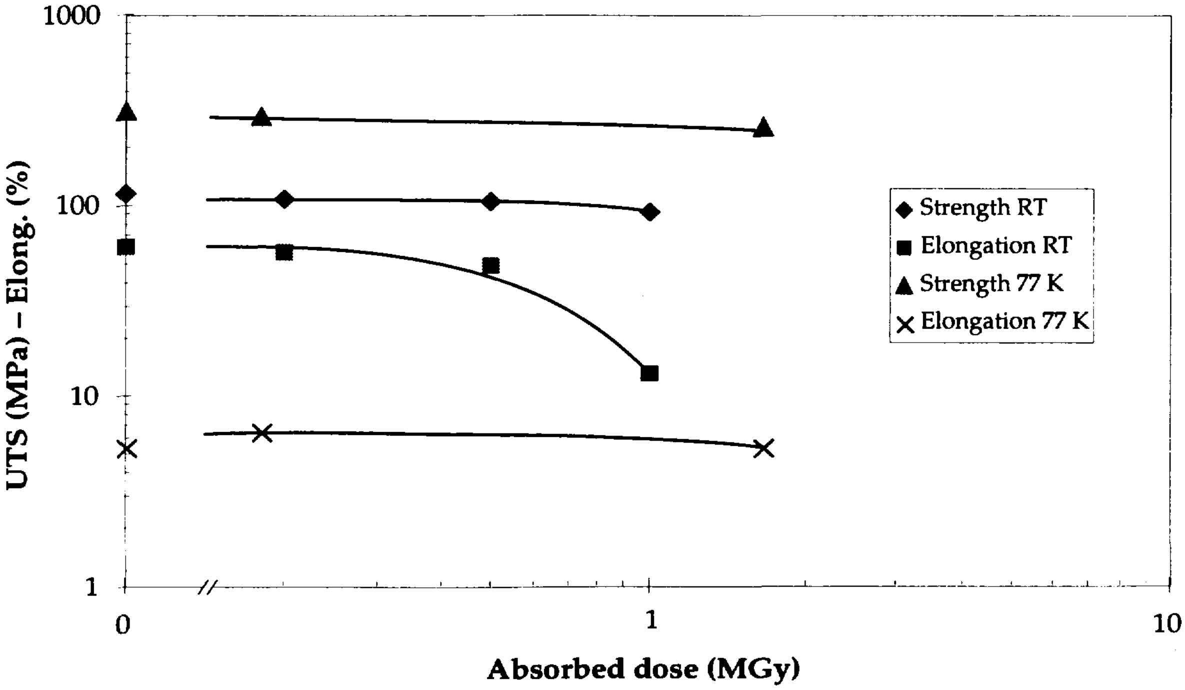


Fig. 4: Mylar M 701

Material: **Polyimide** TIS No. **M 702**
Type **Kapton H**

Supplier: **DuPont de Nemours** UL 94:
Remarks: 125 micron film LOI: n.m.

Radiation test results according to IEC Standard 544

Dose (MGy)	Mechanical test results at RT			Mechanical test results at 77 K	
	Strength (MPa)	Elongation ε (%)	Hardness (Shore D)	Strength (MPa)	Elongation ε (%)
0	**165.0** ± 13.0	**23.5** ± 11.0	67	**274** ± 9	**7.8** ± 0.1
1	**177.0** ± 5.0	**29.5** ± 4.1	64		
3	**171.0** ± 2.0	**25.5** ± 4.5	68		
10	**168.0** ± 2.0	**21.5** ± 3.4	68		
35				**202** ± 14	**7.4** ± 0.3
50	**135.0** ± 6.0	**9.0** ± 1.7	63		
119				**172** ± 1.8	**5.1** ± 0.1
RI =	> **7.7**	**7.3**		> **8.3**	> **8.3**

Radiation effect on Kapton film M 702

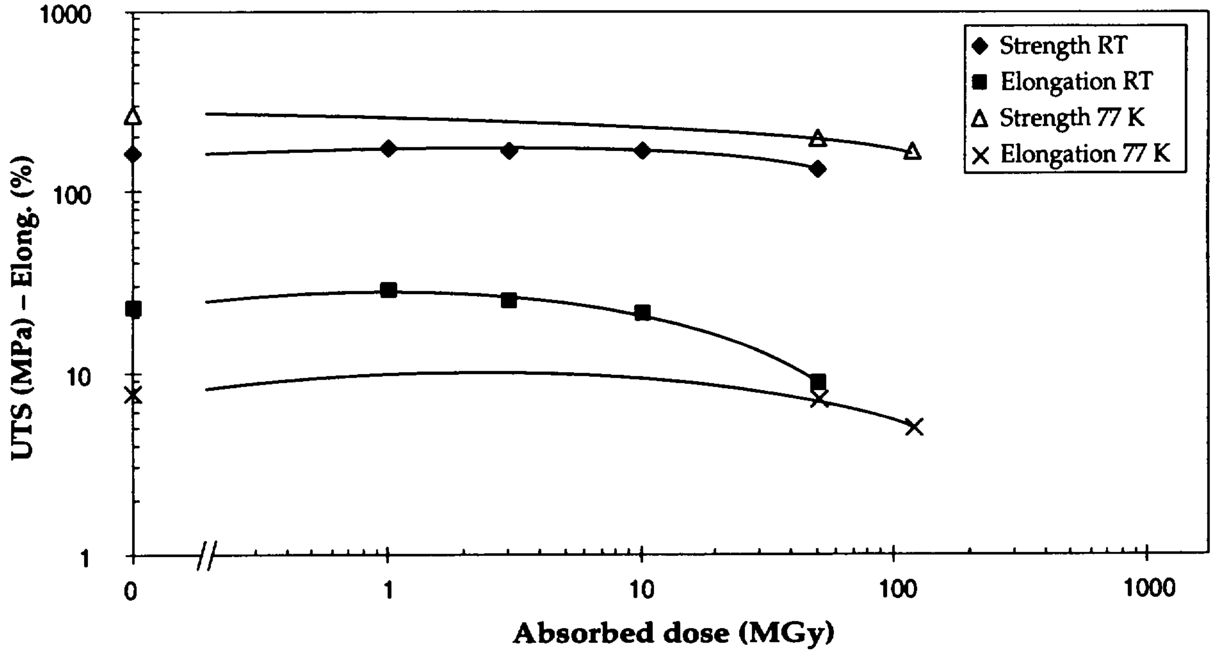


Fig. 5: Kapton H M 702

Material:	**Polyimide**	TIS No. **M 702´**
Type	**Kapton AH** **PI + Al_20_3**	
Supplier:	**DuPont de Nemours**	UL 94:
Remarks:	125 micron film	LOI: n.m.

Radiation test results according to IEC Standard 544

Dose	Mechanical test results at RT			Mechanical test results at 77 K		
(MGy)	Strength (MPa)	Elongation ε (%)	Hardness (Shore D)	Strength (MPa)	Elongation ε (%)	Hardness (Shore D)
0	**113.9** ± 13.0	**62.5** ± 6.3	63	**227** ± 6	**10.0** ± 0.4	
14				**202** ± 6	**10.2** ± 0.1	
35				**175** ± 2	**7.8** ± 0.1	
119				**148** ± 0.7	**4.8** ± 0.1	
RI =				**> 8**	**8**	

Radiation effect on Kapton film M 702

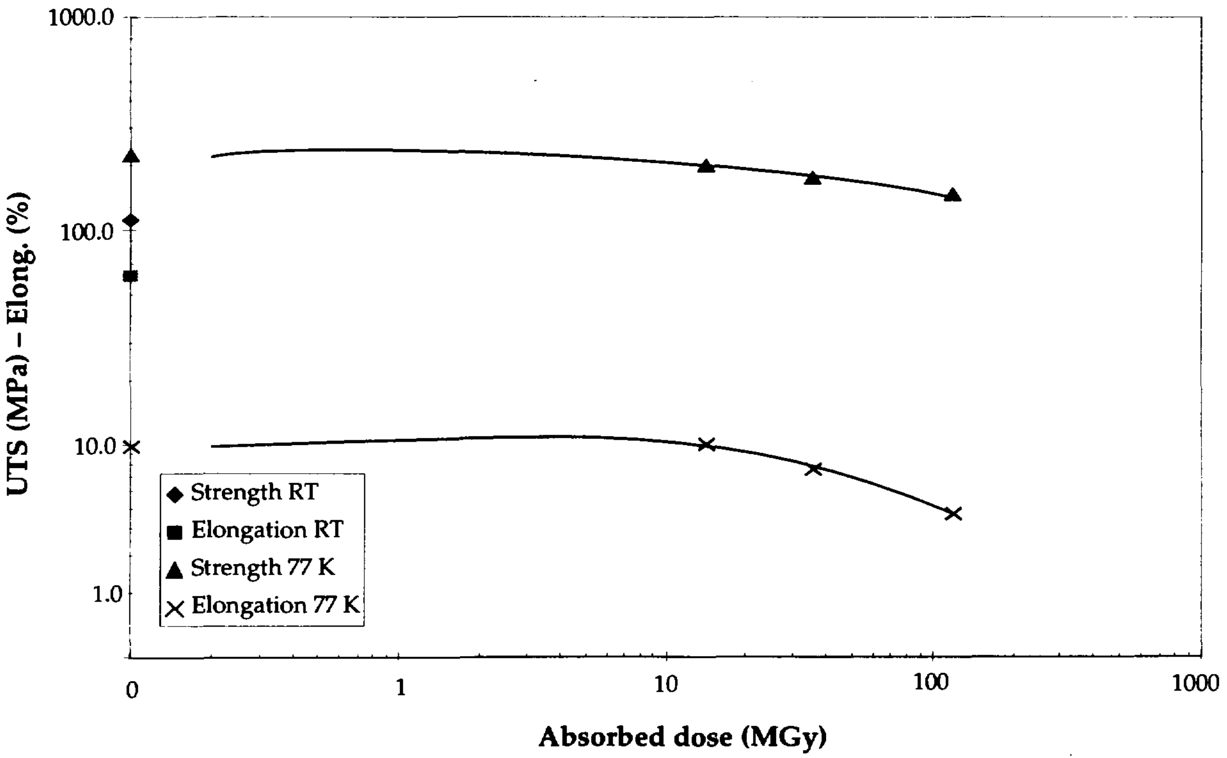


Fig. 6: Kapton AH M 702´

Material: **PEEK** TIS No. **M 703**
Type **Litrex**
amorphous

Supplier: **ICI** UL 94:
Remarks: 125 micron film LOI: n.m.

Radiation test results according to IEC Standard 544

Dose	Mechanical test results at RT			Mechanical test results at 77 K	
(MGy)	Strength (MPa)	Elongation ε (%)	Hardness (Shore D)	Strength (MPa)	Elongation ε (%)
0	**94.0** ± 8.0	**161** ± 12.0	53	**182** ± 9.4	**4.9** ± 0.2
1	**98.0** ± 11.0	**147** ± 14	57		
3	**87.0** ± 6.0	**139** ± 6.5	59		
10	**83.0** ± 6.0	**72** ± 34	62		
14				**165** ± 14	**7.3** ± 0.3
35				**167** ± 3	**7.6** ± 0.2
50	**40.0** ± 3.0	**0.8** ± 0.5	56		
119				**131** ± 0.9	**5.8** ± 0.1
RI =	**7.5**	**6.9**		**> 8.3**	**> 8.3**

Radiation effect on Litrex film M 703

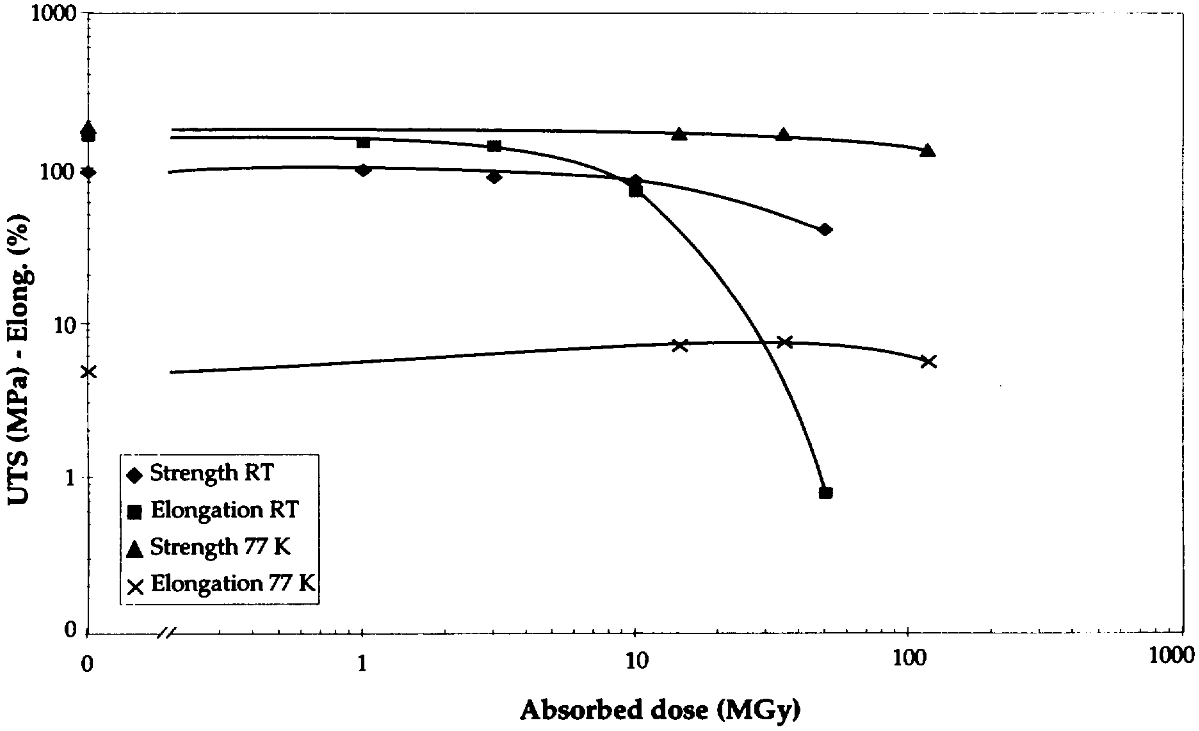


Fig. 7: PEEK M 703

Material: Type	**EPT + acetate copolymer** **85-2/19**	TIS No. **C 763**
Supplier: Remarks:	**kabelmetal elektro** insulation for magnet cables	UL 94: n.m. LOI: 64%

Radiation test results according to IEC Standard 544

Dose	Mechanical test results at RT			Mechanical test results at 77 K	
(MGy)	Strength (MPa)	Elongation ε (%)	Hardness (Shore D)	Strength (MPa)	Elongation ε (%)
0	**11.6** ± 0.3	**351.7** ± 7	29	**115** ± 5	**2.3** ± 0.1
0.18				**99** ± 5	**3.2** ± 0.1
0.5	**11.5** ± 0.5	**210** ± 22	30		
2				**38** ± 4.3	**1.2** ± 0.0
2.5	**10.8** ± 0.2	**145** ± 6.3	29		
5	**7.7** ± 0.5	**33** ± 5.2	31		
RI =	**> 6.7**	**6.1**		**6.2**	**~ 6.3**

Radiation effect on EPR insulation C 763

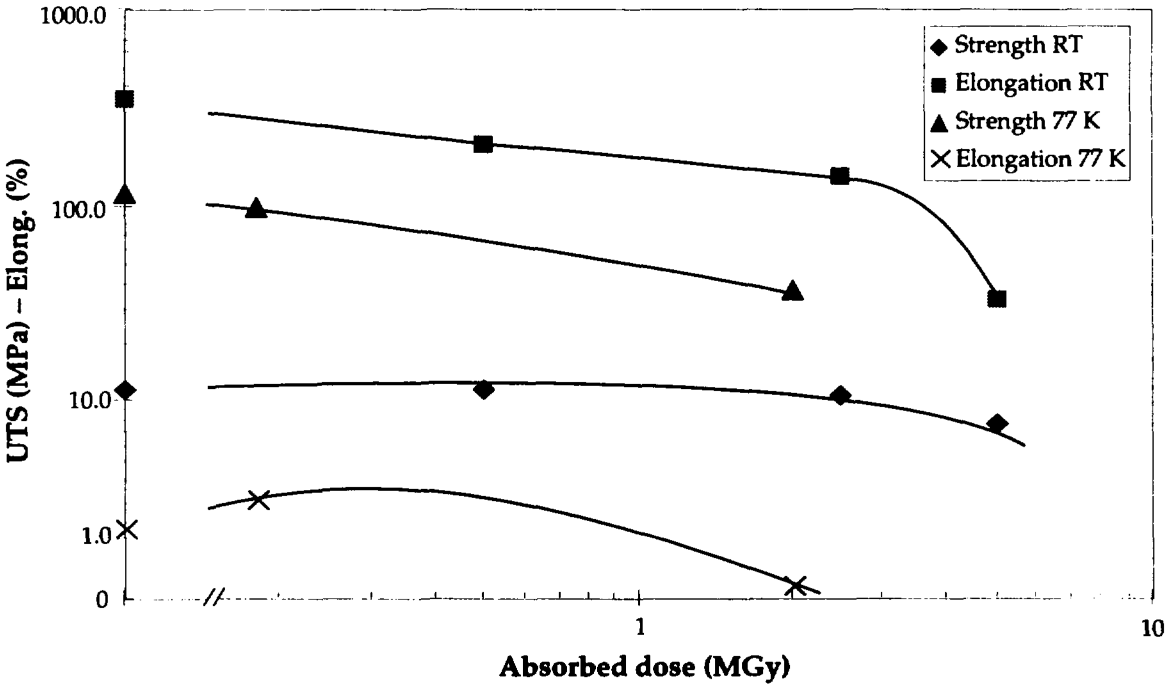


Fig. 8: EPR Insulation C 763

Material:	**VAC-copolymer**	TIS No. **C 764**
Type	**2 YM 011, therm. (85-4/20)**	
Supplier:	**kabelmetal elektro**	UL 94: n.m.
Remarks:	sheat for magnet cables	LOI: 30%

Radiation test results according to IEC Standard 544

Dose	Mechanical test results at RT			Mechanical test results at 77 K	
(MGy)	Strength (MPa)	Elongation ε (%)	Hardness (Shore D)	Strength (MPa)	Elongation ε (%)
0	**10.2** ± 0.4	**569.2** ± 13	40	**66** ± 2	**1.2** ± 0.0
0.18				**41** ± 0	**1.5** ± 0.0
0.5	**11.5** ± 0.3	**379.2** ± 7	45		
2				**51** ± 4.4	**1.4** ± 0.0
2.5	**12.3** ± 0.7	**280** ± 3.2	45		
5	**8.9** ± 0.0	**10** ± 0.0	50		
RI =	> **6.7**	**6.4**		> **6.3**	> **6.3**

Radiation effect on VAC-copolymer sheat C 764

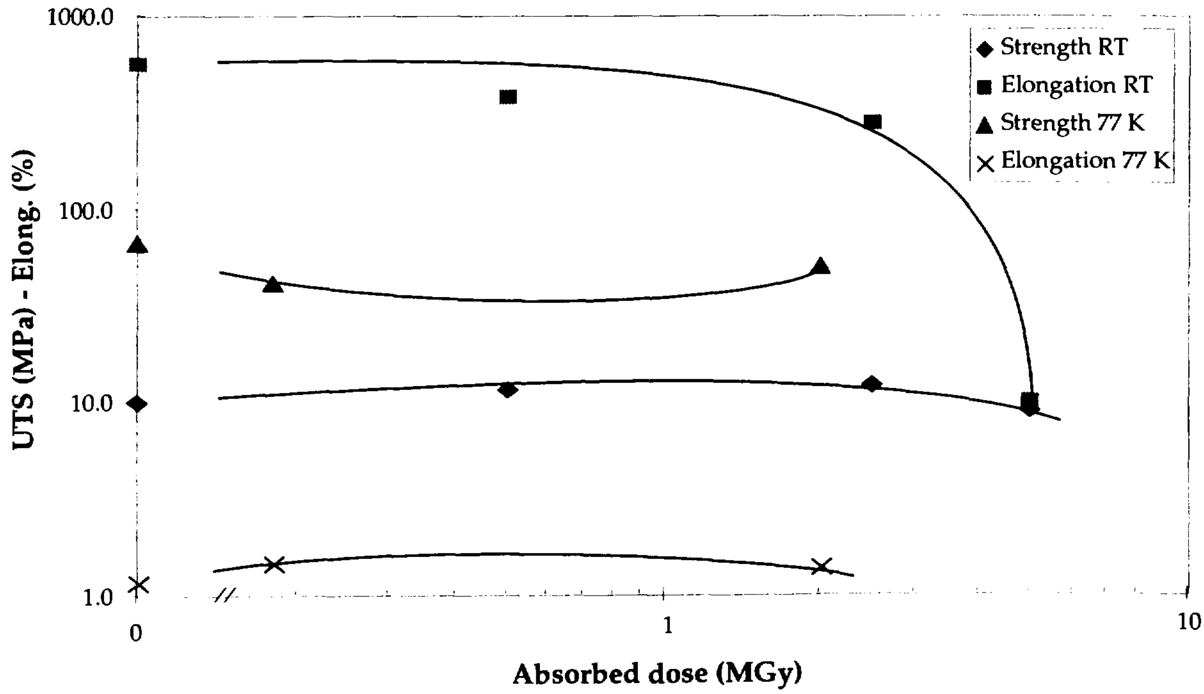


Fig. 9: VAC Sheath C 764

Material:	**Copolymer SiO + PI**	TIS No. **C 1011**
Type	**Olisafe**	
Supplier:	**Filotex**	UL 94:
Remarks:	= Siltem by GE Plastics	LOI: 51%

Radiation test results according to IEC Standard 544

Dose (MGy)	Mechanical test results at RT			Mechanical test results at 77 K	
	Strength (MPa)	Elongation ε (%)	Hardness (Shore D)	Strength (MPa)	Elongation ε (%)
0	**25.2** ± 2.3	**112.5** ± 28	54	**125** ± 2.5	**3.5** ± 0.1
0.2				**175** ± 2.3	**7.8** ± 0.1
0.3	**24.6** ± 2.7	**101** ± 29	55		
0.5	**24.7** ± 1.7	**100.8** ± 16	55		
1	**24.7** ± 2.7	**87** ± 26	54		
2				**113** ± 2	**5.4** ± 0.1
5	**27.5** ± 2.4	**33** ± 12	62		
10	**28.1** ± 3.7	**14** ± 8.4	64		
14				**127** ± 2.6	**6.5** ± 0.1
RI =	> **7**	**6.3**		> **7**	> **7**

Radiation effect on Olisafe insulation C 1011

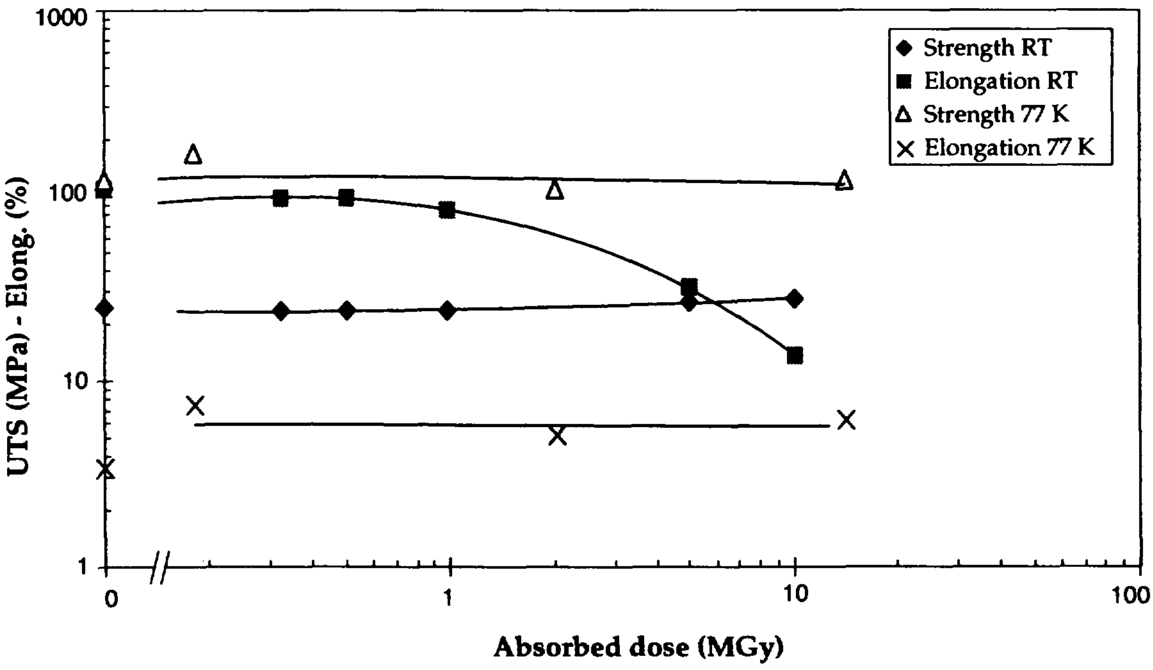


Fig. 10: Olisafe C 1011

Material: **Polyethylene**
Type **DFDM 6005**

TIS No. **C 1027**

Supplier: **BP Chemicals**
Remarks:

UL 94:
LOI: n.m.

Radiation test results according to IEC Standard 544

Dose (MGy)	Mechanical test results at RT			Mechanical test results at 77 K	
	Strength (MPa)	Elongation ε (%)	Hardness (Shore D)	Strength (MPa)	Elongation ε (%)
0	**18.6** ± 1.3	**587** ± 59.0	47	**138** ± 2.5	**2.7** ± 0.1
0.18				**122** ± 2.5	**3.9** ± 0.1
0.2	**15.7** ± 1.0	**425** ± 21.0	48		
0.5	**10.6** ± 0.1	**96** ± 4.0	49		
1	**11.3** ± 0.1	**62** ± 3.0	50		
2				**111** ± 11.0	**4.1** ± 0.1
RI =	**> 6**	**5.4**		**> 6.3**	**> 6.3**

Radiation effect on PE DFDM 6005 insulation C 1027

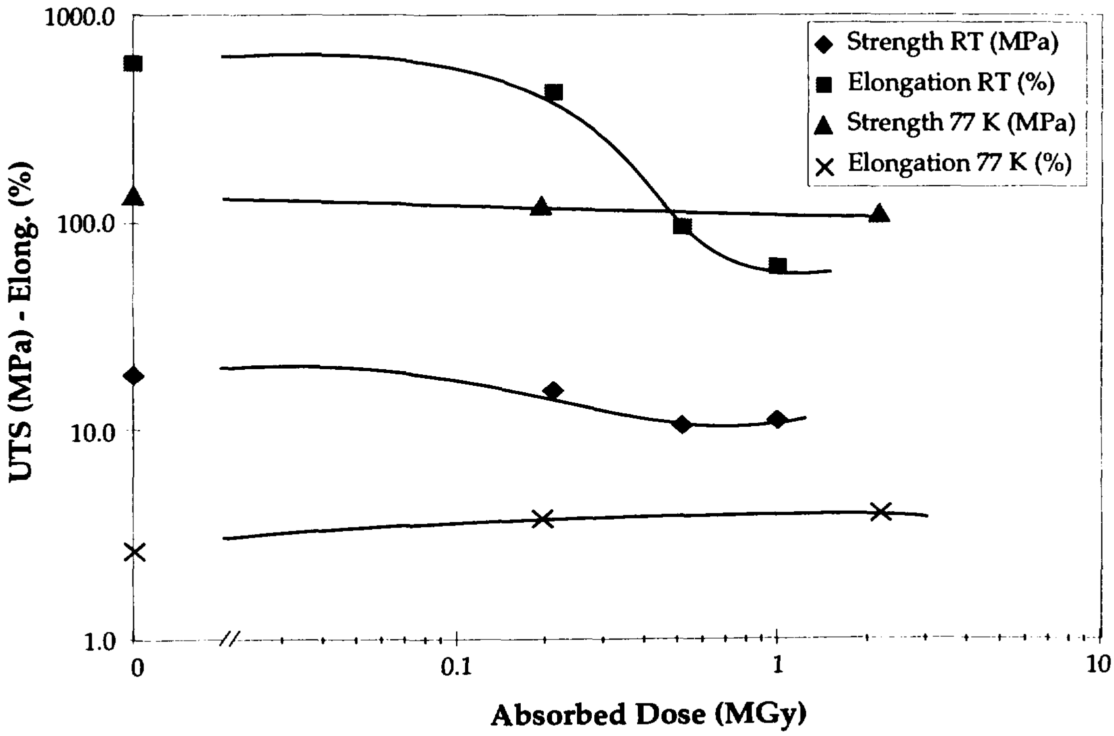


Fig. 11: LDPE C 1027

Material:	**Polyolefin**	TIS No. **C 1028**
Type	**BP D 537**	
Supplier:	**BP Chemicals**	UL 94:
Remarks:		LOI: n.m.

Radiation test results according to IEC Standard 544

Dose (MGy)	Mechanical test results at RT			Mechanical test results at 77 K	
	Strength (MPa)	Elongation ε (%)	Hardness (Shore D)	Strength (MPa)	Elongation ε (%)
0	**10.7** ± 0.7	**632** ± 28.0	29	**86** ± 2.2	**2.0** ± 0.0
0.18				**73** ± 0.4	**2.4** ± 0.0
0.2	**14.0** ± 1.8	**467** ± 24.0	33		
0.5	**14.9** ± 1.0	**342** ± 8.0	34		
1	**7.6** ± 0.6	**155** ± 21.0	37		
2				**69** ± 5.1	**2.4** ± 0.1
3	**6.5** ± 1.0	**27** ± 4	33		
RI =	**> 6.4**	**5.8**		**> 6.3**	**> 6.3**

Radiation effect on a PO BP 537 cable insulation C 1028

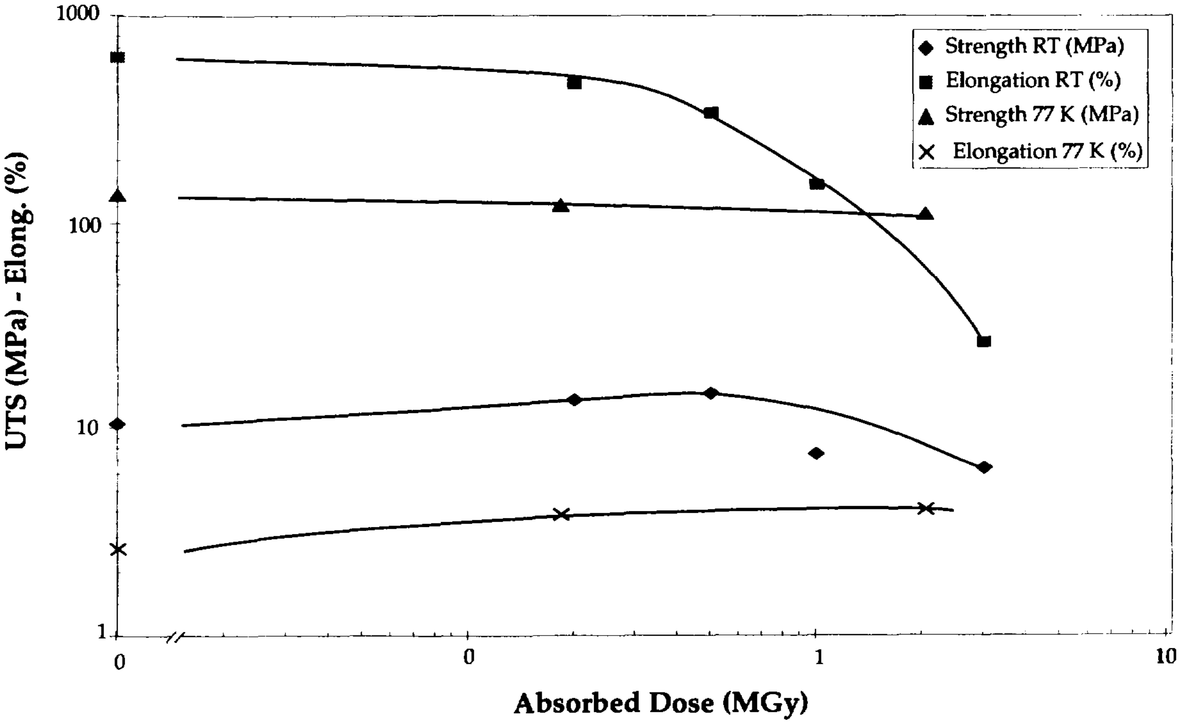


Fig. 12: Polyolefin C 1028

Material: **EPR** TIS No. **C 1047**
Type **?**

Supplier: **kabelmetal elektro** UL 94: n.m.
Remarks: LOI: 23%

Radiation test results according to IEC Standard 544

Dose (MGy)	Mechanical test results at RT			Mechanical test results at 77 K	
	Strength (MPa)	Elongation ε (%)	Hardness (Shore D)	Strength (MPa)	Elongation ε (%)
0	**8.4** ± 0.2	**241** ± 11	24	**112** ± 8.9	**1.4** ± 0.0
0.18				**78** ± 11	**1.6** ± 0.1
0.2	**8.7** ± 0.4	**176** ± 11	26		
0.5	**8.4** ± 0.8	**122** ± 13	27		
1	**8.9** ± 0.2	**75** ± 6	29		
2				**73** ± 8.9	**1.7** ± 0.1
3	**6.2** ± 0.6	**15** ± 5	33		
RI =	**> 6.5**	**6**		**> 6.3**	**> 6.3**

Radiation effect on EPR insulation C 1047

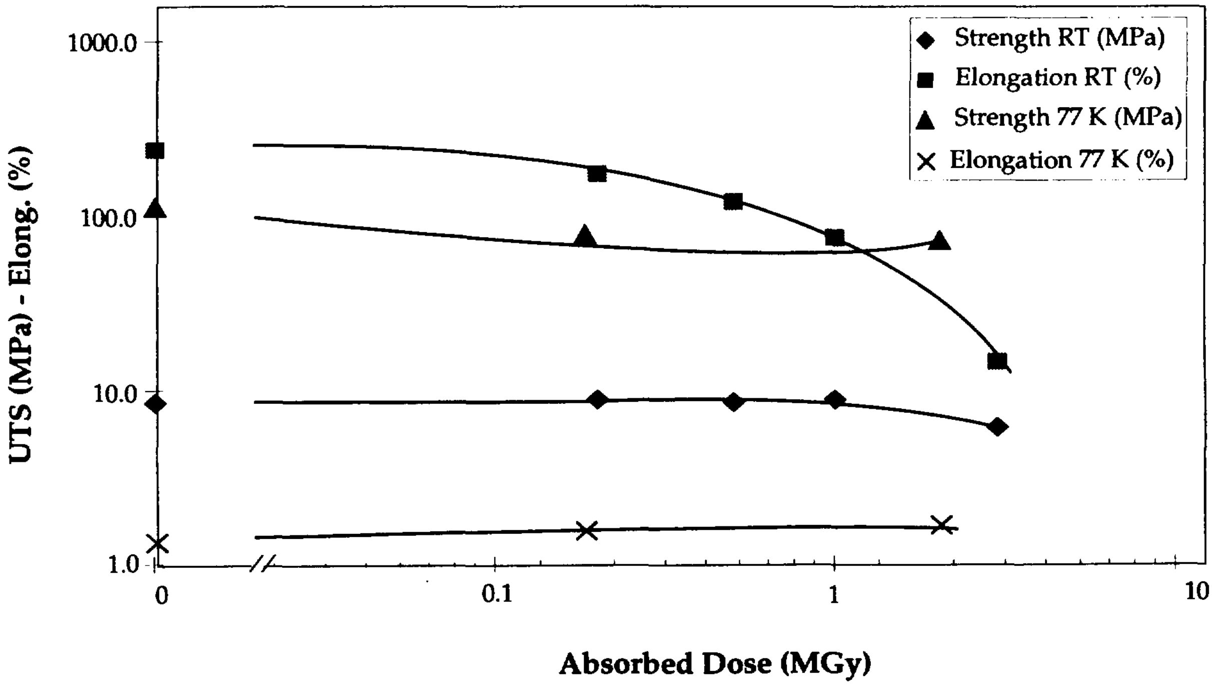


Fig. 13: EPR C 1047

Material: **EVA** TIS No. **C 1048**
Type **?**

Supplier: **kabelmetal elektro** UL 94: n.m.
Remarks: LOI: 29%

Radiation test results according to IEC Standard 544

Dose (MGy)	Mechanical test results at RT			Mechanical test results at 77 K	
	Strength (MPa)	Elongation ε (%)	Hardness (Shore D)	Strength (MPa)	Elongation ε (%)
0	**8.6** ± 0.7	**366** ± 16	28	**72** ± 13	**1.0** ± 0.0
0.18				**62** ± 12	**1.3** ± 0.1
0.2	**8.2** ± 1.8	**294** ± 13	30		
0.5	**7.1** ± 1.0	**234** ± 16	32		
1	**6.5** ± 0.6	**192** ± 15	33		
2				**47** ± 2.6	**1.0** ± 0.0
3	**6.7** ± 1.0	**32** ± 12	35		
RI =	**> 6.5**	**6**		**> 6.3**	**> 6.3**

Radiation effect on EVA insulation C 1048

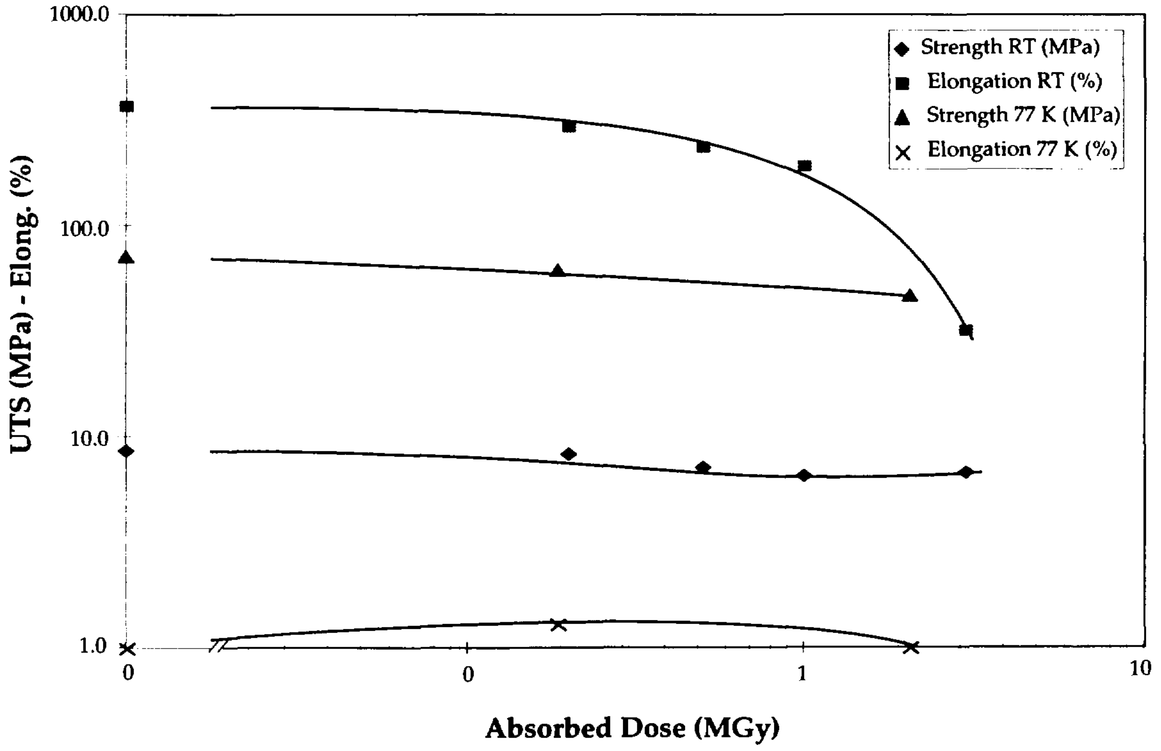


Fig. 14: EVA C 1048

Material: **Polyether-imide** TIS No. **R 533**
Type **Erta PEI**

Supplier: **Erta-Epec** UL 94: V-O
Remarks: based on Ultem 1000 LOI: n.m.

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose	Mechanical test results at RT			Mechanical test results at 77 K		
(MGy)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**171.0** ± 1.1	**> 15**	**3.2** ± 0.1	**312** ± 5	**9.4** ± 0.0	**4.1** ± 0.2
1	**174.1** ± 1.5	> 15	**3.2** ± 0.1	**360** ± 35	**10.4** ± 0.1	**3.7** ± 0.2
3	**179.2** ± 1.2	> 15	**3.2** ± 0.1			
10	**157.9** ± 28.6	**10.9** ± 5.61	**3.2** ± 0.0			
50	**101.8** ± 6.8	**3.27** ± 0.2	**3.2** ± 0.0			
RI =	**> 7.7**	**~ 7**	**> 7.7**	**> 6**	**> 6**	**> 6**

Radiation effect on PEI R 533

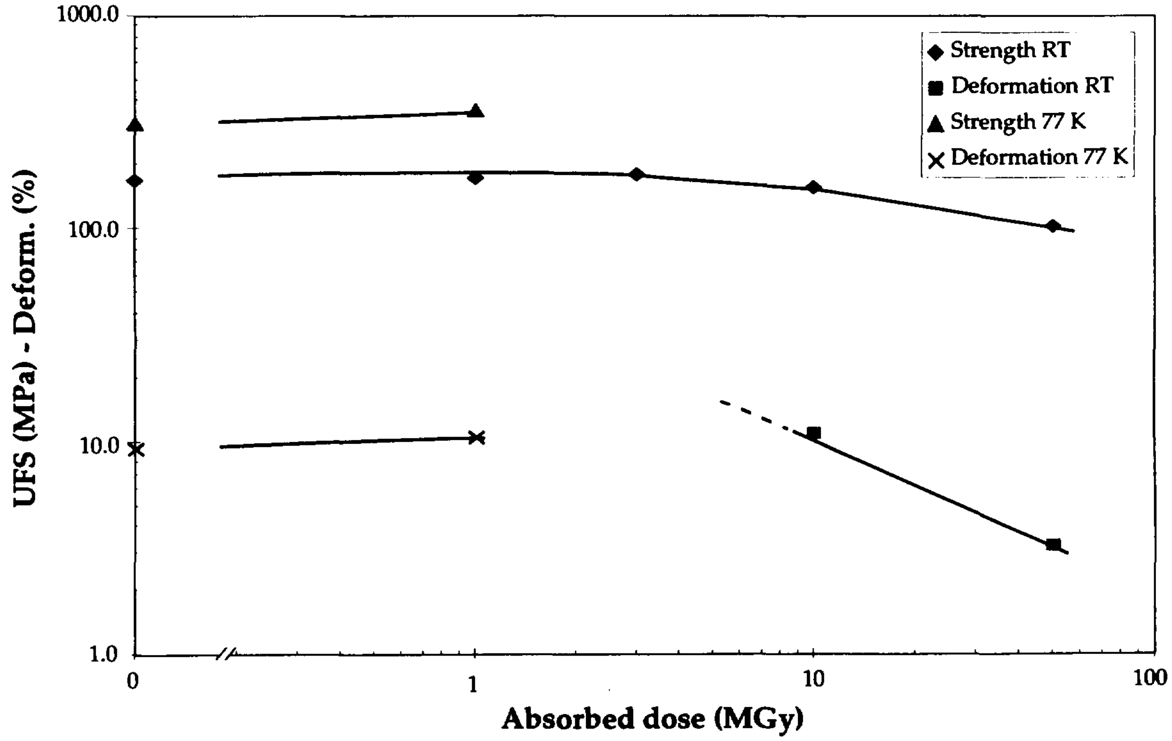


Fig. 15: PEI R 533

Material:	**Polyether-sulfone**	TIS No. **R 534**
Type	**Erta PES**	
Supplier:	**Erta-Epec**	UL 94: V-O
Remarks:	based on VICTREX	LOI: n.m.

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose (MGy)	Mechanical test results at RT			Mechanical test results at 77 K		
	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**140.7** ± 1.4	**> 15**	**2.7** ± 0.1	**254** ± 14	**7.2** ± 0.5	**4.1** ± 0.1
0.5	**134.4** ± 0.8	> 15	**2.8** ± 0.1			
1	**132.0** ± 5.5	**11.6** ± 4.6	**2.9** ± 0.1	**233** ± 3	**7.6** ± 0.1	**3.3** ± 0.2
3	**46.9** ± 3.4	**1.7** ± 0.1	**3.1** ± 0.1			
10	**14.3** ± 6.4	**0.5** ± 0.2	**3.3** ± 0.3			
37				**132** ± 18	**3.6** ± 0.4	**3.3** ± 0.1
RI =	**6.4**	**~ 6**	**> 7**	**> 7.5**	**7.5**	**> 7.5**

Radiation effect on Erta-PES R 534

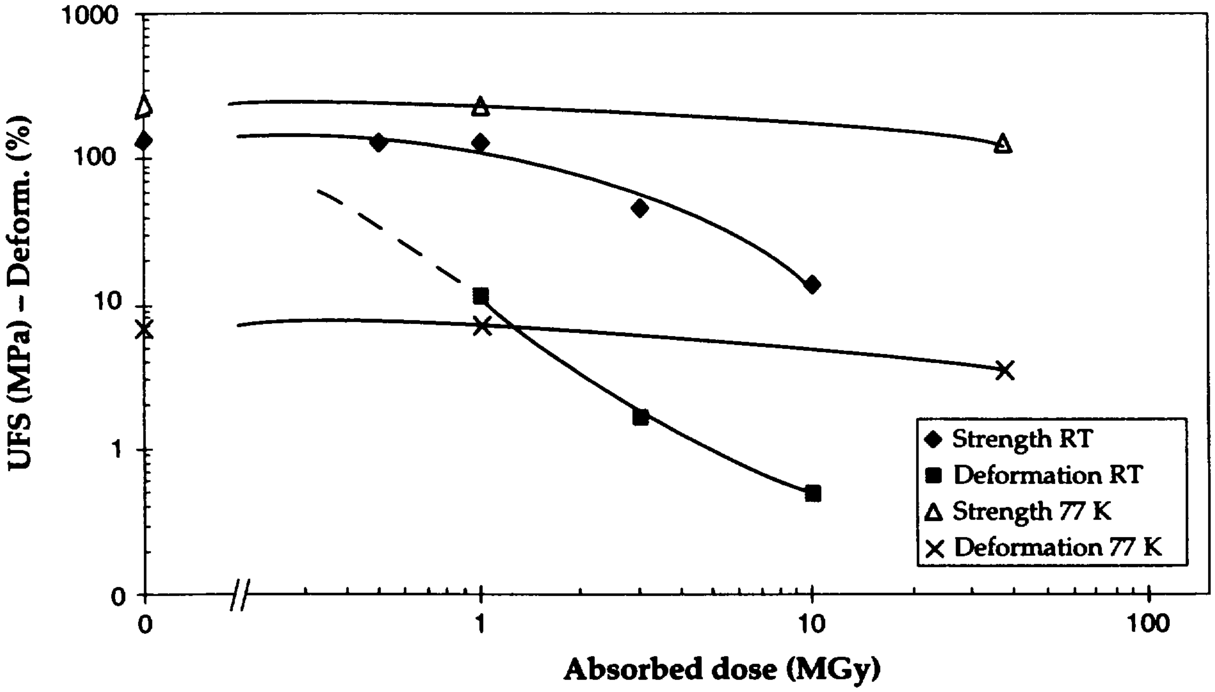


Fig. 16: PES R 534

Material: **Polysulfone** TIS No. **R 535**
Type **Erta PSU**

Supplier: **Erta-Epec** UL 94: HB
Remarks: based on Udel P 3500 LOI: n.m.

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose (MGy)	Mechanical test results at RT			Mechanical test results at 77 K		
	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**120.2** ± 0.8	**> 15**	**2.6** ± 0.1	**247** ± 10	**10.1** ± 0.8	**3.5** ± 0.0
0.5	**114.4** ± 0.3	**> 15**	**2.7** ± 0.1			
1	**101.6** ± 11.4	**9.6** ± 6.7	**2.8** ± 0.0	**247** ± 8	**9.7** ± 0.6	**3.1** ± 0.1
3	**58.2** ± 2.5	**2.1** ± 0.1	**3.0** ± 0.0			
10	**18.8** ± 2.6	**0.71** ± 0.1	**3.0** ± 0.1			
RI =	**6.5**	**~ 6**	**> 7**	**> 6**	**> 6**	**> 6**

Radiation effect on PSU R 535

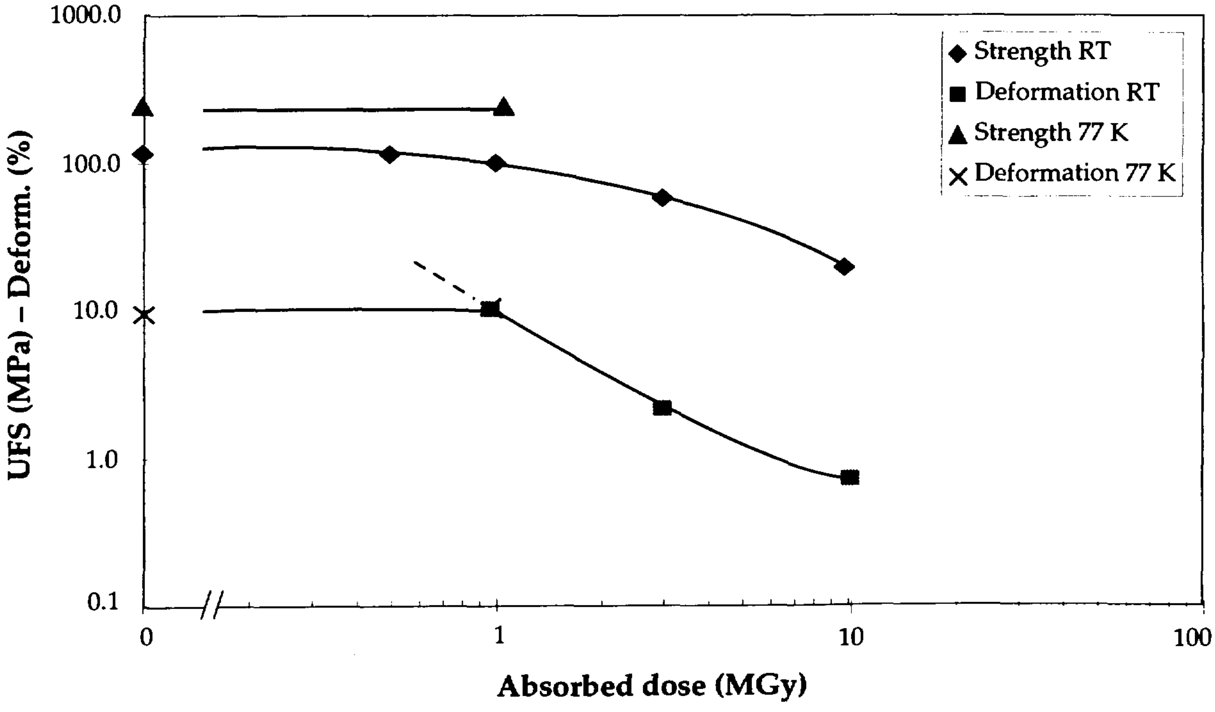


Fig. 17: PSU R 535

Material:	**Epoxy resin**	TIS No. **R 422**
Type	**MY 745 (50) + EPN 1138 (50) +** CY 221 (20) + HY 905 (120) + DY 073 (0.3)	
Supplier:	**Ciba-Geigy**	UL 94: n.m.
Remarks:	used for the ISR dipoles	LOI:

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose (MGy)	Mechanical test results at RT			Mechanical test results at 77 K		
	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**152.6** ± 3.0	**13.1** ± 1.9	**3.8** ± 0.03	**344** ± 19	**3.5** ± 0.5	**6.7** ± 0.9
5	**93.0** ± 2.0	**6.1** ± 0.3	**4.0** ± 0.03			
10	**73.0** ± 3.0	**4.2** ± 0.2	**4.1** ± 0.04			
14				**191** ± 13	**3.5** ± 0.3	**5.3** ± 0.2
20	**13.0** ± 1.0	**1.1** ± 0.1	**3.4** ± 0.04			
35				**124** ± 44	**2.0** ± 0.1	**6.1** ± 0.7
119				**18** ± 5.0	**0.7** ± 0.2	**2.8** ± 1.0
RI =	**6.9**	**6.6**	**> 7.3**	**> 7.3**	**7.7**	**7.7**

Radiation effect on epoxy resin R 422

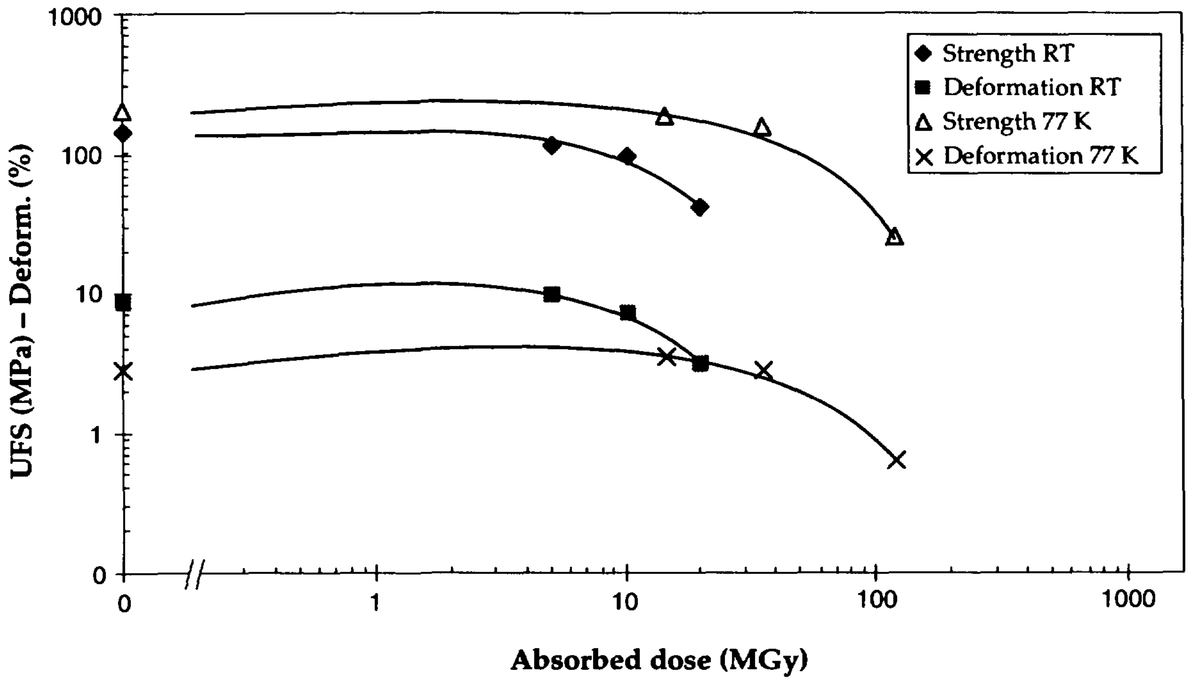


Fig. 18: Araldite MY 745 + EPN 1138 R 422

Material: **Epoxy resin** TIS No. **R 423**
Type **MY 745 (100) + HY 906 (90) +**
DY 073 (1.5)

Supplier: **Ciba-Geigy** UL 94: n.m.
Remarks: used for the SPS dipoles LOI:

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose	Mechanical test results at RT			Mechanical test results at 77 K		
(MGy)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**148.1** ± 14.9	**8.8** ± 1.3	**3.8** ± 0.1	**210** ± 52	**2.9** ± 0.3	**6.9** ± 0.1
5	**118.0** ± 10.0	**10.0** ± 2.0	**3.7** ± 0.3			
10	**98.0** ± 5.9	**7.2** ± 1.4	**4.1** ± 0.4			
14				**187** ± 13	**3.7** ± 0.3	**5.4** ± 0.2
20	**43.0** ± 4.0	**3.2** ± 0.6	**4.2** ± 0.4			
35				**161** ± 8.0	**2.9** ± 0.2	**5.4** ± 0.3
119				**26** ± 3.0	**0.7** ± 0.1	**3.8** ± 0.3
RI =	**7.1**	**7.2**	**> 7.3**	**7.7**	**7.9**	**~ 7.9**

Radiation effect on epoxy resin R 423

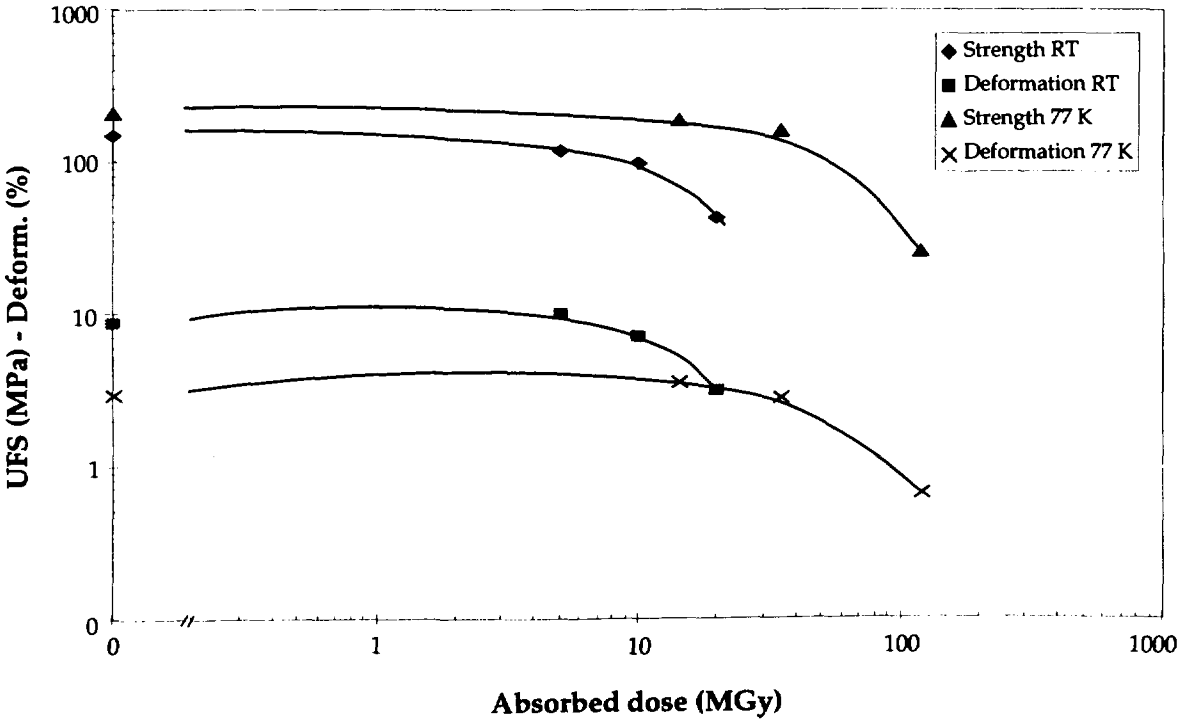


Fig. 19: Araldite MY 745 + MY 906 R 423

Material: **Epoxy moulding compound** TIS No. **R 453**
Type **Araldit NU 511**

Supplier: **Ciba-Geigy** UL 94: n.m.
Remarks: VPI product LOI:

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose	Mechanical test results at RT			Mechanical test results at 77 K		
(MGy)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**158.3** ± 19.9	**1.08** ± 0.1	**17.4** ± 0.6	**286** ± 12	**1.4** ± 0.1	**24.6** ± 0.9
5	**162.5** ± 7.7	**1.06** ± 0.06	**17.7** ± 0.4			
10	**158.9** ± 12.5	**1.06** ± 0.09	**16.8** ± 0.3			
14				**274** ± 16	**1.7** ± 0.1	**16.9** ± 1.6
50	**161.9** ± 6.6	**0.94** ± 0.03	**18.6** ± 0.7			
100	**127.7** ± 5.3	**0.78** ± 0.04	**18.1** ± 0.4			
RI =	> **8**	> **8**	> **8**	> **7.1**	> **7.1**	> **7.1**

Radiation effect on epoxy resin R 453

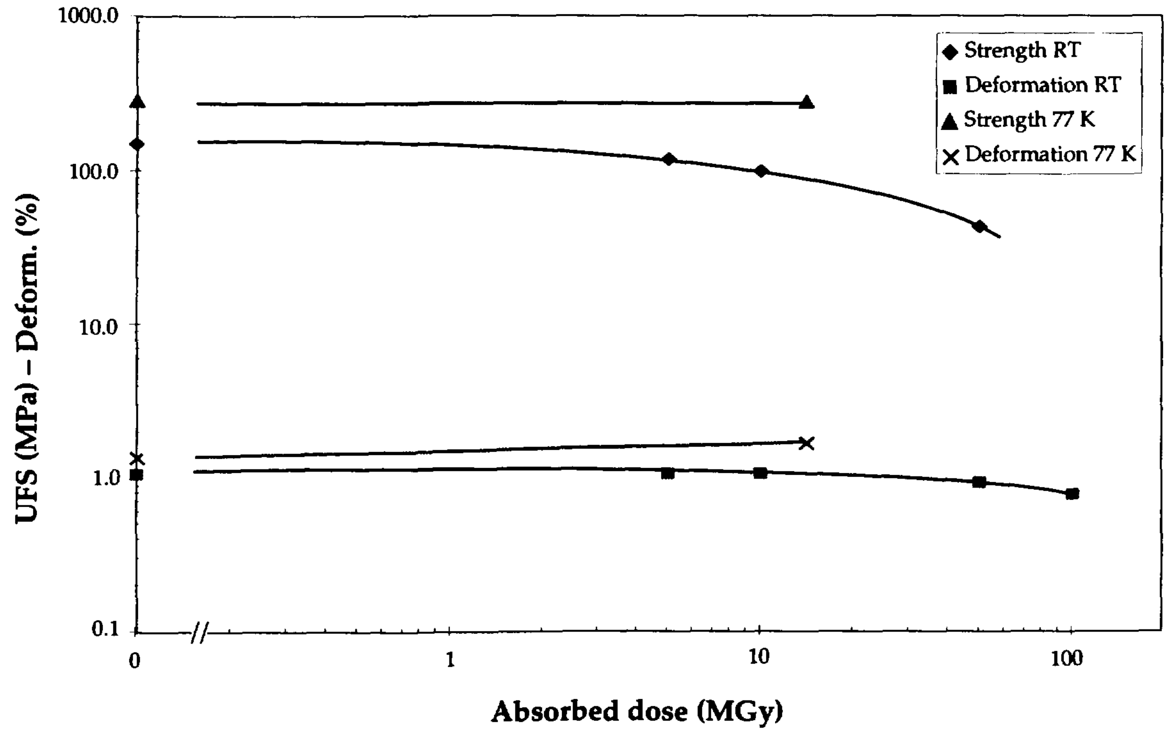


Fig. 20: Epoxy moulding compound R 453

Material: **Epoxy resin** TIS No. **R 455**
Type **XB 3192**

Supplier: **Ciba-Geigy** UL 94: n.m.
Remarks: standard curing LOI:

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose	Mechanical test results at RT			Mechanical test results at 77 K		
(MGy)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**73.1** ± 5.4	0.53 ± 0.1	**14.6** ± 0.3	**121** ± 5	**0.8** ± 0.0	**16.2** ± 1.4
5	**68.1** ± 8.5	**0.48** ± 0.1	**14.7** ± 0.1			
10	**75.2** ± 4.2	**0.53** ± 0.1	**14.6** ± 0.1			
14				**114** ± 17	**1.0** ± 0.1	**13.0** ± 1.3
37				**131** ± 9	**1.2** ± 0.0	**11.8** ± 1.2
50	**68.1** ± 4.3	**0.42** ± 0.0	**15.9** ± 0.4			
100	**59.4** ± 6.6	**0.42** ± 0.0	**15.5** ± 0.9			
RI =	**> 8**	**> 8**	**> 8**	**> 7.5**	**> 7.5**	**> 7.5**

Radiation effect on epoxy moulding compound R 455

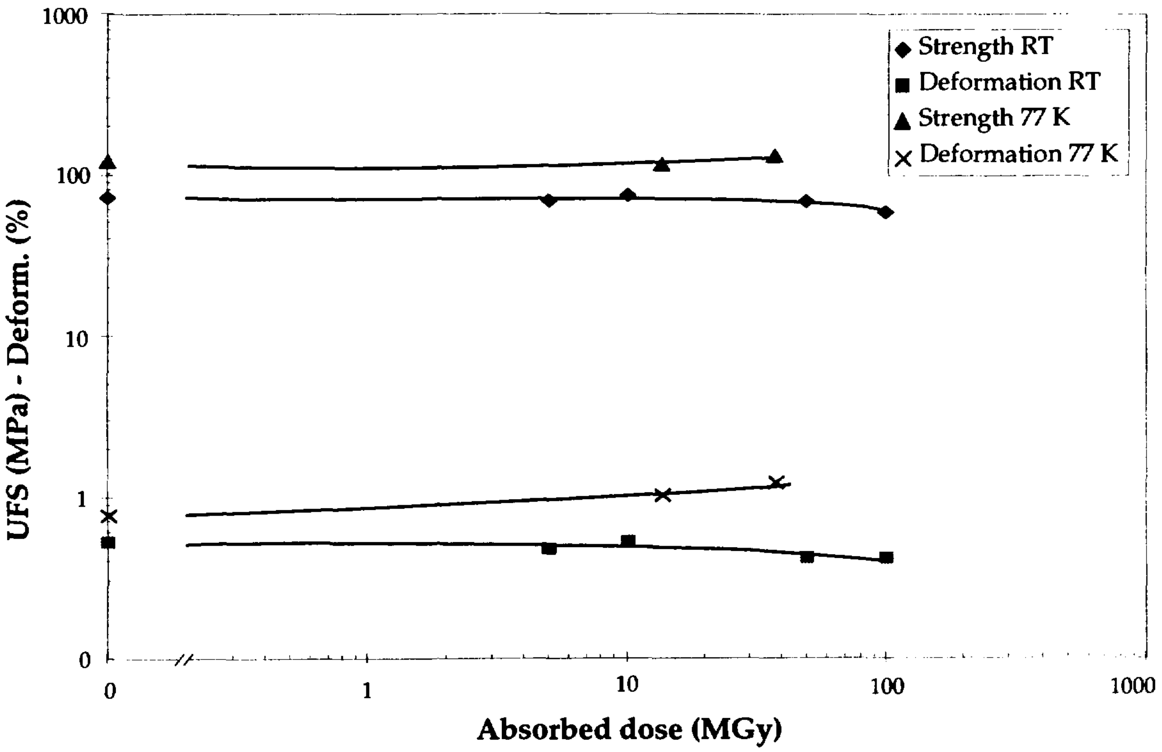


Fig. 21: Epoxy XB 3192 R 455

Material:	**Prepreg**	TIS No. **R 538**
Type	**Vetronite Epoxy G11**	
Supplier:	**von Roll Isola**	UL 94: n.m.
Remarks:	proposed LHC magnets insulation	LOI:

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose (MGy)	Mechanical test results at RT			Mechanical test results at 77 K		
	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**557** ± 23	**2.5** ± 0.1	**29.8** ± 8.8	**986** ± 2	**7.2** ± 0.0	**28.6** ± 0.2
5	**484** ± 16	**2.2** ± 0.2	**25.7** ± 0.9			
10	**448** ± 24	**2.0** ± 0.1	**26.6** ± 0.6			
14				**497** ± 52	**2.6** ± 0.2	**19.8** ± 0.8
37				**226** ± 32	**1.4** ± 0.2	**15.4** ± 1.3
50	**295** ± 22	**1.4** ± 0.1	**26.1** ± 0.5			
100	**211** ± 20	**1.1** ± 0.1	**22.5** ± 1.3			
RI =	**7.7**	**7.8**	**> 8**	**7.2**	**7**	**~ 7.6**

Radiation effect on Vetronite laminate R 538

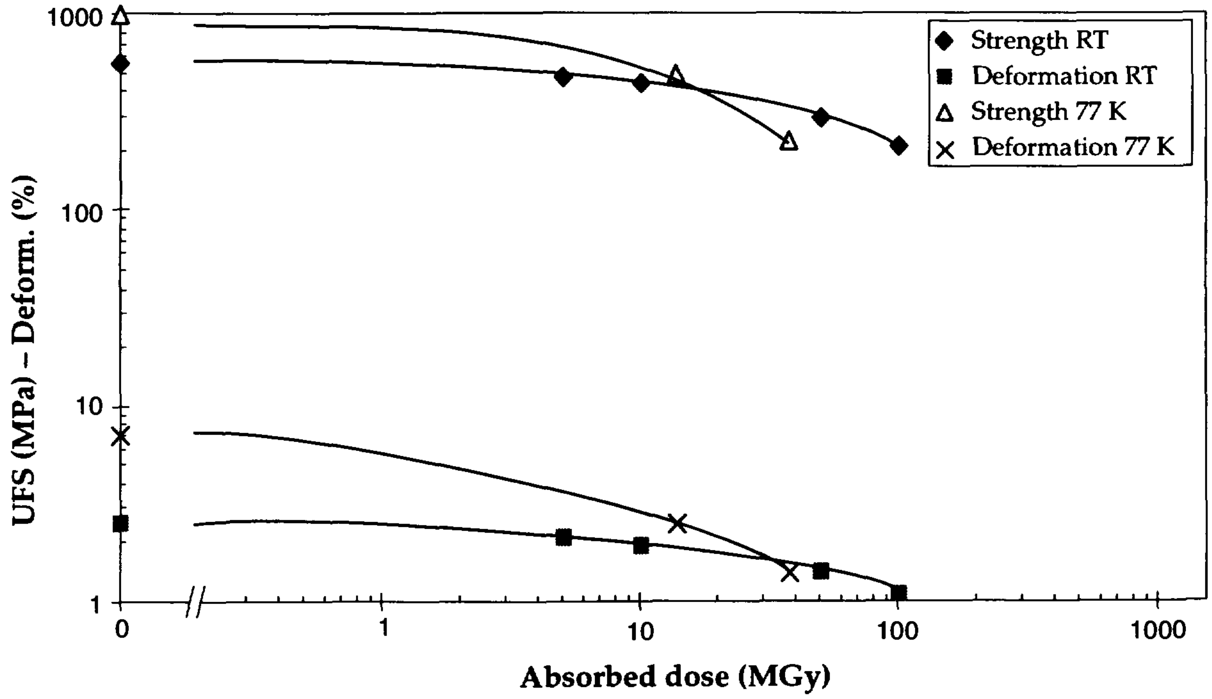


Fig. 22: Vetronite G11 R 538

Material:	**Prepreg**	TIS No. **R 545**
Type	**Epoxy + GF**	
Supplier:	**Isola**	UL 94: n.m.
Remarks:	LHC magnet insulation	LOI: n.m.

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose	Mechanical test results at RT			Mechanical test results at 77 K		
(MGy)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**253.0** ± 21.0	**1.10** ± 0.05	**27.4** ± 0.70	**199** ± 50	**0.9** ± 0.2	**23.5** ± 2.5
14				**205** ± 40	**1.2** ± 0.3	**17.9** ± 1.1
37				**201** ± 23	**1.1** ± 0.1	**20.8** ± 3.0
RI =				**> 7.5**	**> 7.5**	**> 7.5**

Radiation effect on Prepreg R 545

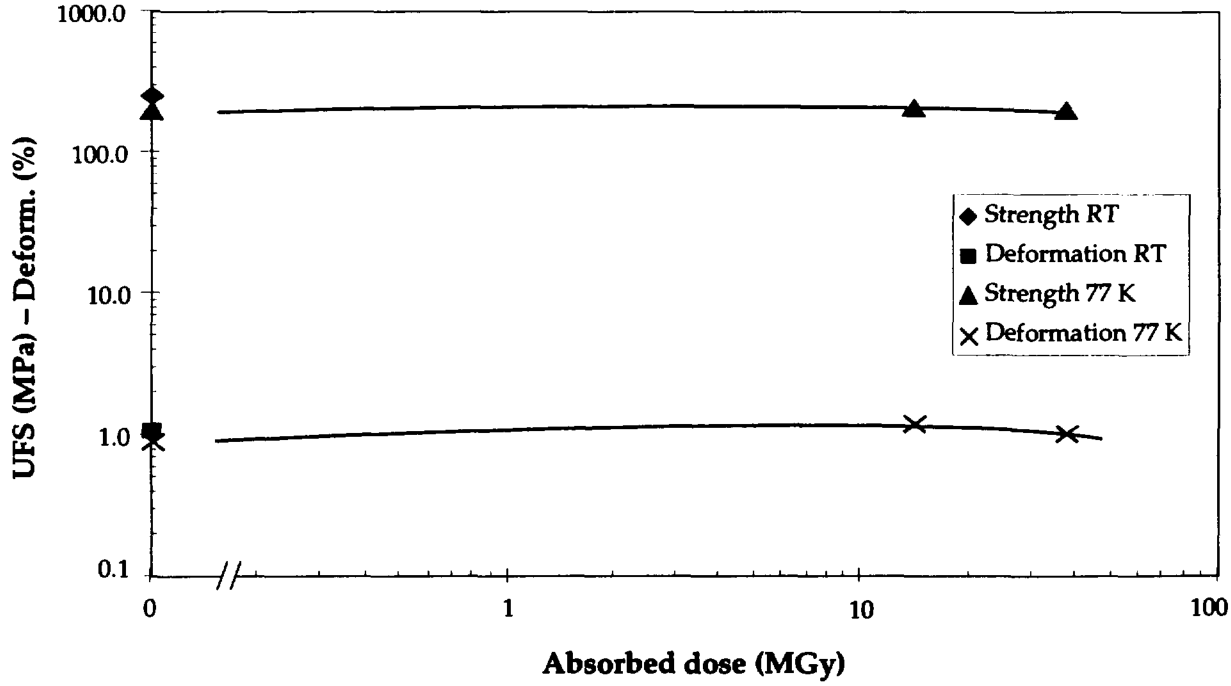


Fig. 23: Laminate Ep + GF R 545

Material: **Prepreg** TIS No. **R 546**
Type **Vetronite**

Supplier: **Isola** UL 94: n.m.
Remarks; LHC magnet insulation LOI: n.m.

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose	Mechanical test results at RT			Mechanical test results at 77 K		
(MGy)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**499** ± 9	**2.9** ± 0.1	**20.2** ± 0.2	**923** ± 27	**5.2** ± 1.1	**29.5** ± 4.4
14	**260** ± 50	**2.0** ± 0.4	**17.0** ± 3.0	**565** ± 7	**3.0** ± 0.2	**22.0** ± 1.0
37	**150** ± 30	**1.5** ± 0.3	**14.0** ± 3.0	**318** ± 16	**1.8** ± 0.2	**21.5** ± 1.6
RI =	**~ 7.3**	**~ 7.6**	**> 7.6**	**7.3**	**7.2**	**> 7.5**

Radiation effect on Prepreg R 546

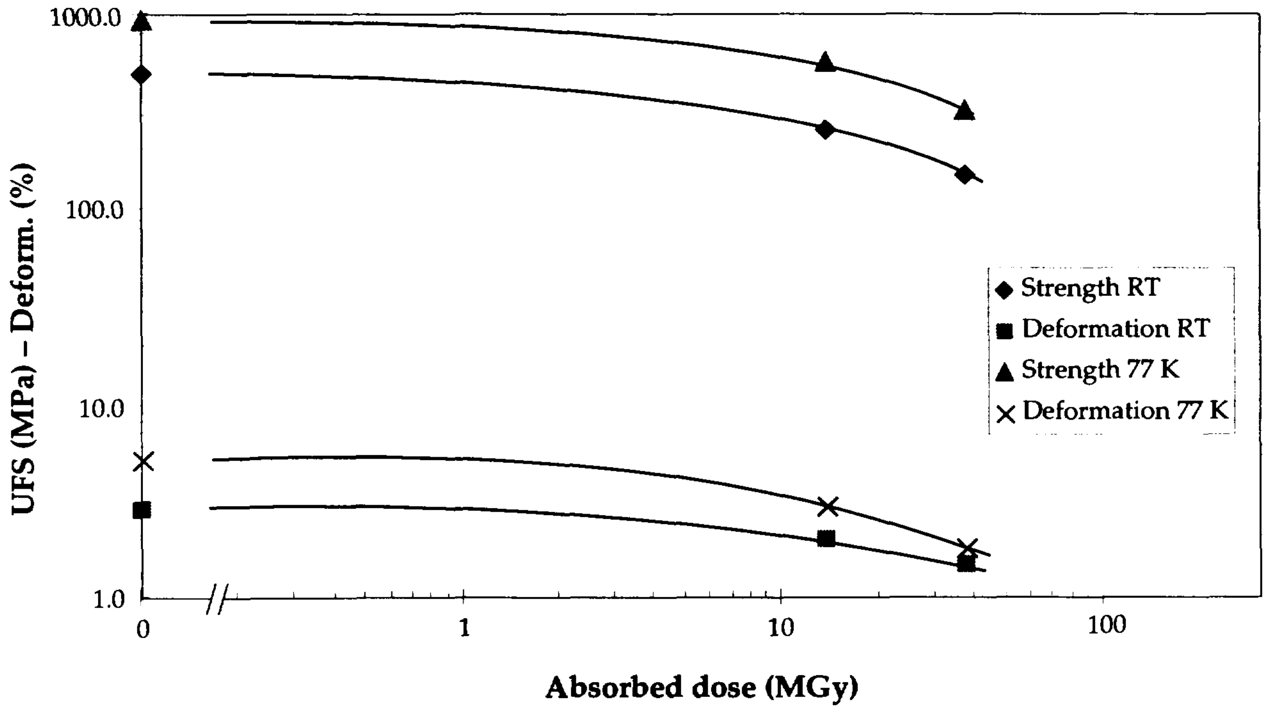


Fig. 24: Vetronite R 546

Material:	**Prepreg**	TIS No. **R 547**
Type	**Epoxy + GF**	
Supplier:	**Isovolta**	UL 94: n.m.
Remarks:	LHC magnet insulation	LOI: n.m.

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose	Mechanical test results at RT			Mechanical test results at 77 K		
(MGy)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0 **19** **156**	**243.8** ± 19.5	**1.06** ± 0.2	**16.5** ± 0.43	**751** ± 26 **607** ± 65 **413** ± 27	**2.5** ± 0.4 **2.4** ± 0.2 **1.9** ± 0.2	**33.4** ± 3.9 **25.3** ± 0.9 **24.1** ± 0.9
RI =				> **8.2**	> **8.2**	> **8.2**

Radiation effect on Prepreg R 547

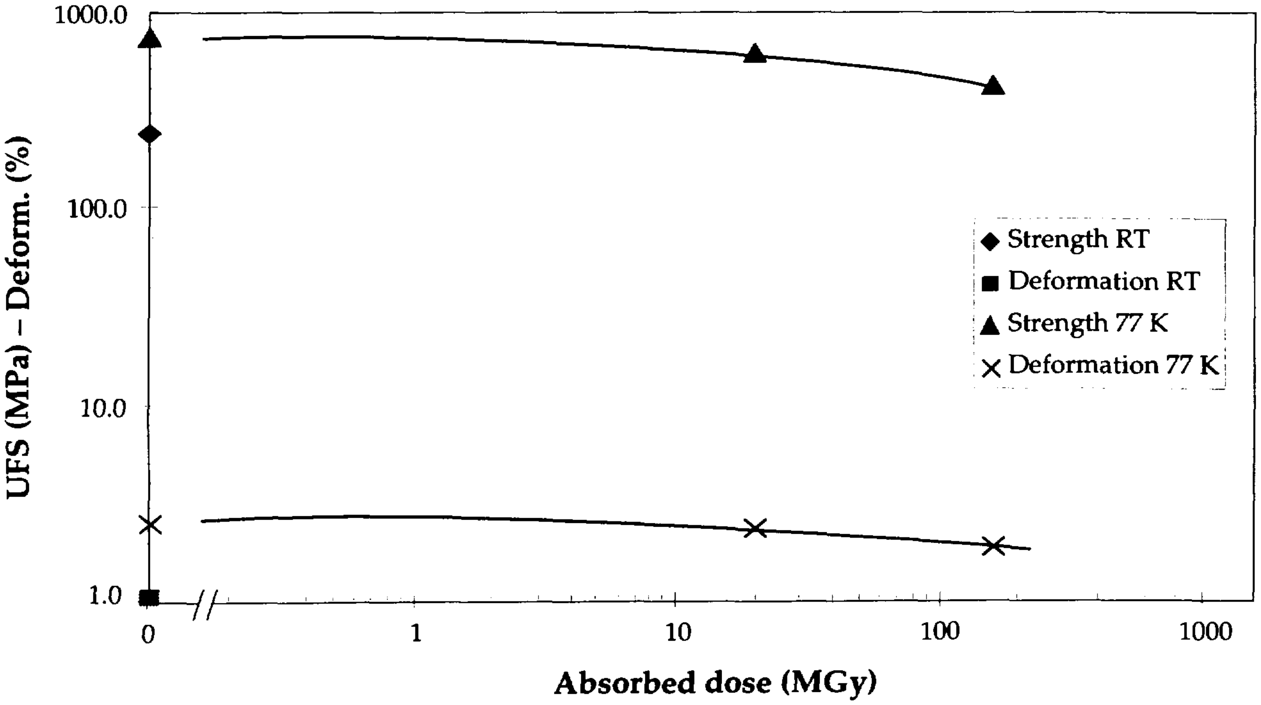


Fig. 25: Laminate Ep + GF R 547

Material: **Prepreg** TIS No. **R 548**
Type **Epoxy + GF + Kevlar**

Supplier: **Isovolta** UL 94: n.m.
Remarks: LHC magnet insulation LOI: n.m.

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose	Mechanical test results at RT			Mechanical test results at 77 K		
(MGy)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**377** ± 9	**2.05** ± 0.02	**33.3** ± 1.4	**569** ± 21	**2.7** ± 0.2	**33.7** ± 0.5
3	**289** ± 8	**1.62** ± 0.07	**30.3** ± 0.8			
19				**472** ± 27	**1.6** ± 0.1	**37.0** ± 1.7
50	**280** ± 5	**1.58** ± 0.06	**29.0** ± 1.0			
100	**139** ± 42	**1.68** ± 1.92	**26.3** ± 3.9			
156				**361** ± 17	**1.4** ± 0.2	**28.6** ± 1.2
RI =	**7.8**	**> 8**	**> 8**	**> 8.2**	**~ 8.2**	**> 8.2**

Radiation effect on Epoxy-glass-Kevlar laminate R 548

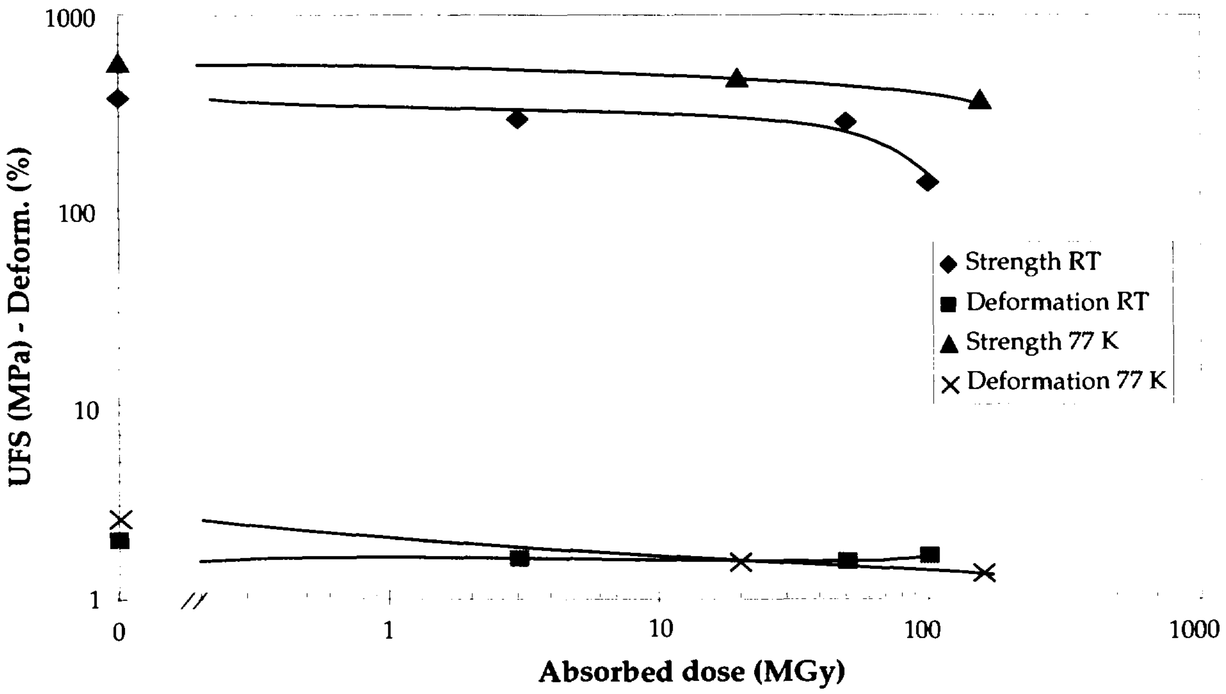


Fig. 26: Laminate Ep + GF + Kevlar R 548

Material: **Composite** TIS No. **R 549**
Type **Epoxy + CF**

Supplier: **Russia** UL 94: n.m.
Remarks: LHC magnet cold support LOI: n.m.

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose	Mechanical test results at RT			Mechanical test results at 77 K		
(MGy)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**826.8** ± 34.7	**1.63** ± 0.1	**52.4** ± 0.56	**848** ± 24	**1.9** ± 0.1	**50.1** ± 1.7
19				**1124** ± 66	**2.3** ± 0.1	**54.1** ± 5.0
156				**716** ± 13	**1.8** ± 0.2	**42.9** ± 1.4
RI =				**> 8.2**	**> 8.2**	**> 8.2**

Radiation effect on Composite R 549

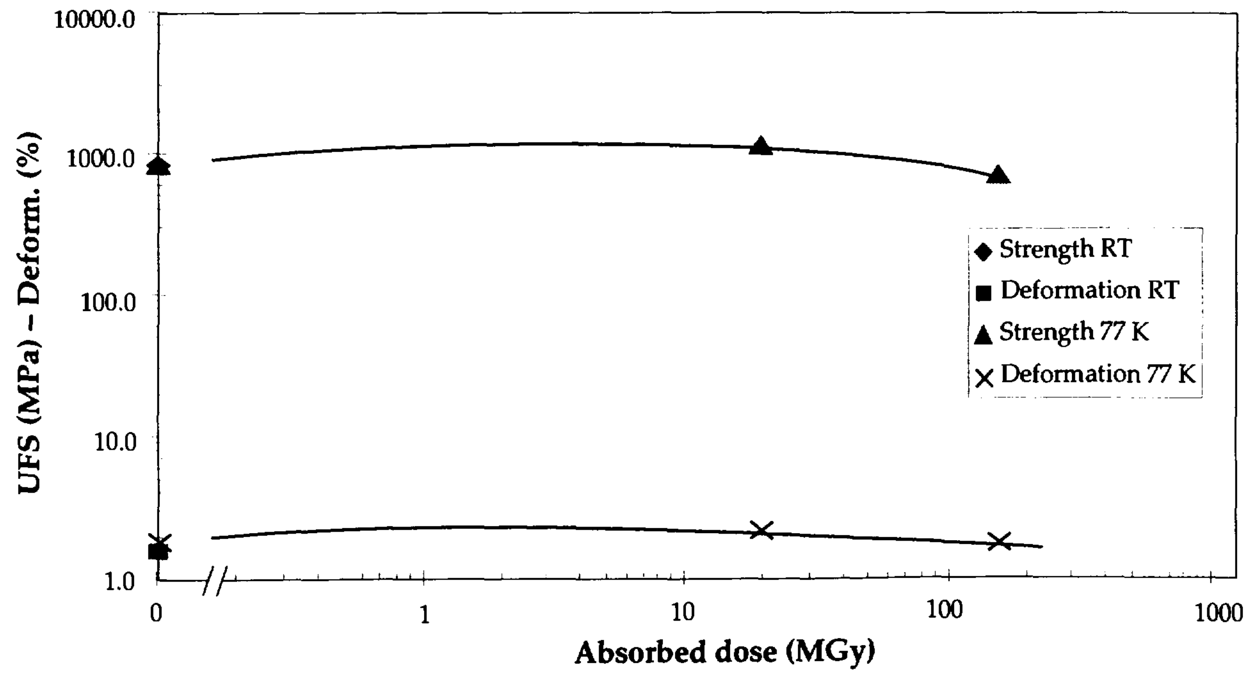


Fig. 27: Carbon-epoxy R 549

Material:	**Composite**	TIS No. **R 550**
Type	**Epoxy + CF**	
Supplier:	**Ciba-Geigy**	UL 94: n.m.
Remarks:	LHC magnet cold support	LOI: n.m.

Radiation test results according to IEC Standard 544 (and ISO 178)

Dose (MGy)	Mechanical test results at RT			Mechanical test results at 77 K		
	Strength (MPa)	Deformation ε (%)	Modulus (GPa)	Strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**1674** ± 135	**1.54** ± 0.05	**112** ± 1.8	**864** ± 23*	**1.1** ± 0.0*	**82.3** ± 3.6
10	**1681** ± 122	**1.65** ± 0.09	**106** ± 1.5			
19				**2288** ± 44	**2.5** ± 0.2	**93.5** ± 2.2
50	**1579** ± 75	**1.56** ± 0.06	**106** ± 0.9			
156				**2206** ± 83	**2.7** ± 0.2	**87.7** ± 2.5
RI =	**> 7.7**	**> 7.7**	**> 7.7**	**7.3**	**> 8.2**	**> 8.2**

* Value expected to be erroneous

Radiation effect on carbon-epoxy R 550

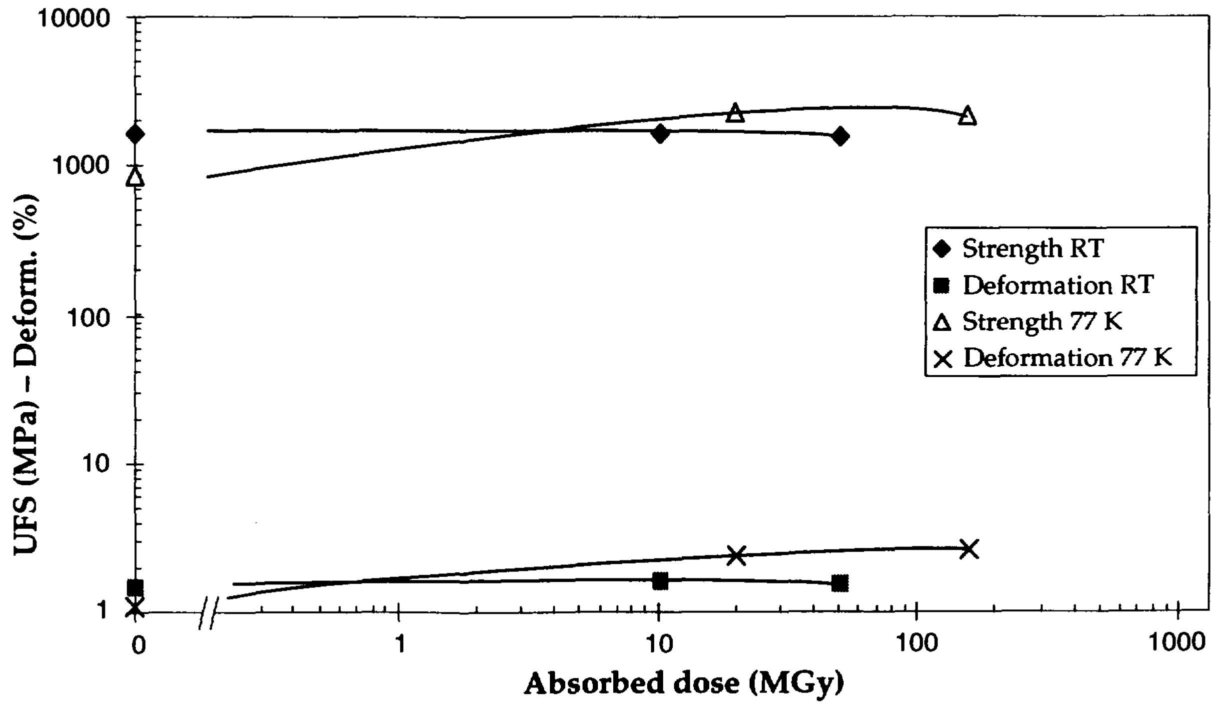


Fig. 28: Carbon-epoxy R 550

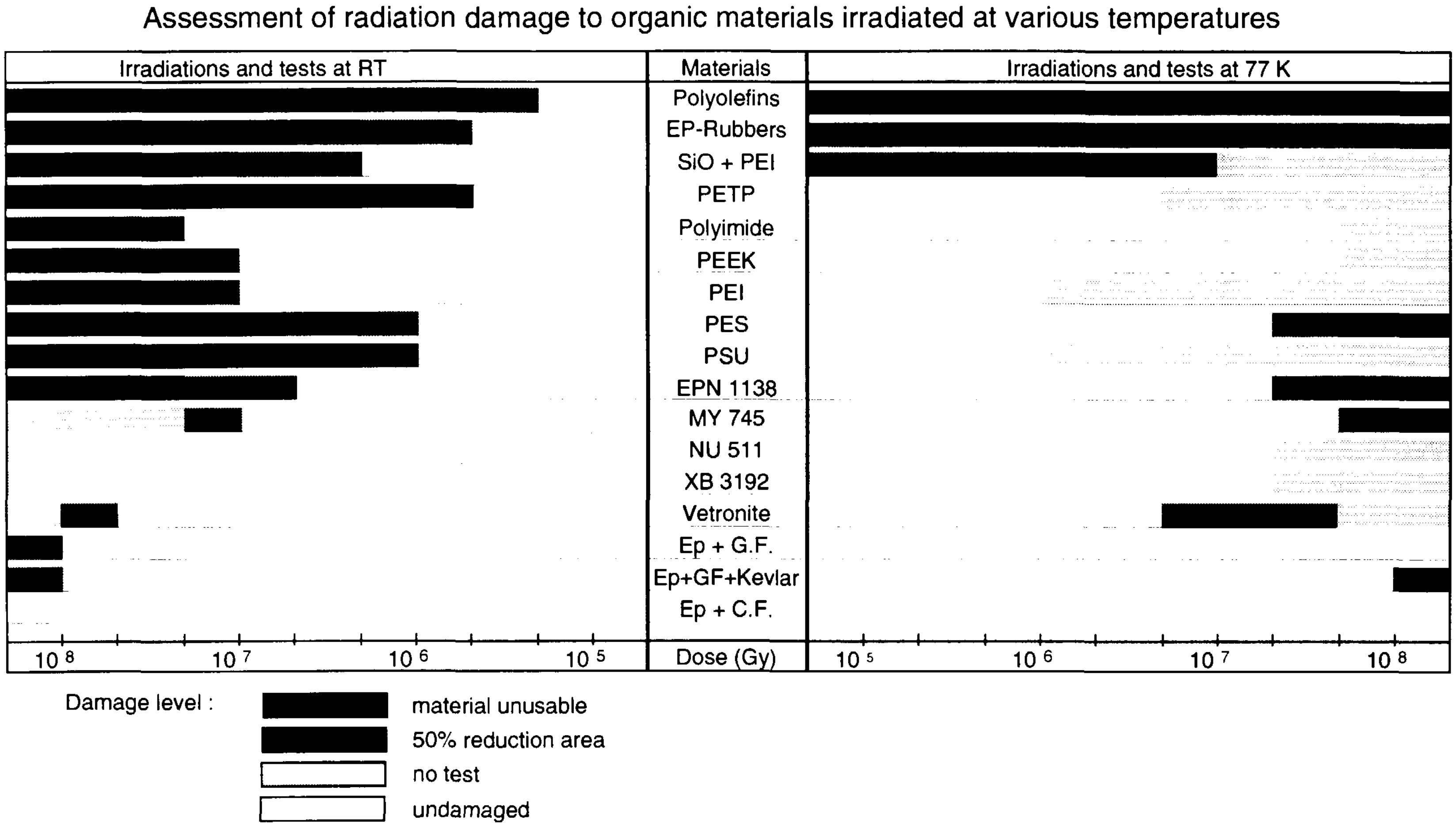


Fig. 29: Overview of radiation resistance at RT and at 77 K

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ISBN 92-9083-086-7