IEC/TR 62283

Edition 2.0 2010-06

TECHNICAL REPORT

Optical fibres – Guidance for nuclear radiation tests

IEC/TR 62283:2010(E)

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Optical fibres – Guidance for nuclear radiation tests

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE V

ICS 33.180.10

ISBN 978-2-88912-031-4

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OPTICAL FIBRES – GUIDANCE FOR NUCLEAR RADIATION TESTS

FOREWORD

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IEC 62283, which is a technical report, has been prepared by subcommittee 86A: Fibres and cables, of IEC technical committee 86: Fibre optics.

This second edition cancels and replaces the first edition of IEC/TR 62283 published in 2003 and constitutes a technical revision.

The main changes with respect to the previous edition are listed below:

– Clause 5 now also covers Industrial environment.
– a new Clause 9 has been added to deal with "Measurement techniques and quality assurance of attenuation measurements".

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86A/1312/DTR	86A/1327/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

In order to restrict the test method of IEC 60793-1-54, *Optical fibres – Part 1-54: Measurement methods and test procedures – Gamma irradiation* to a clear, concise listing of instructions, the background knowledge that is necessary to perform correct, relevant and expressive irradiation tests as well as to limit measurement uncertainty is presented here separately as a "guidance document".

OPTICAL FIBRES – GUIDANCE FOR NUCLEAR RADIATION TESTS

1 Scope

This technical report gives a short summary of the radiation exposure in certain environments and applications and the different radiation effects on fibres. It also describes the most important radiation effect, i.e. the increase of transmission loss, and its strong dependence on a variety of fibre properties and test conditions. These dependencies need to be known in order to perform appropriate tests for each specific application as well as to understand, compare and qualify the test results obtained at different laboratories when performed according to IEC 60793-1-54, *Optical fibres – Part 1-54: Measurement methods and test procedures – Gamma irradiation.*

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60793-1-40, *Optical fibres – Part 1- 40: Measurement methods and test procedures – Attenuation*

IEC 60793-1-46, *Optical fibres – Part 1-46: Measurement methods and test procedures – Monitoring of changes in optical transmittance*

IEC 60793-1-54, *Optical fibres – Part 1-54: Measurement methods and test procedures – Gamma irradiation*

3 Radiation units, dose calculation

The interaction of radiation with matter depends on charge, mass and energy in the case of particle radiation (for example, electrons, protons, neutrons, alphas and heavy ions) and on energy in the case of electromagnetic radiation such as X-rays or gamma quanta. The interaction causes an energy transfer to the respective matter. This leads to ionization and warming up. Additionally structural damage in the material may occur at higher doses, leading to other effects such as changes of refractive index or mechanical properties.

The higher the radiation's energy, the stronger its penetrability and the longer its range. The energy unit is the electron Volt (eV). Usual radiation energies in natural or technical environments range from tens of keV (medical X-rays) to several MeV (fission or fusion reactors and nuclear weapons). Current energies at high-energy physics accelerators vary depending on the type of colliding particles. The highest energy for electron-positron collisions is 100 GeV per beam. For proton-proton collisions the energy per beam is 1 TeV. The new "Large Hadron Collider" (LHC) at CERN uses beams with an energy of 7 TeV. In addition, there are quite a number of other accelerators which operate between these limits.

Note that these energies refer to the colliding particles. The secondary particles, i.e. the ones likely to affect fibres, have much lower energies.

The energy deposited by ionizing radiation in matter is called "energy dose" (or absorbed dose). The old unit is rad, (rd or rad); 1 rad = 100 erg/g (1 erg = 10^{-7} J) but should not be used anymore. The SI unit is the Gray [Gy]; 1 Gy = 1 J/kg = 100 rad.

Some dosimeter types measure the charge released in a gas (for example, ionization chambers). This was used to define another type of dose, the "ion dose". The ion dose unit is the röntgen (non-SI unit), [R]; 1 R = 2,58 × 10^{-4} C/kg, with C = charge unit (coulomb). Conversion of ion dose, D', to energy dose, D, can be performed for ^{60}Co gamma rays (about 1,2 MeV) by

$$D = 0{,}879\,\frac{\text{Gy(air)}}{\text{R}}\;D' \qquad (1)$$

If this unit is used, the values of relevant quantities shall be given in terms of SI units first followed by these non-SI units in parentheses.

The energy transfer of gammas and X-rays to matter depends on their energy as well as on the irradiated material. Therefore, the material has to be added to the dose unit (for example [Gy(Si)], [rad(SiO_2)], [Gy(air)] etc.), and the dose D(d) measured with a dosimeter material d (for example, air) can differ significantly from the dose D(m) deposited in the investigated material m (for example, Si, SiO_2, InGaAs etc.).

The dose ratio between both materials D(m) is given by the ratio of their "photon mass energy absorption coefficient" μ_{en}/ρ:

$$D(m) = \frac{(\mu_{en}/\rho)_m}{(\mu_{en}/\rho)_d}\;D(d) \qquad (2)$$

The μ_{en}/ρ-values can differ significantly, especially for materials of high and low atomic number at energies < 300 keV. They are tabulated for various elements and compounds in reference [1][1].

The dose rate, i.e. the dose exposition per time, should be given in units of Gy/h, kGy/h, or Gy/s.

The intensity of particle radiation is usually characterized by the fluence Φ. The unit is particles/cm^2 or only cm^{-2}. The dose of charged particles (in a certain material depth) can be calculated from their fluence and their (energy-dependent) energy loss per unit of length, dE/dx (= stopping power):

$$D = \frac{\Phi}{\rho}\cdot\frac{dE}{dx} \qquad (3)$$

with ρ = material density. The stopping power can be calculated with the software package "SRIM"[2], see [2]. The particle fluence per time unit is called flux or flux density. The unit is $cm^{-2}\,s^{-1}$.

The neutron dose D_n can be calculated from its fluence Φ_n and the energy and material dependent "fluence dose conversion factor" or "kerma factor" k(E_n,Mat.):

$$D_n = \Phi_n \cdot k(E_n, Mat.) \qquad (4)$$

The kerma-factors are tabulated for a variety of elements and compounds in [3].

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1) Numbers in square brackets refer to the bibliography.

2) SRIM is the trade name of a product supplied by IBM. This information is given for the convenience of users of this Technical Report and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

4 Radiation shielding

Shielding of optical fibres against (especially gamma) radiation is in most cases not reasonably achievable since, for example, gamma rays of 1 MeV are attenuated to 1/10 of their initial intensity only by 5 cm of lead.

However, buried fibre cables that are layed in at least 1 m depth are shielded against 1 MeV gamma rays by about a factor of 10^4.

5 Radiation environments and exposure

5.1 Natural radioactivity

The predominant radiation type is gamma rays. Typical annual dose value for earth cables or undersea cables is <0,004 Gy. The total dose during an expected cable lifetime of 25 years would thus be <0,1 Gy. Distinctly higher values are possible, for example, above uranium or thorium ore deposits. The dose and dose rates are typical and may vary depending on the specific application.

5.2 Nuclear reactors (fission)

Optical fibres can be exposed to gamma rays as well as to thermal and fast neutrons. Dose and fluence values depend strongly on the place within the reactor building and the operating conditions of the reactor (for example the power delivery, normal operation or accident).

Within the containment area, exposure levels range from 0,001 Gy/h to 0,03 Gy/h up to about 1 Gy/h near the primary coolant lines. The dose rate around the fuel rods is of the order of 10^3 Gy/h. In the early stage of an accident, dose rates as high as 10^4 Gy/h will occur within the containment [4].

The neutron flux (= fluence Φ per unit of time) within the containment can range from about 10 $cm^{-2}s^{-1}$ up to about 10^{12} $cm^{-2}s^{-1}$near the fuel rods.

The dose, dose rates and neutron fluence are typical and may vary depending on the specific application.

5.3 Fusion reactors

The primary radiation emitted after the fusion of deuterium (D) and tritium (T) nuclei are 14 MeV neutrons and ^{4}He nuclei (energy about 3,5 MeV). The ^{4}He ions are very short-ranged and will not reach optical fibres that might be used as sensors or to transfer data, whereas the fast neutrons are very penetrating and will also activate the structural materials around the reaction chamber. These materials then emit high gamma ray intensities also after reactor turn-off.

Again, the total dose and neutron fluence values depend strongly on location and operation conditions.

For the future test facility ITER (International Thermonuclear Experimental Reactor), gamma dose rates at the first wall of about 2×10^2 Gy/s and life dose values of 10^7 Gy to 10^9 Gy are expected. The neutron fluence there could reach values up to 10^{20} cm^{-2}.

At inertial confinement fusion (ICF) facilities such as "Laser Megajoule" (France) or "National Ignition Facility" (USA) diagnostic equipment, comprising also optical fibres, is exposed to pulsed radiation of up to 10^3 Gy at dose rates up to 10^{10} Gy/s.

The dose and dose rates are typical and may vary depending on the specific application.

5.4 High-energy physics experiments

Usually, in high-energy physics, electrons or protons with energies as high as several 100 GeV (protons) are used to study elementary particles. In order to increase the reaction energy it is common that two beams collide within a reaction zone which is surrounded by huge detectors analyzing the reaction products. The accelerator tube and the inner parts of the detectors will become highly radioactive, especially if protons collide.

The secondary radiation that threatens the accelerator control instruments and the detector read-out equipment mainly consists of pions (mean energy several 100 MeV), gamma rays and, at radii >50 cm, of neutrons with maximum energies up to more than 100 MeV, but a mean energy of only about 1 MeV to 2 MeV. The radiation intensities strongly depend on the operating conditions (particle energy, beam current), the distance from the beam line, and the emission angle (maximum in beam direction). Particularly in the beam cleaning sections, high radiation levels may occur.

The annual total dose can be of the order of 10^5 Gy to 10^6 Gy and the neutron fluence can reach values from 10^{13} cm^{-2} to 10^{15} cm^{-2}. The dose and dose rates are typical and may vary, depending on the specific application.

5.5 Space environments

Close to the earth the dominating radiations are solar protons, trapped protons and trapped electrons. "Trapped" means trapped by the magnetic field of the earth, within the Van Allen Belts.

The electrons are concentrated in an inner zone (ending at about 2,4 earth radii) and an outer zone (between about 2,8 earth radii and 12 earth radii). Their maximum energy is about 7 MeV. They can be stopped, for example, by about 10 mm Al. During the slowing down process in matter, they produce penetrating X-rays (Bremsstrahlung).

The proton flux decreases with increasing distance from earth. The maximum energy is several 100 MeV. For example, the range of 300 MeV protons in Al is about 24 cm. More than 90 % of the protons have energies below 100 MeV.

In a geostationary orbit (for example, 15° east) the total annual dose behind 3 mm Al is nearly 600 Gy, of which about 550 Gy is caused by trapped electrons and about 50 Gy by solar protons. In a low earth orbit (LEO), height 1 000 km and 70° inclination, the total annual dose of about 823 Gy (behind 3 mm Al) is composed of about 400 Gy trapped electron contribution, about 420 Gy trapped proton contribution and 3 Gy solar proton contribution.

Additionally to the above-mentioned radiation types, cosmic rays are an additional type of space radiation. The "primary" cosmic rays are a low flux of high energetic particles (about 85 % protons, 14 % alpha particles and about 1 % heavier nuclei). Their contribution to the total dose, however, is negligible.

Particle fluences for certain orbits and dose values can be calculated, for example, with the "SPENVIS" system [5]. The dose and dose rates are typical and may vary depending on the specific application.

5.6 Medicine

For radiography purposes (diagnostics) X-rays with energies <100 keV are used. With modern image intensifier techniques dose values $<10^{-3}$ Gy are sufficient to take a series of expressive pictures.

Irradiation of tumours is made with ^{60}Co gamma rays, high energy electrons (20 MeV to 30 MeV), high energy protons (60 MeV to 300 MeV) or heavy ions (for example ^{12}C, 2 GeV to 4 GeV), and thermal or fast neutrons. Dose values within the tumour can reach several Gy per "session". The dose and dose rates are typical and may vary depending on the specific application.

5.7 Military environments

The radiation emitted from a nuclear weapon can be divided into prompt (gamma) radiation emitted during the explosion phase within a time of about 10^{-8} s, and a delayed component (gammas and fast neutrons) becoming effective after times of up to 1 min. Despite the fact that the contribution of prompt radiation to the total dose is less than 10 %, this component can be very destructive because of its high dose rate (for example, 1 Gy within 10^{-8} s, i.e. a dose rate of 10^{8} Gy/s). Therefore, special tests with pulsed radiation sources (for example, flash X-ray generators) would have to be performed to simulate this radiation component.

Total dose and neutron fluence depend on weapon strength (explosive force), the weapon type (contribution of fusion energy), and the distance from the explosion site. The radiation emission for a given explosive force can be increased by increasing the fusion contribution ("neutron bomb" or "radiation enhanced weapon"). According to the "balanced hardening" principle, fibre cables should not withstand extremely high radiation dose values near the center of the explosion, where heat and shock wave will destroy the cable anyway.

Typical (initial) radiation exposure levels are

– prompt radiation dose rate 10^{8} Gy/s to 10^{9} Gy/s (prompt dose 1 Gy to 5 Gy),
– total dose 30 Gy to 100 Gy,
– fast neutron fluence 10^{12} cm^{-2} to 10^{13} cm^{-2} (1 MeV).

With high-altitude (= exo-atmospheric) nuclear explosions the high amount of X-ray energy will not be absorbed and can cause significant damage, even far away from the explosion.

Apart from the initial radiation (emitted within about 1 min after explosion) "fall out" can severely contaminate large areas, dependent on explosion height, direction and strength of the wind, and rainfall. Dose levels up to several tens of Gy can be reached within 10 h to 15 h after explosion in areas of several 100 km^{2}.

Details about radiation emission from nuclear weapons can be found, for example, in [6]. The dose and dose rates are typical and may vary depending on the specific application.

5.8 Industrial environments

Several industrial applications benefit from ionising radiation. Examples are sterilisation and material irradiations, especially plastic materials. For sterilisation either gamma sources with high activities or electron accelerators are used depending on the target material and thickness. Such gamma sources can have activities of up to exa-Becquerel (10^{8} Bq or EBq). Electron accelerators are often used for cross linking of plastic materials. They are operated with energies of up to several MeV. Here not only does the primary electron beam have to be considered, but also the secondary X-ray field. The doses vary between the applications and could be up to some 10 kGy or even MGy.

6 Irradiation facilities and dosimetry

6.1 General

In most environments radiation exposure is caused by different kinds of radiation, as outlined in Clause 5. As long as gamma rays or high energy X-rays are the dominant radiation type it might be sufficient to apply the expected total dose by gamma rays. However, in cases where fast neutrons, protons and even high energy electrons contribute significantly to the total dose, irradiation with these particle types might also become important for reasons that are described briefly in 8.8.

6.2 Continuous gamma irradiation

In most of the radiation environments, the mean gamma energy is around 1 MeV so that irradiation tests can be made with the widely used radioactive isotopes ^{60}Co or ^{137}Cs. Their gamma energy and half-life are about 1,25 MeV (mean value) and 5,3 years or 0,66 MeV and 30,2 years, respectively. Test samples (as well as dosimeters) would have to be covered with the energy-dependent dose build-up layer in order to reach "secondary electron equilibrium". For ^{60}Co gamma radiation a layer thickness of 1,5 mm aluminium is sufficient [7].

Irradiation with distinctly higher gamma energy can also change the fibre degradation mechanism (ratio of ionization and structural damage). Use of low energy gammas (or X-rays), especially below 0,1 MeV, will lead to rapid variation of dose as a function of depth within the fibre sample and to dosimetry errors ("dose enhancement" at interfaces between different materials).

The radiation-induced transmission loss of fibres also depends on dose rate, i.e. on the time that is necessary to reach the expected dose (see 8.7). Irradiation should therefore only be performed with dose rates recommended by the "test procedure" (if not otherwise specified) in order to give comparable results.

Dose rate and/or dose can be measured, for example, with ionization chambers, thermoluminescence dosimeters (TLDs) or radiochromatic film. A dose build-up layer of necessary thickness has to be provided. At high dose rates ionization chambers might show unacceptably high "recombination loss". Dose measurement with calibrated "dosimeter fibres", i.e. fibres with very high and non-annealing increase of attenuation, (see [8], [9], [10], and [11] and the literature cited therein), can give improved results for specific test sample configurations. Using optical fibres for dosimetry requires some experience to be routinely applied.

6.3 Neutron irradiation

Different radiation sources usually produce neutrons with a distinctly different energy spectrum, as outlined in Clause 4. In [12], it is described how neutrons of different energy lead to different fibre degradation mechanisms. To investigate the influence of neutron irradiation on optical fibres it is therefore not sufficient to apply a certain neutron fluence. At least the mean energy at the test facility should be comparable with that of the radiation environment in question.

Radioactive (α, n) neutron sources and spontaneous fission sources (mainly ^{252}Cf) release "fast" neutrons with energies of several MeV. (α, n) sources are a mixture of α-emitters such as Ra, Am or Po with Be. Collision of an α particle with a ^{9}Be nucleus can result in a ^{12}C nucleus and a fast neutron. An Am-Be source with an activity of 1 Ci (= Curie) would only yield about 2×10^{6} n/s (in 4π). Such sources are cheap, but their neutron output is too low for the majority of the necessary tests.

Some fission reactors are used for test purposes. These research reactors can deliver high fluxes (up to about 10^{15} cm^{-2} s^{-1}) of fast (mean neutron energy about 1 MeV) as well as slow or "thermal" neutrons with energies <1 MeV, depending on the reactor design.

Relatively high fluxes of monoenergetic fast neutrons can be obtained with "neutron generators". These are small accelerators where deuterons (d) are accelerated to energies of only 0,2 MeV to 0,5 MeV. The deuterons are focused on a "target" that contains deuterium (D) or tritium (T) and produce neutrons with an energy of about 2,6 MeV or 14,5 MeV, respectively. The neutron output with a deuteron current of 1 mA is about 4×10^{8} s^{-1} or 10^{11} s^{-1}, respectively (in 4π).

Very high intensities of fast neutrons can be produced at "spallation sources". These are accelerators where protons with energies up to 1 GeV and beam currents up to 1 mA are directed on to a heavy metal target (for example, Pb or Hg). In order to produce thermalized neutrons, the target can be surrounded by moderating material, and fluxes up to about 5×10^{14} cm^{-2} s^{-1} are available. Existing facilities are the SINQ source at Paul-Scherrer-Institute (CH), ISIS at Rutherford Appleton Laboratory (UK), and SNS at Oak Ridge National Laboratory (US).

Pulsed reactors (for example, of the TRIGA type) and, especially, "fast burst reactors" are mainly used for nuclear weapons effects testing. They produce neutron pulses with a duration of <50 ms or <0,1 ms, respectively. The neutrons are accompanied by high energetic gammas that contribute about 10 % to the total dose.

Several neutron irradiation places are also available at CERN [13], [14]. The neutrons are secondary products and are mostly released during nuclear reactions with high energetic protons. The energy spectrum is comparable with that of fission neutrons. Comparable sources providing either a secondary quasi mono-energetic neutron beam [15] or an atmospheric neutron spectrum [16] are available at the Uppsala Neutron Beam Facility of TSL, Sweden.

For some special situations, it is possible to simulate the effect of neutrons of one energy (for example, fission neutrons with a mean energy of about 1 MeV) by neutrons with distinctly different energy, for example, fusion neutrons with about 14,5 MeV. From reference [3], it can be calculated that 14,5 MeV neutrons will cause the same dose in SiO_2 as a fluence about 10 times higher of 1 MeV neutrons. On the other hand, it is known that 14,5 MeV neutrons cause only about 2,5 times higher structural or displacement damage (in Si) than the same fluence of 1 MeV neutrons. One therefore has to know if and when fast neutrons degrade optical fibre performance by their deposited dose rather than by their displacement damage (see 8.9).

The fluence of fast as well as of thermal neutrons is mainly determined by activation analysis or fission chambers. For thermal neutron detection, a fission chamber contains, for example, ^{235}U instead of ^{238}U for fast neutrons. Correspondingly, one has to choose for activation analysis isotopes with high cross section for fast or for thermal neutrons. The dose of the respective fluences can be calculated with the material- and energy-dependent fluence dose conversion factors tabulated in [3]. The fluence of thermal neutrons can also be determined by calibrated dosimeter fibres with B-doped core [9]. For neutron energies >2,5 MeV, it has to be considered that high energetic "recoil protons" out of the hydrogen (H) containing coating or cable materials can increase the dose in deeper layers of a fibre spool or in a cabled fibre by up to a factor of about five, dependent on neutron energy and hydrogen content [12], [17].

6.4 Proton irradiation

The only environment where greater lengths of optical fibres might be exposed to considerable fluences of high energetic protons are the radiation belts of the earth (see 5.5) and, especially, of Jupiter. Fibres are increasingly used, for example, for data bus systems of satellites (usually multimode step-index (MM SI) with pure SiO_2 core of high OH content) or in fibre amplifiers or fibre lasers of "free space laser communication" systems (rare earth doped and polarization maintaining single-mode (SM) fibres).

In reference [18], it was shown that ^{60}Co gamma and 60 MeV proton irradiation up to a dose of 10^3 Gy (= 10^5 rad) leads to nearly the same radiation-induced fibre loss increase. Obviously, the proton-induced loss seemed to be about 25 % lower. For an explanation, see 8.9. This general observation was also confirmed with rare earth doped fibres [19].

Since proton doses of 10^3 Gy are only obtained during several years in a "LEO" (see 5.5), it is usually sufficient to make fibre tests up to the total dose (electron plus proton plus X-rays) with cheaper and more convenient gamma irradiations. This does not hold for the semiconductor components of a whole system where protons cause distinctly higher displacement damage than gamma irradiation up to the same dose. For proton dose values of 10^4 Gy to 10^5 Gy as they might be obtained during longer Jupiter missions, the structural damage caused by protons will be higher than the already existing defect concentration in as drawn fibres, leading to higher loss increase (see 8.9). Therefore fibre tests can no longer be made with gamma rays. The proton energy should be comparable with the mean energy in the respective space environment in order to have comparable ratios of ionization and displacement damage.

Proton irradiations can take place at linear accelerators and, especially, cyclotrons that deliver protons with energies between about 10 MeV and several 100 MeV. Such machines are often used as injectors for research facilities in the GeV energy range (see 5.4).

For accurate, expressive fibre tests, the irradiated length should be at least 5 m to 50 m, depending on fibre type. The fibres can be coiled up to spools, but their diameter should be greater than 5 cm to 10 cm, at least with multimode (MM) fibres. Often the fibre temperature has to be varied. These conditions can only be met at facilities which deliver higher energies (>30 MeV), where protons can leave the vacuum beam tube. The narrow beam diameter should be widened up by additional scatter foils so that, at distances between about 1 m and 5 m behind the scatter foil, a relatively homogeneous proton flux distribution is achieved across diameters between about 5 cm to 25 cm. The penetration depth of the protons should be calculated and the sample arrangement carefully chosen to avoid self shielding effects and larger energy variations across the sample. Such test facilities are, for example, described in [20], [21].

Dosimetry can be made by activation foils, ionization chambers , TLDs or radiochromatic film. Dose measurements with calibrated "dosimeter fibres" can give improved results for specific test sample configurations (see 6.1). The proton fluence can be calculated from the dose with the energy and material dependent proton "stopping power" (= energy loss per length unit) that is tabulated in [22]. Calculations for spacious, thicker samples where the proton energy decreases with increasing depth are facilitated by the computer program "SRIM" (see [2]).

6.5 Electron irradiation

In space environments most of the electrons are already stopped by the outer satellite shell because of their low energy (< 7 MeV, see 5.5), producing penetrating X-rays. The effect of space electrons on optical fibres can therefore be simulated with sufficient accuracy by irradiation with ^{60}Co gamma rays. At accelerators high energy electrons have to be considered.

In cases where electron irradiation is explicitly demanded, one can use Van de Graaff generators. Their maximum energy ranges from about 1 MeV to 10 MeV. For homogeneous irradiation of fibre coils the narrow beam should leave the vacuum beam tube through a thin metal foil. This foil can at the same time act as a scattering foil that widens the beam. With electrons of such relatively low energy it is also possible to wave the narrow beam across the spool by means of electromagnetic deflectors, like in a TV tube.

Electron irradiation is often made with betatrons and (smaller) linear accelerators. Here the electrons have distinctly higher energy (from about 25 MeV to several 100 MeV) and cause nuclear reactions and considerable displacement damage, i.e. the ratio of structural damage and ionization is higher than it would be in space. High energy electrons should therefore only be used for lower dose values (<10^3 Gy), as long as the electron-induced defect concentration is lower than that in unirradiated fibres (see 6.3). Up to these doses no significant differences were observed between ^{60}Co gamma rays, 10 MeV electrons, and 25 MeV electrons.

In cross linking irradiations of cable materials the fibres in the cables can also be exposed to electrons and secondary X-rays. The dose deposed in the fibres depends on the electron energy, the cable and coating materials and their thicknesses. Furthermore, structural changes in the cable materials can introduce additional stress to the fibre, leading to increasing attenuation. Therefore the separation of mechanical and radiation-induced losses is difficult, demanding a careful analysis of the respective contributions.

Dosimetry can be made with ionization chambers, scintillation detectors, TLDs, radio-chromatic film or dosimeter fibres (see 6.1).

6.6 Pulsed irradiation

If a higher radiation dose is applied within a very short time, i.e. with an extremely high dose rate, the radiation-induced fibre loss can reach tremendous values (see 8.8). During such a short time, annealing mechanisms cannot reduce the induced absorption like during an irradiation up to the same dose within seconds, minutes or even days (space). Therefore continuous irradiations are not suitable to simulate the effects of nuclear detonations or those at ICF facilities.

The most convenient and cheapest way to simulate such high dose rates are flash-X-ray facilities where voltages of several 10^6 V are instantaneously applied to a field emission tube, leading to an electron current of several 10^3 A up to several 10^4 A. The electrons are focused on a heavy metal target (W or Ta) where they produce penetrating bremsstrahlung (X-rays) with a continuous energy spectrum. Irradiation of a fibre spool can conveniently be made in air. With the smaller machines where the X-ray dose is too low, irradiation can be made by the original electron beam. The metal target is removed, and the beam leaves the field emission tube through a thin Ti window. An additional scattering foil widens the beam so that smaller fibre spools can be homogeneously irradiated at distances between about 50 cm and 150 cm. Because of the limited range of low energetic electrons, one often uses helical single layer spools. The test fibre length has to be short anyhow since the loss increase immediately after the end of a 10 ns radiation pulse can reach values up to 1 dB/cm, dependent on dose, fibre type, wavelength and fibre temperature.

Dosimetry can be made with TLDs, radiochromatic film, "differential calorimeters", or calibrated semiconductor diodes. Calibrated dosimeter fibres which are arranged in the same way as the fibre under test can give the most accurate and reliable results.

7 Radiation effects on optical fibres

Radiation can change nearly all properties of optical fibres, dependent on radiation type, radiation energy, radiation dose, dose rate, and also on fibre type. For simplicity one should only consider the most probable radiation types, energies, dose, and dose rate values that fibres can experience, as discussed in 5.1 to 5.7.

The most obvious effect of ionizing radiation is an increase of attenuation. This is observable with all radiation types in all fibre types already at lowest dose values. This most important radiation effect is therefore treated in more detail in Clause 8.

From the Kramers-Kronig dispersion relations it is known that any increase of attenuation is accompanied by a change of the refractive index. With graded index (GI) fibres where the dopant concentration varies across the fibre core diameter, the radiation-induced loss and therewith the refractive index changes might depend on the respective dopant concentrations. This has been investigated in the context of Fibre-Bragg-Gratings in more detail (see 10.3).

Irradiation of GI fibres should thus change the index profile and lead to a change of bandwidth. This question is investigated in [23] and the literature cited therein. Increase as well as decrease of bandwidth seems to be possible. With longer fibre sections, noticeable bandwidth degradation only occurs when the radiation-induced loss has mostly reached intolerably high values. At accelerator installations with longer fibre sections or during cable cross linking with electrons this might need to be considered, but usually only relatively short fibre lengths (10 m to 100 m) are necessary for most of the fibre applications in radiation environments. Therefore, bandwidth generally poses no major problem.

An effect that has to be considered after high gamma dose values (for example, nuclear facilities) and especially after higher fluences of high energetic neutrons or protons is changes of the breaking stress (BS). The influence of high gamma doses (10^6 Gy) and of 14 MeV neutron fluences of about 10^{13} cm^{-2} is described, for example, in [17], [24], [25] and the relevant literature cited therein. The fast neutron irradiations seemed to reduce BS by about 3 % to 4 %, whereas irradiation up to the corresponding gamma dose (about 500 Gy) seemed to have no effect. In [24], it is shown that gamma irradiation up to 10^6 Gy usually leads to a BS increase between about 2 % and 11 %. Other authors investigated the change of BS with fibres produced with different coatings [26]. They conclude that only nylon and fluoropolymers are unsuitable coating materials leading to a BS increase. After gamma dose values $>10^7$ Gy, however, fibre BS seems to decrease (see [27]).

Thermal neutrons produce a more than 10^6 times lower dose in SiO_2 than the same fluence of 14 MeV neutrons. Therefore they usually induce only negligible loss increase. However, the isotope ^{30}Si is transformed by thermal neutron capture into the isotope ^{31}P. This will change the refractive index and increase radiation-induced loss. However this effect usually has no practical significance.

At the end of 6.2, it is pointed out that fast neutrons can transfer a considerable portion of their kinetic energy to the nuclei of H atoms of the coating or cabling material. For neutron energies >2,5 MeV these recoil protons can reach the fibre core, even of single-mode (SM) fibres. Apart from an increase of dose this will lead to an increase of fibre attenuation around 1 383 nm, the water peak (see [28]).

If not only the fibre itself but a cable is exposed to radiation, the material surrounding the fibre can increase the dose deposited in the fibre due to secondary radiation produced in the cable material. This effect occurs mainly for particle radiation, especially heavier particles, and depends on the particle energy. Numerical simulations might be needed to calculate the total dose deposited in the fibre.

Polytetrafluorethylene (PTFE) is perhaps the most radiation-sensitive polymer. It already becomes brittle after dose values below 10^3 Gy. Since the cladding of polymer optical fibres (POFs) is usually made of fluoro polymers, the light-guiding properties of POFs could be affected before their radiation-induced loss increase reaches intolerably high values (see [29] and [30]).

8 Radiation-induced transmission loss

8.1 Overview

The extent of fibre attenuation increase during irradiation depends on the fibre parameters and the manufacturing procedure, including, for example, the purity of the raw materials, doping of the core and in case of single-mode fibre cladding material, pre-form manufacturing process, drawing conditions, and others. The great efforts of all manufacturers in optimizing fibre quality have led to fibres with strongly reduced radiation sensitivity, compared with the early ones. Nevertheless, there still exist more or less pronounced differences in the radiation hardness between fibres of the same type made by different companies.

Alternatively the radiation-induced loss depends strongly on most of the test conditions, including the temperature, the measurement wavelength, the injected light power, the dose rate and the irradiation history, as will be shown in the following Clauses. In cases where it is essential to select the most radiation-hard piece of a given fibre type, one has to be aware of these dependencies in order to obtain reproducible and fully comparable results.

There exist neither theoretical descriptions nor deterministic models which would be able to predict the radiation effects in optical fibres. Only empirical models were developed that might be used to extend the parameter range of experimental data obtained with the respective product. They might also be used to analyse experimental results to isolate specific influences. The reason that no precise *ab-initio* calculations can be successfully applied is the impossibility to define and know all necessary input parameters.

8.2 Fibre type

Different fibre types exhibit distinctively different radiation sensitivities. Whereas it is nearly impossible to predict the radiation sensitivity of specific optical fibres, some general statements can be made which apply to the commonly used class of glass optical fibers.

By far the most important factor is the dopants of the fibres. Aluminium (which is commonly used in combination with rare-earth elements) and phosphorus are known to lead to very high radiation-induced attenuation. Pure-silica core fibres of high quality, on the other hand, tend to exhibit much lower losses under radiation. For single mode fibres a fluorine-doped core showed the lowest losses under steady-state exposures, in comparison to pure-silica core and Ge-doped fibres [31]. Exceptional radiation hardness can also be expected from hollow-core photonic crystal fibres. Since most of the light is guided in air, less material defects contribute to the attenuation [32]. In particular, for single-mode fibres the inner cladding dopants should also be considered.

The coating material and other manufacturing parameters also influence the radiation sensitivity. The impact varies with different fibre types and might even be opposite for different manufacturers [33]. To select a product in this respect, application-specific tests are advised.

8.3 Radiation history

Presumably all fibres show more or less pronounced differences in loss increase when irradiated a second time under identical conditions. Some types show higher loss increase, some types a lower one. Other fibres just quickly reach the last attenuation level observed at the end of the previous irradiation. This also depends on the time between successive irradiations and on the residual loss from the previous irradiation, i.e., on the loss annealing behaviour. In order to get comparable results one should therefore imperatively use a new, virgin fibre sample for each test.

8.4 Wavelength dependence

The radiation-induced loss of all fibres depends strongly on the wavelength of the transmitted light. There is a pronounced maximum in the UV, with a factor of more than 1 000 higher loss than in the region of minimal loss. This factor depends on fibre type and radiation dose. Another, usually lower maximum is to be observed in the far IR, around 2 500 nm. Figure 1 (taken from reference [25]) shows this typical wavelength dependence. The resulting loss minimum for this Ge-doped GI fibre is situated around 1 650 nm at the beginning of an irradiation and shifts to values around 1 050 nm at higher dose values. Additional examples and the loss increase towards the far IR can be seen more clearly in some figures of [34].

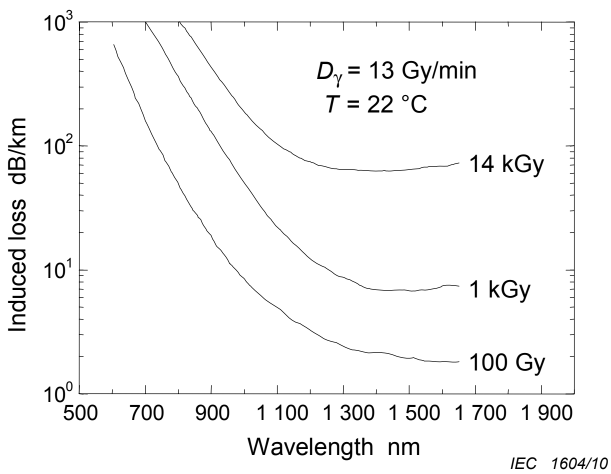


Figure 1 – Wavelength dependence of the radiation-induced loss of a Ge-doped graded index fibre (50/125 µm)

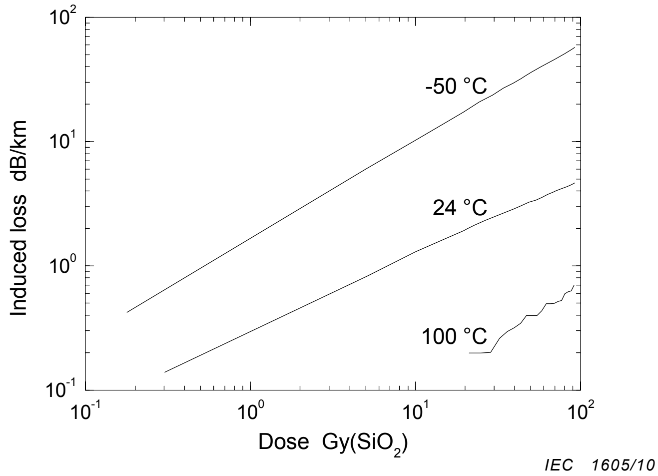
A similar behaviour can also be seen for other fibre types. In [35] the authors compare the spectral attenuation increase of a P-doped, Ge-doped, and pure-silica core fibre after 5 Gy (P-doped) and 100 Gy (Ge- and un-doped). No dose variation was done in this study to follow the shift of the loss minimum.

At shorter wavelengths, the signal to noise ratio, i.e., the ratio of loss increase and signal drifts or noise, is much higher so that the test fibre length generally has to be distinctly shorter than for measurements between about 800 nm and 1 600 nm. The length must be shorter in cases of limited dynamic range of measuring systems such as optical spectrum analyzers or if photobleaching effects are to be expected (see 8.6).

8.5 Temperature dependence

The radiation-induced loss of nearly all fibre types decreases with increasing temperature. The reason is that colour centres anneal faster with increasing temperature ("thermal annealing"). Figures 2a and 2b show this behaviour for a Ge-doped and an undoped SM fibre, respectively. The dose (or irradiation time) dependence of the temperature influence for both fibre types is distinctly different. In Figure 7 of reference [8], it is shown that fibres doped with Ge+P even show an inverse temperature dependence between –50 °C and +75 °C, i.e., an increase of loss with temperature, but a slight decrease when the temperature is raised to 98 °C.

These results show that the fibre temperature has to be kept at a given value (within a few °C) in order to obtain unambiguous and comparable results, that the test fibre length might be adjusted to the expected higher or lower loss at a certain temperature, and that it is a daring undertaking to present a relatively simple procedure for calculation of the radiation-induced loss at a higher or lower temperature from measurements taken at room temperature, as done in [18] and [36]. In order to avoid erroneous extrapolations, one should perform at least one measurement at the temperature of interest.



NOTE $\dot{D} \approx 0{,}05$ Gy/s, λ = 1 309 nm, P = 20 µW.

Figure 2a – Ge-doped single-mode fibre

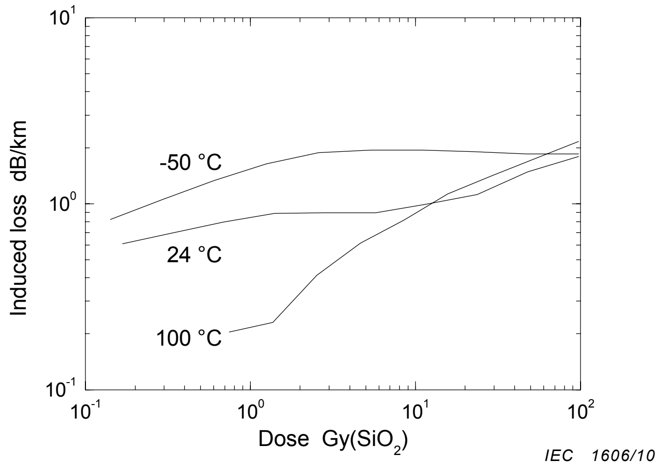


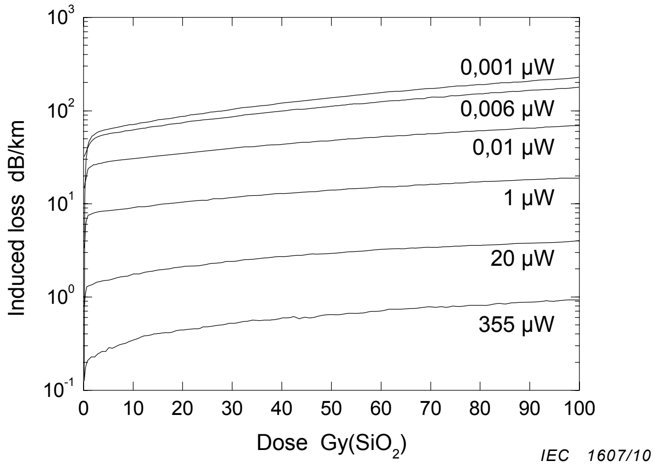
Figure 2b – Undoped single-mode fibre

Figure 2 – Temperature dependence of the radiation-induced loss

Even small temperature variations may lead to distinctively different results. If high precision measurements are done, e.g. to compare samples over longer periods of time, the samples should have exactly the same temperature to see the difference of the samples and not the temperature effect. In [37] it is shown that already 5 °C difference might lead to a difference of the radiation-induced attenuation of >10 % even though both temperatures used (25 °C and 29 °C) are called "room temperature".

8.6 Light power dependence, photobleaching

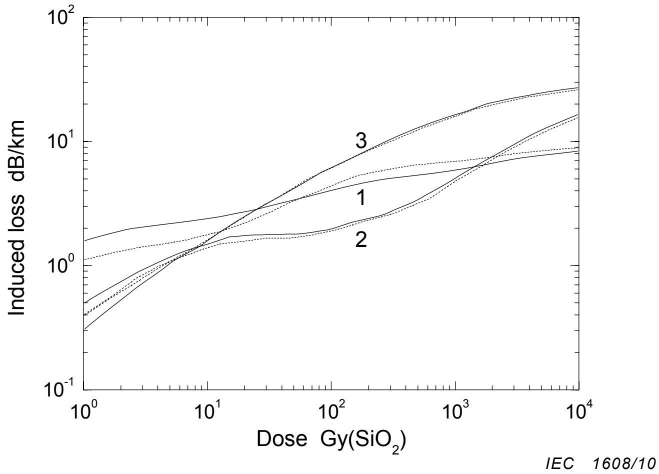
Particularly with some of the fibres manufactured before 1985 with undoped silica core of low OH content, the radiation-induced loss increase could very much depend on the intensity of the light that was used for the loss increase measurement.



NOTE Ḋ ≈ 0,05 Gy/s, λ = 1 309 nm, T= 22 °C.

Figure 3 – Light power dependence of the radiation-induced loss of an undoped single-mode fibre

Figure 3 shows an example where the loss increase was more than a factor of 200 lower when the light power was increased from 0,001 µW to 355 µW. This effect is known as "photobleaching", i.e. the colour centre annealing rate is enhanced by the transmitted light. This is the reason why it was recommended [38] and [39] to keep the measuring light power <1 µW. However Figure 3 shows that light power reduction from 1 µW to 0,001 µW still led to more than a factor of 20 higher loss increase.



Key

1 MM SI, pure SiO_2 core, high OH

λ = 865 nm, —— P = 0.1 µW, ······· P = 75 µW

2 SM, pure SiO_2 core, low OH

λ = 1 309 nm, —— P = 1 µW, ······· P = 100 µW

3 SM, Ge-doped core

λ = 1 309 nm, —— P = 1 µW, ······· P = 100 µW

NOTE Ḋ ≈ 0.22 Gy(SiO_2)/s, room temperature.

Figure 4 – Light power dependence of the radiation-induced loss in modern MM SI and SM fibres

With fibres that show strong photobleaching, the test sample length should be kept relatively short in order to prevent higher loss increase towards the sample end where the light intensity will be more and more attenuated. On the other hand it is incorrect with such fibres to calculate an induced loss in dB/km from the loss measured (in dB) with a length *L* (in metres) by multiplication with the factor 1 000/*L*. In order to get realistic results, test sample length and light power should be adjusted to the intended field of application.

In fact, today the situation is less complicated. All modern Ge-doped SM and GI fibres, as well as most of the undoped fibres with low or high OH content show negligible photobleaching at 1 300 nm or 1 550 nm. This is shown in Figure 4 for a MM SI fibre and two SM fibres. However, it is pointed out in Figure 3 of [34] that a Ge-doped GI fibre showed no photobleaching at 1 300 nm, whereas its loss at 830 nm decreased by nearly a factor of 5 when the light power was increased from 0,1 µW to 800 µW. The wavelength dependence of photobleaching is discussed in [40], and it is demonstrated that the photobleaching effectiveness actually increased from 1 300 nm to 670 nm. But this is only of limited practical value since the radiation-induced loss strongly increases with decreasing wavelength, so that more effective bleaching light of shorter wavelength will be attenuated very soon and becomes less effective.

If photobleaching is expected one should also take the core diameter into account when comparing results at presumably the same light powers.

8.7 Dose rate dependence

Figures 5a and 5b show the dose rate dependence of the radiation-induced loss for two different fibre types: a Ge-doped SM fibre (Figure 5a) with moderate annealing rate and a MM SI fibre with pure SiO_2 core of high OH-content (Figure 5b) that shows relatively fast annealing (see 8.10). The faster the annealing, the stronger the dose rate dependence. This can be explained by a competition between colour centre population and depopulation: the lower the dose rate, the longer the time to reach a certain dose, the more colour centres anneal already during irradiation. Saturation is reached when the colour centre production rate becomes equal to the colour centre annealing rate. The loss increase of the fibre of Figure 5a saturates after a dose of about 10^4 Gy. Since the annealing rate is proportional to the number of already existing colour centres (i.e. to the induced loss), the saturation loss value increases with increasing dose rate. The loss increase of fibres with negligible or very slow annealing is (nearly) independent on dose rate. Such fibres could, for example, be used for radiation dosimetry ("dosimetry fibres", see 6.1).

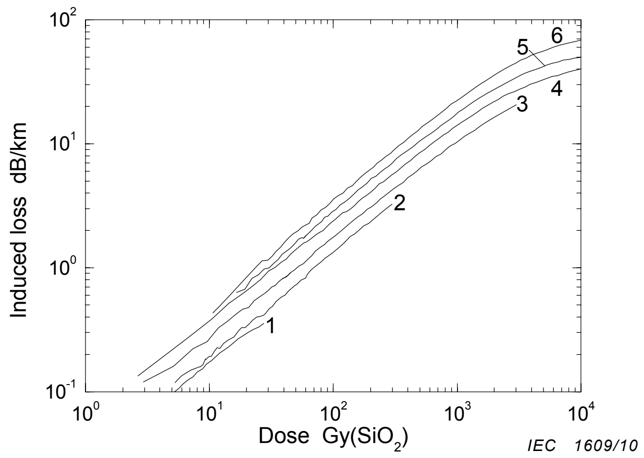


Figure 5a – Ge-doped single-mode fibre λ = 1 309 nm, *P* = 20 µW

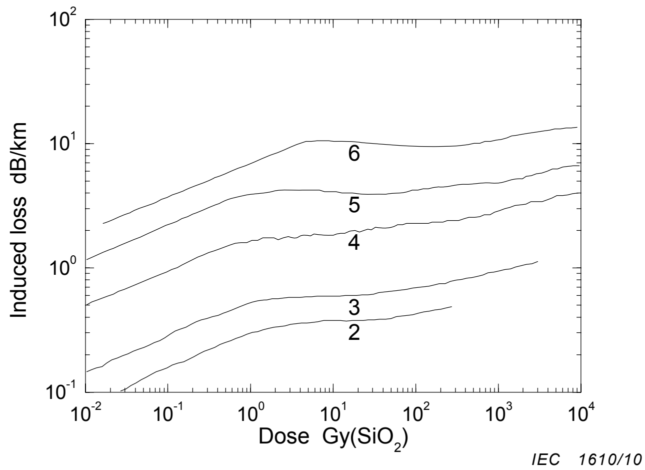


Figure 5b – Multimode step-index fibre with pure silica core of high OH-content; λ = 865 nm, *P* = 10 µW

Key

1 $\dot{D} \approx 5 \times 10^{-4}$ Gy/s	4 $\dot{D} \approx$ 0,045 Gy/s
2 $\dot{D} \approx$ 0,0025 Gy/s	5 $\dot{D} \approx$ 0,2 Gy/s
3 $\dot{D} \approx$ 0,01 Gy/s	6 $\dot{D} \approx$ 1,6 Gy/s

Figure 5 – Dose rate dependence of the radiation-induced loss; *T* = 22 °C

Usually, it is not possible to perform fibre tests up to a given dose with the expected dose rate of the intended application. This would often last several years (space, nuclear power plants). One therefore has to perform "accelerated" tests where the expected life dose is applied within several hours or days. Such a procedure will surely be suited for selecting the radiation-hardest one out of a set of otherwise comparable fibres. In order to obtain a realistic estimate for the actual loss increase, one could perform measurements with distinctly different dose rates and extrapolate the results (loss increase for a given dose as a function of dose rate) down to the dose rate of interest. However, there exist some (more or less convenient) approaches [18], [36], [41] for the calculation of the loss increase expected with a lower (or higher) dose rate from a measurement with only one dose rate that is easier to attain. The method proposed in [41] is very simple and should be correct for dose values and samples where the radiation-induced loss is described by a single power-law behaviour over the dose range of interest. The accuracy of the loss increase thus predicted for a dose rate which is orders of magnitude lower than that during the actual measurement depends strongly on the accuracy of the dose rate measurement. For fibres showing a more complex kinetic response, several measurements at very different dose rate levels have to be performed.

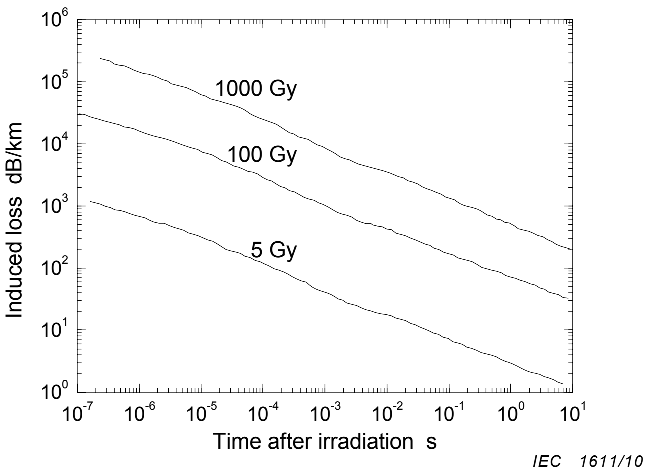
Fibres doped or co-doped with phosphorous are known to show a very low dose rate dependence. This explains why they can also be used for dosimetry. It has even been reported [42] that an inverse dose-rate dependence (higher induced loss at lower dose rates) was observed. However, this does not seem to be the general case, since this behaviour is strongly wavelength-dependent.

8.8 Pulsed irradiations

In 8.6, it was shown that the radiation-induced loss observed with a certain dose increases with dose rate. During continuous irradiations with ^{60}Co gamma sources the dose rate is usually in the range of 0,001 Gy/s up to 10 Gy/s at the most. Usual dose values for military tests range from 1 Gy to 1 000 Gy per pulse. Since the pulse length with most of the usual test facilities is only between about 1 ns and 50 ns, the dose rates can here reach values between about 10^7 Gy/s and 10^{12} Gy/s. This leads to tremendous loss values immediately after the radiation pulse end. Figure 6 (taken from reference [43]) shows the result obtained with a Ge-doped GI fibre at room temperature. The loss increase can reach values between 10^5 dB/km and 10^6 dB/km immediately after the pulse end, dependent on fibre type, wavelength and fibre temperature. Since the necessary high bandwidth receivers have a noise level not far below 0,1 μW, the test fibre length should only be around 10 cm for the highest dose values in order to be able to measure a loss increase up to 10 dB with a light power of 1 μW.

With ultra-fast spectrometers based on detector arrays it is possible to record the spectral attenuation decrease with ms resolution. The experimental setup should consider homogenous light power distribution, the linear and dynamic range of the spectrometers and variations of the white light source used [44].

Many of the pulsed irradiations are performed with high energetic electrons with a velocity distinctly above the velocity of light in the irradiated fibre. During irradiation one therefore observes a "luminescence light" pulse of high intensity which can overload the receiver, preventing measurements immediately after pulse end. Since most of the light comes from the Cerenkov effect, its intensity increases with $1/\lambda^3$, so that the receiver could easily and adequately be protected by a high pass filter that blocks all light below the wavelength of interest.



NOTE Effective pulse width was 30 ns, λ = 840 nm, P = 10 μW, room temperature.

Figure 6 – Annealing of the radiation-induced loss of a Ge-doped GI fibre after pulsed electron irradiation with dose values of 5 Gy(SiO_2), 100 Gy(SiO_2) and 1 000 Gy(SiO_2), respectively

From Figure 6, it can be seen that loss annealing begins immediately after pulse end and leads to a loss reduction by a factor of more than 1 000 (dependent on fibre type and temperature) already 10 s after pulse end. Because of the limited dynamic range of most of the high bandwidth receivers, one could for example use a new, longer fibre sample for measuring the loss annealing at times greater than for example 10^{-3} s. Another possibility is to conduct the light (with a 1:2 splitter) to a high bandwidth receiver for the short time regime as well as to a low bandwidth receiver, with low noise level, for times $>10^{-3}$ s.

With fibres that are doped with Ge+P the loss annealing ends after about 10^{-5} s as can be seen in Figures 5a and 5b of reference [45]. Thereafter, the loss is approximately of the same size as after a continuous irradiation with a dose rate of only 0,05 Gy/s up to the same dose of 100 Gy (Figures 13a and 13b of reference [45]).

Photobleaching also has to be considered with pulsed irradiations, i.e. the loss annealing can be accelerated by increasing the power of the measuring light, dependent on fibre type, wavelength and fibre temperature. However, measurements that were made with the same fibre type of high photobleaching sensitivity as those of Figure 3 show that it becomes effective not before about 10^{-5} s after the end of the radiation pulse (Figures 6a and 6b of reference [45]).

8.9 Radiation type dependence

At the first attempt it seems to be reasonable to assume that different types of ionizing radiation will lead to the same fibre loss increase, provided they deposit the same dose. This was, for example, stated in [46] for ^{60}Co gamma and 14 MeV neutron irradiation. Actually, it was found (see [17]) that 14 MeV neutron fluences up to 10^{13} cm^{-2} cause an about 2,5 times lower loss increase than gamma irradiations with the same dose rate up to the same dose. The reason for this discrepancy might be that the authors of reference [46] did not consider the dose contribution of ionizing "recoil protons" out of the hydrogen containing fibre coating material (usually "UV acrylate", see [12]).

The ionization density of protons, alpha particles and heavier ions like the reaction products of 14 MeV neutrons with matter is much higher than that caused by X-rays, gamma rays and electrons. This can lead to charge carrier recombination and saturation effects in more dense ionization tracks and, as a consequence, to a lower loss increase, as discussed in more detail in [17]. This is at least valid at the beginning of an irradiation, as long as the concentration of defects within the fibre core that can act as "precursors" of light absorbing "colour centres" is given by the fibre production process.

X-rays and gamma rays above an energy of about 0,7 MeV, as well as highly energetic electrons, protons, alpha particles and heavier ions can also lose a fraction of their energy through "non ionizing collisions" that cause structural damage within the fibre core, i.e., new defects that can act as precursors of colour centres. The structural damage caused by heavier ionizing particles can become orders of magnitude higher than that caused by the same dose of gamma rays or electrons. Therefore it is to be expected that heavier, more densely ionizing particles will finally lead to a higher loss increase than gamma rays or electrons of the same dose rate, above a certain fluence value, when the concentration of defects caused by neutrons become higher than that of the already existing ones. In [17], it is estimated that this will happen for a 14 MeV neutron fluence above 5×10^{13} cm^{-2} .

However, in Figures 5a and 5b of reference [17], it is shown that fibres with higher loss increase during gamma irradiation will also show higher loss increase during fast neutron irradiation with the same dose rate. Therefore, the following procedure could help to reduce the number of more expensive and more difficult irradiations with protons or fast neutrons: as a first step one selects with ^{60}Co gamma irradiations the most radiation hard one out of a greater number of otherwise comparable fibres (see also 8.6). For neutron and proton fluences $<10^{13}$ cm^{-2} the loss increase caused by the gamma rays should also be an upper limit for neutron and proton irradiations. Neutron and proton irradiations could become necessary only for higher particle fluences.

8.10 Loss annealing

In the majority of the publications on optical fibre irradiation tests, the fibres are irradiated with one fixed dose rate up to one dose of interest, i.e. the irradiation time remains constant. In cases where the annealing, i.e. the loss decrease after the end of irradiation, is also measured, one therefore always observes approximately the same annealing time (= time that is necessary to decrease, for example, to 1/2 or 1/e of the loss immediately at the end of irradiation). Therefore, the predominant opinion is that the annealing time is a fixed fibre property (at a given temperature), comparable for example with the lifetime of excited states in nuclei, atoms or crystals.

Actually, the annealing time is a strong function of the irradiation time and dose rate. In Figure 6, it can be seen that after pulsed irradiations, annealing to 1/2 of the initial loss value takes only about 10^{-6} s. In reference [47], it is shown that after continuous ^{60}Co gamma irradiation at constant dose rate, the annealing time increases nearly linearly with irradiation time and therefore total dose, at least with irradiation times from about 1 s up to about 5 days. This effect may depend on the precise conditions and fibre type. In [17], it is shown that increase of annealing time with irradiation time is also valid for 14 MeV neutron irradiations.

The reason for this behaviour might be that the fibre loss is caused by a set (or continuum) of colour centres with different half-life where, with increasing irradiation time, the respective longer-lived centres dominate. This is discussed in more detail in references [41] and [48].

In cases where measurement of the loss annealing is also demanded, one thus has to consider its dependence on the irradiation time.

8.11 Conclusions

In the previous Subclauses, it was outlined that the radiation-induced fibre loss depends on the radiation history (previous irradiations) as well as on almost all test parameters.

In order to obtain expressive, comparable and reproducible results one should therefore by all means use a new fibre sample for each test.

The test fibre length has to be adjusted to the respective test parameters and measurement equipment. This should not be the enormous lengths that were often prescribed formerly, when the stability of the measuring equipment was by orders of magnitude worse than that of present high quality light sources and optical power meters. In particular for pulsed irradiations with highest dose rates, fibre sample lengths would have to be quite short.

Photobleaching still has to be considered, but modern low loss fibres are distinctly less sensitive than older ones. Moreover, at longer wavelengths (1 300 nm, 1 550 nm) photobleaching is usually negligible.

Since nearly all fibres show distinctive annealing, the loss measured after a certain dose depends on the dose rate, i.e., on the irradiation time. Timesaving, less expensive "accelerated" tests usually yield loss values which are too high. However, extrapolation methods exist for the expected loss after longer exposure times from several shorter measurements at higher dose rates.

Fibre loss also depends on the radiation type. More densely ionizing heavier particles such as protons or the reaction products of fast neutrons cause lower loss increase than X-rays, gamma rays or electrons of the same dose rate. On the other hand, it is known that heavier particles of the same dose produce distinctly more defects in the fibre core material. These defects can act as precursors of new colour centres. When their concentration becomes higher than that of the already existing ones, the loss of heavier particles grows faster, above certain fluence values, and will surpass that of X-rays, gamma rays and electrons of the same dose rate after the same irradiation time.

In view of all these reservations and complications, one should distinguish two types of fibre irradiation tests:

a) Tests to find the most radiation-hard fibre in a set of otherwise comparable ones. Such tests should be performed under exactly prescribed, standardized conditions, with continuous as well as pulsed irradiations, in order to obtain repeatable and comparable results. It is very unlikely or seldom that the fibre with the best test results at these "normal" conditions would be distinctly worse in other situations – if at all.
b) Tests with this best fibre under realistic conditions, i.e. with expected dose rate, temperature, transmission length, light power, radiation type, etc. Submitting only one fibre to all these more realistic tests would save time and money.

9 Measurement techniques and quality assurance of attenuation measurements

In general, the rules of IEC 60793-1-40 and IEC 60793-1-46 also apply to the measurements of radiation-induced attenuation. Several specific aspects were mentioned in the previous Clauses and are summarised in the following.

The fibre test length should primarily be adjusted to the total induced attenuation at the end of irradiation. Extremely low values, e.g. below some tenth of dB, should be avoided to reduce the possible influence of measurement instabilities. On the other hand, very high induced losses, e.g. above 10 dB, might lead to non-linear behaviour, caused either by photobleaching or limited dynamic ranges of the used equipment.

Sample preparation should consider all possible side effects of low bending radii, especially for step-index fibres and at higher wavelengths. Launch conditions should follow the recommendations cited above, especially when testing multi-mode fibres. Self shielding of fibre layers should also be avoided for X-ray and particle irradiations. Finally, charged particle equilibrium should be established within the sample.

Slow measurements, e.g. with scanning monochromators, should take into account possible rapid effects taking place in the fibres at high dose rates. Launch conditions should be chosen according to respective standards.

The final report presenting the results of irradiation tests should include information about uncertainty and, if possible, the reproducibility of the measured data. Topics to be considered for this are outlined in [37] and the references therein.

10 Radiation effects on passive fibre optic components

10.1 Connectors

Fibre optic systems in satellites and space stations or sensor systems in nuclear engineering facilities may exhibit a lot of plug connections. Because of the usually very limited power reserve, they should show negligible insertion loss increase during irradiation. In older connector types the fibres were often fixed with thicker epoxy layers. Such materials show swelling or become brittle. Both effects can cause microbending or additional lateral offset of the connections. Loss increase of up to nearly 0,3 dB was measured after dose values of 10^4 Gy [49].

Military fibre cables often have lens connectors which are less sensitive against dirt and misalignment. Usual glass lens pairs can lead to loss increases up to 0,6 dB after 10^4 Gy [49], whereas gradient index (GRIN) lens pairs could cause a loss increase up to 50 dB (at 865 nm) after dose values $<10^4$ Gy.

Reference [49] describes the test method and cites further publications about connector tests.

10.2 Couplers and multiplexers

The radiation sensitivity of such components depends mainly on their fabrication method. Fused couplers and wavelength multiplexers show loss increases between about 0,001 dB and 1,1 dB, dependent on manufacturer, wavelength, coupling ratio and output lead. The fibre loss itself was compensated by introduction of an identical reference channel (same fibre type, same radiation dose). Couplers which consist of two coupled GRIN lenses (micro optic couplers) showed loss increases up to 50 dB (at 865 nm) after dose values $<10^4$ Gy [49].

10.3 Fibre Bragg gratings

Fibre Bragg gratings are also used predominantly as temperature or strain sensors in radiation environments, e.g. in space or nuclear facilities. Since their principle does not rely on the amount of light transmitted but rather the periodical structure of refractive index, the radiation-induced loss is usually no problem in the application, if the fibre leads are carefully selected.

The radiation-induced variation of refractive index leading to a shift of the Bragg wavelength is comparably small and also does not vary to the same extent between different gratings as the radiation-induced attenuation does within different fibres. Nevertheless several studies identified clearly different radiation sensitivities of different fibre gratings, based on different fibres and different manufacturing methods [50]-[53].

Almost all the currently available FBGs are produced by inscribing the periodic structure laterally into the fibre with UV lasers. Depending on the behaviour of the Bragg peak during the inscription process, FBGs are usually classified into the following types.

Type I:

This is the standard FBG type and the only one available commercially off the shelf. The used optical fibres are made photosensitive to UV light by doping them with Ge, B, Ce, N, In, Sn or Sb. Often the photosensitivity is significantly increased by loading the fibre with Hydrogen. Type I gratings erase at relatively low temperatures of about 200 °C, which makes their use as sensors in harsh environments somewhat limited. Type I FBGs show the highest sensitivity of the Bragg wavelength to radiation, although the effect is much smaller than the sensitivity of the RIA of optical fibres. An analysis of FBGs made from very different optical fibres with different dopants, whose RIA differed over several orders of magnitude, showed a variation of their Bragg wavelengths of around 50 pm to 200 pm at 100 kGy [51]. There is also no large influence on the radiation sensitivity of the production parameters, except the hydrogen loading. FBGs made from hydrogen loaded fibres show significantly higher radiation sensitivity than FBGs made from unloaded fibres.

Type IIa:

After a long exposure of highly Ge doped optical fibres, usually co-doped with B or N, the inscribed grating slowly erases and then forms again, but with a negative change of the refractive index. The resulting FBGs are termed type IIa. They are spectrally indistinguishable from type I gratings, but are stable to surrounding temperatures of up to 500 °C. The radiation sensitivity of type IIa FBGs is usually better than type I gratings. There are type IIa with reported radiation induced wavelength changes as low as 12 pm at 50 kGy [52].

Type II:

If the energy in a single laser pulse passes a threshold, the index modulation increases dramatically. The resulting FBGs are the result of physical damage to the fibre core. They show a distinctly different spectral behaviour compared to type I and IIa gratings, with strong coupling to the cladding. They are stable to temperatures of up to 800 °C. Due to the physical damage, they are mechanically very fragile and should only be used where the high temperature range is needed. Type II FBGs are quite radiation-insensitive with radiation-induced wavelength changes around 20 pm at 100 kGy [51].

There is a new, not yet commercially available, method of inscribing FBGs into optical fibre with ultra short (fs) pulsed Infrared lasers. The big advantage of this method is that the fibre does not have to be photosensitive or hydrogen loaded. The resulting gratings can also be classified into types I and II and are called type I-IR and type II-IR. Gratings written by this method into photosensitive fibres show similar radiation sensitivity to UV gratings [53]. However, with this method it is possible to easily inscribe gratings into highly radiation resistant F doped fibres ([31]). These gratings can have a radiation induced wavelength shift of as low as 5 pm [53].

Other test results and description of measurement methods can also be found in [54], [55], [56] and further references cited therein.

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NOTE Numerous radiation effects test results of optical fibres are published in:

Proceedings of Conferences organized by SPIE (The Society of Photo-Optical Instrumentation Engineers) like:

Photonics for Space Environments

Fiber Optics in Adverse Environments

Fiber Optics Reliability: Benign and Adverse Environments

Optical Fiber Reliability and Testing

and others

The proceedings are published by SPIE, Bellingham, Washington DC.

Proceedings of the Annual International Nuclear and Space Radiation Effects Conference (NSREC), published in

IEEE Transactions on Nuclear Science, Number 6 of each Volume.

Proceedings of RADECS (RADiation and its Effects on Components and Systems), published by IEEE.

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