SECTION 12. OPTICAL FIBRES

12.1. INTRODUCTION

The transmission of digital or analogue information by conversion of the information into the modulations of a light beam is a useful technique for long-range communication or in an electrically noisy environment. RF radiation and magnetic fields can produce electrical transients in metallic conductors, leading to the corruption of data. RF and magnetic fields have no effect on light beams. Plastic and hollow waveguides are sometimes used, but for ruggedness, reliability and high data rates, fibres made from silica glasses are the most highly developed form of optical link. The effect of radiation on silica glasses has been intensively studied and it is possible to say at the outset that, although the effect of radiation on silica materials is considerable, it is tolerable if materials control is exercised. Apart from a general discussion of radiation effects in silica fibre materials, this Section also contains an account of some models for predicting optical loss in fibres.

12.2. DEFECT CENTRES AND ABSORPTION SPECTRA IN SILICA AND GLASSES

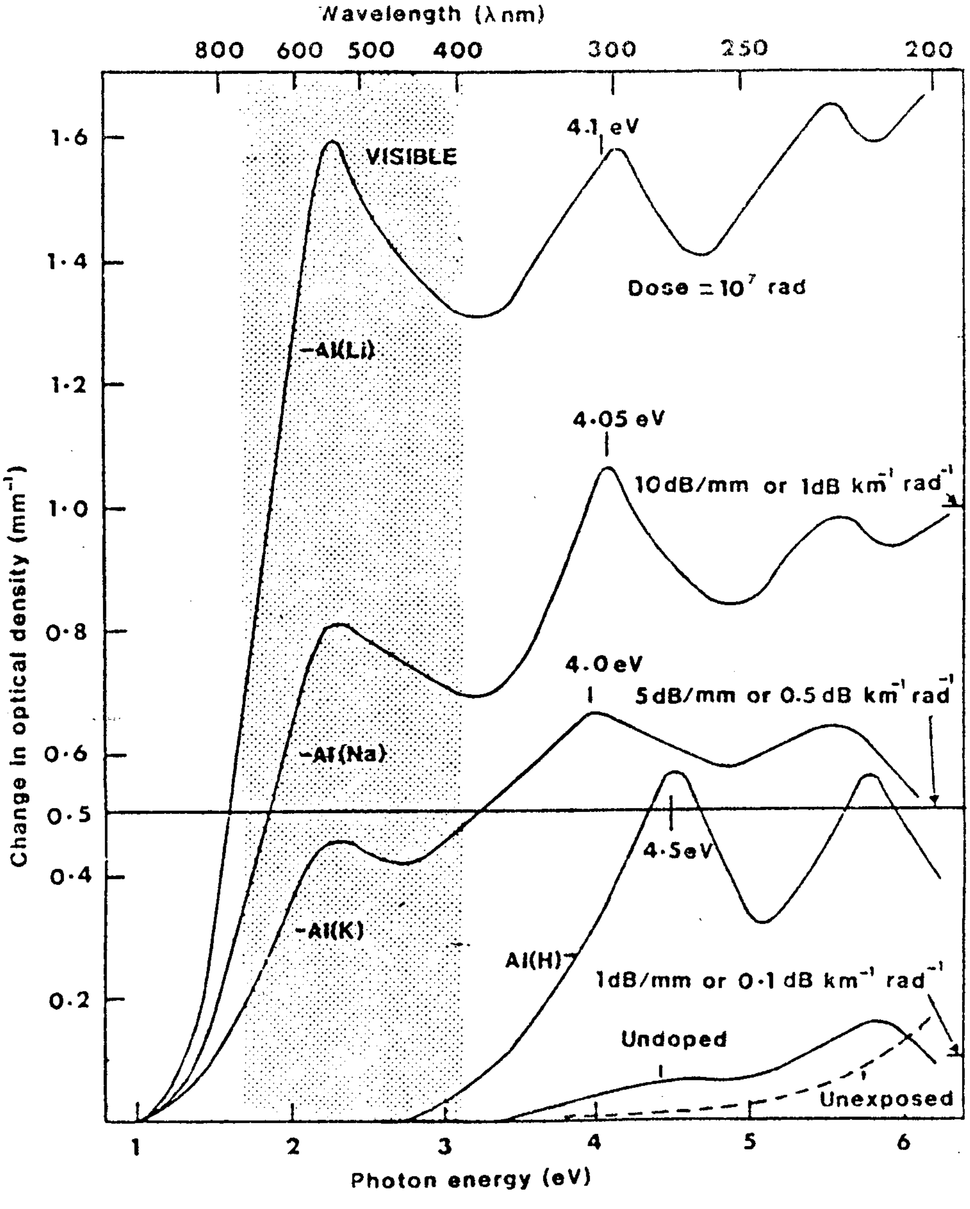
12.2.1. General

In this discussion, optical fibre materials will be regarded as being composed of a glassy silica network (O-Si-O-Si structures) in which varying degrees of imperfection are introduced by bond strain or network disrupting atoms. Initially, then, exposure of an ideal silica network, crystalline or amorphous, to ionising radiation should produce no coloration whatsoever, because all bonds are satisfied. Ionisation does not give rise to the displacement of any atoms (as it does in the case of alkali halides) and hence no "colour centres" are formed. In fact, the purest form of silica, pyrolytic fused silica, can be irradiated to a very high dose (10^8 rad) without visible coloration appearing. While pure synthetic crystalline silica (quartz) undergoes no visible coloration, spectroscopy in the UV region reveals a radiation-induced absorption peak. This is probably due to impurities remaining from the additives used for crystal growth. Natural quartz is very impure; when irradiated to a dose of 10^5 rads, strong "smoky" brown coloration is produced. As will be seen later, pyrolitic silica, when intentionally doped or even when subjected to strains during fibre drawing, displays colorations which, in the 10^6 rad range, are visible to the naked eye and may be significant at doses as low as 10^3 rad.

12.2.2. Ionisation effects

Most of the radiation effects in optical fibres are caused by impurities (or strains) introduced intentionally or unintentionally during fabrication. The fabrication process often consists of many stages and is becoming increasingly sophisticated. For example, Figure 12.1 shows the absorption spectra of pure and doped silica material irradiated with ionising radiation (Lell, 1962). Whereas there are two optical absorption peaks in pure fused silica, the alkali-doped samples exhibit three such peaks. The intensities of the latter are larger by at least a factor of 10, having a specific radiation-induced loss value of 1 $dB.km^{-1}$ rad^{-1} in the UV region versus 0.2 $dB.km^{-1}$ rad^{-1} for pure silica and a value of about 0.8 at 600 nm versus 0.1 dB km^{-1} rad^{-1} for pure silica. Aluminium doping, also shown in Figure 12.1, shows the type of effect which the addition of other intentional network-forming dopants can produce. The contrast between alkali and aluminium illustrates a characteristic difference between network disrupting agents (such as alkali) and network formers (Al, B, P). Each disrupting alkali atom produces a non-bridging Si-O group which can then trap a radiation-generated free hole before it recombines. These same trapped-hole species appear to be present in vapour-deposited silica fibre and other heat-treated silicas, probably because thermal treatments can break Si-O-Si bonds and hence create non-bridging oxygens. The hole is trapped in one of the p-orbitals of the oxygen atom.

A common radiation-induced effect in glasses is the production of a yellow or "smoky" coloration. This is produced by the "tail" of a UV absorption peak which intersects the visible region in the blue. An Al colour centre is thought to be the main defect in "smoky" quartz (O'Brien, 1955). Other workers (Friebele et al., 1978) find a similar state of affairs in their spectral measurements for phosphorus-doped optical fibres.



Approximate specific radiation-induced loss values are noted

FIGURE 12.1 - TYPICAL RADIATION-INDUCED LOSS PEAKS IN FUSED SILICA DOPED WITH ALUMINIUM AND ALKALI METALS, FROM 200 to 900 nm (AFTER LELL)

The absorptions occurring in multicomponent optical glasses are usually orders of magnitude stronger than those which occur in the pure or doped silicas discussed above (see Section 11). This is understandable when it is realised that such glasses contain relatively large percentages of alkali or other network-disrupting oxides (Na_2O, CaO, BaO etc.). Each atom of the metal can support a non-bridging oxygen ion of the type which can trap holes. Thus, soda glass is visibly affected at a few thousand kilorads while the effect of a few hundred rads on lead-oxide glass fibre is large enough for a fraction of a metre to provide the sensing element of a personnel dosimeter now under development in the USA. Fulmer Research Laboratories have tested some multicomponent glasses developed for fibre cores by British Telecom. Based on US results, it is expected that, if the exposure dose is in the kilorad range, the use of multicomponent glasses will not even be possible for short runs of fibre.

12.2.3. Particle-induced defects

The studies which have contributed most to our understanding of bulk damage in silica were performed by Arnold and co-workers (1973), using electrons and ions. Studies by Levy (1960) have confirmed that reactor neutrons produce similar defect centres. Early work suffered from the fact that the silica used was often relatively impure.

For present purposes, we need only note that a significant rate of generation of new displacements will only occur in silica samples operating in intense particle beams (e.g. in nuclear equipment). For example, Primak (1980) has described the heavy irradiation of fused silica bars in a fusion-neutron simulation source and calculated the relative defect production rates for neutrons in the fusion energy range. It is not likely that the electron and proton fluxes found within spacecraft will generate a significant number of new defects.

12.3. PREDICTION MODELS FOR OPTICAL FIBRE LOSS VERSUS DOSE

12.3.1. Fundamentals

As mentioned earlier, the fundamentals of the production of colour centres in silica-containing materials have been worked out in great detail by, amongst others, Mitchell and co-workers of Reading University (1956); Weeks and co-workers at Oak Ridge (1960, 1964) who investigated bulk silica, and groups at Reading and Fulmer, including Holmes-Siedle (1974, 1980), who studied thin-film silica physics. These investigations form a body of work which provides a base for models of the effect of radiation on the optical properties of fibres. A preliminary prediction model is outlined below.

An engineering term for the deterioration of optical performance is introduced here, namely dB of loss per kilometre per rad, L_0. The sense of this term, used in engineering for comparing fibres, must be limited because of the known saturation of radiation-induced loss at high doses (10^5 to 10^6 rads) and the decay of loss with time after a pulse of radiation. However, as a means of conveying orders of magnitude in sensitivity - as in the present discussion - the term is useful. Radiation-induced absorptions in fibres in the 0.4 to 1.5 µm range tend to lie in the range 10^{-2} to 10 $dB.km^{-1}.rad^{-1}$. Figure 12.2 shows the simple arithmetical relations between transmission, optical density and loss (loss in dB is found by multiplying optical density by 10; absorption coefficient is a scientific unit which can be easily related to oscillator strength). Figure 12.3 shows how the optical path length of the irradiated sample bears a linear relation to the loss expressed in the usual engineering term, dB per km. We can thus extrapolate simply from short lengths to kilometre distances.

Finally, if radiation-induced loss increases linearly with dose, we can express the characteristic radiation sensitivity of a fibre in terms of "specific radiation-induced loss" in $dB.km^{-1}$ $.rad^{-1}$ at a given wavelength. This should be a characteristic of the material, not altered by sample thickness or type of ionising radiation; it constitutes a useful performance parameter for a fibre system.

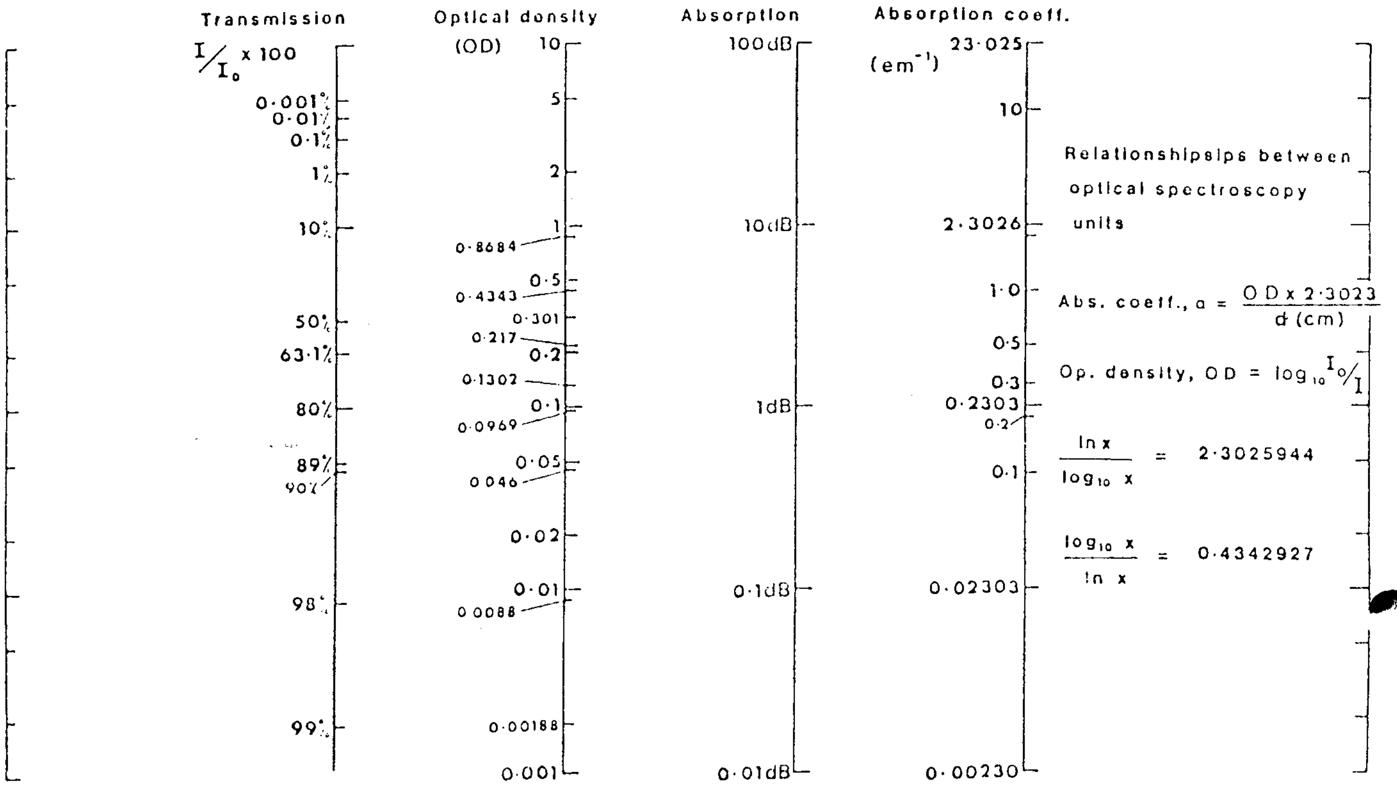


FIGURE 12.2 - CONVERSION CHART FOR FINDING RELATIONSHIPS BETWEEEN OPTICAL ABSORPTION UNITS

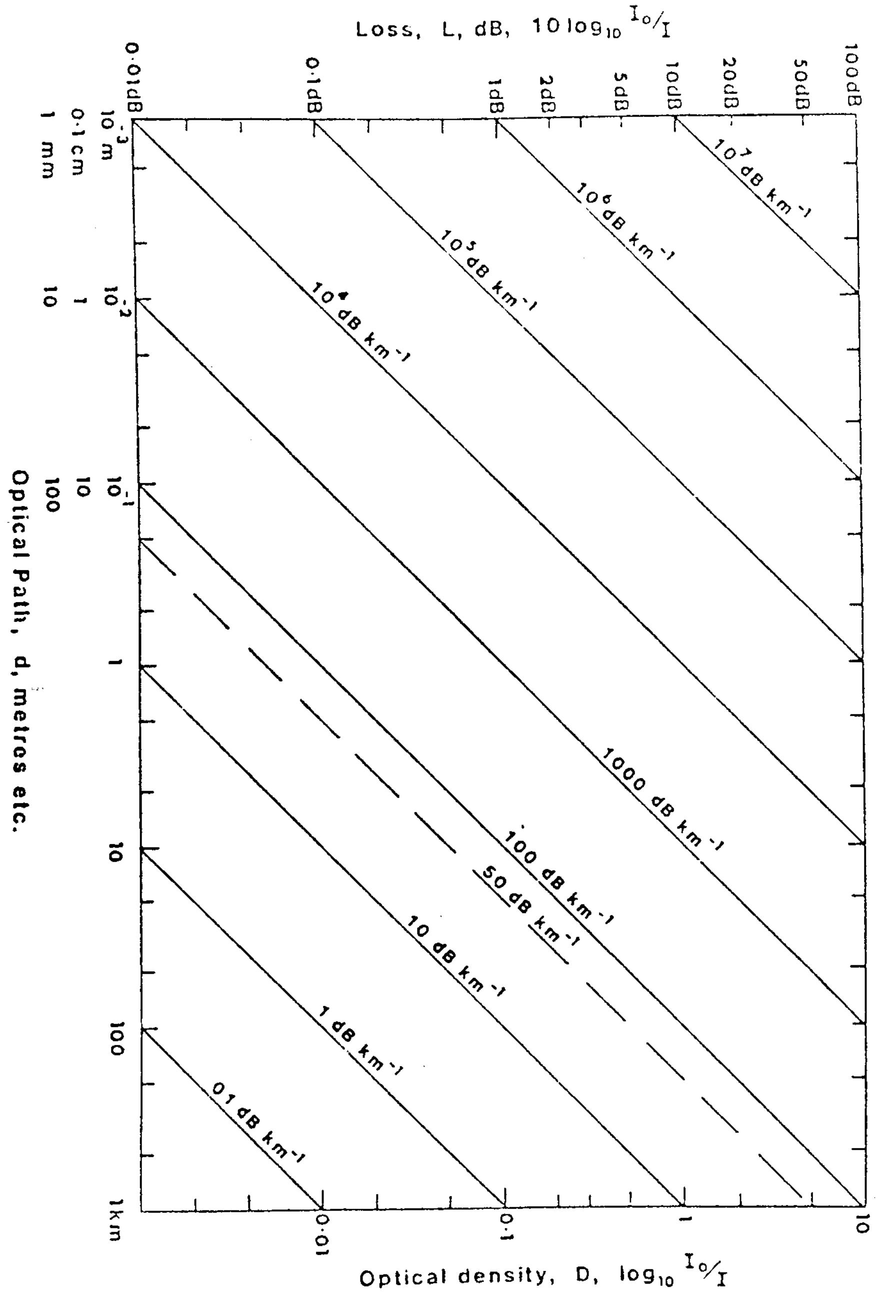


FIGURE 12.3 - CHART FOR CALCULATING LOSS PER KM FROM VALUES OF ABSORPTION AND PATH LENGTH

12.3.2. Simple mathematical model

It is reasonable to expect the build-up in the number of occupied colour-centre defects in (and, hence, the optical absorption of) irradiated silica to be proportional to dose if the fraction occupied is small. The plot or "growth curve" of detectable absorption against dose could thus have the form of a straight line over several decades before the fraction occupied becomes large. At this point, the curve will first become sublinear and finally saturate (become flat). A review of the data of Friebele (1979) shows that the loss versus dose curves do follow this scheme. It appears that the low-dose, linear regions of the curves in a variety of different silica materials have a slope lying between 10^{-2} and 1 $dB.km^{-1}.rad^{-1}$ for the wavelength value 0.82 µm.

Thus, as a model for fibre degradation, upper and lower limits can be postulated as shown in Figure 12.5. This corresponds to an equation:-

$$L = L_o D \qquad (L \ll L_{sat}) \qquad \text{......12(i)}$$

where L = loss and D = dose.

The slope L_o, representing the "specific radiation-induced loss", is constant for a given material and, at a light wavelength of 0.82 µm, has the values 1.0 and 10^{-2} for the upper and lower bounds respectively. L_{sat} is the saturation value of loss.

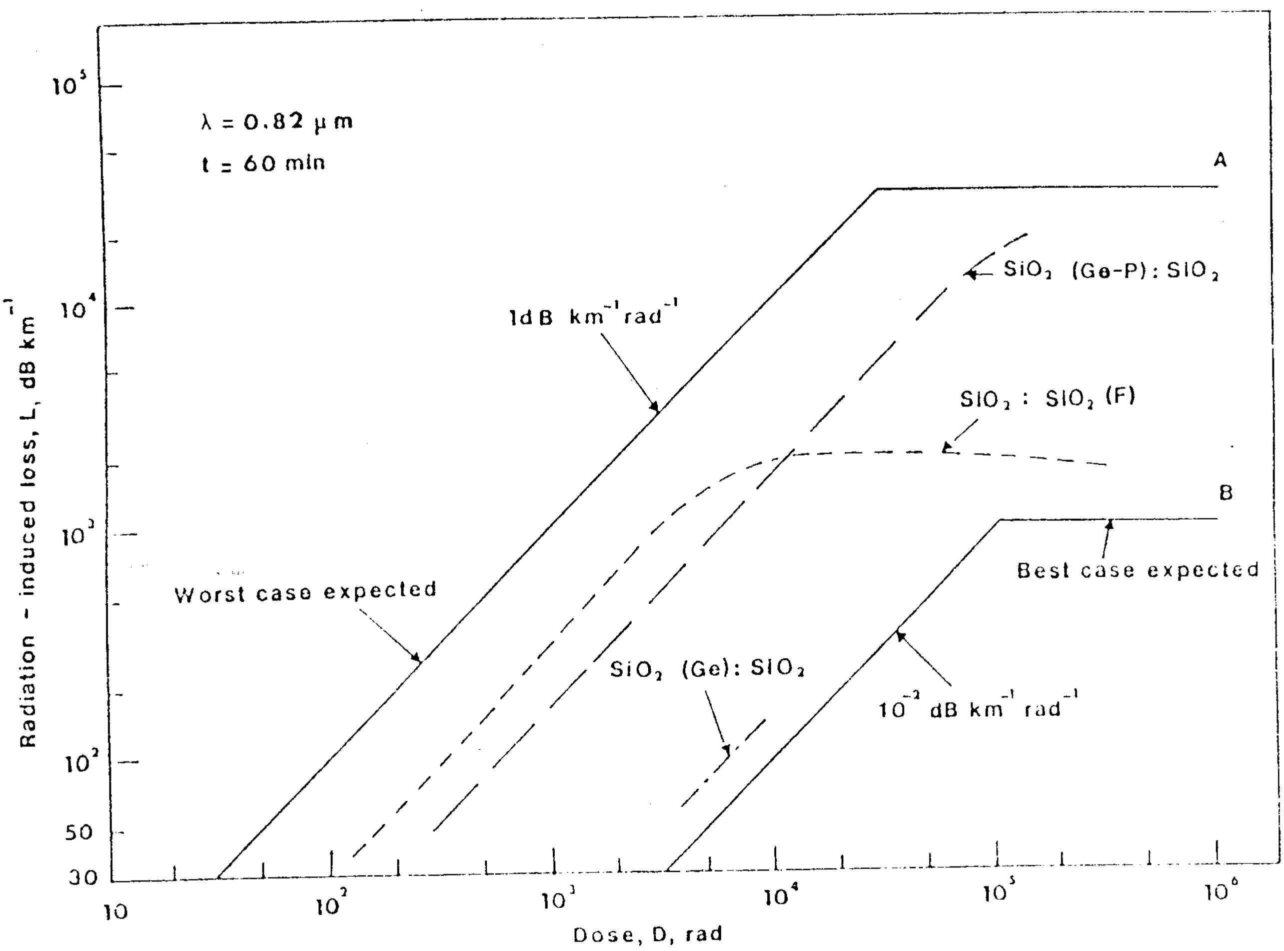
L_o will be a function of defect concentrations N_1, N_2, etc., the peak absorption wavelength, λ_{peak}, the wavelength of observation, λ_{obs}, the oscillator strength of the defect, S, and the capture cross-section of the defect for charge-carriers. If 'f' is a function of the shape of the absorption band (i.e. of the broadening and "tailing") and the separation between λ_{obs} and λ_{peak}, then the form might be:

$$L_o \propto S_1 \sigma_1 N_1 f(\lambda) + S_2 \sigma_2 N_2 g(\lambda) \nu ., \text{etc.} \qquad \text{......12(ii)}$$

The CVD silica used in fibres is deposited rapidly in layers containing varied amounts of dopant, subjected to several transient heat treatments and then to collapsing and drawing stresses. Therefore, it may not behave as simply as these models imply. For example, the experimental growth curves given by Friebele (1979) show signs of at least two saturating processes. Such effects can be handled mathematically by providing in the equations for the filling of several centres. The question of the creation of new centres by particles can be accommodated by making L_o a function of particle flux. Some preliminary experiments by Mattern and co-workers (1975) suggest that neutron displacement effects are of small significance, even in intense reactor environments.

12.4. MODERN VAPOUR-DEPOSITED FIBRE TECHNOLOGY

Figure 12.4 shows a graph compiled after review of the results of recent irradiation of communications fibres of the more advanced type. Such fibres are all made by the successive deposition of silicon dioxide layers on a former or "bait". The constituents used are of the very highest purity, but the refractive indices of different regions are manipulated by the addition of dopants to the stream of silicon tetrachloride which is the source of the silica. The common dopants are gases containing germanium, phosphorus and fluorine. Some forms have as their core section an ultrapure undoped silica, very similar to Suprasil (e.g. the fibre marked "SiO_2: SiO_2(F)" in Figure 12.4). The two solid lines marked "worst case expected" (A) and "best case expected" (B) form approximate boundaries for all of the data of the above type which was included in a survey by Holmes-Siedle (1980). It will be seen that, initially, the curves rise in a linear fashion and, in case B, with a slope of 10^{-2} dB.km^{-1} .rad^{-1}.



Upper and lower limits (lines A and B respectively) found during a survey of radiation-induced loss in all-silica optical fibres (mainly those tested by E. Friebele, plus some Fulmer experiments). Some examples of experimental results are given, showing the influence of core doping. The first set of symbols represents the core material with doping in brackets: the second represents the cladding material, with doping, if any, again in brackets.

FIGURE 12.4 - UPPER AND LOWER LIMITS

12.5. FIBRES DRAWN FROM SUPRASIL RODS

Plastic-coated silica (PCS) fibres are quite different from the above in several respects. Fabrication is less sophisticated and the fibres produced are not so rugged under the conditions used for splicing or interconnection. A silica rod (of "bulk" - Outer surface Vapour-deposited - OVPO-type, made for many years for other purposes such as optical blanks and made of Suprasil, Amersil, Spectrosil, Corning 7940 or one of the other long-used synthetic silicas) is drawn in an oxyhydrogen flame and then immediately passed through a bath of coating polymer. These PCS fibres are quite low in cost but, with this method, it is difficult to achieve numerical apertures less than 0.15. Low numerical apertures are required for high-rate communication. However, diagnostic instruments and local area networks may not require high data-rate transmission and could employ PCS fibres.

Data for Suprasil by Mattern et al (1975) together with the "best case" line B from Figure 12.4 are plotted in Figure 12.5. The curves for the build-up of absorption as a function of dose for undrawn rods of Suprasil fall below this line. As might be expected, there is an opportunity during the drawing procedure for impurities to be diffused or stresses to be introduced into the fibre. The radiation-induced loss in silica is known to be associated with the presence of impurities (alkalis, hydrogen, etc.). It is therefore not surprising that the one point recorded for "BTL fibre", made from Suprasil, lies above that for the bulk Suprasil road and near to the "best case" line, i.e. the loss is worse because defects have been introduced by processing. In a fibre made from pure Suprasil, coated with plastic (PCS), by Galileo Corp., which was tested by Friebele, Sigel et al in 1978, the loss is already 5 $dB.km^{-1}$ at a dose of 10^2 rads. As can be seen from the diagram, the build-up curve peaks at 10^4 rads and then reduces again. Another curve, F, has a similar shape, but shows a lower loss at all points. The data show a difference of three orders of magnitude in the radiation-induced loss to be found in ultrapure silica rods at the same dose level (as is illustrated by the response of Suprasil SS1, Suprasil SSWF (curve C) and Corning 7940 at 10^8 rads (Point 'o' in Figure 12.5). Even nominally pure silica fibres should therefore be carefully selected and tested.

The effort devoted to the selection of fibres will be influenced by the loss which can be tolerated, the lengths which are in highly exposed locations and the total lengths used.

Radiation-induced loss of ultrapure silica in bulk and fibre forms as a function of radiation dose. Curve B is the lower limit, found by A.Holmes-Siedle in an earlier survey of all-silica (non-plastic fibres. Apart from point D, all other results are for gamma rays at low dose rate (about 100 $rad.sec^{-1}$). Dotted line, solid lines and open circles - from Mattern et al 1974; chain-dotted and curve E - Evans and Sigel, 1978; curve F -Sigel et al 1979; filled circle - Evans and Sigel, 1975.

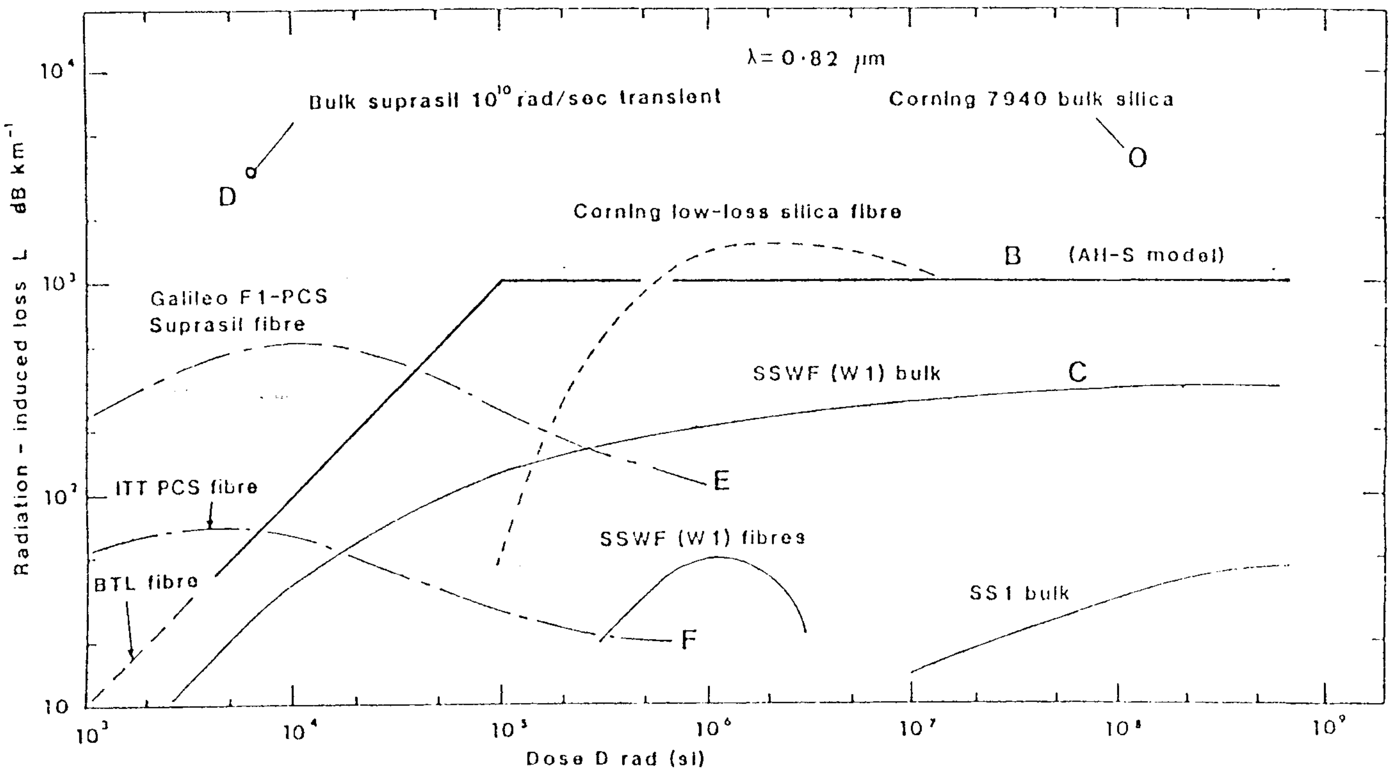


FIGURE 12.5 - RADIATION-INDUCED LOSS OF ULTRA-PURE SILICA

12.6. RECENT DEVELOPMENTS

Modern long-wave IR fibre materials, based on ZrF_4, have been irradiated (Tanimura, Sibley et al, 1985) with 1.7 MeV electrons.

At 10^8 rads, there was intense absorption in the UV and visible regions (absorption coefficient over 100 cm^{-1}).

12.7. FIBRE LUMINESCENCE

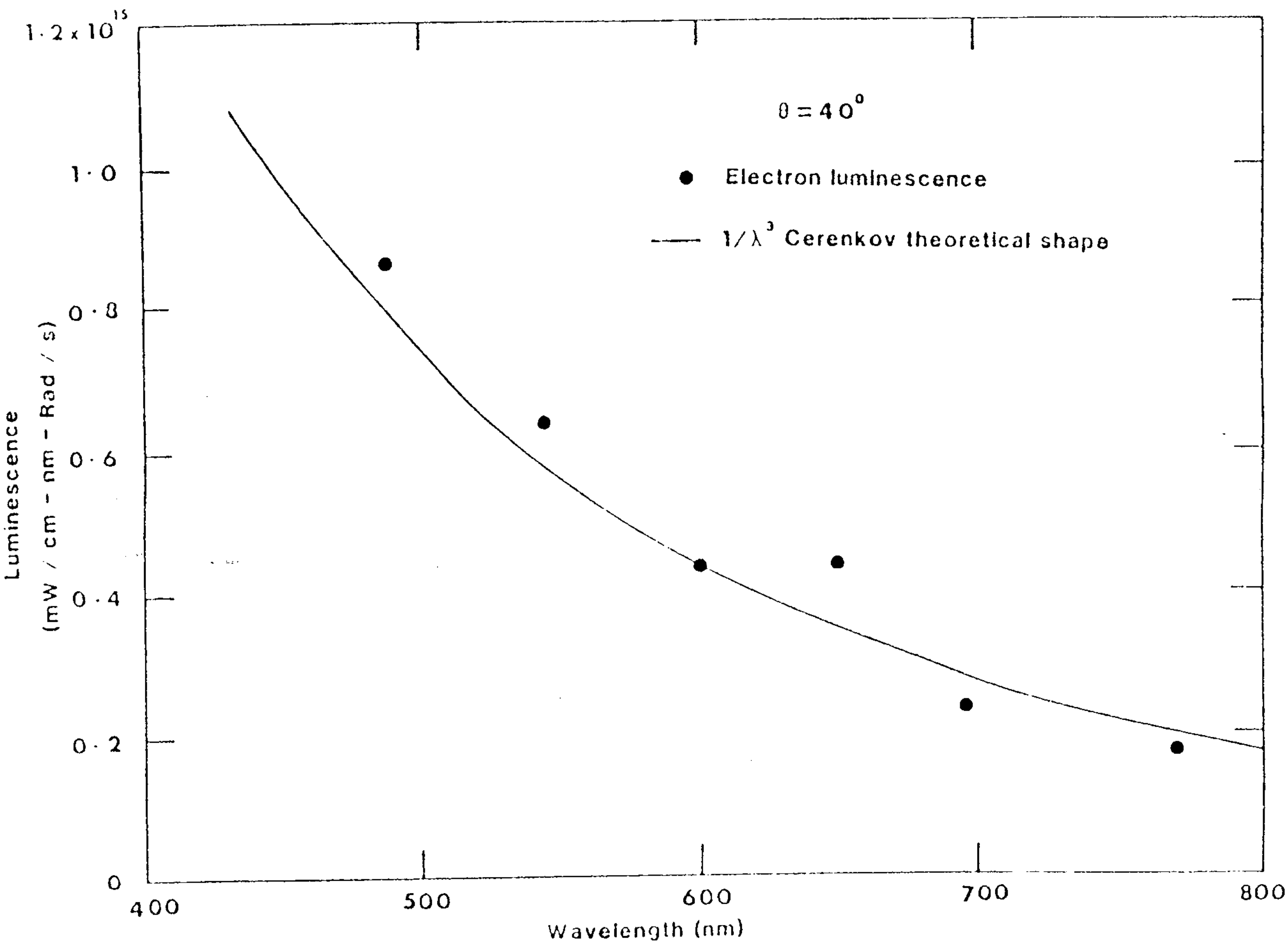
Mattern and co-workers (1975) measured the radiation-induced luminescence energy delivered to a photosensor connected to a fibre during a pulse of X-rays. The dose rate was over 10^{10} $rad.s^{-1}$ The constant calculated for the light yield from Corning Type B silica fibre at 800 m was:

$$2 \times 10^{-14} \ mJ.cm^{-1}.nm^{-1}.rad^{-1}.$$

We will assume the following values for a fibre cable exposed to a dose rate of 1 $rad.s^{-1}$:

Dose rate:	1 rad.s ,
Length of cable:	10^4 cm (100 metres),
Bandwidth of sensor:	300 nm,
Responsivity of photodiode:	1 A/W

The calculated output of a photosensor under these conditions is 6×10^{-11} A. This is unlikely to produce any problems in the form of "background" interference in normal electrical or light signals which would normally generate far higher current values. On the other hand, Mattern mentions that other materials may yield higher efficiencies. However, Lyons et al (1980) find that the luminescent efficiency of five modern fibre types is even lower than the above. Both neutron and X-ray pulses in the 10^2 - 10^4 rad range produced results indicating luminescence yields in the range 10^{-17} to 3×10^{-15} $mJ.cm^{-1}.nm^{-1}.rad^{-1}$. Thus, the above value of 2×10^{14} $mJ.cm^2.nm^{-1}.rad^{-1}$ is the highest so far found. The luminescence spectrum of one case is shown in Figure 12.6.



Luminescence induced by pulsed electron irradiation in a step-index fibre vs. emission wavelength. The solid curve is the theoretical Cerenkov shape and the points are experimental (after Lyons et al).

FIGURE 12.6 - LUMINESCENCE INDUCED BY PULSED ELECTRON IRRADIATION

12.8. CONCLUSIONS

As the optical paths in fibre optic systems may be very long, radiation-induced loss effects due to space or reactor radiation may be quite severe. Multicomponent glass fibres will show greater loss under radiation than ultrapure synthetic silica fibres. Selection by means of radiation testing is strongly advised.

Optical fibres may be subject to "annealing" and test programmes should take this into account in defining temperatures and dose rates. High dose rate testing may not adequately represent a low dose rate service environment.

Considering that, at the present time, European manufacturers and users have no procedures for the "Hardness Assurance" of fibres, there is a need to establish a programme for radiation testing of European fibre technology.

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