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Guideline for the measurement of high power damage sensitivity of single-mode fibre to bends — Guidance for interpretation of result

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National foreword

This Published Document is the UK implementation of IEC/TR 62547:2013. It supersedes PD IEC/TR 62547:2009 which is withdrawn.

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A list of organizations represented on this committee can be obtained on request to its secretary.

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Guidelines for the measurement of high-power damage sensitivity of single-mode fibre to bends – Guidance for the interpretation of results

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

GUIDELINES FOR THE MEASUREMENT OF HIGH-POWER DAMAGE SENSITIVITY OF SINGLE-MODE FIBRE TO BENDS – GUIDANCE FOR THE INTERPRETATION OF RESULTS

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IEC 62547, 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 published in 2009, and constitutes a technical revision.

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

- updates related to B6 (bend-insensitive) category single-mode fibres);
- update to analysis for test method 2: Maximum temperature specification.

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

Enquiry draft	Report on voting
86A/1494/DTR	86A/1508/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- withdrawn,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.

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GUIDELINES FOR THE MEASUREMENT OF HIGH-POWER DAMAGE SENSITIVITY OF SINGLE-MODE FIBRE TO BENDS – GUIDANCE FOR THE INTERPRETATION OF RESULTS

1 Scope

This technical report describes two methods for the measurement of the sensitivity of single-mode optical fibres to high-power damage at bends:

- test method 1 – Failure time characterisation as a function of the launch power and bend conditions (bend angle and bend diameter);
- test method 2 – Equilibrium temperature measurement.

Results from the two methods can only be compared qualitatively.

The results in this report are predominantly on un-cabled and un-buffered fibres. Cabled and buffered fibres are expected to respond differently, because the outer layers can affect the ageing process. Note also that test method 2 testing cannot be applied to buffered or cabled fibres.

These methods do not constitute a routine test to be used in the evaluation of optical fibre.

The parameters derived from the two methods are not intended to be specified within a detailed fibre specification.

The catastrophic failure modes arising and which are described in this document in general occur at bending radii much smaller than specified in the single-mode fibre specification IEC 60793-2-50 or than would be recommended based on mechanical reliability considerations alone.

This report includes several annexes, including a discussion on the rationale for the approaches adopted, metrics for assessment, guidance, examples and some conclusions from initial studies.

2 Normative references

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

IEC 60793-1-47, *Optical fibres – Part 1-47: Measurement methods and test procedures – Macrobending loss*

IEC 60793-2-50, *Optical fibres – Part 2-50: Product specifications – Sectional specification for class B single-mode fibres*

IEC 60825-1, *Safety of laser products – Part 1: Equipment classification and requirements*

IEC 60825-2, *Safety of laser products – Part 2: Safety of optical fibre communication systems (OFCS)*

IEC 61300-2-14, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 2-14: Tests – High optical power*

IEC/TR 61292-4, *Optical amplifiers – Part 4: Maximum permissible optical power for the damage-free and safe use of optical amplifiers, including Raman amplifiers*

3 Background

Optical network operators have been considering the use of high-power lasers, for example fibre Raman amplifiers, in the central office with typical launch powers in the region of 500 mW to ~ 2 W. For standard installation practices where optical fibre minimum bend diameters are limited to 60 mm, these powers have not constituted a problem. However there is good evidence that bends tighter than the recommended 50 mm minimum bend diameter mistakenly occur in practice. It is believed that these generally arise after installation from maintenance practices which are difficult to mitigate against as the technicians servicing such networks often work independently and can come from different organizations.

Tight bends arising at system installation stage should generally be identified and eliminated following provisioning by OTDR testing or from link loss measurements. Experimental evidence shows that high-power damage can occur relatively quickly at bends less than 15 mm diameter using standard single-mode fibres (e.g. category B1.3). Damage occurs when the coating temperature increases at tight bends as the coating absorbs the light lost at the bend. Damage can take the form of coating ageing, pyrolysis[1] and burning and (if the temperature increases above 700 °C) catastrophic softening of the glass. Burning of the coating can result in a fire. Background references are available in references [1][2] to [15] and in IEC/TR 61292-4.

The rationale for studying the resilience of optical fibre and coatings to high-power damage at bends is described in Clause A.1. Telecommunications operators can adopt a range of options to avoid the risk of damage, see Clause A.2. There is now a broad agreement from a number of laboratories on the catastrophic failure modes of the optical fibre including the thresholds for damage at high powers in bent optical fibres. Some observations are given in the following list:

- Research has clearly shown that high optical power at tight fibre bends can cause catastrophic damage within a few days. Tests on a range of different fibres including B1, B4 and B6 primary coated fibre categories have shown that catastrophic damage can conveniently be grouped into two regimes:
  - Regime 1. Catastrophic failure of the glass (R1);
  - Regime 2. Catastrophic failure to the fibre coating (R2).

  A third regime, R3, has been identified in which catastrophic damage does not occur. Here the temperature does not reach a sufficient level to cause short-term catastrophic damage but over the longer term, coating ageing and a change in some of the physical properties of the coating may result.

  A further description of the observed regimes of damage is included in Clause A.5.
- R1 and R2 failures have been observed in both primary and secondary coated fibres. Some single-mode fibre categories and coating types are more resilient than others, See references [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], and [12].
- Coating ageing can take a considerable time (e.g. reference [2]). However, it is an indicator of potential R1 or R2 damage. Refer to Clause A.5.

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[1] Pyrolysis is a thermochemical decomposition of organic material at elevated temperatures without the participation of oxygen.

[2] Figures in square brackets refer to the bibliography.

- Arguably at present, the greatest risk of damage to single-mode fibre systems is due to the use of high-power Raman pumps at 1 480 nm, hence much of the testing has been carried out at this wavelength. Whilst there are general indications that the absorption spectra of cured coating materials are generally flat in the 1 450 nm to 1 625 nm range, in specific coating formulations absorption features could make a coating especially sensitive at a particular wavelength.

  Also, bend loss in single-mode fibres generally increases with wavelength, so risk of damage due to high carried power at tight bends may increase at longer wavelengths. More testing is needed to examine fibre bend loss characteristics and the absorption spectra of cured coating materials to ensure that wavelength dependent effects are accounted for.
- For laboratory testing and high-power system operation, there are important safety issues to be considered including a risk of flame and fire. These issues are addressed in 4.1.
- The subject of high-power damage sensitivity is in development and the following are areas for further work:
  - As discussed above, much of the testing so far has been carried out at or near to 1 360 nm or 1 480 nm and the effect of a significant change to the test wavelength is not known. Experimental results for damage testing at wavelengths near 1 550 nm and 1 625 nm would be useful; see also reference [11].
  - Coating absorption. Some studies have examined the effects of changing coating composition and the ambient environment, see – references [13] and [14].
  - The testing of fibres with different primary coatings (both coloured) and of different outer diameter (OD), e.g. 200 μm.
  - The effect of fibre production variability and for example, testing the effect of fibres with different MAC (MFD [μm]/cut-off wavelength [μm]) numbers but with the same profile type. Similarly testing of fibres with small differences in coating uniformity, composition or degree of coating cure needs to be considered.
  - Testing diverse bend geometries; the impact of bend loss variations.
  - The impact of ambient temperature.
- For the most sensitive fibre tested so far the threshold for damage (R2) for a bend loss of 4 dB bend is ~ 200 mW, see reference [15].
- The use of different fibre secondary coatings (buffer layers to an OD of ~ 800 μm) can lower or raise damage thresholds, see reference [15].

NOTE 1 Catastrophic failure occurs when the bend loss and consequent coating absorption drives the fibre temperature far above the maximum temperature for environmental tests of conventional UV curable acrylate coatings, as specified in IEC 60793-2-50.

The purpose of this report is to define measurement techniques to characterize the robustness of optical fibre to damage of this type. However, if new fibres are developed to minimize the possibilities of high-power damage at bends, other transmission and compatibility issues shall be considered – see Clause A.3.

NOTE 2 Also in ITU-T, a recommendation associated with high-power optical systems has been developed, see ITU-T Recommendation L.68 [16].

Throughout this technical report, illustrative data is presented for particular B1 and B4 fibre categories identified by letter from A to G from studies documented in references [2], [3], [7], [15]. Data on B6 category fibres is present in reference [11].

4 Test procedures

4.1 Safety

4.1.1 Safety issues

There are a number of important issues both for testing and for operational systems use:

- eye safe working;
- risk of fire/flame;
- risk of atmospheric pollution from coating by-products;
- risk of fibre fuse initiation;
- risk of damage to downstream components.

Some discussion on these issues is covered. However, an individual assessment of risk should be carried out prior to commencing a programme of tests depending on previous experience with high-power lasers, the local working practices and the test laboratory configuration. Also, it is recommended for first tests that an operator monitors the experiment continually so that the failure conditions with specific fibre categories and/or coating types can be correctly determined. The use of a video camera to monitor the fibre bend at high power can provide a safer working environment.

4.1.2 Eye safe working

All necessary safety procedures shall be taken in accordance with IEC 60825-1 and IEC 60825-2. These test procedures involve the use of optical powers that can constitute potential ocular and skin hazards for test personnel.

At 1 480 nm, the risk of retinal damage is much reduced compared with shorter wavelengths, as incoming radiation will mainly be absorbed in the cornea, see reference [17]. Nevertheless, care shall be taken to ensure that accidental exposure cannot occur and that high powers are only switched on once the fibre (and test condition) has been set up. Also, the use of optical instruments for viewing can be more hazardous than not.

Laser light blocks should also be used to trap and mask radiation leaking from the test bend.

4.1.3 Risk of fire/flame

WARNING In the case of samples that can sustain a flame, care shall be taken to ensure that sample holders are non-flammable and robust clamps are used to hold the fibres in position during testing.

4.1.4 Risk of atmospheric pollution from coating by-products

At high powers and elevated coating temperatures, volatile components in the fibre coating will be driven off. As this occurs, and with time, the coating volume reduces, oxidation occurs and the coating discolours. The aged or damaged coating volumes involved are small as the damage region at a fibre bend is generally extremely localized. To reduce the risk of local atmospheric pollution, it is recommended that the fibre bend test zone is hooded and an extract fan is run continuously to capture particulate and purge potentially hazardous air borne coating by-products.

4.1.5 Risk of fibre fuse initiation

At high optical powers and with appropriate triggering, it is possible to initiate the ‘fibre fuse effect’ (see reference [18]). Generally, launch powers of ~ 2 W to 3 W are required to trigger this effect and the laser supply can be protected from such a risk by incorporating an optical isolator or a fibre taper just after the laser source.

4.1.6 Risk of damage to downstream components

With some fibre samples and with the high power being lost from the fibre at a bend, there may be a risk to downstream components, for example where a test fibre is jointed to a different fibre category or at a further bend. To mitigate this risk, all components used shall be rated at the power to which they could be exposed.

4.1.7 Risk avoidance

A number of steps can be taken to reduce identified risks:

- Access to the test laboratory can be restricted to authorized users.
- Warning lights external to the laboratory can alert visitors of the high-power laser hazard. Laser safety spectacles can be made available for lab users and visitors.
- A video camera can be used to monitor the test bend and reduce the need to view the test fibre directly. This reduces the risk of exposure to high-power radiation.
- The laser control system could incorporate optical monitoring for the duration of the experiment. This can allow the driving PC to auto-shutdown the laser when a failure event is identified.
- Fibres can be carefully clamped and/or taped in position in robust clamps for the duration of the tests.
- Fire extinguishing equipment should be on-hand.

4.2 General

A suitable experimental arrangement for high-power damage testing is illustrated in Figure 1. The apparatus description applies to both test methods. However, in test method 1 the infrared (IR) camera is not necessary and can be replaced by a normal colour camera – useful for experimental monitoring purposes. The test condition suggested is as follows:

- two-point bend geometry (where the fibre is fixed at two points and allowed to form a bend in free space);
- 180° configuration.

Other test conditions are discussed in Clause A.4.

4.3 Apparatus

4.3.1 Light source

A suitable high-power source at 1 360 nm or 1 480 nm is proposed for the nominal test wavelength (although the performance at other, typically longer, wavelengths needs to be considered as discussed in Clause 3). Launch powers from 100 mW to 1 500 mW or even to 5 W (reference [15]) need to be considered.

4.3.2 Isolator

An optical isolator or fibre taper that can act as a ‘fuse’, protecting the laser shall be used.

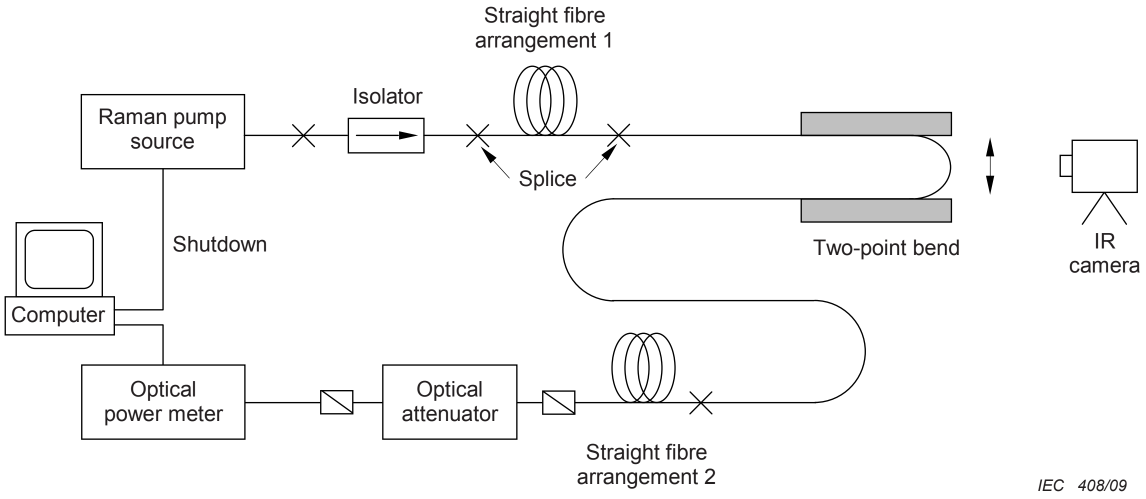

Figure 1 – Example of experimental layout

4.3.3 Bend jig

The fibre is constrained according to the two-point bend method, forcing the fibre into an oval configuration (see A.7.3 and reference [19] for a detailed discussion), of 180° although, the performance in other bend geometries and angles needs to be considered, see A.5.3. Detail on the clamping of fibres is described in A.4.2.

4.3.4 Receiver

Optical power monitoring device, which ensures stability and consistency between tests.

4.3.5 Attenuator

A 99:1 fused fibre coupler and/or a variable attenuator can be used to reduce the power level for conventional optical detectors. Alternatively a suitable high-power detector could be used for monitoring purposes.

4.3.6 Computer

Supervisory software on the controlling computer can be used to automatically shut down the laser within a few seconds in the event of signal loss and/or fibre failure.

4.3.7 Camera

The use of a video camera to monitor the fibre bend at high power can provide a safer working environment.

4.3.8 Thermal imaging camera

The maximum fibre temperature near to the bend apex can be measured using a forward looking infrared (FLIR) camera. Suitable cameras include the Thermacam^{TM} PM695 from FLIR Systems with a sensitivity of ~1 °C.

4.3.9 Oven

A temperature controlled oven can provide a high temperature ageing environment for fibre and coatings.

4.3.10 Sample

Several tens of metres of test fibre before the test bend position to provide a supply of fibre for testing. After the test bend position, the fibre is spliced to a further length of test fibre and then via the attenuator to a monitoring detector.

The primary coating colouring material used to identify individual fibres in a bundle provides an additional variable when it comes to high-power assessment. So far, most reported results have been on uncoloured fibres. Knowledge of the absorption spectra of the pigments used to colour fibre coatings could be valuable in helping to identify potentially sensitive colorants.

Most work has been conducted on primary coated fibres (to ~ 245 μm OD) where coating or fibre damage can readily be observed. For buffered or secondary coated fibres (to ~ 900 μm OD) where the outer coating may be opaque and/or inflexible, the experimental set-up needs further consideration particularly regarding fibre clamping.

Because presence of dusts or impurities located at the surface of the coating can modify its power absorption or its thermal aging, it is recommended to clean surface of the coated fibre over the length that will be placed into the clamping arrangement.

4.4 Test method 1 – Failure time characterization as a function of the launch power and bend conditions (bend angle and diameter)

4.4.1 Description and procedure

As illustrated in Figure 2, the evaluation of the high-power damage performance of a particular fibre sample consists of a number of individual tests of the time to failure determined for a range of combinations of bend diameter and input power. For the most efficient use of experimental time, it is recommended that testing begins at the smallest diameters (~4 mm) and at high powers. The power level at the test point – which may be different from that output from the laser – can be determined using a standard calibration technique. Alternatively, power measurements can be made just before the test bend is set-up and a splice is made to the monitoring photo-detector. The required fibre bend is set up in a suitable holder and the optical power switched on.

Experimental progress can be monitored using a photo-detector and a controlling computer to log the received power as a function of time as described in Figure 1 and illustrated in the results shown in Figure A.6 and Figure A.7. Regime 1 failures (R1) are recorded – see Clause A.5 for a description of the various failure conditions – usually within tens of minutes for standard category B1 or B4 fibres. The power can then be reduced for a new test and the experiment repeated. Regime 2 failures (R2) can then be identified, generally with longer times to failure. Then if the power is further reduced in a new test(s), a point is reached at which R2 failure does not occur – even at three or more times the exposure time seen for the latest R2 failure. When this time is reached, the test at this bend diameter can be stopped and, if the coating properties are found to have been changed as a result of the test, the condition are defined as sub-catastrophic damage, R3 (see Clause A.5 for an additional discussion and a description of the three failure regimes). Additional tests follow at larger bend diameters as illustrated below. Damage results can then be plotted, as for example in Figure 2.

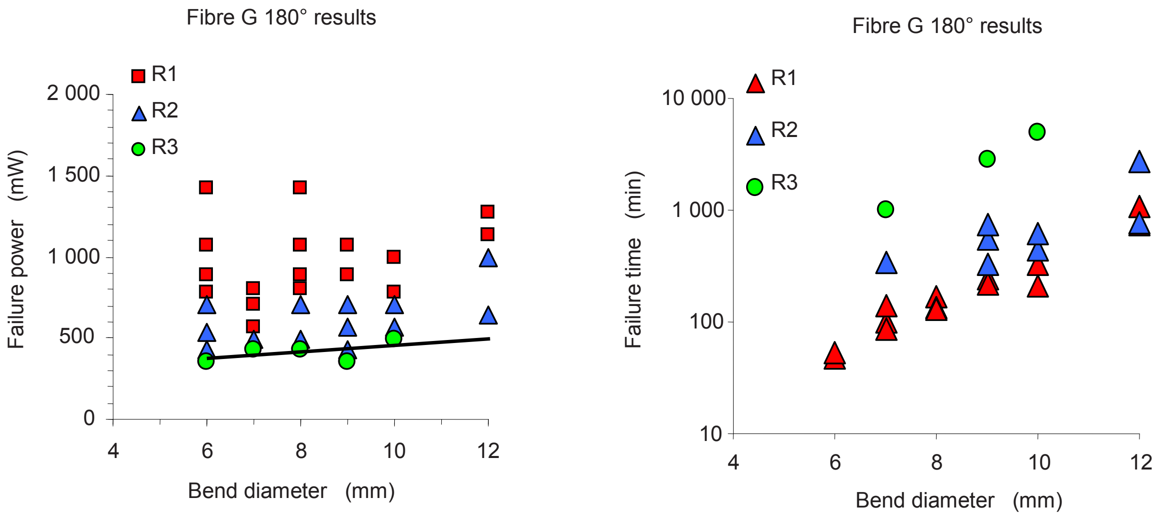

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Figure 2 – Damage results for fibre 'G'

In a set of tests, the damage trends for R1, and R2 failure types can be observed over a range of diameters giving confidence that the definition of the R1-R2 and R2-R3 boundaries is consistent and reliable. All of the R3 results that are reported here are for real experimental tests, with some exceeding several days.

Note also that

- The minimum time to failure seems to grow exponentially with bend diameter. For a given bend diameter, if the optical power is increased, the minimum time to failure does not seem to decrease. This is likely to be due to increased heat transfer by radiation as the temperature increases but the effect can also be explained by a drop of both primary and secondary coating refractive indices as temperature increases whereas the refractive index change of silica is negligible. Then a much smaller fraction of light is dissipated in the coating, see reference [20].
- Not all fibre categories show the same trends or damage phenomena at all bend diameters. For example, for 180° bends in fibre 'D' see A.5.2 and Figure A.8.
- At smaller bend angles e.g. 90°, the failure power is higher and the failure times are extended compared with similar diameter bend at 180° – see A.5.3 and Figure A.9.
- Some failure time trend inconsistencies have been observed in at least one fibre category – see A.5.4 and reference [10].
- Bend-insensitive fibres (e.g. IEC B6/ITU-T G.657 fibres) are expected to offer improved resilience and different relationships from those results shown in Figure 2 (see also 4.5.3.3 and reference [11]).

4.4.2 General comments and conclusions on test method 1

General comments and conclusions on Test Method 1 are:

- Test method 1 can be arduous; Regime 1 and Regime 2 failures in conventional category B1 and B4 fibres have been observed after more than 3 days exposure for bend diameters in excess of 10 mm. The complete characterization of a conventional B1 or B4 optical fibre category can take several months. With more resilient fibres and coatings, testing will take more time.
- The use of buffer or secondary coatings can lower or raise the threshold for high-power damage depending on the coating type – see references [5] and [15].
- The effect of different coloured primary coatings requires research.

- The impact of ambient temperature on high-power damage thresholds requires investigation.
- Smaller angle bends (than 180°) generally require higher powers to create the same damage effects, see A.5.3 and Figure A.9.
- Test method 1 can allow thresholds for catastrophic high-power fibre damage to be established, see A.6.2 and e.g. Figure A.13. These thresholds can give a system operator a benchmark of resilience to catastrophic damage depending on the available system margin (which limits the allowable bend loss).
- It has been reported that consistent and repeatable failure power and failure time results can be obtained for similar tests on the same fibre, see reference [2]. However, fibres with different MAC numbers but of the same profile type and manufacturer are likely to have slightly different failure powers and times to failure for similar test circumstances as a difference in bend loss is expected for the same test bend condition. Similarly, small differences in manufacturing tolerances, for example in coating uniformity, composition or degree of coating cure, could provide an inconsistency in results. More work is required to determine the significance of such variations.
- An alternative evaluation criterion could be established using this technique as a method for assessment of fibre resilience to failure under bending and high power for a particular test geometry and duration, if agreed between supplier and customer. Then, if the fibre survives the test duration, the fibre performance is acceptable. However, such a criterion does not give a complete picture as the test geometry (bend diameter and angle) only gives a snapshot of performance and it is known that extrapolation may be difficult, see references [10] and [14]. Also, the test duration is likely to be much less than the normal lifetime of a fibre and damage effects are known to be non-linear and cumulative.
- The preferred test procedure is a full characterization.
- Users should be aware that time-to-failure tests for 2-point, 180° bends with a diameter of less than ~6 mm may not allow differentiation between the high-power damage sensitivity of different fibre and coating types, see references [10] and [24].

NOTE The thresholds determined by test method 1 generally occur at smaller bending radii and higher coating temperatures than described in the single-mode fibre specification IEC 60793-2-50.

4.4.3 Reported items for test method 1

The items reported are as follows:

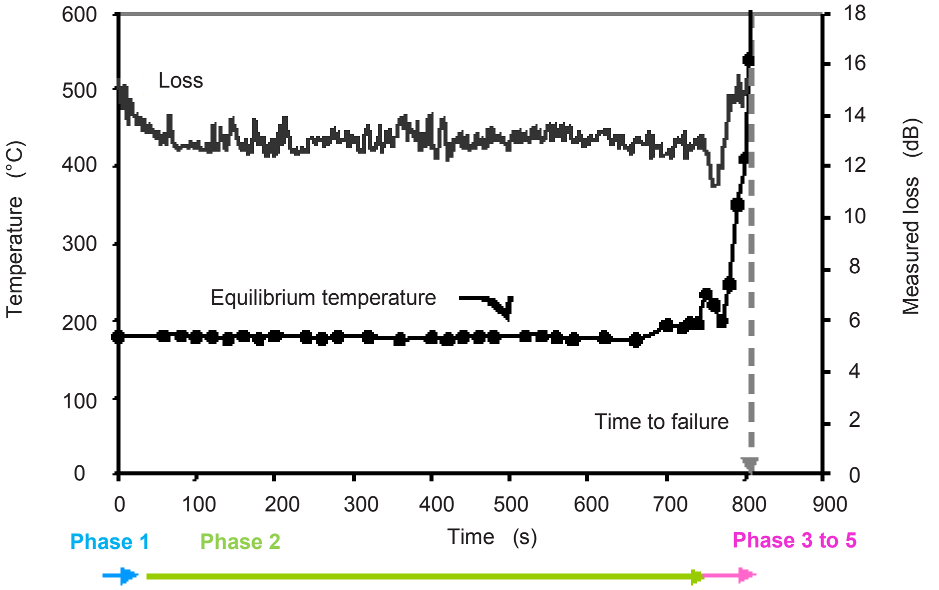
- fibre (sub-)category; fibre identification;
- launch power and wavelength;
- bend diameter;
- macrobend loss with time;
- failure condition R1, R2, or R3;
- time to failure.

4.5 Test method 2 – Equilibrium temperature measurement

4.5.1 General

The experimental arrangement for test method 2 is as described in Figure 1. It has been observed that as soon as the power is launched into the fibre the coating temperature at the bend quickly reaches a plateau, see Clause A.8 and reference [10] for a complete discussion. The maximum coating temperature near to the bend apex has been observed to remain relatively stable during the major part of the test, but a change of coating colour can be seen over time. The temperature during this phase is called the “equilibrium temperature”. This phase can last several days. In reference [24], the use of a forward looking infrared (FLIR) camera (see Figure 4) to measure equilibrium temperature is described. A software feature in this camera allows the maximum temperature in a section of the camera field of view to be monitored straightforwardly.

Near failure, when the coating is discoloured, the coating temperature can rapidly increase above 500 °C and smoke released from the coating can warn of imminent failure. The coating can then burn off over several centimetres commencing near to the bend apex and, if heating is sufficiently rapid, the silica can reach softening point. An example of such a time evolution is shown in Figure 3.



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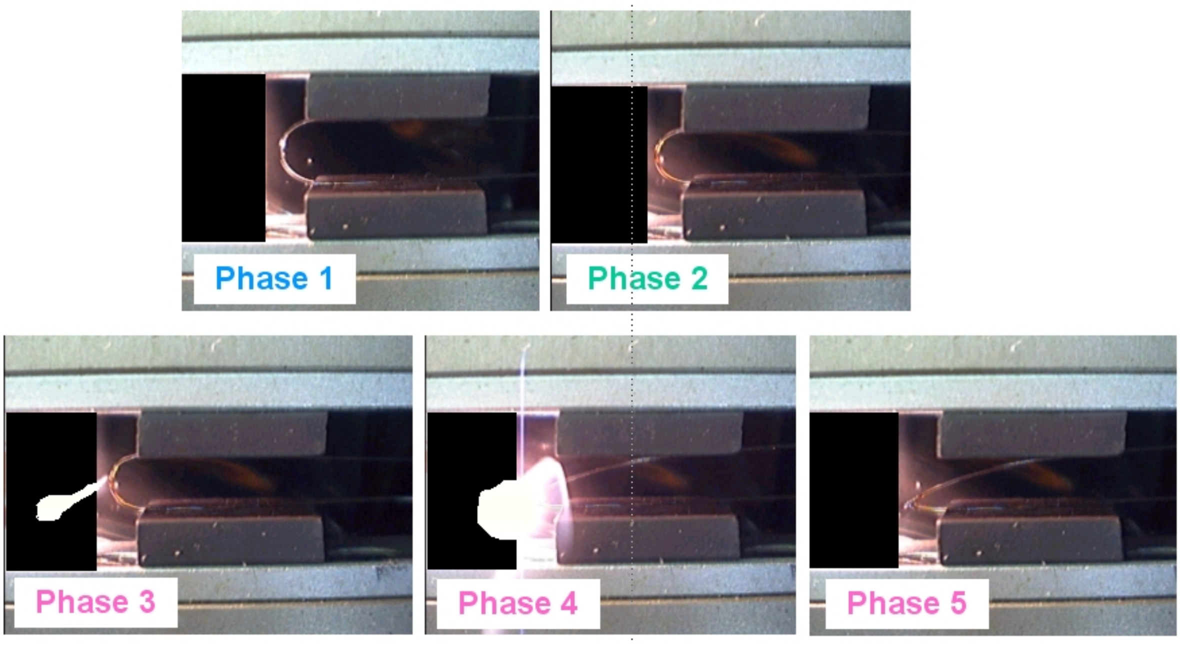

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NOTE 1 P = 3,2 W, bend diameter = 5 mm, λ = 1 360 nm, see reference [10].

NOTE 2 Photographs taken at consecutive phases indicated in the top graph.

Figure 3 –Example of time evolution of catastrophic high-power loss and related maximum temperature reached by the coating near to the top of the bent fibre (apex)

4.5.2 Coating heating measurements and power lost at bend

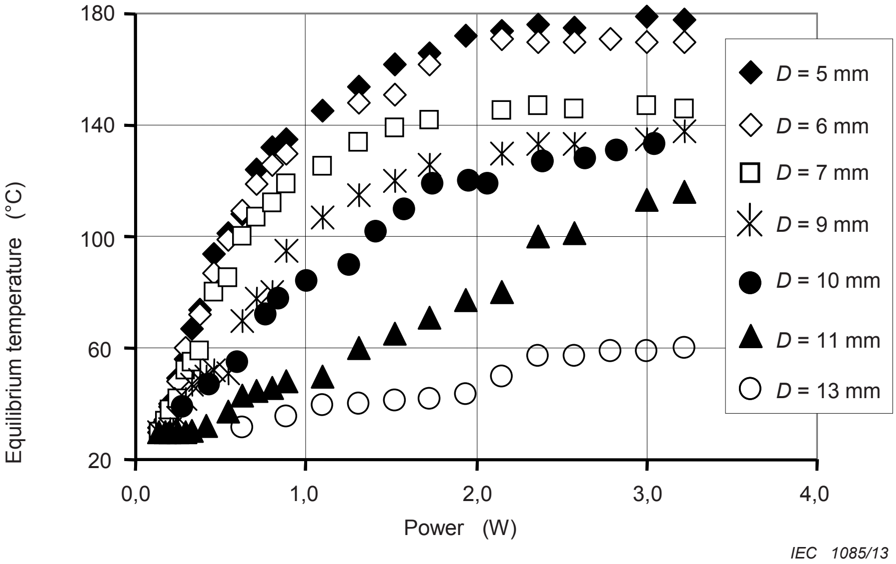
As with test method 1 (see 4.4.1), the evaluation of the performance of a particular fibre sample consists of a series of individual tests at a range of combinations of bend diameter and input power for which the maximum fibre temperature near to the bend apex can be measured using a FLIR camera (see Figure 4).

The analysis in Figure 5 points out that both power level and bending diameter impact the coating temperature, see reference [10]. For bend diameters below 10 mm, it has been reported that the temperature was not a linear function of the power: it first increased linearly with launch power but begins to stabilize from ~ 1 W.

IEC 1084/13

NOTE The cross-mark indicates the location of the maximum temperature.

Figure 4 – Sample FLIR camera output of the fibre bent under high power



IEC 1085/13

Figure 5 – Dependence of the coating equilibrium temperature as a function of launched power and bend diameter for an IEC B1.2/ITU-T G.654 single-mode fibre (see reference [10])

4.5.3 Analysis – test method 2: equilibrium temperature

4.5.3.1 General

Test method 2 can be applied in two ways:

- full characterization of a fibre failure time relationship with equilibrium temperature;
- determining equilibrium temperature only.

4.5.3.2 Analysis – test method 2: Characterization of a fibre failure time relationship with equilibrium temperature

A full characterization of a particular fibre's equilibrium temperature and failure time relationship would take some time to complete. Analysis (see Clause A.8 and reference [10]) has shown that an equilibrium temperature may be determined in a given test fibre to forecast a 25 year lifetime. This analysis consists of three distinct parts:

- determine the maximum allowed equilibrium temperature, according to the master curve which is determined for a given fibre category. An example is shown in Figure A.20, Clause A.8;
- measure the equilibrium temperature versus launched power and diameter as shown in Figure 5;
- for each bend diameter, determine the maximum launched power to forecast a 25 year lifetime. This can be simply deduced from Figure 5, once the maximum allowed temperature has been established (see Figure A.14).

This supposes that thermal degradation mechanisms of the coating are unchanged over this range of temperature and assumes that the relationship between equilibrium temperature and time established at the temperature at which time to failure is measured (between ~145 °C and 110 °C in reference [10]) can be extended for a 25-year lifetime (~80 °C in reference [10]).

4.5.3.3 Analysis – Test method 2: maximum temperature specification

A relatively fast use of test method 2 is to compare the equilibrium temperature as a function of launch power and bending diameter (see example in Figure 5) to the maximum allowed temperature for environmental tests for which the fibre under test has been specified. (For single-mode fibre specification IEC 60793-2-50, this maximum temperature is specified as +85 °C for 30 days; alternatively it could be agreed between supplier and customer.)

Reference [11] shows modelling of this maximum temperature for different categories of single-mode fibres (B1.3 and B6 category fibres) based on measurements performed at 1 360 nm. Extrapolations to wavelengths at 1 550 nm and 1 625 nm have been made, see Figure 6. The estimated variations are assumed to be lower than ±20 %. These results clearly show the advantageous use of bend-insensitive fibres (e.g. B6_a2 and B6_b3), allowing higher maximum safe power at smaller bend radii.

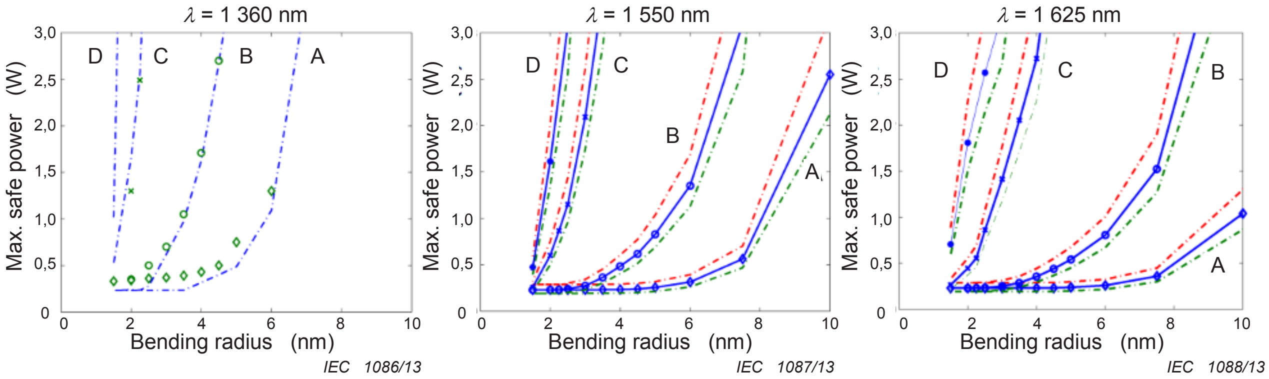


Figure 6a – Calculated from experimental test data at 1 360 nm

Figure 6b – Extrapolated for 1 550 nm

Figure 6c – Extrapolated for 1 625 nm

NOTE A (B1.3), B (B6_a1), C (B6_a2) and D (B6_b3).

Figure 6 – Maximum safe powers for 25 year life time as a function of bend radius enabling a safe coating temperature of ~80 °C for four single-mode fibre (sub-) categories

4.5.3.4 Determining the maximum equilibrium temperature using oven ageing

An alternative approach to that described in 4.5.3.2 for determining an equilibrium temperature threshold is described in Clause A.9 using coating degradation data from oven ageing tests. This approach should help fibre suppliers to more readily define threshold temperatures for specific coating types. The procedure uses the results from oven ageing tests to determine the temperature at which rapid coating ageing begins. As temperatures rise and with extended ageing (~30 days), coating volume reductions increase. A safe equilibrium temperature is defined when the volume reduction is just less than ~ 1 % for 30 days exposure. The volume reduction test is relatively straightforward and confirms a safe threshold temperature for high-power damage against which the fibre suppliers can test. To avoid duplication of effort by fibre manufacturers, coating suppliers could be asked to provide characteristic coating ageing data (as shown for example in Clause A.9 and Figure A.21) – see discussion in A.9.2.

NOTE The volume reduction as described above generally occurs at higher temperatures than maximum temperature for environmental tests allowed in the single-mode fibre specification IEC 60793-2-50.

4.5.4 Test conditions for test method 2

Test conditions for test method 2 are as follows:

- a 180° two-point bend test geometry;
- one or more bend diameters (distance between the flats) can be chosen, e.g. D = 5 mm, D = 10 mm and D = 15 mm, depending on the magnitude of the investigation.

  NOTE Experiments have shown that the equilibrium temperature at the R2-R3 catastrophic damage boundary increases as bend diameter reduces.
- a launch power from 100 mW to 3 000 mW;
- an agreed design for a test fixture enclosure to limit airflow over the sample;
- a test interval of 1 min. The equilibrium temperature is reached in approximately 10 s so results recorded after 1 min should be representative.

Agreement on these test conditions is required.

4.5.5 Conclusions on test method 2

The method to define the maximum equilibrium temperature shall be established by

- determining the maximum allowed equilibrium temperature, according to the master curve for a given fibre category, an example of which is shown in Clause A.8. This method is time consuming,
- ensuring that the fibre under test is heat-resistant below this temperature (e.g. the value of +85 °C adopted in the single-mode fibre specification IEC 60793-2-50 and/or to be agreed between supplier and customer),
- using coating ageing data from oven ageing tests as outlined in Clause A.9.

As with test method 1, thresholds for catastrophic high-power fibre damage can be established for test method 2, see A.6.3 and e.g. Figure A.14 and A.15. These thresholds can give a system operator a benchmark of resilience to catastrophic damage.

For a better understanding of high-power failure mechanisms, some additional work may also be necessary to determine the following:

- The impact of buffer or secondary coatings, and the inherent difficulties of localized temperature measurement of buffered fibres, jumper leads and cables.
- The significance of different coloured primary coatings.
- The consequence of fibre production variability and for example, testing the effect of fibres with different MAC numbers but with the same profile type. Similarly testing of fibres with small differences in coating uniformity, composition or degree of coating cure needs to be considered.
- The impact of ambient temperature on the maximum equilibrium temperature.
- The measurement capability of the FLIR camera and the degree of localization of the maximum temperature occurring in bent optical fibre.
- The effect of source wavelength on coating heating.
- Confirming that extrapolation of the equilibrium temperature/failure time relationship remains valid for longer lifetimes (and therefore for lower equilibrium temperatures).
- Data from oven ageing testing of coatings with time and temperature.

Note that test method 2 is not really suitable for the testing of buffered fibres as the procedure provides a surface temperature measurement; this may not reflect the temperatures experienced in coating sub-layers.

4.5.6 Reported items for test method 2

The items reported are as follows:

- fibre (sub-)category; fibre identification;
- launch power and wavelength;
- bend diameter;
- macrobending loss;
- FLIR camera set-up conditions, including emissivity and maximum temperature recording settings.

  NOTE An emissivity, e = 0,98 for primary coated fibres was used in reference [10] whereas an emissivity of e = 1,0 was applied in tests reported in reference [24]. Tests on buffered fibres are expected to demand different emissivity values depending on buffer coating composition.

- equilibrium temperature at a prescribed bend diameter(s) after a fixed time as agreed between supplier and customer.

5 Conclusions

Time to failure as a function of fibre bend diameter and launch power can straightforwardly give a picture of the performance of optical fibres in bends at high power. However, a full characterization of one fibre category using this technique could take several months. The time to carry out complete testing of innovative damage-resistant fibre and coating designs (an example is described in Clause A.10) may be prohibitive if a full characterization of failure regimes is to be performed. The compromise solution of testing at small diameters and high powers does not give a complete picture. Extrapolation of the results of tests at small diameters to large diameters has been shown to be too conservative, see A.5.3 and references [10] and [24].

Fibre coating ageing appears to be driven by temperature – the higher the temperature the faster a coating ages (see Clause A.9) – so this seems to be a good choice of metric for rapid fibre assessment once the maximum temperature to avoid coating degradation is known. The measurement of equilibrium temperature for a particular configuration of bend and launch power takes only tens of seconds to perform. However, further investigations on the coating degradation process may be required, for example, as in reference [21], to confirm that the relationship as given by the master curve for a given fibre (as discussed in 4.5.3.2 and shown in Figure A.20) can be used to extrapolate to lifetimes of more than 25 years.

The advantage of maximum temperature testing according to test method 2 is discussed in 4.5.3.3, showing the advantageous use of bend-insensitive fibres (e.g. B6_a2 and B6_b3), which allow higher maximum safety power at smaller bend radii. Using modelling (e.g. reference [11]) measurement data obtained at 1 360 nm can be extrapolated to wavelengths at 1 550 nm and 1 625 nm.

In addition, fibre coating suppliers could be asked to provide data on the oven ageing characteristics of fibre coatings as described in Clause A.9, so that an alternative approach for deriving a threshold for a safe equilibrium temperature can be established. These assessment techniques are comparatively recent and several areas requiring further study have been identified – see 4.5.5 – and in particular the practicality of equilibrium temperature measurement of buffered fibres.

It should be noted that testing using test method 1 inevitably leads to a test where failure does not occur, i.e. the condition for sub-catastrophic damage. One laboratory (e.g. as described in reference [15]), uses a test time which is at least three times longer than for the closest R2 failure. However, there can be no assurance that this test time is sufficiently long and consequently, the result is a negative one. On the other hand, test method 2 testing gives a positive result, provided that the recorded equilibrium temperature needs to be less than the allowed temperature for environmental tests for which the fibre under test has been specified.

For both test methods, the impact of buffer coatings introduces additional complexity to testing. This is an important issue since, as discussed in Clause A.1, both primary coated and buffered fibres are used by telecom operators close to high-power sources, regenerators or Raman pumps. Whilst the risk to jumper cables linking equipment racks in a telecom environment can be evident, potential hazards can also arise in splice trays or in associated fibre handling trays. Given that buffer coatings can both reduce and increase the failure time – see reference [7] – some further work is needed to determine the suitability of test methods 1 and 2 for buffered fibres. The design of ruggedized patch-cords increases the complexity of estimating the damage threshold due to high power. Ruggedized patch-cords may be more resistant to degradation if the design reduces the availability of oxygen at the fibre coating interface. Any investigation would also need to include the impact of mechanical stress on the susceptibility to high-power damage in tight bends and the relationship between equilibrium temperature and failure time.

Annex A
(informative)

Robustness of fibres against damage from exposure to high power at bends

A.1 Rationale

With maximum operating powers of from 200 mW to more than 500 mW, the risk to fibre networks from high-power damage at fibre bends has been assessed by one telecommunications operator to be ‘locally high’. As system powers increase and more systems are deployed future risks will increase.

Since fibre losses near 1 480 nm can be low (~0,2 dB/km), the risk of damage can extend quite far from a high-power source or a system amplifier in a telecom system. System operators need to be concerned about risks of damage to primary coated fibres, buffer or secondary coated fibres and jumper cables as well as to system fibres and fibres in joint closures up to perhaps 20 km from a high-power source, depending precisely on the fibre loss, the launch power and the fibre damage threshold.

The purpose of this annex is to describe test procedures to characterize the robustness of fibres against damage from exposure to high power at bends. IEC 61300-2-14 [26] describes the test and measurement procedures for high optical power handling and damage threshold characterization of fibre optic interconnecting devices. However, it does not consider the problem of damage at fibre bends.

A.2 Options for telecommunications operators

Operators can employ one or more of the following options to address the high-power fibre damage issue:

a) limit the optical power launched;
b) improve fibre handling and management systems;
c) improve the technology for fibres and coatings considered to be at risk for this failure mechanism.

In the long term, risk mitigation will probably be addressed by a combination of b) and c). Some technology improvements offer significant advantages, e.g. see Clause A.10.

A.3 Criteria for assessment

Concerning solutions that relate to improved fibre technology, there are two options that might be considered:

a) improved glass design;
b) more resilient fibre coatings.

The options for new fibre and fibre coating technologies need to be discussed, reviewed and analysed, see references [8] and [15]. Some factors that may need to be considered include:

- compatibility with existing fibre systems, e.g. B1 or B4 category single-mode fibres;
- the need to consider issues for both primary and secondary coated fibres;
- potential downstream effects;
- increased sensitivity to other performance parameters, for example:

  - splice or connector losses;
  - micro-bending loss;
- coating ‘strippability;
- impact on working practices;
- field traceability of fibres with improved technology;
- long life reliability issues for fibres with improved technology and potential changes to testing procedures.

Some trade-offs in performance are anticipated, depending on the proposed solution. Telecommunications operators need to understand the trade-offs so that fair, comparative assessments are possible.

A.4 General testing conditions

A.4.1 Two point bend geometry

For all installations of optical fibres in high optical power systems, the exact bend radius in the cable tube, building, optical fibre distribution frame, the rack, the splice cassette, enclosure, etc. from end to end of the entire network should be determined. Care should be taken to ensure the appropriate bend radius is not less than that which is suitable. Despite this, studies of fibre bends in the ‘central office’ or Telco exchange buildings have shown that tightly bent fibres with bend diameters less than 60 mm arise much too often. Generally, these come about because of human error in handling and loading fibres into storage trays or bending fibres around and between equipment racks. Primary coated, buffered or secondary coated fibres and jumper cables are all subject to this problem, with the bent fibres being bent in a 2-point bend configuration often of 90° or up to 180°.

A number of laboratories have adopted the two-point bend for high-power damage testing because this is the type of bend that is seen most often in networks. Also, a stable configuration can be set up for testing in the laboratory where fibres do not need to be pressed against a form to achieve the required geometry. This avoids any variable thermal contact or tensioning issues during high-power damage testing.

A.4.2 Fibre clamping arrangements

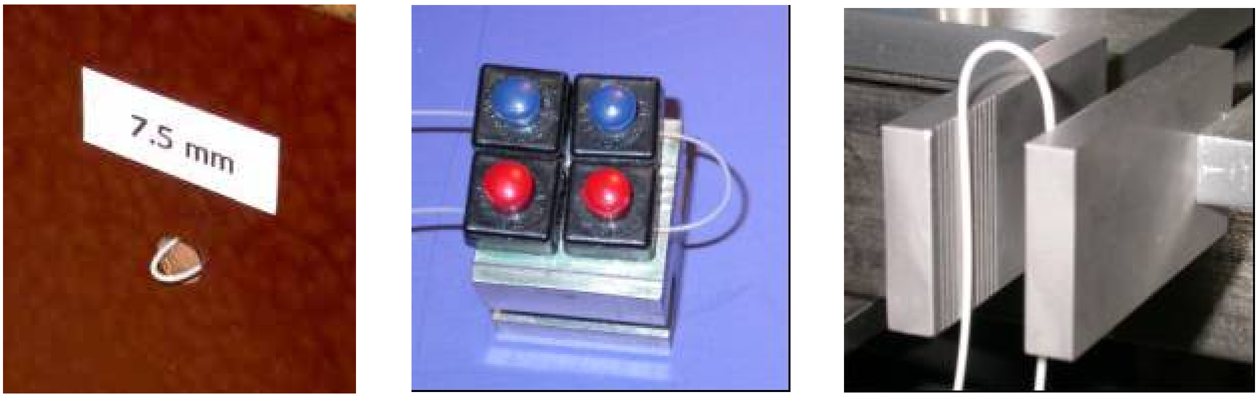
A range of different clamping arrangements have been used for holding both primary and secondary coated fibres in 180° 2-point bend configurations for high-power damage testing. Some of these are presented in Figure A.1, from left to right:

- a reamed hole in tunnel (a stable, machineable insulating material), particularly suitable for primary coated fibre as its thermal (insulating) properties would not affect the fibre failure conditions;
- a ‘V’ groove clamping arrangement with magnetic clamps;
- a motorized ‘V’ groove assembly to accurately position fibres to the required separation, (down to 10 μm), particularly suitable for secondary coated fibre. This assembly was used for 2-point bend loss measurements in Clause A.7.

Clamps should provide stable, non-flammable platforms for high-power testing. Preferably the clamps should be non-conducting so that they do not act as heat sinks or modify the local thermal environment.

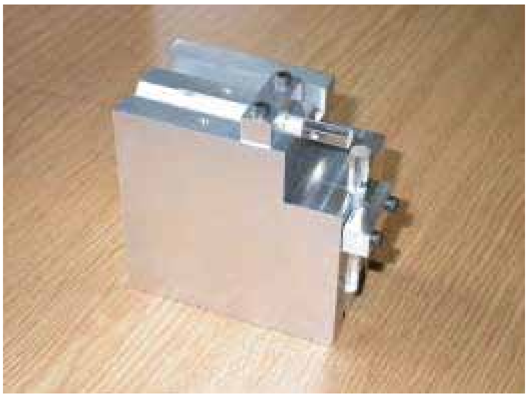
An alternative two-point bending fixture for testing primary coated fibre consisting of bevelled slots in a machineable, thermally insulating ceramic has also been demonstrated, see reference [6]. This device has the advantage of avoiding contact between the fibre and an optically absorbing or thermally conductive surface.

The bend diameter identified in a test may refer to the diameter of the hole or the separation of plates into which the coated fibre is inserted or it may refer to the diameter of the region of minimum bending, halfway about the oval bend. The terminology should be clearly identified.



IEC 414/09

Figure A.1 – Clamping arrangements for high-power damage testing in 180° bends



IEC 415/09

Figure A.2 – Clamping arrangement for high-power damage testing in 90° bends

A.5 Damage observations

A.5.1 General

High-power damage is driven by the increase in temperature of the fibre coating due to the optical loss at the bend. The level of damage and the time taken for it to occur depends on the level of optical power, the fibre bend diameter, the detailed optical flux flow in both the optical cladding and polymer coating, and the absorption of the coating as a function of coating oxidation at the wavelength of interest. The increase in temperature is not linear with time but increases as a function of coating oxidation, the increase being rapid close to failure, see Figure 3 and reference [10] for discussion.

Figure A.3 and Figure A.4 show typical regime 1 (R1) and regime 2 (R2) failure characteristics.

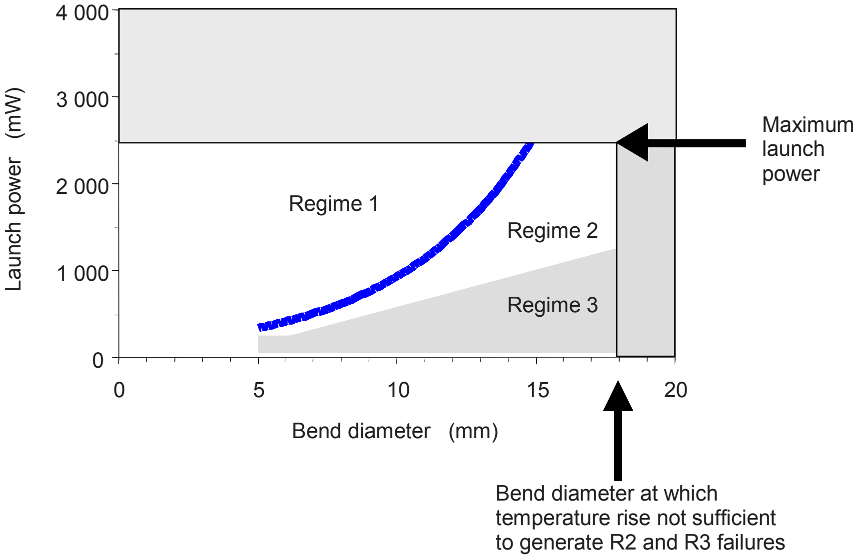
Sub-catastrophic damage R3 is variable in nature. At one extreme, close to the conditions required for R2 damage, the fibre primary coating layer can become quite severely aged but should not be burnt as that would indicate an R2 failure. Such R3 damage can result in a fibre with a colourless coating becoming darkened and of reduced diameter where higher temperatures have been experienced in the vicinity of a bend. At the other extreme, coatings may appear almost unaffected by high-power affects, particularly where the test conditions are relatively far away from those which would result in a catastrophic failure, as illustrated in Figure A.5.


IEC 416/09

Figure A.3 – Typical R1 failure characteristics with a loss of greater than 10 dB


IEC 417/09

Figure A.4 – Typical R2 failure characteristics



IEC 418/09

Figure A.5 – A schematic illustration of the three regimes

In some early experiments it was thought that fibres were resilient because monitored temperatures remained relatively low even after a few hours of testing. Observations have shown that testing needs to be carried out for sufficiently long periods, see references [14] and [15]. Sample monitor plots for R1 and R2 failure types are shown in Figure A.6 and Figure A.7.

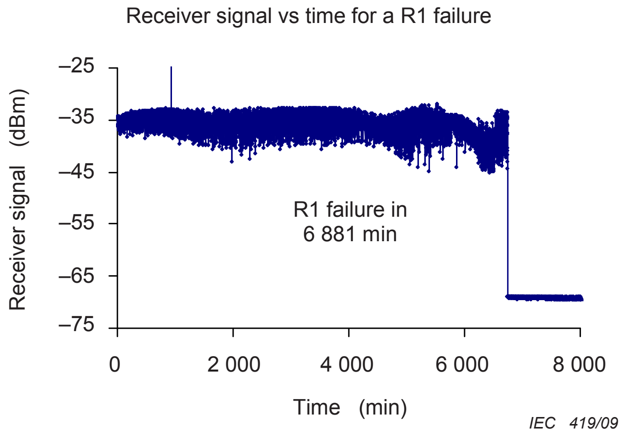


Figure A.6 – Monitor signal changes – Typical for an R1 failure

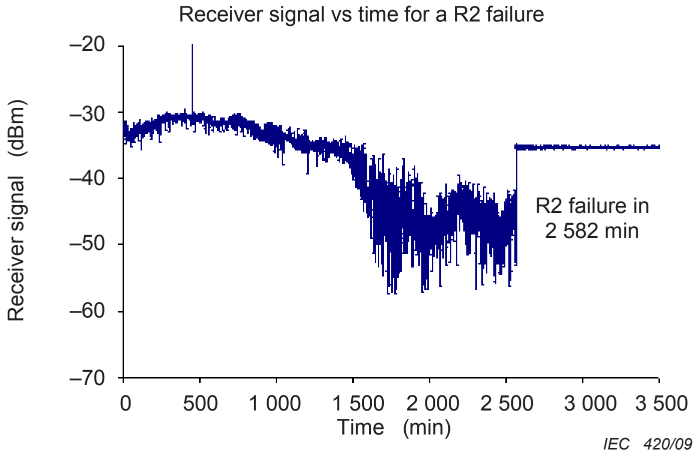


Figure A.7 – Monitor signal changes – Typical for an R2 failure

In Figure A.6, the R1 failure occurs at 6 881 min with a high loss, mimicking a fibre break. In the R2 failure example of Figure A.7, failure occurs at 2 582 min, when the fibre coating is oxidized or burnt off. Once this happens the fibre is resistant to further high-power damage, see reference [2], but because the coating has been removed it may fail during subsequent handling. It is good practice to visually inspect fibre failure at bends using a microscope after the laser has been switched off to confirm the failure characteristics.

A.5.2 Exemplar results for fibre 'D' by test method 1

As discussed in 4.4.1, not all fibres show the same features, see Figure A.8.

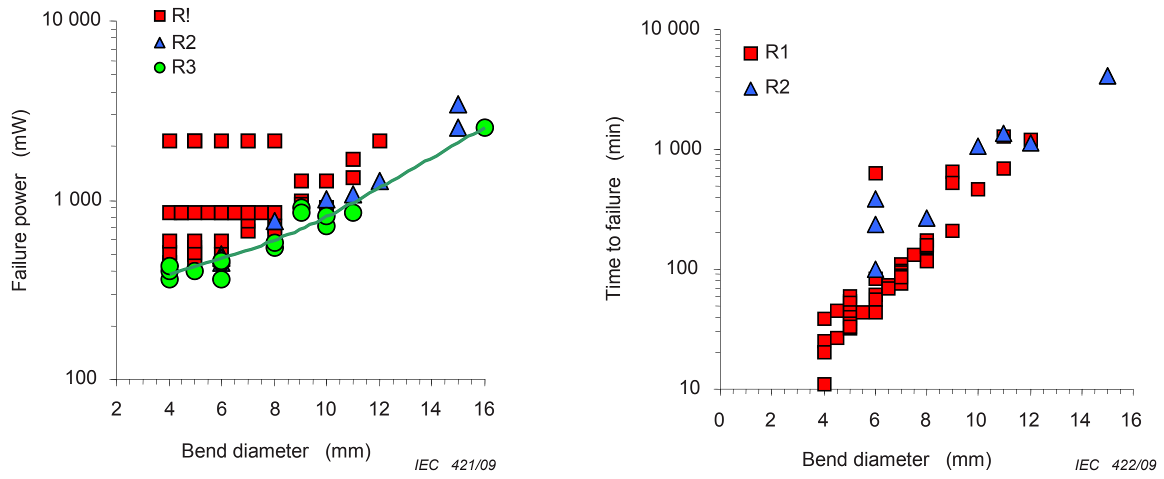


Figure A.8 – Damage results for fibre sample ‘D’

For fibre ‘D’ results, note that:

- the R2 region is small and not distinct – compare these results with those of fibre ‘G’, in Figure 2;
- the power required for R1 failures and for the R2 – R3 boundary increases with bend diameter;
- R2 time to failure is 4 100 min (68 h) at 15 mm diameter.

A.5.3 High-power damage results for 90° bends for fibre ‘D’ by test method 1

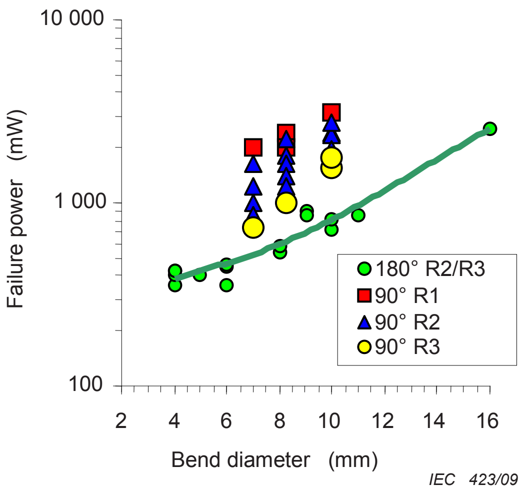


Figure A.9 – High-power damage results at 90° and 180° for fibre ‘D’

Referring to Figure A.9, note the following:

- catastrophic damage is still observed for 90° bends but
  - the time to failure is longer than for 180° bends,
  - there is a larger more distinct R2 region;
- bend loss reduces substantially as bend angle is reduced below 180° – as is shown in Figure A.11. See reference [7] for a full discussion.

A.5.4 Test method 1 – R1 and R2 failure times – Some trend inconsistencies

The failure times at 1 360 nm and three different launch powers are given in Figure A.10. Measurements, see reference [10], were performed on bend diameters ≤ 10 mm, allowing results to be obtained in a reasonable time. Each point of the figure corresponds to an average of at least 3 measurements. Fibre A data corresponds to that in reference [10].

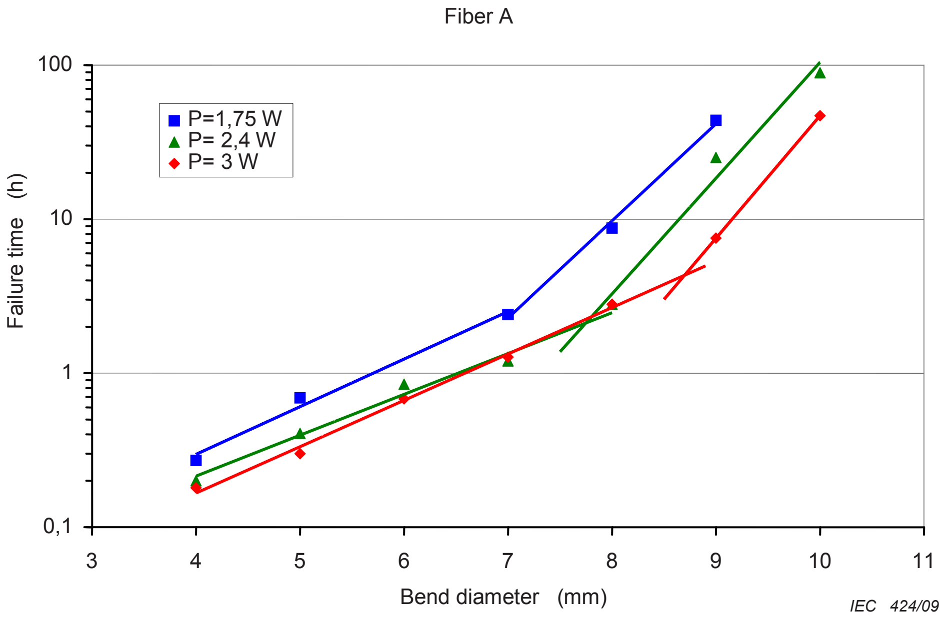


Figure A.10 – Time to failure versus bend diameter at different launched powers

Time to failure depends on bend diameter and launched power. The larger the bend diameter and the lower the power, the longer is the time to failure. The differences in time to failure can be explained by the differences in bend losses, which are broadly exponential functions of bend diameter, see Clause A.7. When the bend diameter is increased, there appears to be a transition to a longer time to failure that cannot be linearly extrapolated from small diameter data. For a diameter of 10 mm and a power of 3 W, the measured time to failure is about 47 h (and not 11 h if extrapolated by a straight line function on a log scale).

This raises the issue of relevance when testing and comparing fibres in more severe conditions than normal operating conditions in order to reduce the duration of tests.

A.6 Analysis – System limits to high optical power

A.6.1 General

Given that catastrophic damage in both primary coated and secondary coated fibres has been observed, the impact on system design and operation can be readily determined. First consider the bend loss performance of fibre ‘D’, shown in Figure A.11, see Clause A.7 for a full discussion. Bend loss measurements were made generally in accordance with IEC 60793-1-47 but with modifications as per Clause A.7.

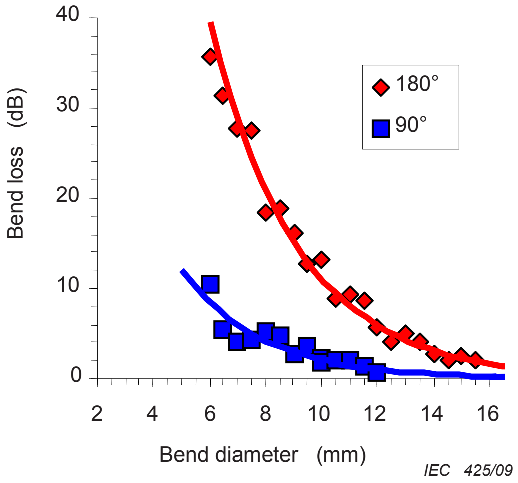


Figure A.11 – Bend loss performance at 180° (and 90° for comparison) for fibre ‘D’

A.6.2 Test method 1 – System limits to high optical power

In Figure A.12, the bend loss is plotted versus the required input optical power at the R2 – R3 damage boundary for five different fibre categories. These results are derived by combining the bend loss versus diameter data and the failure power versus bend diameter data from for example, Figure A.11 and Figure A.8 for fibre ‘D’.

In operational systems, the available system margin limits the bend loss that can be introduced before a system fails. For an increase in loss due to a bend of say 4 dB, Figure A.12, the maximum optical power just needed to cause short term catastrophic damage (R2-R3 boundary) varies significantly between the primary coated fibres tested, ranging from 1,6 W for fibre ‘D’ to 300 mW for fibre C. Given the danger of operating at the R2 – R3 boundary, it is suggested that the allowed power for fibre C should be reduced by, for example, 20 % giving a maximum power of 240 mW.

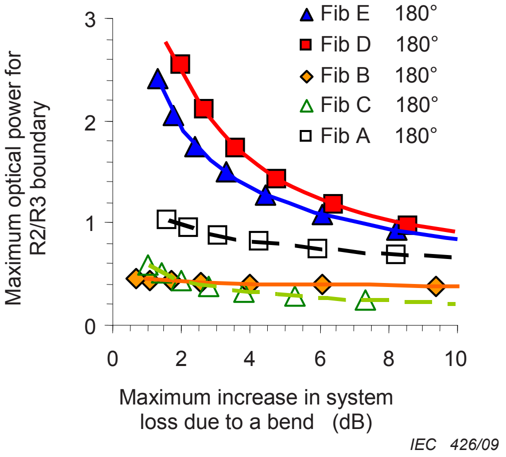


Figure A.12 – Power limitation for primary coated fibre

Importantly, it has been found that secondary coated fibre can be more sensitive to high-power damage than primary coated fibre, see Figure A.13 and reference [15]. For fibre ‘D’, given a bend loss of 4 dB, the maximum optical power drops from 1,6 W to ≈ 400 mW. Again, reducing this further by 20 % as a safety margin would bring the allowed power to 320 mW.

Interestingly, the 90° bend geometry is more sensitive to catastrophic damage for a given loss than the 180° bend geometry. This is because for a given bend loss the bend diameter in the 90° geometry is smaller than that for the 180° geometry.

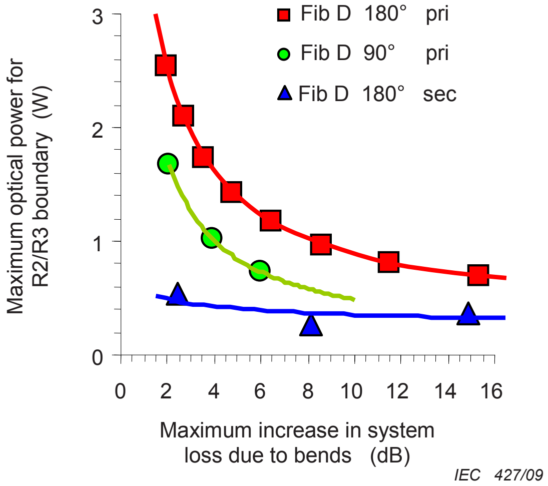


Figure A.13 – Comparison of power limitation for primary and secondary coated fibre 'D'

To avoid R1 or R2 catastrophic failure of fibre or coating in the most sensitive fibre tested so far, and for a bend loss of 4 dB, the maximum operating power shall be less than 200 mW, see reference [15].

A.6.3 Test method 2 – System limits to high optical power

As with test method 1, test method 2 can allow thresholds for catastrophic high-power fibre damage to be established. These can give a system operator a benchmark of resilience to catastrophic damage depending on the available system margin, if 180° bend losses of the fibre are considered instead of diameters (see Figure A.14 and Figure A.15).

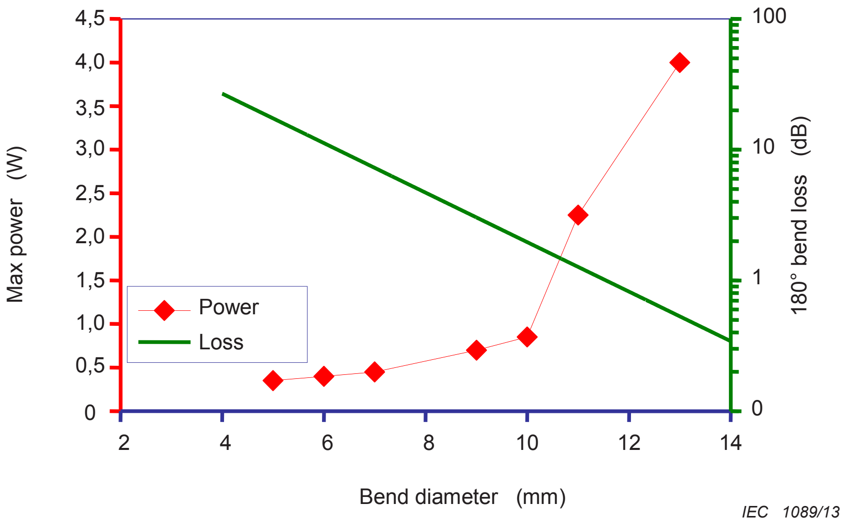


Figure A.14 – Maximum optical power ensuring a 25 year lifetime and 180° bend loss versus bend diameter (from reference [10])

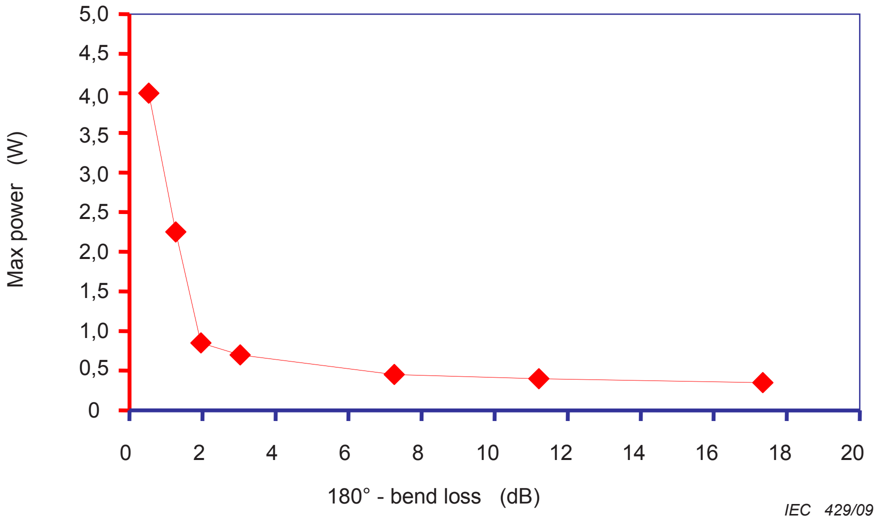


Figure A.15 – Maximum optical power ensuring a 25 year lifetime versus 180° bend loss

A.7 Two-point bend loss measurements

A.7.1 Introductory remark

Refer to IEC 60793-1-47 but with the following amendments including 180°, 2-point configuration and the following notes.

A.7.2 Background

Investigations of bend loss of 2-point, 180° bends at a single wavelength show fibre-lay-dependent fluctuations. Evidence of such fluctuations and also in the spectral performance has previously been reported, see reference [21]. The finite thickness of the cladding is believed to lead to the oscillatory structure in the bend loss as a function of the bend diameter and wavelength, caused by interference between the whispering gallery modes within the cladding, guided at the cladding outer surface or buffer-air interface. The oscillations depend on the optical path difference between the waveguide and core guided modes. The precise fibre positioning and/or clamping arrangement (to sub-mm accuracy) and any slight twist on the fibre in the holder could all cause a variation in loss at a specific wavelength. Losses will also be dependent on the polarization state of light entering the bend.

An optical spectrum analyser (OSA) can be used to try to understand macro bend loss for the range of B1 and B4 fibre categories and to explore the nature of the spectral fluctuations. The bends investigated include 2-point bends for 180°, 135° and 90° bends. Each fibre category and bend diameter was characterized over the 1 400 nm to 1 600 nm range at the same OSA test settings. Since the spectra show loss fluctuations, a reasonably large number of measurements at different diameters were made in an attempt to improve curve fitting.

Theoretical analysis and experimental data suggests that, neglecting the oscillatory noise in spectral loss plots, bend loss at a given wavelength follows a function of the form:

$$\text{Bend loss (dB)} = \text{A} \exp(-\alpha D)$$

where D is the diameter of the bend.

Such a simplistic approach allows inter-fibre comparisons to be made somewhat straightforwardly but acknowledges that

- results are fibre lay dependent. Loss for a specific bend condition is difficult to reproduce,
- any twist of the fibre in the clamping arrangement is likely to further confuse analysis,
- the 2-point bend configuration results in a non-circular fibre geometry (for a 180° bend the fibre shape is an oval). The shape of the curve in a two-point bend is not elliptical and hence should be declared as oval. Elliptical implies that the functional form is $x^2/a^2 + y^2/b^2 = 1$. This curve has a finite radius of curvature at all points, varying between limits set by ‘a’ and ‘b’. However, the two-point bend has infinite radius of curvature as it leaves the face plates. The infinite radius of curvature ($1/R = 0$) is used as a boundary condition in the analysis in references [15] and [18].

A.7.3 Experimental arrangement

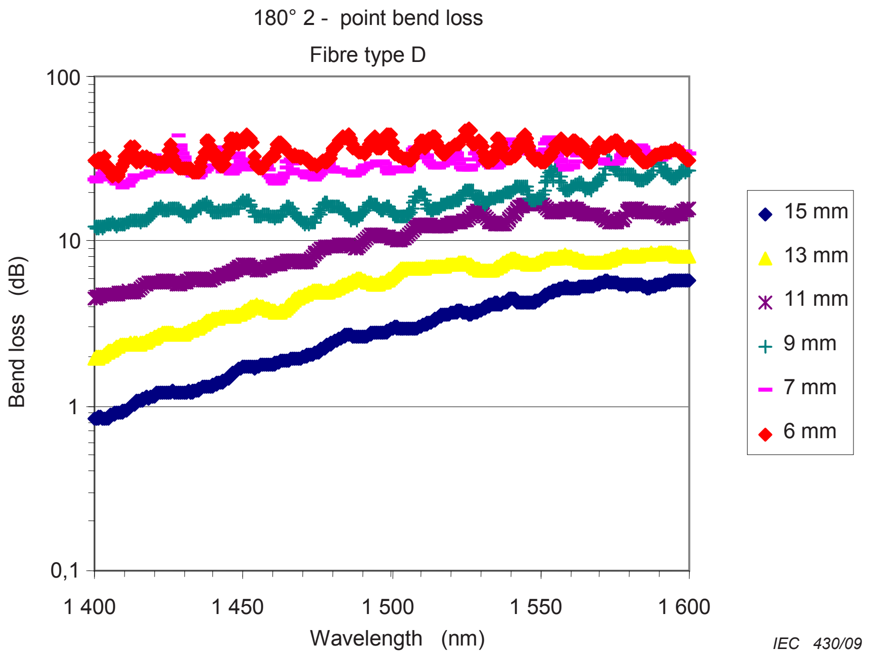
Radiation from a broadband source can be coupled into the test fibre and then via a long length (~ 1 km) to the OSA. The long fibre length is used to strip out any potential cladding modes before the detector. The reference launch power should be relatively stable (~< 0,3 dB) over the entire spectral range (1 400 nm to 1 600 nm) for most measurements. This gives a high level of confidence in the measurement technique.

The OSA, fibre and clamping arrangement is set up (fibres can be taped in position to improve stability) so that reproducible output is obtained from the OSA; a reference measurement is then made. For 180°, 2-point bends refer to A.4.2 for fibre clamping arrangements. The motorized V-groove assembly technique allows the fibre to be laid in place, tested and then accurately moved under computer control to other required diameters. Small diameter increments can be made and the fibre then re-measured.

OSA scans follow for each bend diameter (the instrument settings remaining unchanged throughout). A further reference measurement can be made at the end of a sequence of tests. Reference measurements can be cross-checked to ensure that there is no drift during the process and loss measurements determined by subtracting one measurement result from another.

A.7.4 180°, 2-point bends

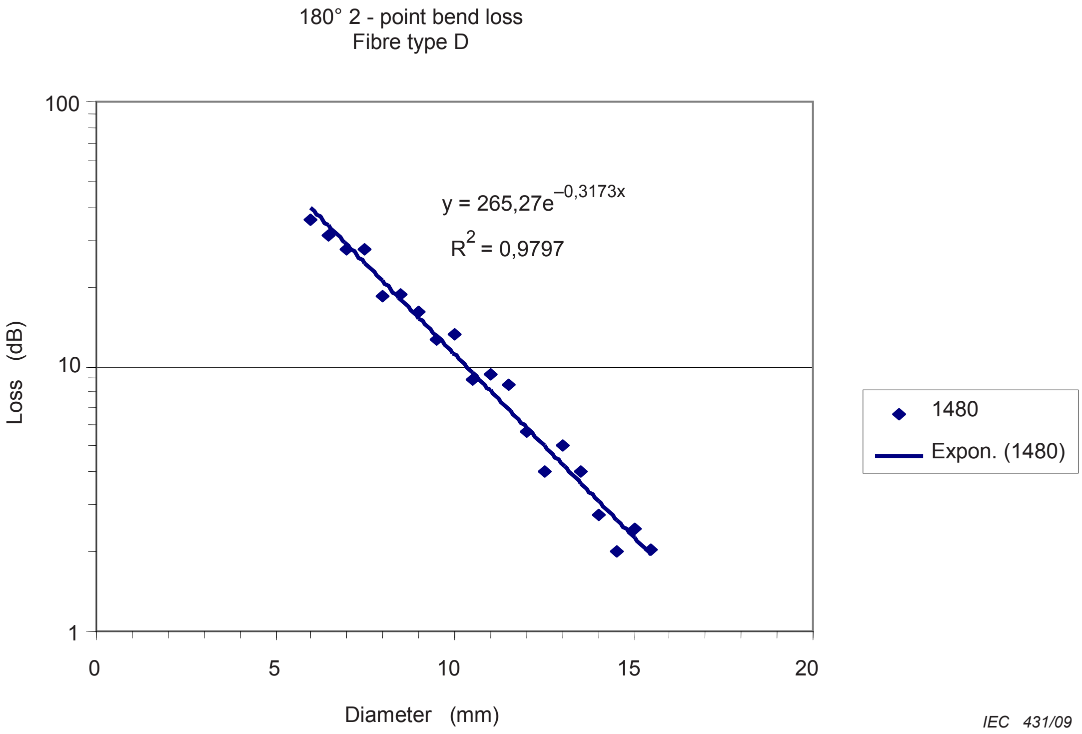
Sample results are shown below for fibre ‘D’, a category B1 optical fibre showing typical features. This data should be used cautiously as there is a variation in bend loss depending precisely on the way the fibre is inserted in the test rig. Note that in Figure A.16, the dimensions refer to bend diameter in mm.



IEC 430/09

Figure A.16 – 180° 2-point OSA bend loss for fibre ‘D’

Data at required wavelengths may be extracted to allow bend performance at any diameter to be determined. For clarity, only the 1 480 nm data is shown in Figure A.17.



IEC 431/09

Figure A.17 – 180° 2-point bend loss at 1 480 nm for fibre ‘D’

As can be seen in Figure A.17, a high level of confidence may be obtained with an exponential fit to some twenty different bend diameter measurements.

A.7.5 135° and 90°, 2-point bends

A number of techniques for holding the fibres have been investigated. However, some introduced tension on the fibre which tends to be difficult to control without a lot of mechanical engineering effort. Other techniques require the fibre to be taped in position. However this proves difficult for smaller aperture bends and is not suitable for use in high-power bend tests.

One chosen method was to locate the fibre in narrow bore silica tubes (400 μm internal diameter, 6 mm outer diameter) and then position the silica tubes accurately in pre-aligned V-grooves so that the fibre bend configuration could be accurately determined. Fixtures can be made up to allow fibres to be located at angles of 135° and 90° and at a range of bend diameters.

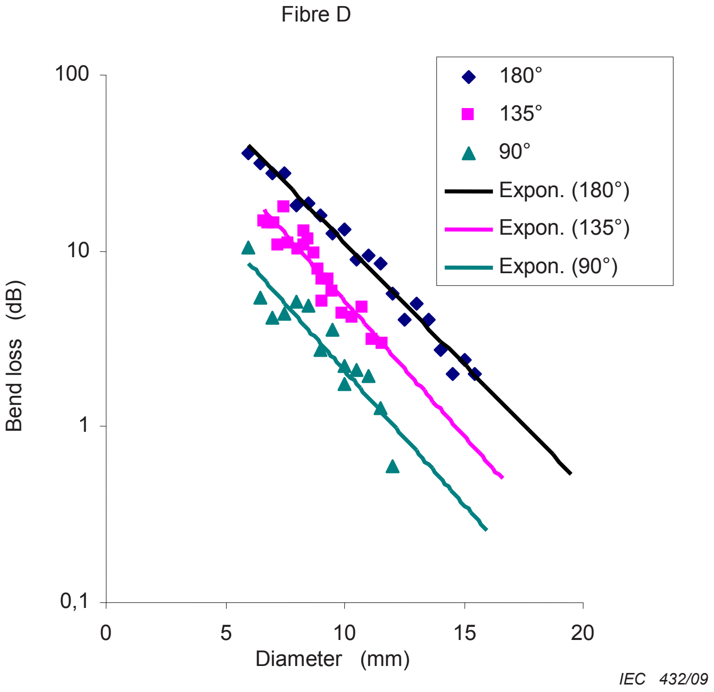


Figure A.18 – 2-point bend loss for fibre ‘D’ at various angles

Increased loss is observed in moving from 90° to 135° to 180° bends for each of the fibre categories. The results for fibre ‘D’ are shown in Figure A.18. Loss increases at longer wavelengths are not shown here.

A.7.6 Inter-fibre comparison at 1 480 nm

The bend loss performance of a range of fibres whose high-power damage behaviour has been the subject of earlier studies (references [2], [3], [7] and [15]) is shown in Figure A.19. Fibres A to E are conventional B1 and B4 category single-mode fibres. Fibre F is a low bend loss sub-category B6_a1 fibre which when coating effects are neglected should offer improved high-power damage resilience.

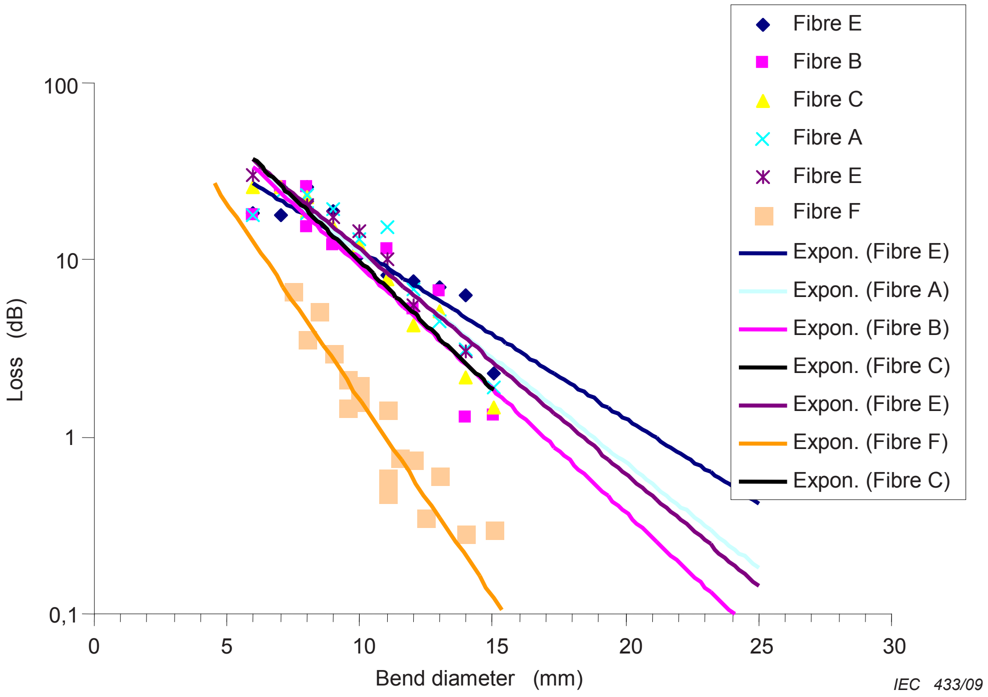


Figure A.19 – 180° 2-point bend loss at 1 480 nm for a range of fibres

The results shown in Figure A.16 to A.19 are for bending radii much smaller than specified in the single-mode fibre specification IEC 60793-2-50 and are not recommended for normal system use. However, these results give a clear indication of macrobend performance as a function of bend diameter or wavelength and are useful for bend loss inter-comparison and high-power damage resilience assessment purposes.

A.8 Determination of the maximum coating temperature for a 25 year lifetime using the equilibrium temperature test method

In 4.5.2 and reference [10], equilibrium temperature thresholds are described. Clause A.8 describes the rationale.

Figure A.20 was obtained for different power and bending conditions as function of equilibrium temperature for a specific fibre (IEC B1.2/ITU-T G.654), see reference [10]. This master curve is obtained by assuming that time to failure follows an Arrhénius law. A change of slope is obtained around Tc ~150 °C and suggests a change in thermal degradation kinetics of the coating. Fibre failure mechanisms under high-power seem to be led, in first order, by thermal ageing of the coating. It is hypothesized that different operating conditions inducing the same maximum coating temperature would lead to equivalent lifetimes.

Extrapolation of the Arrhénius law to lower temperatures gives a lifetime longer than 25 years for equilibrium temperature below 77 °C. This assumes no further transitions in slope at lower temperatures, as were exhibited at ~150 °C.

The maximum failure time measured was obtained after more than 500 h for a diameter of 7 mm under 0,8 W. The equilibrium temperature remained constant from the first minutes of the test up to more than 400 h (at ~110 °C).

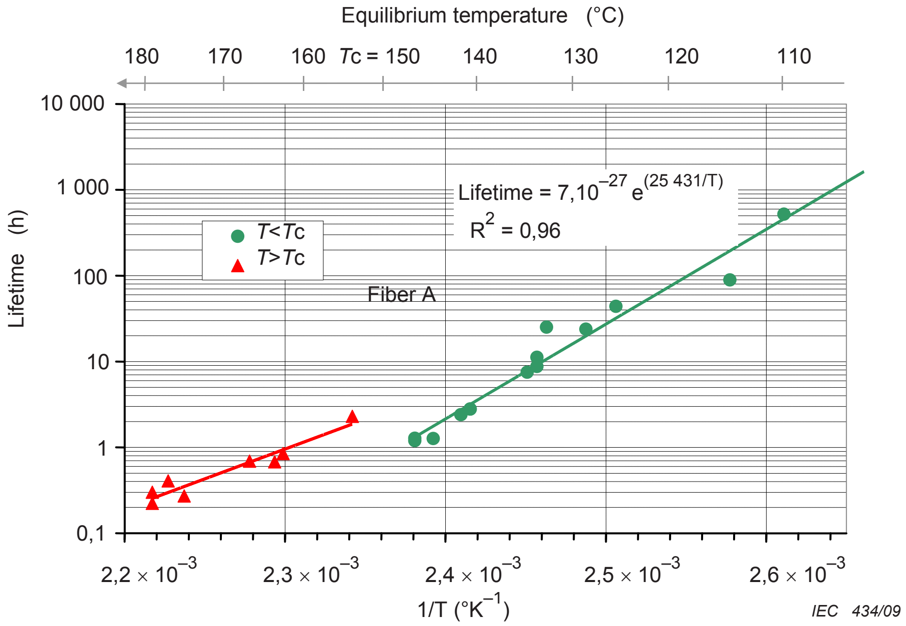


Figure A.20 – Time to failure versus inverse of equilibrium temperature using an IEC B1.2/ITU-T G.654 single-mode fibre for bend diameters varying from 4 mm to 10 mm and launched power in the range 0,8 W to 3,2 W

An alternative approach for determining an equilibrium temperature threshold is described in Clause A.9. It is expected that fibre coating suppliers may be able to provide a maximum operating temperature for a given volume change as illustrated in Clause A.9 and Figure A.21 to meet target lifetimes of greater than 25 years.

A.9 Dry heat, thermal ageing of fibre coatings in an oven

A.9.1 General

Following the methodology outlined in reference [22], Figure A.21 shows coating volume reduction with time as a result of dry baking a primary coated fibre in an oven at a range of temperatures. Volume reductions are determined from outside diameter measurements of the coating using a micrometer and depend on the precise coating formulation. This test technique can be used as a measure for fibre coating resilience to thermal ageing.

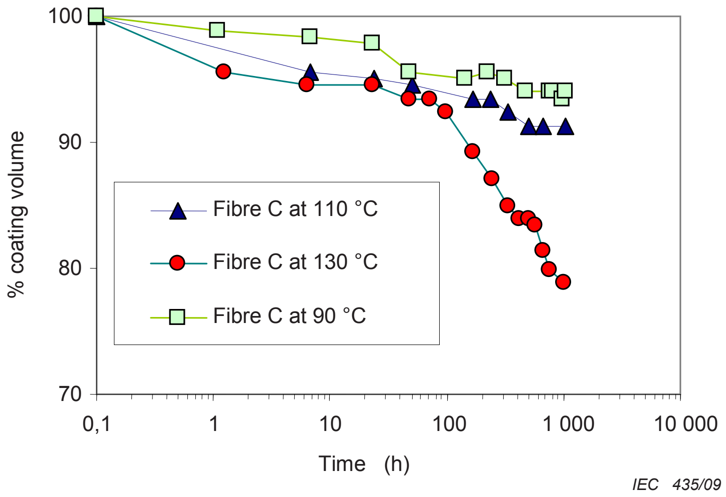


Figure A.21 – Effect of baking primary coated fibre ‘C’ (reference [15]) in an oven at constant temperature

Under normal operating conditions where the fibre is not subject to tight bends and the optical power is low, fibre coating temperatures of >85 °C would not usually be observed.

NOTE 85 °C is the limit of operation for acrylate coated fibres as specified by IEC 60793-2-50.

However, when tight bends occur and optical powers are >~200 mW, fibre coating temperatures in excess of 85 °C have been reported, e.g. see references [10], [13] and [24].

The test temperatures shown in Figure A.21 were selected for illustrative purposes and for comparison with the equilibrium temperatures observed for R1 or R2 catastrophic failures in fibre 'C'. For the sample shown, there appears to be accelerated degradation from 130 °C – most noticeable after ~100 h exposure. Also, further high-power damage tests on this fibre, pre-aged for 1 000 h (~42 days) at 130 °C, have shown a five-fold reduction in failure time compared with pristine fibre for the same test conditions. Clearly from the results for dry heat oven ageing, 130 °C is much too high an equilibrium temperature for this fibre. A direct comparison of oven heating with the heating of fibres in a bend under high power is difficult as under bend conditions the heating is internal and the heating zone is more localized. Nevertheless, there is a strong correlation between coating temperature increase and lifetime duration for at least one fibre category. The temperature increase at a fibre bend seems to be more relevant than fibre loss to estimate the risk of damage as two system configurations can lead to the same loss (in dB) but with different temperatures at the bends and thus different lifetimes.

Recent results, reference [24], have shown that a fibre (fibre 'C') that is sensitive to high-power fibre damage has been observed to have a low equilibrium temperature and a coating that is sensitive to thermal ageing – as shown by oven ageing tests. These results show a link between coating ageing, high-power damage and initial equilibrium temperature and indicate that a 'high-power damage safe' volume reduction threshold could be of the order of 1 % to ~2 % for current, conventional UV acrylate coatings – see reference [24] for further discussion.

This work shows a potential pathway for progress to confirm coating resilience to high-power fibre damage. Dry heat oven ageing tests could provide characteristic coating ageing data (as shown in Figure A.21). In this example, at the point when a volume reduction threshold of ~1 % for extended ageing (~30 days) at rising temperatures is broached, a safe equilibrium temperature limit is established.

The volume reduction test is straightforward but confirms a safe temperature threshold for high-power damage against which the fibre suppliers can test. However, further analysis may be necessary to confirm these results across a wider range of fibre categories and coating types.

A.9.2 Technical input required

To support progress in this activity, more detailed plots of the type shown in Figure A.21 and at a finer temperature resolution are required. As indicated by reference [23], where there is a discussion of ageing affects in one acrylate coating type, much of this information is probably already known by the fibre coating suppliers; however, this information may be in a different format than is shown in Figure A.21.

A.10 Example of a fibre resilient to failure under bending and high power

References [8], [13] and [14], describe a coating solution that offers improved resilience to failure under high power and bending.

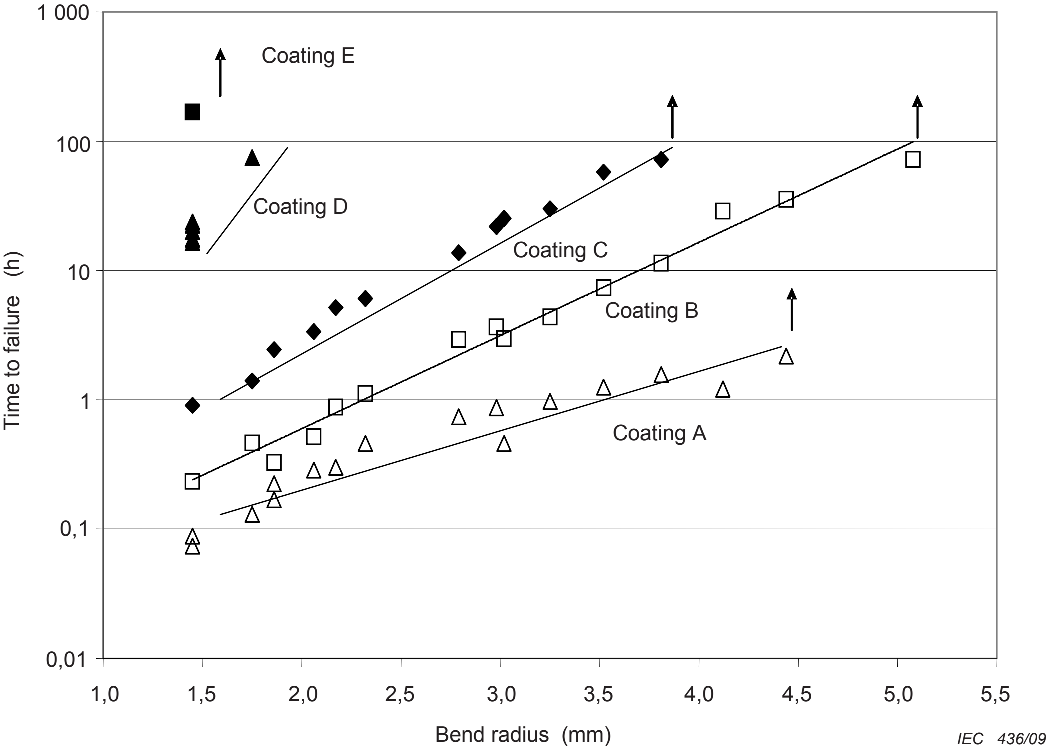
A series of UV curable acrylate inner coatings were formulated with varying amounts of a compound that lowered the overall refractive index of the coating. The refractive index of silica, the cladding material for the category B1.D fibre used in this study, is 1,443 9 at 1 541 nm and room temperature. The values of refractive index for the formulated inner coatings ranged from above to below that of silica, as shown in Table A.1. These fibres were tested under an extreme condition of a 1,5 mm minimum bend radius with input power of 1,5 W at 1 480 nm. The time to failure and the fraction of input power entering the coating at the bend is shown in Table A.1.

Table A.1 – Dependence of high-power damage on power entering coating

Coating	**Coating refractive index**	**Power entering coating** %	**Time to failure** min
A	1,49568	99	5
B	1,47948	97	15
C	1,46298	96	60
D	1,44275	95	1 200
E	1,41798	23	No failures

The amount of power entering the coating decreases and the time to failure increases as the refractive index of the inner primary coating approaches that of silica. Coating E did not fail after seven days in this extreme test.

Times to failure for less extreme bend radii are shown in Figure A.22. Both coatings D and E may be considered practically impervious to this failure mode for typical in-service bend radii.



NOTE Upward arrow indicates a test which was survived by the fibre.

Figure A.22 – Time to failure for different coatings as a function of bend radius

Coatings D and E serve to inhibit the failure mode by somewhat different physical mechanisms. Coating E keeps most of the leaked light in the glass cladding where it is guided around the bend and down the fibre. Coating D collects the preponderance of light from the cladding but over an extended length compared to that of the higher index coatings. Coatings D and E both suppress temperature rise of the coating that fuels the failure mode.

For the results described in Clause A.10, the bend diameter refers to the minimum bend diameter in the bend rather than the plate separation or hole diameter, which is the definition used for bend diameter elsewhere in this report. In a two-point bend configuration, the minimum bend diameter is a factor of 1,198 less than the equivalent plate separation bend diameter The fibre reference designations, A – E in this annex, are not for the same fibre categories as those similarly designated in other clauses of this report.

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