International Telecommunication Union

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

Series G

Supplement 59

(02/2018)

SERIES G: TRANSMISSION SYSTEMS AND MEDIA,
DIGITAL SYSTEMS AND NETWORKS

Guidance on optical fibre and cable reliability

ITU-T G-series Recommendations – Supplement 59

ITU-T

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Supplement 59 to ITU-T G-series Recommendations

Guidance on optical fibre and cable reliability

Summary

Supplement 59 to ITU-T G-series Recommendations provides guidance regarding the long-term reliability of cabled optical fibres. This Supplement uses currently accepted models combined with current experience to describe items that can impact the performance of an optical fibre over time. This Supplement describes "optical reliability" for fibres, "mechanical reliability" for fibres and describes how optical cables impact these properties.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
1.0	ITU-T G Suppl. 59	2016-09-30	15	11.1002/1000/13123
2.0	ITU-T G Suppl. 59	2018-02-09	15	11.1002/1000/13585

Keywords

Mechanical reliability, optical fibre and cable reliability, optical reliability.

* To access the Recommendation, type the URL http://handle.itu.int/ in the address field of your web browser, followed by the Recommendation's unique ID. For example, http://handle.itu.int/11.1002/1000/11830-en.

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Introduction

Supplement 59 to ITU-T G-series Recommendations provides information on long-term reliability of optical fibre and cable. ITU-T has established optical fibre and cable Recommendations, such as [b-ITU-T G.651.1], [ITU-T G.652], [b-ITU-T G.653], [b-ITU-T G.654], [b-ITU-T G.655], [b-ITU-T G.656], and [ITU-T G.657]. Also, ITU-T standardized optical cables are described in some ITU-T L-series Recommendations. This Supplement also provides more detail on optical fibres reliability described in [ITU-T G-Sup.40].

Supplement 59 to ITU-T G-series Recommendations

Guidance on optical fibre and cable reliability

1 Scope

This Supplement gives end user guidance on the long-term performance of optical fibre and cables. Although it is difficult to address all situations and to guarantee long-term performance, this Supplement helps end users to understand general long-term behaviour of optical fibres and cables, as well as providing guidelines to help minimize the number of mechanical and optical failures during the expected lifetime of the fibre and cable.

2 References

[ITU-T G.650.1] Recommendation ITU-T G.650.1 (2018), *Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable*.

[ITU-T G.652] Recommendation ITU-T G.652 (2016), *Characteristics of a single-mode optical fibre and cable*.

[ITU-T G.657] Recommendation ITU-T G.657 (2016), *Characteristics of a bending-loss insensitive single-mode optical fibre and cable*.

[ITU-T G-Sup.40] ITU-T G-series Recommendation – Supplement 40(2010), *Optical fibre and cable Recommendations and standards guideline*.

[ITU-T L.126] Recommendation ITU-T L.126/L.27 (1996), *Method for estimating the concentration of hydrogen in optical fibre cables*.

3 Definitions

None.

4 Abbreviations and acronyms

This Supplement uses the following abbreviations and acronyms:

CAPEX Capital Expenditure

FTTx Fibre To The x

MDU Multi-Dwelling Unit

MTBF Mean Time Between Failures

MTTR Mean Time To Repair

RIA Radiation-Induced Attenuation

5 Conventions

None.

6 General comments on reliability

Optical cables were first deployed commercially in 1977. Thus, our knowledge of their performance in the field extends over 40 years. Much information provided in this Supplement is speculative, although at the time of publication significant spontaneous fibre breakage in fibres in use for decades is not known. Detailed analysis of attenuation characteristics and mechanical attributes for cabled fibres that have been installed for 25 years [b-Hopland 2015] [b-Hopland 2013] indicate that the optical properties are very stable over time. With this background, accumulated field knowledge combined with accelerated aging can be used to estimate the reliability of optical cables.

Reliability falls into two major categories:

– mechanical (whether the fibre will break during the cable lifetime);

– optical (whether optical transmission will deteriorate during the cable lifetime).

It is hard to separate optical fibre reliability from that of optical cable, as the two are intimately related, but this Supplement focuses primarily on fibre attributes and how they relate to cabled optical fibre.

General trends in optical transmission require consideration in evaluation of optical reliability. The general trend is towards more information travelling down optical fibres. Optical cables are trending toward higher fibre counts in smaller optical cables resulting in potential for more residual strain on the individual optical fibres. There is also a trend towards the use of more of the optical spectrum and thus a desire to preserve the attenuation across the full spectrum from 1 260 to 1 625 nm to allow maximum opportunities for bandwidth upgrades.

In general, the reliability of an optical cable during the course of its deployment is strongly affected by the attention paid to the reliability during the phases of work carried out before the cable is put into service.

These phases can be described in *i)* to *vi)* as follows.

i) Optical fibre manufacture (fibre drawing and primary protection, storage)

The manufacturing phase of the fibres is critical from the point of view of reliability of the optical cable during commercial operation. In this phase, it is recommended that tests be carried out to ensure that optical and mechanical degradations do not adversely impact system performance during the lifetime of cable deployment and storage.

ii) Optical cable structure design

The structural characteristics of optical cables (fibre protection, strength member, filling materials, protections sheaths, armour, etc.) should be chosen so that they will comply with the limits stated in *i)* for stress and for minimum bending radius, during phases *iii)* to *vi).*

Important inputs for the definition of these characteristics are the installation method and mechanical stress (cable directly put underground, laid in ducts, laid on external poles, etc.) and, possibly, also the path that the cable will follow.

Finally, the choice of the characteristics of the cable should also be compliant, without degradation of the characteristics of the fibres, with the maximum temperature or humidity ranges that the cable has to withstand during its lifetime.

iii) Fibre insertion into the optical cable (cabling)

The cabling of the optical fibres should comply with all conditions set out in *i)* and *ii)*

iv) Infrastructure design for cable laying

The infrastructure for the cable-laying installation should be designed and implemented in order to protect, as far as possible, the cable from external damage different to the types indicated in *i).*

v) Laying operations

Even in this phase, attention should be placed on maximum stress and minimum bending radius of the fibres in order to respect the limits mentioned in *i).*

vi) *Lifetime of deployed optical cables*

Faults during the lifetime of deployed optical cables can be divided into two categories: internal and external.

Internal faults (fibre breakage, increase of attenuation, etc.) are related to the quality of the optical fibres. With the adoption of the reliability objectives listed out in *i)* and *ii)*, these internal faults should be kept to a minimum or not present at all.

External faults are those caused by external elements (excavations by other services, floods, landslides, etc.). The incidence of this type of fault mainly depends on the quality of the protection used in the laying of the cable (depth of the excavation, dimensioning of the infrastructure of overhead lines, etc.). External faults are outside the scope of this Supplement.

The main purpose of this Supplement is limited to the study of the reliability objectives quoted in point *i)*, i.e., the following:

– illustrate the processes by which fibre quality degrades from the points of view of mechanical strength and of the increase in attenuation;
– list the test methods to check these degradations;
– give the quality objectives currently adopted during the fibre manufacturing process.

It should be clearly pointed out that in this framework the reliability objectives during the commercial life of optical cables and the input for defining those to be considered during the production of the fibres (point *i*) are not specified in ITU-T documents. Examples of the main factors that have an impact on the choice of the reliability objectives to be considered during the commercial life of optical cables are outlined in Appendix II.

However, the 40 years of satisfactory operating experience of optical cables and their wide deployment in all parts of telecommunications networks (from the access network to intercontinental deployment) is a guarantee that the reliability objectives currently adopted in ITU-T documents for the production of optical fibres described in clauses 7 and 8 are suitable to ensure very high reliability with respect to internal faults in all operating conditions.

7 Optical reliability

In the 40 years of commercial optical cable deployment, several mechanisms have been identified that degrade the optical performance of glass fibres. These mechanisms can be considered as starting points in identifying processes that need to be accounted for to ensure the optical performance of manufactured and cabled fibres specified in ITU-T G.65*x* series Recommendations. This clause focuses on three known mechanisms that have an impact on optical reliability:

– bending loss (microbending and macrobending);
– chemical attacks (hydrogen being the most common contributor);
– radiation sensitivity.

Many of the tests performed on optical fibre and cable found in IEC and ITU-T documents have been developed to ensure long-term reliability of optical cables. All tests focus on optical reliability and monitor fibre or cable attenuation during the course of the test to see whether any change occurs. If the change is under the recommended threshold, the optical cable is expected to operate in the field for a reasonable period of time (typically 20-30 years) without significant degradation in transmission properties.

7.1 Bending loss

Bending loss falls into two types: macrobend and microbend. In the simplest terms, macrobends are visible bends on the scale of several millimetres in radius and microbends are very small, of the order of a few micrometres in radius. Bends occur on many length scales in optical fibres and separating macrobends from microbends can often be difficult, especially in the transition region between the two phenomena. For single-mode fibres, both effects cause increasing loss with increasing wavelengths, in particular threatening the higher wavelengths (C- and L-bands between 1 530 and 1 625 nm).

Optical fibre with improved macrobend performance is the subject of [ITU-T G.657]. One key attribute discussed in this Supplement is the loss as a function of bend radius for several fibre types. From an installation and deployment perspective, the concept is that, as long as an installer deploys an optical cable with macrobends that are greater than or equal to the minimum design radius, the impact of macrobend loss on the deployed link can be quantified. With known macrobend properties, deployment guidelines for optical cable as well as storage guidelines for optical fibres in splice boxes can be developed.

Microbending loss occurs in single-mode fibre when small transverse perturbations in the fibre axis result in the coupling of energy out of the fundamental mode and into lossy higher-order and radiation modes. Significant microbending loss can occur, even when the magnitude of the perturbations is of the order of nanometres, at the appropriate frequency along the fibre axis, so that strong (sometimes resonant) mode coupling occurs. The spectral dependence of microbending loss varies with the axial distribution of the perturbations. Microbends can result from temperature changes causing the cables to expand and contract or swelling of the fibre coating or cabling materials as they react with the external environment. Fibres and cables are exposed to many stress tests including temperature changes, humidity, liquid water and other solvents to estimate how the optical cable will perform over the deployed lifetime. Typical stress tests standardized in the IEC 60793-1 series are listed in Appendix VI.4 of [ITU-T G-Sup.40].

7.2 Hydrogen

Hydrogen is a small molecule that can easily diffuse into the glass structure. Hydrogen can react with glass to create irreversible absorption peaks (type 1) that add to the optical loss or interstitial molecular hydrogen that can be present in the glass adding to the attenuation (type 2) [b-Lemaire]. Both mechanisms are of concern in deployed optical cables, as they can add to the overall attenuation of the optical cable.

Interstitial hydrogen (type 2) is only a problem where optical cable is subject to high partial pressures of hydrogen. One application where this type of hydrogen is of concern is underwater cables. Optical cables used in deep water, over 100 m below the surface of the water, are put in hermetic packages, most commonly stainless steel tubes, to prevent type 2 absorption from occurring. Type 2 absorption in optical cables deployed in shallow water (less than 100 m in depth) increases due to hydrogen, and the impact increases with depth. The impact of type 2 hydrogen is reversible. Once the cable is removed from the water, the hydrogen diffuses out of the cable and attenuation returns to normal.

Hydrogen can react with defects in the glass matrix. These type 1 defects are most apparent in ITU-T G.652.B fibres. These defects form as hydrogen reacts with the glass resulting in OH groups which – if created in sufficient quantity in the light guiding portion of the optical fibre – add to the attenuation of the optical fibre across the full usable spectrum. In sufficient quantity, these defects can cause the optical fibres to become unusable.

In 2001, ITU-T specified full spectrum ITU-T G.652 fibre. These ITU-T G.652 fibres differed from their predecessors in that the glass that transmits the light is stabilized so that, under typical deployment conditions, type 1 hydrogen defects do not form in sufficient quantity to adversely impact the transmission properties of the optical fibre. At the time of publication, most optical fibres meet this specification, providing more reliable long-term optical performance. If ITU-T G.652 fibres are exposed to hydrogen concentrations significantly higher than those that occurs in ambient conditions, these defects may form and degrade the optical performance of the fibre. More information on hydrogen in optical cables is provided in [ITU-T L.126].

7.3 Impact of nuclear radiation

The exposure of germanium-doped optical fibres to doses of ionizing radiation can cause defects to form in the atomic structure of the glass, resulting in an increase in absorption losses (radiation-induced attenuation: RIA). Radiation testing is currently performed at high dose rates over short time intervals. The results of these accelerated tests are then used to estimate the increase in the fibre attenuation over the estimated useful lifetime when the radiation exposure is at typical background levels. Experience with optical cables deployed since 1977 indicates that background radiation does not appear to affect the attenuation performance of deployed cables under normal conditions. [b-IEC TR 62283] provides guidance, which still needs refinement before accurate predictions can be made, for nuclear radiation tests.

7.4 Attenuation stability

The expected lifetime of optical fibres is typically more than 30 years. The purpose of aging tests is to help an end user predict optical properties during the life of the optical cable. These tests look at cyclically changing conditions that may be encountered over the course of a year, localized events such as bends, as well as degradation in performance over the cable lifetime. A number of tests that have been developed in both IEC SC86A as well as ITU-T SG15 are listed in Appendix VI.4 of [ITU-T G-Sup.40].

Many of the tests performed are for cyclical type events and are time based, e.g.:

– temperature cycling of optical fibre and cable;
– humidity aging of optical fibre and cable;
– macrobend tests of optical fibre and cable;
– crush and impact tests of optical cable;
– other tests.

In these tests, there are requirements that help to predict worst-case performance under a given set of adverse conditions that represent those in the field. When an optical cable is deployed, it is expected that increases in attenuation will be less than or equal to those observed in these tests.

Tests used to determine whether there is any degradation of optical fibre attenuation over time is a complex topic. These tests are more difficult, as the only way to be sure whether a product will have the desired properties after many years of deployment is to deploy the optical cable in the desired environment and wait to see if the attenuation increases, but this is impractical. Tests can reveal changes that are due to the attenuation of the glass itself or that may be the result of uneven forces in bent cabling materials being transferred to the optical fibres. Accelerated aging is often done at higher temperatures and higher moisture levels and is assumed to give insight into the long-term performance of the optical fibre and cabling materials. When performing these tests, care is required to ensure that high temperature degradation mechanisms are not activated, resulting in an unrealistically short lifetime estimate. Accelerated aging tests give an indication of how cabling materials age, developing anisotropic stress on the optical fibres, and attenuation changes over time can be observed. Materials available at the time of publication have been developed to minimize the impact of aging on attenuation, and temperature or humidity tests are used to validate that the material system will protect the performance of the optical fibre.

With over 40 years of experience of deployed optical cables and an assumption that any degradation effect will have a linear relationship with time, it can be assumed that, other than the hydrogen effect, any new degradations to optical performance that will result in more than a few hundredths of a decibel per kilometre over the life of the optical cable are unlikely to be observed.

8 Mechanical reliability

Studies of optical fibre mechanical reliability investigate the probability of afibre breaking during its lifetime of deployment. A comprehensive study of mechanical reliability is provided in [b-IEC TR 62048], which contains work done in IEC as well as information from COST 218 (European Cooperation in the field of Scientific and Technical research) work prior to [b-IEC 60793-1-33]. The studies predict the reliability of fibre based on small defects or flaws in the glass, likely formed in the manufacturing process, that increase when the glass is under the effect of different types of stress, mechanical or environmental, that it could experience during storage, cabling, installation, deployment or lifetime. Essential to these predictions are: a) understanding the initial distribution of flaws; and b) determining how the distribution changes with time due to stress, environment or both and due to scheduled events (like cabling, installation, long-term field use) and unscheduled events, such as accidental cable dig-up [b-Bhaumik].

8.1 General comments on mechanical strength of optical fibres

In general, glass optical fibre has a distribution of flaws and consequently a distribution strength. Figure 1 shows an example of distribution of breaking stresses observed for 10 m lengths of fibre [b-Mazzarese]. Figure 1 shows the results for over 100 km of fibre and the results highlight the various regimes of fibre strength. In this type of testing, most optical fibre breaks occur in the high strength intrinsic region shown as region I in Figure 1. The larger flaws are found in the extrinsic region II on the graph, within the lower failure probability zone.

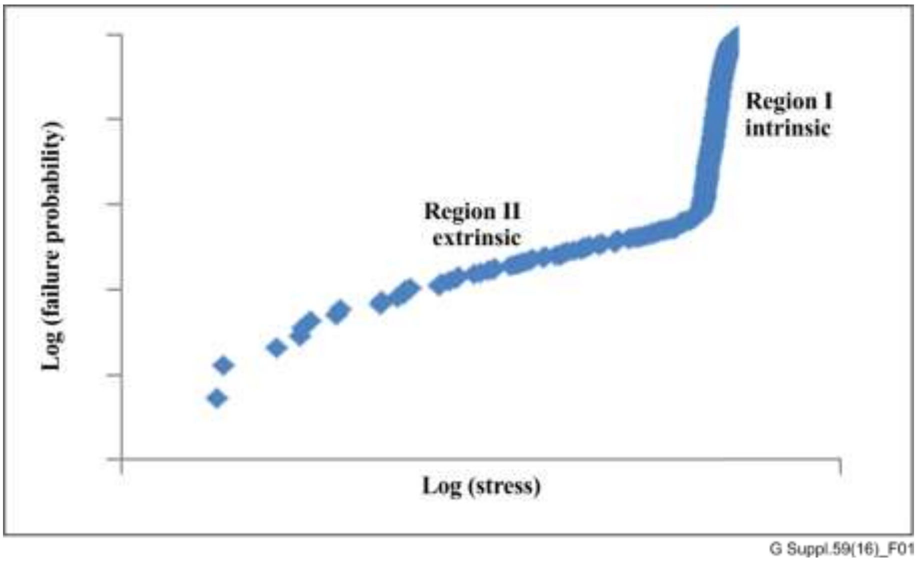

Figure 1 – Failure probability for over 100 km of fibre tested at 10 m gauge lengths [b-Mazzarese]

The estimates for fibre reliability are based on a flaw distribution that has two regions: a strong "intrinsic strength" and a weaker "extrinsic strength". The intrinsic region is characteristic of short lengths of fibres and can be determined by testing small amounts of fibre. The intrinsic strength has median value typically greater than 3 GPa (about 450 kpsi). The extrinsic strength distribution characterizes larger flaws that occur at a much lower frequency and that are typically found only by testing long lengths (typically 10-20 m) of fibre, as in the testing represented above. The maximum allowable flaw size in a population of optical fibre is fixed by proof testing the fibres and removing the weakest flaws; this action is normally applied to 100% of commercial fibre by manufacturers at the end of the drawing and coating phases. At the time of publication, optical fibres are proof tested to 0.69 GPa proof stress (100 kpsi), which screens flaws that have a depth of 0.5 µm or larger.

Proof testing characterizes only a narrow part at the far end of the extrinsic curve. Short gauge-length tests, on the other hand, usually sample less than 100 m from a sample population up to a few kilometres at most, thus defining the intrinsic strength region, but yielding few data about the extrinsic strength region. A large gap remains in the flaw size distribution between the results of the two characterization approaches and flaws in this missing range could be the cause of mechanical failures in most optical cables. Understanding this range is essential.

Other factors that have an impact on fibre mechanical lifetime are the environmental conditions at the glass surface, mainly represented by water, but also including chemicals, temperature and stress on the glass. This is where cable design becomes critical. Optical fibre coatings combined with cabling materials, gels and water blocking agents are designed to keep corrosive materials, e.g., water, away from the glass optical fibre. Thus, characterizing the unaged fibre for mechanical strength along with dry aged fibre should give a good estimate of what will be observed in the field. This has been validated as it is a rare event for a mechanical failure to occur in the cabled portion of the fibre without an external mechanism, e.g., a tree fall or accidental cable dig-up. One exception to this is the relatively short length of optical fibres in splice enclosures. Here, the optical fibre can come directly in contact with moisture or water. Consequently, tests on temperature- or humidity-aged samples only need to consider changes in the intrinsic properties.

Note that the reliability model shown in clause 8.2 deals with coated fibres, which can predict the lifetime of fibres inside a cable. Once the coating is stripped off for splicing, the mechanical strength drops and the fibre does not maintain the original mechanical strength. Correlation of mechanical strength between coated and stripped fibre is not well understood (i.e., high strength at the coated state may not guarantee high strength after coating removal), and thus minimizing permanent stress to the stripped section of the fibre is essential.

8.2 Power law theory

One widely used model, that accounts for the high strength intrinsic region as well as the extrinsic region, is the power law lifetime equation that appears in [b-IEC TR 62048], Equation 8-1. This model is used to help explain factors that impact reliability. Many of the variables in the model can be difficult to calculate precisely, so it is recommended that, when estimating fibre lifetimes, a conservative approach be employed.

$$t_\mathrm{f} = t_\mathrm{p}\left(\frac{\sigma_\mathrm{p}}{\sigma_\mathrm{a}}\right)^n \left\{\left[1 - \frac{\ln(1-F)}{N_\mathrm{p}L}\right]^{\frac{n+1}{m_\mathrm{d}}} - 1\right\} \qquad (8\text{-}1)$$

The variables used in the equation and conservative values often used in calculations are given in Table 1.

8.3 The time to failure or fibre lifetime

The proof stress is given in various ITU-T G.65*x* series Recommendations and the details of the test method to evaluate the other mechanical parameters are given in [b-IEC 60793-1-30]. The applied load is determined based on cable design and application. Further information on these parameters is given in clauses 9 and 10. The failure probability is often set by the service provider; an example of values that are used in calculations are given in Appendix I. The proof test break-rate (N_p) is not readily available, but it is suggested that a value of one break per 100 km be used when more reliable information is unavailable. In Equation 8-1, n and m_d are unknowns that are difficult to measure, but are essential to determining the lifetime. These parameters are discussed in clause 8.4.

Table 1 – Variables used in Equation (8-1)

Symbol	Parameter	Description/example
t_f	time to failure (lifetime)	calculated
t_p	proof test time	see clause 8.5
σ_p	proof stress	0.69 GPa (100 kpsi)
σ_a	applied load	see clause 10
F	failure probability	see Appendix II
N_p	proof test break rate	one break per 100 km
L	length under tension	determined by application
n	stress corrosion parameter	see clause 8.4
m_d	Weibull *m* from the fibre dynamic tensile strength	see clause 8.4

8.4 Static and dynamic stress corrosion parameter and impact on reliability

The three fibre parameters that have the greatest impact on the lifetime predicted in Equation 8-1 are the proof stress (σ_p) , the stress corrosion parameter (*n*) and the Weibull slope (*m*). As explained in clause 8.1, the proof stress is set by the manufacturer and is used as a screen to eliminate the largest flaws. The stress corrosion parameter must be measured and that measurement can be challenging. This parameter represents the susceptibility of the fibre glass to withstand stress corrosion and subsequent increase of flaws due to the water effect.

Though the stress corrosion factor is shown as a constant in Equation 8-1, the value obtained is dependent on the conditions under which the parameter is measured. The limits of this parameter are the static stress corrosion parameter (n_s), which tends to provide higher values of *n*, and the dynamic stress corrosion parameter (n_d), which tends to provide lower values. What further complicates this analysis is that it has been shown that the value of *n* is dependent on the rate of strain applied to the fibre. In the work of COST 218 [b-IEC 60793-1-33], it was shown that the value of *n* varied from a value of ~17 for the fastest tests to ~40 for very slow tests. The power law reliability model does not specify which value of *n* should be used in the equation; nevertheless, lower values mean a more conservative approach (worst case).

Larger values of *n* result in longer time until failure in Equation 8-1. Alternatively, a larger value of *n* implies that a larger permanent strain can be allowed in the fibre by the cable design. Thus, conservative engineering principles suggest that a fibre supplier shows that their fibre demonstrates a value for the dynamic stress corrosion parameter greater than 18 [b-IEC 60793-2-50]; consequently, $n \approx 20$ is typically used in predicting typical lifetimes. Values higher than 20 do not translate into demonstrable enhanced fatigue resistance.

If the cable manufacturer or end-user should wish to design for more aggressive loading of the optical fibres or for longer anticipated lifetime in service (e.g., up to 100 years), the value of *n* for the fibre population should be characterized carefully and by the appropriate methodology to obtain the most accurate determination of the stress corrosion parameter. For example, [b-IEC 60793-1-33] indicates that any silica fibre mechanical test should determine the fracture stress and stress corrosion properties under conditions that model the practical applications as closely as possible. In such a situation, the static stress corrosion parameter approach to characterizing the *n*-value can be useful, representing a stress situation most similar to installed fibre. Since it has been found that large, extrinsic region flaws (the danger to long lengths of fibre under stress) exhibit a stress corrosion factor larger than found in the intrinsic strength flaws [b-Griffioen 1993], [b-Craig], [b-Glaesemann 1992], [b-Breuls], [b-Yuce] static stress corrosion parameter is arguably both less conservative and more accurate.

The Weibull slope (*m*) corresponds to the slope of failure probability in the extrinsic region, i.e., the slope in region II in Figure 1. Accurate characterization of this parameter requires measuring the mechanical strength of many kilometres of fibre, using a long gauge length test and determining the *m* value from information, such as that shown in Figure 1. This low-strength tail often determines the long-term mechanical reliability of deployed fibre cables.

8.5 Relationship between proof stress and proof testing on reliability

Proof testing screens out the largest flaws in optical fibre. [ITU-T G.650.1] explains test methods and parameters for proof testing where load is applied on optical fibre for as short a time as possible, yet sufficiently long to ensure the glass experiences the proof stress, typically for much less than 1 s. As the proof test level increases, smaller flaws are removed from the fibre, reducing the chance the fibre will break when strained. ITU-T G.65*x* series Recommendations available at the time of publication state that the fibre should be proof tested to a minimum stress of 0.69 GPa (100 kpsi). Further, in many IEC documents, it is suggested that the long-term load on such proof-tested cabled fibres should not be greater than 20% of the proof test load, generally in agreement with an *n*-value of $n_d = 20$.

8.6 Handlability of optical fibre

The fibre lifetime model describes how flaws can grow over time under stress. As these flaws grow, the optical fibre becomes weaker. When no tension is on the fibre, they may have sufficient strength to retain their mechanical integrity, but it may become difficult or impossible to handle or splice the fibre. This is sometimes referred to as "brittle fibre" in the field. Many mechanisms can result in this occurring, such as coating abrasions or delamination that expose bare glass to aggressive elements. When the fibre strength is less than 2 GPa, the fibre becomes difficult to handle and splice [b-Griffioen 1995].

8.7 Tests that measure aspects of mechanical reliability

[ITU-T G-Sup. 40] provides some details on tests for mechanical reliability of optical fibre and cable. Below is an additional list of IEC test method documents that address measurements of parameters discussed in this Supplement:

- [b-IEC 60793-1-30] Fibre proof test
- [b-IEC 60793-1-31] Tensile strength
- [b-IEC 60793-1-33] Stress corrosion susceptibility
- [b-IEC 60793-1-50] Damp heat (steady state) tests
- [b-IEC 60793-1-51] Dry heat (steady state) tests
- [b-IEC 60793-1-53] Water immersion tests

It is well understood that the environment surrounding an optical fibre can affect the results of these tests. As a result, end users may require additional tests to support local conditions. Examples include tensile strength and attenuation tests after fibre is exposed to cable filling compounds, wasp sprays, fuels or other environments in which the fibre may be exposed.

Experimental evidence shows that high-power (500 mW to 2 W) damage can occur relatively quickly at bends less than 15 mm diameter. Damage occurs when the coating temperature increases at bends, as the coating absorbs the light lost at the bend. Damage can take the form of coating ageing, pyrolysis and burning, and if the temperature exceeds 700°C, catastrophic softening of the glass. Burning of the coating can result in a fire. [b-IEC TR 62547] provides guidance on the measurement of high-power damage sensitivity of single-mode fibres to bends.

9 Strain due to bends tension, to axial tension or a combination of the two mechanisms

Flaws grow in an optical fibre when it is under stress. This stress can be the result of axial tension, a small bend in the fibre or a combination of the two mechanisms. In determining the stresses imposed on optical fibres, it is essential to understand the deployment conditions and installation practices, as well as the cable design.

When a glass fibre is bent, the outer radius of that bend is subject to tension that can lead to fractures. Appendix I gives an example of how this property may affect reliability of optical fibres in splice boxes. Overhead cables are often pulled tight to minimize sag. If some of this tension is transferred to the fibre, it must be accounted for in determining the long-term reliability of the suspended cable.

Axial tension and bending tension are additive. Thus, both forces must be considered when the two forces occur together. This combined force may need to be considered when small diameter optical cables containing ITU-T G.657 fibres are installed inside buildings.

10 Impact of cable properties on reliability

Optical fibres are placed in cables. These cables can help protect the fibre in several ways including:

– limiting the tensile stresses on optical fibres through the use of load-bearing elements;
– limiting fibre bend diameter;
– protecting the fibre from crush and impact;
– protecting the fibre from chemical attacks, including water and hydrogen.

Choosing cabling materials is an important design consideration and although the cabling material can protect the fibre, interactions between the glass fibre and the cabling materials that may occur over time also require consideration.

10.1 Fibre strain and cable strain

One of the functions of the optical cable is to limit the strain on the optical fibres contained within it. When there is no strain on optical fibres, they can last for a very long time. When a fibre is under strain, the impact of weak flaws of the fibre increases and can eventually lead to failure. In order to extend the life of fibres, optical cables are designed with strength elements that take some or the entire load. It is also necessary to be sure that loading the optical cable does not induce excessive attenuation due to bends in the optical fibre that may occur when the cable is loaded.

10.2 Installation load versus long-term load

During installation, optical cable may be subject to short-duration loads that are higher than the loads to which they are exposed once deployed. As a general rule, a short-term load may be a few hours while a long-term load may be several months or even years.

Installation loads as described are short in duration. The [b-IEC TR 62048] model clearly shows this, as the fibre lifetime is related to the ratio of stresses raised to the power of the stress corrosion factor. As a result, the shorter the load time, the higher the stress an optical fibre can withstand without breaking. The recommended value for short-term loads on the optical fibre is 60% of the proof stress level.

Long-term loads are a bit more complex. This criterion of 20% of the proof test level for 0.69 Gpa (100 kpsi) fibre comes from [b-Glaesemann 1991]. Currently there is a push to deploy higher fibre count optical cables with fewer load-bearing materials. One solution being considered is optical fibres that are proof tested at levels greater than 0.69 GPa (100 kpsi). Current work has shown that for optical fibres proof tested at levels higher than 0.69 GPa (100 kpsi) the formula needs to be modified [b-Mazzarese]. The current recommended criteria are as follows:

– maximum short-term strain on optical fibres is 60% of the proof test strain;

– 0.69 GPa (100 kpsi) proof-tested fibre: Maximum long-term strain: 20% of proof test strain;
– 0.69-1.38 GPa (100-200 kpsi) proof-tested fibre: Maximum long-term strain: 17% of proof test strain;
– there is no recommendation for proof test levels greater than 1.38 GPa (200 kpsi) at the time of publication.

Appendix I

Lifetime expectation in the case of small radius bending of single-mode fibre

NOTE – The reliability of a small bending radius is a topic undergoing study by ITU-T and IEC.

I.1 Introduction

Fibres under installation at a reduced bending radius including multi-dwelling units (MDUs) and closures may impose concerns with respect to fibre lifetime expectation. Important parameters that determine the expected lifetime are the extrinsic and intrinsic strengths in a fibre. The required values of these parameters have to be offset against the accepted failure rate in the network, including the probability of other failures that may occur in the network during its operational lifetime (e.g., failures due to re-working or re-configuration in the link, or due to other causes of cable or cabinet damage). In assessing the result of this, the major question is whether single-mode fibres as specified in [ITU-T G.657] fulfil the requirements for a sufficiently long lifetime expectation. More background is given to this question in this appendix.

I.2 General aspects of failure characteristics under small radius bending

In general, the estimation of mechanical failure probability or the lifetime of a bent fibre is calculated using the power law theory, as described in [b-IEC TR 62048]. [b-IEC TR 62048] describes two strength regions, intrinsic and extrinsic. The intrinsic strength region is length independent and dominant for very small radius bending (typically <3 mm). In the extrinsic region, the mechanical failure probability of bent fibre increases proportionally with the fibre bending length, assuming the bending radius is constant. Transition between these regions is hard to determine and depends on many variables.

It is desirable that a bent region in a fibre link be as short as possible. An example image of failure probabilities with respect to the bending radius for 1% proof strain level is shown in Figure I.1. In this calculation, the minimum allowed dynamic stress corrosion susceptibility parameter n_d of 20 and the mean number of break N_p per length during a proof test of 0.01 km^{-1} are used as an example. In Figure I.1, the values of mechanical failure probability within 20 years are plotted for a fibre with one turn bend length for each bend radius (logarithmic scale). From Figure I.1, two regions are observed: an intrinsic region and an extrinsic region tail. The failure probability in the extrinsic region is affected by the proof strain level. On the other hand, the failure probability in the intrinsic region depends on the intrinsic strength of the fibre, and is close to the theoretical strength of the glass.

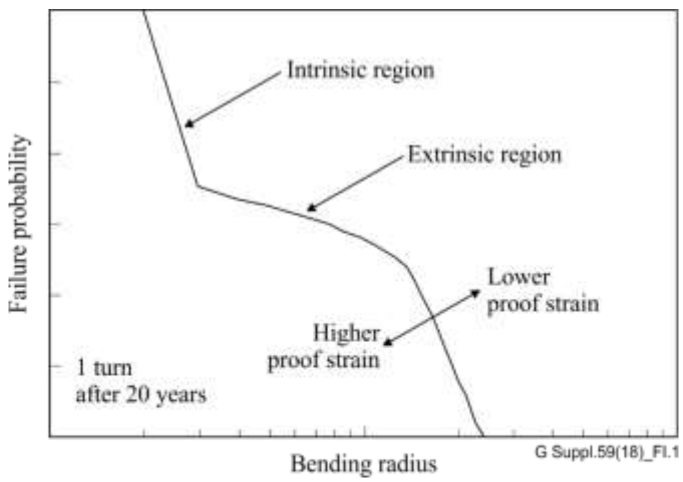

Figure I.1 – Example of calculated relationship between failure probability and bending radius for uniformly bent one-turn fibres after 20 years

Figure I.2 shows the dependence of time to failure on the bending radius. These experimental results show that very small radii cause reliability degradation.

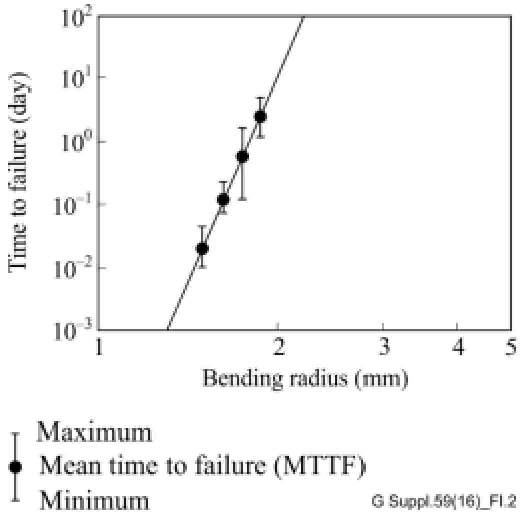

Figure I.2 – Example of time to failure under ultra-small bending radius

Fibre storage at a certain radius in fibre management systems and in closures needs evaluation with respect to fibre lifetime. For these applications, the loop size should be chosen to be large enough that fibres are in the extrinsic region.

In many applications, loose fibre storage loops have a 30 mm radius with approximately 1-10 m of fibre stored at a splice point. With improved macrobend fibre, as described in [ITU-T G.657], the size of these loops could be reduced resulting in smaller enclosures, but the amount of fibre required, 1-10 m, for splicing will likely remain the same. Smaller storage loops result in higher stress in the fibre and thus potentially induce an increased risk of mechanical failure. Table I.1 uses the well-known power law theory of optical fibre reliability (see [b-IEC TR 62048]) to show a 20 year failure probability as a function of loop size and fibre length, assuming a worst-case value for the dynamic stress corrosion susceptibility parameter $n_d = 20$ as stated in [b-IEC 60793-2-50]. Typical values of n_d, which are greater than the specified minimum, produce lower calculated failure probabilities than those in Table I.1. However, measurement of n_d can vary with test method and it is recommended that a conservative value of this parameter be used.

Table I.1 – 20-year failure probability for fibre stored in loose coils, proof tested at 1%

Length	Radius			
	15 mm	20 mm	25 mm	30 mm
1 m	2.7×10^{-6}	3.8×10^{-7}	8.0×10^{-9}	2.1×10^{-10}
10 m	2.7×10^{-5}	3.8×10^{-6}	8.0×10^{-8}	2.1×10^{-9}

It can be seen from this example that using smaller coils will increase the failure probability. Typical values of proof stress, which are greater than the specified minimum, produce lower calculated failure probabilities than those in Table I.1. The differences in calculated failure probabilities with a variation in proof stress levels are reduced as bend diameter is decreased.

I.3 Network and network failure examples

For lifetime calculations, a simple network is considered to consist of, for example, a 1 000 fibre distribution cable with a tree structure as indicated in Figure I.3. Depending upon the installation and customer connection procedures of the operator, the individual fibres or groups of fibres are stored in cassettes in the main distribution cable or in the branches. For simplicity and as a worst-case scenario, it is assumed that all 1 000 fibres pass five cabinets or enclosures with a storage cassette in every individual fibre link and in every cabinet or enclosure.

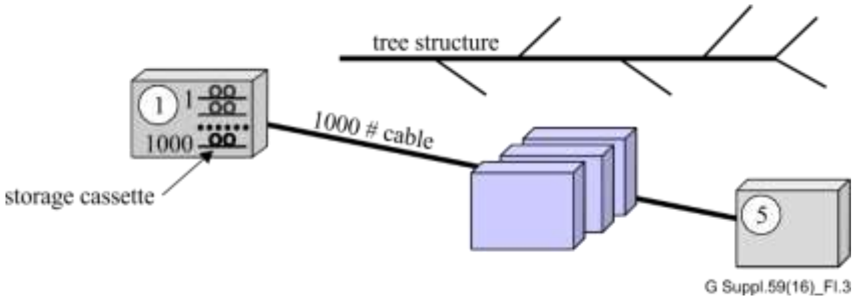

Figure I.3 – Simplified network structure

In this particular network structure, a failure rate per individual single fibre cassette of 0.001% (10^{-5}) in 20 years will result in a 5% probability that in 20 years there will be one single spontaneous break in the total network. This probability needs to be compared with the probability of other failures that may occur in the distribution network during its 20 year operational lifetime. Such failures may be due to re-work or re-configuration in the link or due to other causes of cable or cabinet damage. For most access network situations, it may be assumed that the stated failure probability due to spontaneous fibre breakage is much lower than the failure probability due to other causes. Each operator has to determine the accepted failure rate based on more precise data on the outside plant failure rate statistics.

I.4 Fibre lifetime considerations

Apart from the intrinsic fibre strength characteristics and the fibre environment, the main parameters that determine the failure rate per cassette are the length of the stored fibre and the bending radius, R, of the storage. Shorter storage length will have a positive influence, whereas a reduced bending radius will have a negative influence. Applying the [b-IEC TR 62048] lifetime model, with more details in [b-Matthijsse] on fibres available at the time of publication, with a standard setting of proof stress and normal proof test performance, the resulting maximum storage length for a 20 year lifetime as a function of the fibre bend radius is indicated in Figure I.4, for different values of the dynamic stress corrosion susceptibility parameter, n_d, assuming a maximum failure rate of 0.001% (10^{-5}). Note that a value of $n_d = 18$ is the minimum value as stated in [b-IEC 60793-2-50].

From an optical bend loss point of view, bend loss insensitive fibres, as described in [ITU-T G.657], can be stored in smaller cassettes than the usual 30 mm radius cassettes. For a storage length per cassette of, for example, 100 cm, i.e., 2 × 50 cm for a single fibre, the bend radius can be lowered from the current 30 mm value down to 15 mm or even lower depending upon the guaranteed n_d-value without violating the 0.001% mechanical failure rate per cassette in 20 years.

A second storage issue is at the entrance and exit ports in the fibre management system. The required small volume for optical access network components is not only dependent upon the storage area, but also on the minimum bend radius of the input and exit ports. The effect of this can be taken into account in several ways. For the purpose of this appendix, it is assumed that in every storage cassette, four additional 90° bends are required for guiding the fibres into and out of the storage areas. It is also assumed that the additional failure rate due to these additional bends should be limited to less than 10% of the accepted failure rate of 0.001% per cassette (so 10^{-6}). This results in the minimum values as indicated in the middle column of Table I.2.

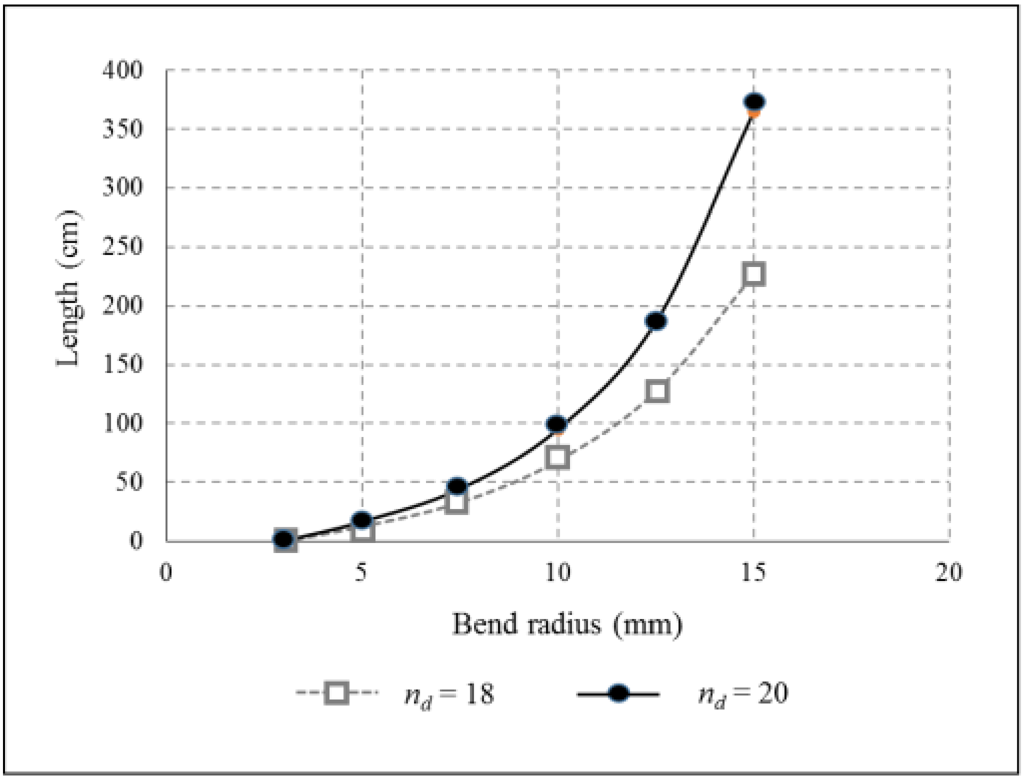

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Figure I.4 – Maximum storage length for a bent fibre and different values of the dynamic stress corrosion parameter n_d

Table I.2 – Minimum value of non-storage bend radii

n_d-Value	Four 90° bends	Single 180° bend
18	R_{min} = 9.5 mm	R_{min} = 5.9 mm
20	R_{min} = 7.8 mm	R_{min} = 4.8 mm

In the right column, the minimum radius in the case of a single 180° erroneous bend is given. Also for this situation, a maximum additional failure rate per individual cassette of 0.1 × 0.001% is assumed. All figures relate to single fibre management and are given for two different values of the dynamic stress corrosion parameter, n_d.

Optical cables are traditionally designed to separate bending forces from axial tension. This assumption is not valid for drop cables used in building applications (e.g., with ITU-T G.657 fibres). These new cables may be subject to bends and tension simultaneously. In these conditions, the strain from all sources should be taken into account to accurately predict the mechanical lifetime at the bend. The resulting failure probability when bends and tension are present can be calculated using the strip calculation found in [b-IEC TR 62048].

An example of the data regarding mechanical failure rate under tension is described in Table I.3.

Table I.3 – Failure probabilities per metre of bent fibre and per number of turns, with indicated bend radius, for bend stress only, and for bend stress plus extra axial tension (30% of proof test tension) over 20 years

Bend radius (mm)	Bend stress only (without extra axial tension)		Bend stress plus extra axial tension	
	(Failure prob./m)[a]	ppm (turn)[b]	(Failure prob./m)[a]	ppm (turn)[b]
5	6.1×10^{-05}	~1.9	9.7×10^{-05}	~3.1
7.5	2.3×10^{-05}	~1.1	4.6×10^{-05}	~2.2
10	1.1×10^{-05}	~0.66	2.8×10^{-05}	~1.7
15	2.7×10^{-06}	~0.26	1.4×10^{-05}	~1.3

[a] Failure probabilities per metre of bent fibre.

[b] Parts per million, ppm.

I.5 Notes on calculating values in Tables I.1, I.2 and I.3

Equation 8-1 was used to calculate the values provided in Tables I.1, I.2 and I.3. The values used in the equation were as follows:

t_f		based on stability for 20, 25 or 30 years
t_p	proof test time	0.05 s
σ_p	proof stress	100 kpsi (0.69 GPa
σ_a	applied load	see below
F	failure probability	calculated or provided
N_p	proof test break rate	1 break per 250 km
L	length under tension	by example see below
n_d	stress corrosion parameter	18 and 20 are used in examples
m_d	Weibull *m* from the tensile strength test	2.359

The total applied load on fibres is a combination of bending stress and axial stress. Tables I.1 and I.2 simply have bending stress and Table I.3 includes additional axial stress that is added to the bending stress. The bending stress is calculated using Equation I-1:

$$\sigma_a = \frac{E_0}{8D}\left\{1 + \frac{9}{32D}\right\} \qquad \text{(I-1)}$$

where E_0 is the zero-strain Young's modulus, which has values of 70.3 to 73.8 GPa, and D denotes the bending diameter in millimetres.

NOTE – Values found in Tables I.1, I.2, and I.3 are calculated with E_0 = 72 GPa.

When an optical fibre is bent, the maximum stress is on the outside of the bend. The length of fibre under stress in bending needs to be corrected to account for the non-uniform stress on the outside of the fibre. Equation I-2 can be used to convert the length of fibre in a bend to an equivalent length of fibre in tension.

$$L = 0.4L_B\left(\frac{n_d \cdot m_d}{n_d + 1}\right)^{-1/2} \qquad \text{(I-2)}$$

I.6 Conclusion

The examples given support a 20 year operational lifetime for an appropriately installed network equipped with bend-insensitive fibres as described in [ITU-T G.657] and bend radii less than 30 mm with acceptable failure rates.

Appendix II

Long-term reliability of deployed optical fibre cables

II.1 Introduction

The purpose of this appendix is to give some general information on the main factors affecting the definition of the reliability objectives for the external faults of optical cables during their lifetime. The reliability objectives for the external faults are mainly related to the specific configuration of the telecommunication networks and to the specific operating strategies of each network operator.

II.2 Factors having an impact on the objectives for the reliability of deployed optical cables

II.2.2 The position of the optical cable in the telecommunication network

Tolerance for failure may not be equivalent throughout the optical network. A service provider must consider several factors in making this decision. Table II.1 gives an example of the different role an optical cable can play in the various parts of an optical network. Table II.1 shows that depending on the portion of the network being considered, a failure impacts different numbers of users and may be more or less complicated to repair.

Table II.1 – Example relationship between application area of optical fibre cable and impact of failure

	Users per fibre	Impact of failure
Multi-dwelling unit (MDU)	1	One customer down, truck roll
Access network, fibre to the x (FTTx)	10-100	Several customers down, need for immediate repair
Trunks and metro applications	100-1 000	Government reportable incident, need for immediate repair
Long haul	100-10 000	Government reportable incident, need for immediate repair
Submarine	100-10 000	International reportable incident. Failure extremely costly (ship must be used)

II.2.3 Laying conditions

Faults caused by external causes mainly depend on the quality of the protections used in laying the cable (depth of the excavation, dimensioning of the infrastructure of overhead lines, etc.).

The goodness of the protections depends on the amount of capital expenditure (CAPEX) available for the specific cable plant. This aspect differs for each network operator.

II.2.4 Time to repair

The reliability objectives are also related to the mean time to repair (MTTR), i.e., the expected time needed to repair a failure. It is obvious that with a MTTR of 2 h, it is possible to tolerate a number of faults higher than in the case of a MTTR of 8 h.

The MTTR directly depends on the maintenance organization or strategy, which differ among the various network operators.

II.2.5 Duplication of cables or systems

The presence in the telecommunication networks of spare cables or systems for rerouting traffic during repair time is another important aspect influencing the choice of a reliability objective for an optical cable.

The presence of duplicated cables or systems depends on the choice of each specific network operator.

II.3 Example of objectives for the reliability of laid optical cables

Even if the reliability objectives to be respected during the commercial life of optical cables are not generally specified in ITU-T Recommendations, some indications are given in two cases: repeatered submarine optical cables and for low-cost sustainable telecommunications infrastructure for rural communications in developing countries.

The main information related to these two cases is summarized in clauses II.3.1 and II.3.2.

II.3.1 Submarine cables

The reliability of the submarine portion of an optical fibre submarine cable system is generally characterized by the following.

i) The expected number of repairs requiring intervention by a cable ship and due to system component failures during the system's designed lifetime. The usual requirement for system reliability is less than three failures requiring cable ship intervention during the system's designed lifetime.

ii) The system designed lifetime: the period of time over which the submarine optical fibre cable system is designed to be operational in conformity to its performance specifications. Usually, a system's designed lifetime is a period of 25 years starting at the provisional acceptance date of the system, i.e., the date following installation when the system is compliant with performance specifications.

The wet plant is more critical than the dry plant in terms of reliability because the MTTR is greater. Typical MTTR values give around 2 weeks for wet plant repair instead of 2 h for dry plant.

For further information see [b-ITU-T G.977] and [b-ITU-T G-Sup.41].

II.3.2 Low-cost sustainable telecommunications infrastructure for rural communications in developing countries

Compared with no service at all, a useful target would be that a break in a rural location may occur perhaps once a year and be repaired in 3-4 days.

It must be noted that, however, natural events may damage the backhaul infrastructure (optical cables or wireless antennas and repeaters) that connects extremely remote areas through impervious areas, which may need many days before restoration, thus exceptionally reducing the availability.

In Appendix I of [b-ITU-T L.1700], an operator of an Asian least developed country for optical cables in mountainous area is quoted to have put the following.

– As an acceptable mean time between failures (MTBF): 7-9 months. This means more than one fault per year;

– As an acceptable MTTR: 2-4 weeks (summer-winter).

For further information see [b-ITU-T L.1700].

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Printed in Switzerland
Geneva, 2018