International Telecommunication Union

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

Series G
Supplement 59
(09/2016)

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 G-SERIES RECOMMENDATIONS

TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

For further details, please refer to the list of ITU-T Recommendations.

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. The document 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

* 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.

FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications, information and communication technologies (ICTs). The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this publication, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

Compliance with this publication is voluntary. However, the publication may contain certain mandatory provisions (to ensure, e.g., interoperability or applicability) and compliance with the publication is achieved when all of these mandatory provisions are met. The words "shall" or some other obligatory language such as "must" and the negative equivalents are used to express requirements. The use of such words does not suggest that compliance with the publication is required of any party.

INTELLECTUAL PROPERTY RIGHTS

ITU draws attention to the possibility that the practice or implementation of this publication may involve the use of a claimed Intellectual Property Right. ITU takes no position concerning the evidence, validity or applicability of claimed Intellectual Property Rights, whether asserted by ITU members or others outside of the publication development process.

As of the date of approval of this publication, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this publication. However, implementers are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database at http://www.itu.int/ITU-T/ipr/.

Table of Contents

Introduction

Supplement 59 to the ITU-T G-series Recommendations provides information on long-term reliability of optical fibre and cable. ITU-T establishes optical fibre and cable Recommendations such as [ITU-T G.651.1], [ITU-T G.652], [ITU-T G.653], [ITU-T G.654], [ITU-T G.655], [ITU-T G.656], and [ITU-T G.657]. Also, ITU-T standardized optical cables as described in some of the 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

The scope of this Supplement is to give the end user guidance on the long-term performance of optical fibre and cables. Though it is difficult to address all situations and to guarantee long-term performances, this supplement helps understand general long-term behaviour of optical fibres and cables and provides guidelines to help the end users minimize the number of mechanical and optical failures during the expected lifetime of the fibre and cable.

2 References

[ITU-T G.651.1] Recommendation ITU-T G.651.1 (2007), *Characteristics of a 50/125 µm multimode graded index optical fibre cable for the optical access network.*

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

[ITU-T G.653] Recommendation ITU-T G.653 (2010), *Characteristics of a dispersion-shifted, single-mode optical fibre and cable.*

[ITU-T G.654] Recommendation ITU-T G.654 (2016), *Characteristics of a cut-off shifted single-mode optical fibre and cable.*

[ITU-T G.655] Recommendation ITU-T G.655 (2009), *Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable.*

[ITU-T G.656] Recommendation ITU-T G.656 (2010), *Characteristics of a fibre and cable with non-zero dispersion for wideband optical transport.*

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

[ITU-T G-Sup.40] Supplement ITU-T G.Sup40 (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

None.

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 is less than 40 years and much information provided in this Supplement is speculative, although today significant spontaneous fibre breakage in these old fibres is not known. Detailed analysis of attenuation characteristics and mechanical attributes for cabled fibre that have been installed for 25 years [b-Hopland 1] [b-Hopland 2] indicate that the optical properties are very stable over time. With this background we can use our accumulated field knowledge combined with accelerated aging to estimate the reliability of optical cables.

Reliability falls into two major categories:

– Mechanical reliability (will the fibre break over the cable lifetime)

– Optical reliability (will optical transmission be maintained over the cable lifetime)

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

General trends in optical transmission must be considered in our evaluation of optical reliability. The general trend is towards more information traveling down optical fibres. Optical cables are trending toward higher fibre counts in smaller optical cables resulting in the potential for more residual strain on the individual optical fibres. There is a trend towards the use of more of the optical spectrum and thus a desire to preserve the attenuation across the full spectrum from 1260 to 1625 nm to allow the most opportunities for bandwidth upgrades.

In general, the reliability of an optical cable during the course of its deployment is strongly impacted 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 as follows:

i) *Manufactory of the optical fibres (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 the commercial operation. In this phase it is recommended that tests be carried out to ensure that optical and mechanical degradations will not adversely impact system performance during the lifetime of the cable deployment and storage.

ii) *Design of the optical cable structure*

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

Important inputs for the definition of these characteristics are the foreseen installation method and mechanical stress (cable directly put underground, laid in ducts, laid on external poles, etc.) and, possibly, also an indication of 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 excursions that the cable has to face during the lifetime.

iii) *Insertion of the fibres in the optical cable (cabling)*

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

iv) *Design of the infrastructure for the cable laying*

The infrastructure for the cable laying installation should be designed and implemented in order to preserve as much as possible the cable, from external damages different from those indicated in point *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 point *i)*.

vi) *Life of the deployed optical cable*

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

The internal faults (fibre breakage, increase of attenuation, etc.) are those related to the quality of the optical fibres. With the adoption of the reliability objectives pointed 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 for other services, floods, landslides, etc.). The number of this type of faults mainly depends on the quality of the protections 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 the quality of the fibres degrades from the point of view of mechanical strength and from that of the increase in attenuation;

– list the test methods to check these degradations;

– give the quality objectives currently adopted during the manufacturing process of the fibres.

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. Examples of the main factors that have an impact on the choice of the reliability objectives to be considered during the commercial life of the optical cables are outlined in Appendix II.

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

7 Optical reliability

In the 30 years of commercial optical cable deployment, several mechanisms have been identified that deteriorate the optical performance of glass fibres. These mechanisms can be considered as starting points in identifying processes that need to be accounted for to assure the optical performances of manufactured and cabled fibres prescribed in ITU-T G.65x 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 were developed to help assure long term reliability of optical cables. All the tests focused on optical reliability and monitored the fibre or cabled attenuation during the course of the test to see if 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 the transmission properties.

7.1 Bending loss

Bending loss falls into two types, macrobend loss and microbend loss. In the simplest terms macrobends are visible bends on the scale of several millimetres in radius and microbends are very small, in the order of a few microns 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 up to 1625 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 have nanometre scale size if they occur 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 be a result of 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 test standardized in IEC can be found 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 meters 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 useable spectrum. In sufficient quantity these defects can cause the optical fibres to become unusable.

In 2001 ITU-T introduced full spectrum ITU-T G.652 fibre. These ITU-T G.652 fibres differed from their predecessors in that the glass that is transmitting 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. Today 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 what 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 doses 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 the typical background levels. We have experience with optical cables deployed since 1977 and background radiation does not appear to impact the attenuation performance of deployed cables under normal conditions. Document [b-IEC TR 62283] provides guidance for nuclear radiation tests, but it still need refinement before accurate predictions can be made.

7.4 Attenuation stability

The expected lifetime of optical fibres is typically more than 20-30 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 cyclical conditions as may be encountered with changing conditions over the course of the 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 time based, for example:

– 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
– And other tests

In these tests there are requirements that help to predict worst case performance under a given set of conditions that are representative of adverse field conditions. 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 if 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 if 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. Attenuation tests can reveal changes that are due to the attenuation of the glass itself or that may be the result of uneven forces in the cabling materials bending being transferred to the optical fibres. Accelerated aging is often done at higher temperatures and higher moisture levels and are assumed to give insight into the long term performance of the optical fibre and cabling materials. When performing these tests one must be careful that high temperature degradation mechanisms are not activated resulting in an unrealistically short lifetime estimate. Accelerated aging tests give an indication of how the cabling materials age, developing anisotropic stress on the optical fibres, and one may see attenuation changes over time. Current materials have been developed to minimize the impact of aging on attenuation, and temperature/humidity tests are used to validate that the material system will protect the performance of the optical fibre.

With 30 years of deployed optical cables and an assumption that any degradation effect will double with twice the time we can assume that other than the hydrogen effect, we are unlikely to see any new degradations to optical performance that will result in more than a few 100ths of a dB per km over the life of the optical cable.

8 Mechanical reliability

Mechanical reliability of optical fibre studies the probability of a fibre breaking during the lifetime of a deployed optical fibre. 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 could experience during storage, cabling, installation, deployment, 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 un-scheduled 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 metre lengths of fibre [b-Mazzarese]. The figure 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 the figure. The larger flaws are found in the extrinsic Region II on the graph, within the lower failure probability zone.

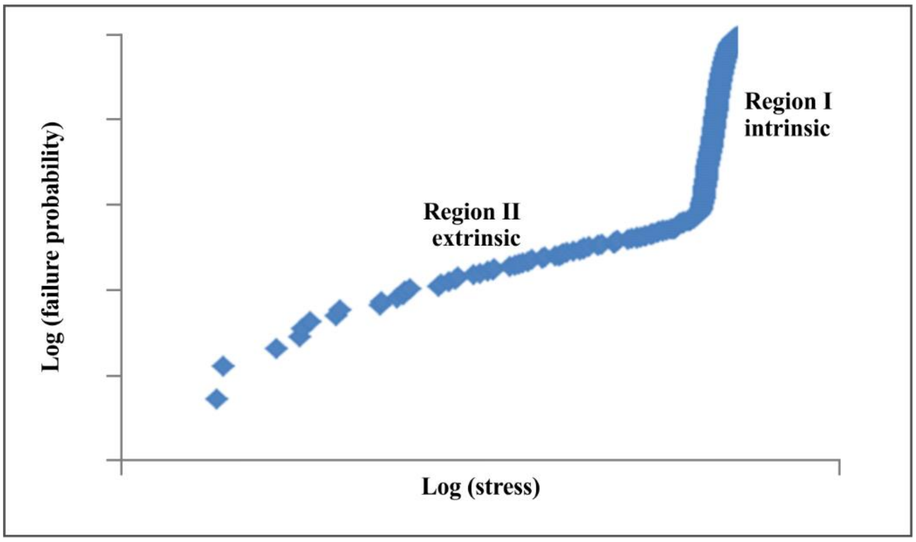

Figure 1 – Failure probability for over 100 km of fibre tested at 10 m gauge lengths [b-Mazzarese]

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 metre) 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, removing the weakest flaws, and this action is normally applied to 100% of commercial fibre by manufacturers at the end of the drawing and coating phases. Currently optical fibres are proof tested to 0.69 GPa proof stress (100 kpsi), which screens flaws that have a depth of 0.5 micron 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 metres from a sample population up to a few kilometres at most, thus defining the intrinsic strength region but little of the extrinsic. 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 such as 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 such as 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/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] and shown as equation 8-1 in this Supplement. This model will be 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 is employed.

$$t_f = t_p \left(\frac{\sigma_p}{\sigma_a}\right)^n \left\{ \left[1 - \frac{ln(1-F)}{N_p L}\right]^{\frac{n+1}{m_d}} - 1 \right\} \quad (8\text{-}1)$$

The variables used in the equation and conservative values often used in calculations are given below:

Parameters	Description/example
t_f is the time to failure (lifetime)	calculated
t_p is the proof test time	see clause 8.5
σ_p is the proof stress	0.69 GPa (100 kpsi)
σ_a is the applied load	see clause 10
F is the failure probability	See Appendix II
N_p is the proof test break rate	1 break per 100 km
L is the length under tension	determined by application
n is the stress corrosion parameter	See clause 8.4
m_d is the Weibull *m* from the fibre dynamic tensile strength	See clause 8.4

8.3 The time to failure or fibre lifetime is often the parameter of interest.

The proof stress is given in various ITU-T G.65X 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 are 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 1 breaks per 100 km be used when more reliable information is unavailable. In this equation n and m_d are unknowns that are difficult to measure and essential in determining the lifetime. These parameters will be discussed in 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 manufacturers 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 means 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] and n~20 is typically used in predicting typical lifetimes. Higher values than 20 will 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 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-Griffioen2], [b-Craig], [b-Glaesemann2], [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 8-1. Accurate characterisation 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 what is shown in Figure 8-1. 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. Recommendation [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 much less than one second. As the proof-test level increases smaller flaws are removed from the fibre reducing the chance the fibre will break when strained. The current ITU-T G.65X series Recommendations 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 Handleability 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 delaminations that expose bare glass to the aggressive elements. When the fibre strength is less than 2 GPa the fibre becomes difficult to handle and splice [b-Griffioen1]

8.7 Test proceedures that measure aspects of mechanical reliability

Supplement [b-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] Fibre Tensile Strength

– [b-IEC 60793-1-33] Stress Corrosion Factor

– [b-IEC 60793-1-50] Damp Heat Aging

– [b-IEC 60793-1-51] Dry Heat Aging

– [b-IEC 60793-1-53] Water Immersion

It is well understood that the environment surrounding and optical fibre can impact 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 increases above 700°C catastrophic softening of the glass. Burning of the coating can result in a fire. Document [b-IEC TR 62547] provides guidance for 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, 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 impact reliability of optical fibres in splice boxes. Overhead cables are often pulled tight to minimise 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 G.657 fibres are installed inside of 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:

- Limit the tensile stresses on optical fibres through use of load-bearing elements
- Limit fibre bend diameter
- Protect the fibre from crush and impact
- Protect the fibre from chemical attacks including water and hydrogen

Choosing cabling materials is an important design consideration and though cabling material can protect the fibre one must also consider interactions between the glass fibre and the cabling materials that may occur over time.

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. 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. One also needs 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 vs. 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 IEC 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 criteria of 20% of the proof-test level for 0.69 GPa (100 kpsi) fibre comes from work done by Glaesemann [b-Glaesemann1] in 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 load on optical fibres is 60% of the proof-test load
- 0.69 GPa (100 kpsi) proof-tested fibre: Maximum long term load = 20% of proof-test load
- 0.69-1.38 GPa (100-200 kpsi) fibre: Maximum long term load = 17% of proof-test load
- There is no recommendation for proof-test levels greater than 1.38 GPa (200 kpsi) at this time.

Appendix I

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

NOTE – The reliability of a small bending radius is an ongoing topic under ITU-T and IEC study.

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 strength 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-work 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 the relevant Recommendations fulfil the requirements for a sufficiently long life time 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 clause 8.2 and in [b-IEC TR 62048]. Both these texts describe 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 is 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 $\boldsymbol{n_d}$ of 18 and the mean number of break ***Np*** per length during a proof test of 0.01 km^{-1} are used as an example. In the figure, the values of mechanical failure probability within 20 years are plotted for a fibre with 1 turn bend length for each bend radius. 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.

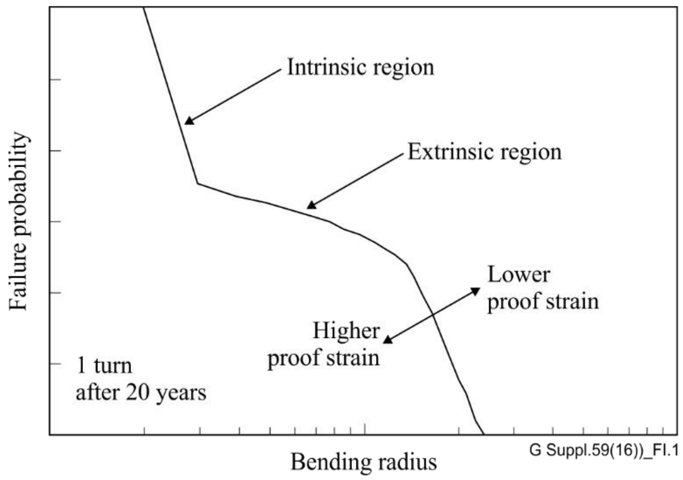

Figure I.1 – Example of calculated relationship between failure probability and bending radius for uniformly bent one-turn fibres after 20 years

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.

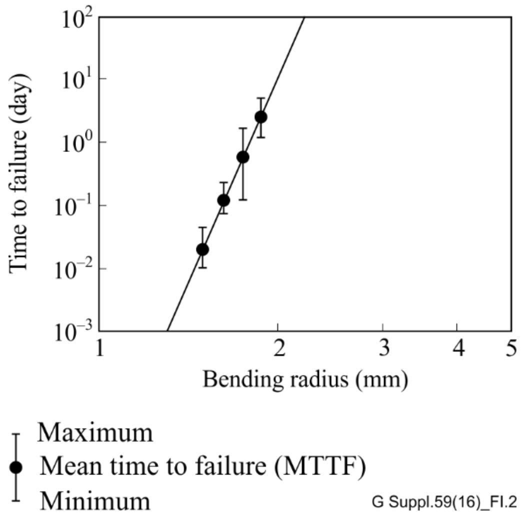

Figure I.2 – Example of time to failure under ultra-small bending radius

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 below uses the well-known power law theory of optical fibre reliability (see clause 8.2 and [b-IEC TR 62048]) to show a 25-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 = 18 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, care should be taken that n_d values are obtained from the same test method [b-IEC 60793-1-33].

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

Length	15 mm radius	20 mm radius	25 mm radius	30 mm radius
1 m	5.0×10^{-6}	4.7×10^{-7}	7.9×10^{-9}	1.9×10^{-10}
10 m	5.0×10^{-5}	4.7×10^{-6}	7.9×10^{-8}	1.9×10^{-9}

One can see 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 1000-fibre distribution cable with a tree structure as indicated in Figure I.3. Depending on 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 situation, it is assumed that all 1000 fibres are passing 5 cabinets or enclosures with a storage cassette in every individual fibre link and in every cabinet or enclosure.

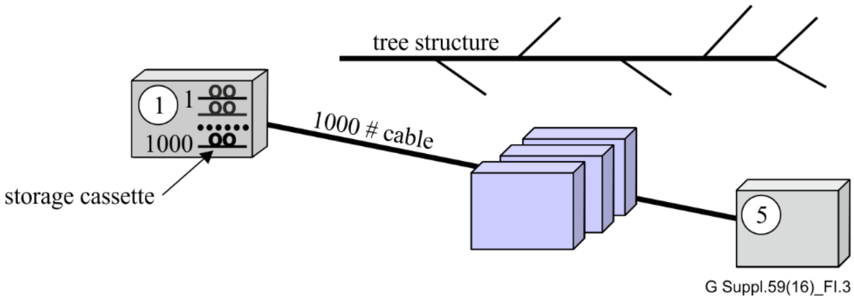

Figure I.3 – Simplified network structure

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-OFT] on current fibres 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].

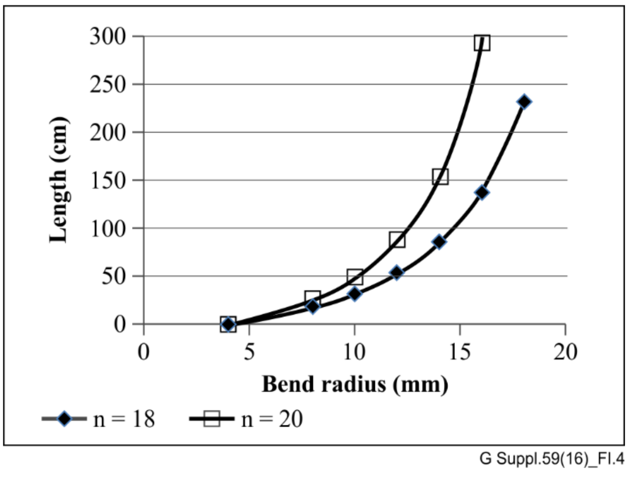

Figure I.4 – Maximum storage length for a bent fibre and different values of the dynamic stress corrosion parameter n_d

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 one 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 $\boldsymbol{n_d}$-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 on 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-degree 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.

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

nd-value	Four 90° bends	Single 180° bend
18	R_{min} = 15.0 mm	R_{min} = 12.6 mm
22	R_{min} = 11.1 mm	R_{min} = 9.2 mm

In the right column, the minimum radius in case of a single 180-degree 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 are given for two different values of the dynamic stress corrosion parameter, $\boldsymbol{n_d}$.

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 + extra axial tension (30% of proof test tension) over 30 years

Bend radius (mm)	Bend stress only (without extra axial tension)		Bend stress + extra axial tension	
	(Failure prob./m)[a)]	ppm (turn)[b)]	(Failure prob./m)[a)]	ppm (turn)[b)]
5	1.02×10^{-04}	~3.2	1.72×10^{-04}	~5.4
7.5	4.20×10^{-05}	~2.0	9.3×10^{-05}	~4.4
10	2.09×10^{-05}	~1.3	6.20×10^{-05}	~3.9
15	6.08×10^{-06}	~.06	3.67×10^{-05}	~3.5

a) Failure probabilities per metre of bent fibre.
b) Parts per million, ppm.

I.5 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. The table below gives an example of the different role an optical cable can play in the various parts of an optical network. The table 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	1 customer down, truck roll
Access network, Fibre to the X (FTTx)	10-100	Several customers down, need for immediate repair
Trunks and Metro Applications	100-1000	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 depends on the quality of the protections used in the laying of the cable (depth of the excavation, dimensioning of the infrastructure of overhead lines, etc.).

The goodness of the protections depends by the amount of CAPEX (Capital Expenditure) available for the specific cable plant. This is an aspect different 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 hours it is possible to tolerate a number of faults higher than in the case of a MTTR of 8 hours.

The MTTR is directly depending from the maintenance organization / strategy, which is different among the various network operators.

II.2.5 Duplication of cables/systems

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

The presence of a duplicated cables/systems depends by 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, 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 the following.

II.3.1 Submarine cables

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

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 conformance with 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 the 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 hours 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 approximately three to four days on average.

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] it is quoted that an operator of an Asian least developed country for optical cables in mountainous area have put:

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

– as an acceptable MTTR (mean time to repair) 2-4 weeks (summer-winter).

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

Bibliography

[b-ITU-T G.977] Recommendation ITU-T G.977 (2015), *Characteristics of optically amplified optical fibre submarine cable systems.*

[b-ITU-T G-Sup.41] ITU-T G-series Recommendations – Supplement 41 (2010), *Design guidelines for optical fibre submarine cable systems*.

[b-ITU-T L.1700] Recommendation ITU-T L.1700 (2016), *Requirements and framework for low-cost sustainable telecommunications infrastructure for rural communications in developing countries.*

[b-IEC 60793-1-30] IEC 60793-Part1-30 (2010), *Optical fibres – Part 1-30: Measurement methods and test procedures – Fibre proof test.*

[b-IEC 60793-1-31] IEC 60793-1-31(2010), *Optical fibres – Part 1-31: Measurement methods and test procedures – Tensile strength.*

[b-IEC 60793-1-33] IEC 60793-1-33 (2001), *Optical fibres – Part 1-33: Measurement methods and test procedures – Stress corrosion susceptibility*.

[b-IEC 60793-1-50] IEC 60793-1-50: (2014) *Optical fibres – Part 1-50: Measurement methods and test procedures – Damp heat (steady state) tests*

[b-IEC 60793-1-51] IEC 60793-1-51 (2014), *Optical fibres – Part 1-51: Measurement methods and test procedures – Dry heat (steady state) tests*.

[b-IEC 60793-1-53] IEC 60793-1-53 (2014), *Optical fibres – Part 1-53: Measurement methods and test procedures – Water immersion tests*.

[b-IEC 60793-2-50] IEC 60793-Part 2-50 (2016), *Optical fibres – Part 2-50: Product specifications – Sectional specification for class B single-mode fibres*.

[b-IEC TR 62048] IEC TR 62048 (2014), *Optical fibres – Reliability – Power law theory*.

[b-IEC TR 62283] IEC TR 62283 (2010), Optical fibres – *Guidance for nuclear radiation tests*.

[b-IEC TR 62547] IEC TR 62547 (2009), *Guidelines for the measurement of high-power damage sensitivity of single-mode fibres to bends – Guidance for the interpretation of results.*

[b-Bhaumik] Sudipta Bhaumik, *Impact of adverse cable handling on lifetime of optical fiber,* Conference Proceedings for WAI's 85th Annual Convention (Interwire 2015).

[b-Breuls] Breuls, A. et al, *Strength and fatigue of zirconia induced weak spots in optical fibre*. SPIE, (September 1993).

[b-Craig] Craig, SP, et al, *The strength and fatigue of large flaws in silica optical fibre.* ECOC, pp. 205-208 (1982).

[b-Glaesemann1] Glaesemann, G.S. and Gulati, S.T. *"Design Methodology for the mechanical reliability of optical fiber"*, Optical Engineering, Vol. 30 No. 6, pp. 709-715 (1991).

[b-Glaesemann2] Glaesemann, GS, et al, *Examining the mechanical behaviour of intrinsic and extrinsic flaws in optical glass fiber*. 94th annual meeting of the Am. Cer. Soc., 4-JXVI-92, (1992).

[b-Griffioen1] Griffioen et al, *Handleability of aged optical fibers*, Proceedings of the 54th International wire and cable symposium (1995).

[b-Griffioen2] Griffioen, W, et al, *COST 218 evaluation of optical fibre lifetime models*. SPIE Vol. 1791, Optical Materials Reliability and Testing (1992).

[b-Hopland 1] Svend Hopland, *''Revealing the losses in installed fiber and cable links consisting of cables of different ages by OTDR measurements at several wavelengths''*. Proceedings of the 64th International Wire and Cable Symposium (2015).

[b-Hopland 2] Svend Hopland, Jan Nordli, Pratik Shah, Kate Roberts, Robert Alexandersson, Bertil Arvidsson, *''Investigating the quality of old optical fibre cables''*. Proceedings of the 62nd International Wire and Cable Symposium (2013).

[b-Lemaire] Lemaire, *Reliability of fibers exposed to hydrogen: prediction of long-term loss increases*, Optical Engineering. Volume 30/Number 6/pp 780 – 789 (1991).

[b-Mazzarese] David Mazzarese, Mike Kinard, Kariofilis (Phil) Konstadinidis, *Long Term Cable Reliability Design Criteria*. Proceedings of the 62nd International Wire and Cable Symposium (2013).

[b-OFT] Matthijsse, P., and Griffioen, W. (2005), *Matching optical fiber lifetime and bend-loss limits for optimized local loop fiber storage*, Optical Fibre Technology, Vol. 11, No. 1, January, pp. 92-99.

[b-Yuce] Yuce, HH, et al, *Aging behaviour of low strength fused silica fibres*. SPIE. Vol. 1366, Fiber optics reliability benign and adverse environments IV, p. 120-128 (1990).

SERIES OF ITU-T RECOMMENDATIONS

Series A	Organization of the work of ITU-T
Series D	General tariff principles
Series E	Overall network operation, telephone service, service operation and human factors
Series F	Non-telephone telecommunication services
Series G	**Transmission systems and media, digital systems and networks**
Series H	Audiovisual and multimedia systems
Series I	Integrated services digital network
Series J	Cable networks and transmission of television, sound programme and other multimedia signals
Series K	Protection against interference
Series L	Environment and ICTs, climate change, e-waste, energy efficiency; construction, installation and protection of cables and other elements of outside plant
Series M	Telecommunication management, including TMN and network maintenance
Series N	Maintenance: international sound programme and television transmission circuits
Series O	Specifications of measuring equipment
Series P	Terminals and subjective and objective assessment methods
Series Q	Switching and signalling
Series R	Telegraph transmission
Series S	Telegraph services terminal equipment
Series T	Terminals for telematic services
Series U	Telegraph switching
Series V	Data communication over the telephone network
Series X	Data networks, open system communications and security
Series Y	Global information infrastructure, Internet protocol aspects and next-generation networks, Internet of Things and smart cities
Series Z	Languages and general software aspects for telecommunication systems

Printed in Switzerland
Geneva, 2016