Invited Paper

Reliability engineering – basics and applications for optoelectronic components and systems

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ABSTRACT

The foundation pillars of successful technical products are performance, cost, and reliability. The development of reliable components and the operation of highly available systems is a comprehensive engineering task combining probability theory, materials science, and experience. Components have to be as reliable as necessary in order to build systems that are dependable and cost efficient during the whole life cycle. Reliability engineering is an ongoing process starting at the conceptual phase of a product design and continuing throughout all phases of a product life cycle. The primary objective is to identify and eliminate potential reliability problems as early as possible. While it may never be too late to improve the reliability of a product, corrections are orders of magnitude less expensive in the early design phase rather than once the product is manufactured and in service.
This paper comprises an introduction to basic reliability engineering terms, reliability analysis methods such as reliability block diagrams, failure mode and effects analysis, Markov processes, the concept of redundancy, failure rate prediction models and the physics of failure approach, qualification and accelerated reliability testing. Examples of electronic and optical components, as well as complex opto-electronic systems and networks are given for illustration.

Keywords: Reliability, Availability, Failure Rate, optical components

1. INTRODUCTION

Reliability plays an important role in the concept of system or cost effectiveness, Fig. 1 [1]. System / cost effectiveness is a measure for the ability of an item to meet service requirements of defined quantitative characteristics with the best possible ratio of usefulness to life cycle cost and therefore is a prerequisite for profitable and sustainable technical systems in the market.

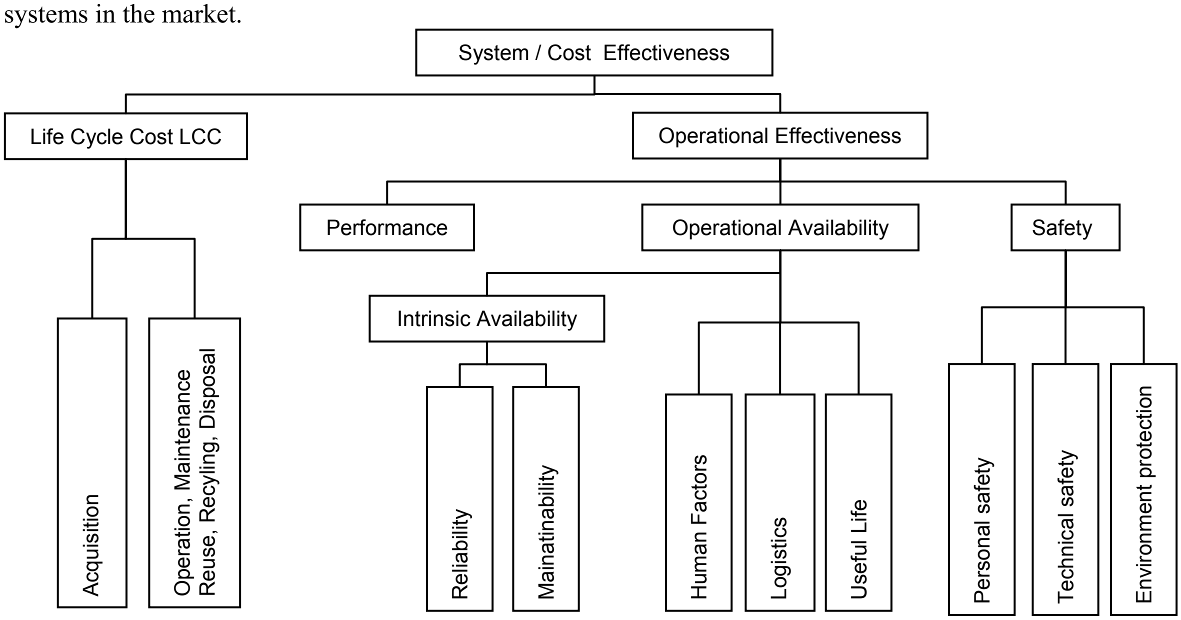

Figure 1: System / Cost Effectiveness for complex equipment and systems

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For a complex system, higher reliability generally leads to higher development costs and lower operating costs, so that the optimum life cycle cost is in between extremely low and high reliability figures, see Fig. 2. The objective of reliability engineering is to develop methods and tools to evaluate and demonstrate reliability, maintainability, availability, and safety (RAMS) of components, equipment, and systems, as well as to support developers and manufacturers in integrating these characteristics into their products. RAMS aspects are of growing importance because of the increased complexity of equipment and systems and the high cost incurred by loss of operation. Equipment and systems have to be more than only being free of defects and systematic failures when they are put into operation. The expectation is that they perform the required function failure free for a stated time and have a fail-safe behaviour in case of critical failures. Whether an item will operate without failures for a stated period of time cannot be answered by yes or no. Experience has shown that only a probability for this occurrence can be given. This probability is a measure for the item's reliability.

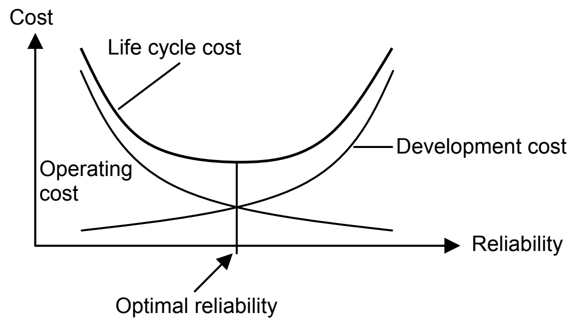

Figure 2: Generic correlation between life cycle cost and reliability

2. BASIC DEFINITIONS

Basic definitions of reliability and related terms are taken from [1] and IEC standards [2],[3].

2.1 Reliability

Reliability is a characteristic of an item, expressed by the probability that the item will perform its *required function* under *given conditions* for *a stated time interval.* It is generally designated by *R.* From a qualitative point of view, reliability can be defined as the *ability of an item to remain functional.* Quantitatively, reliability specifies the *probability that no operational interruptions* will occur during a stated time interval. This does not mean that *redundant* parts may not fail; such parts can fail and be repaired. The concept of reliability thus applies to *nonrepairable* as well as to *repairable* items. To make sense, a numerical statement of reliability (e.g., R = 0.9) must be accompanied by the definition of the *required function,* the *operating conditions,* and the *mission duration.* In general, it is also important to know whether or not the item can be considered new when the mission starts.

An *item* is a functional or structural *unit* of arbitrary complexity (e.g. component, assembly, equipment, subsystem, system) that can be considered as an *entity* for investigations. It may consist of hardware, software, or both and may also include human interaction.

The *required function* specifies the item's task. For example, for given inputs, the item outputs have to be constrained within specified tolerance bands (performance parameters should be given with tolerances and not merely as fixed values). The definition of the required function is the starting point for *any reliability analysis,* because it also *defines failures.*

Operating conditions have an important influence on reliability, and must therefore be specified with care. Experience shows that the failure rate of semiconductor devices will double for an operating temperature increase of 10 -20K.

The required function and/or operating conditions can be *time dependent.* In these cases, a *mission profile* has to be defined and all reliability statements will be related to it. A representative mission profile and the corresponding reliability targets should be given in the *item's specifications.*

In reliability theory, τ represents the failure-free operating time, thus τ is a nonnegative random variable, i.e. $\tau \geq 0$ and its distribution function $F(t)=0$ for $t<0$, or a positive random variable, i.e. $\tau > 0$ and $F(0)=0$. $R(t)$ represents a survival

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function and expresses the probability *Pr* that an item will operate failure-free in the interval (0,t], usually with the assumption R(0) = 1, i.e. the item is operating when "switched-on" at time zero.

$$R(t)= Pr\{\tau > t\} = 1- F(t) \qquad (1)$$

A more stringent assumption in investigating failure-free operating times is that at $t = 0$ the item is free of *defects* and *systematic failures*. Nevertheless, τ can be very short, for instance because of a transient event at turn-on.
A distinction has to be made between *predicted* and *estimated/assessed* reliability. The first one is calculated on the basis of the item's reliability structure and the predicted failure rate of its components the second is obtained from a statistical evaluation of reliability tests or from field data with known environmental and operating conditions.

2.2 Failure

A failure occurs when an item stops performing its required function. This simple definition can be difficult to apply to complex systems. Besides their *relative frequency,* failures should be classified according to the mode, cause, effect, and mechanism:

1. *Mode:* The mode of a failure is the *symptom* (local effect) by which a failure is observed; for example, opens, shorts, or drift for electronic components; light intensity decrease, wavelength shift, fiber melting for optical components; brittle rupture, creep, cracking, seizure, or fatigue for mechanical components.

2. *Cause:* The cause of a failure can be *intrinsic* (early failure, failure with constant failure rate, and wear out failure), or *extrinsic*. Extrinsic causes often lead to *systematic failures (*due to errors, misuse or mishandling in design, production, or operation) which are *deterministic* and should be considered like *defects.* Defects are present – but often not manifest or discovered - *at* $t = 0$.

3. *Effect:* The effect (consequence) of a failure can be different if considered on the item itself or at higher level. A usual classification is: *nonrelevant, partial, complete,* and *critical failure.* Since a failure can also cause further failures in an item, a distinction between *primary failure* and *secondary failure* is important.

4. *Mechanism:* Failure mechanism is the physical, chemical, or other process resulting in a failure.

Failures are also classified as *sudden* and *gradual.* Sudden and complete failures are termed *catastrophic failures,* gradual and partial failures are termed *degradation failures.* A failure is not the only cause for an item being down. The general term used to define the down state of an item *is fault.* Fault is thus a state of an item and can be due to a *defect* or *a failure.*

2.3 Failure rate and mean time to failure

The *failure rate* plays an important role in reliability analysis. It can be expressed heuristically or derived analytically. The failure rate $\lambda(t)$ of an item showing a continuous failure-free operating time t is defined as

$$\lambda(t) = \lim_{\delta t \downarrow 0} \frac{1}{\delta t} \cdot \Pr\{t < \tau \le t + \delta t \,|\, \tau > t\} \qquad (2)$$

It shows that the failure rate $\lambda(t)$ fully determines the reliability function R(t). For many electronic components one can assume the failure rate to be nearly constant and thus time independent, $\lambda(t)= \lambda$.
The generic reliability function in equation (1) then leads to

$$R(t) = e^{-\lambda t} \qquad (3)$$

The failure-free operating time τ is in this case *exponentially distributed.* Only in this case, the failure rate λ can be estimated by $\hat{\lambda} = k / T$, where *T is a given (fixed) cumulative operating time* and *k* the *total number of failures during T.* This result is a consequence of the *memoryless property* (see section 3.2) of the exponential distribution function. The *mean* of a failure-free operating time $\tau \ge 0$ is given in the *general case* by

$$MTTF = E[\tau] = \int_0^\infty R(t)dt \qquad (4)$$

where *MTTF* stands for *mean time to failure.* In the *special case* of a constant failure rate $\lambda(t) = \lambda$, $E[\tau]$ takes the value $1/\lambda$. It is common usage to define

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$$MTBF = \frac{1}{\lambda} \qquad (5)$$

MTBF should be reserved for items with constant failure rate λ.

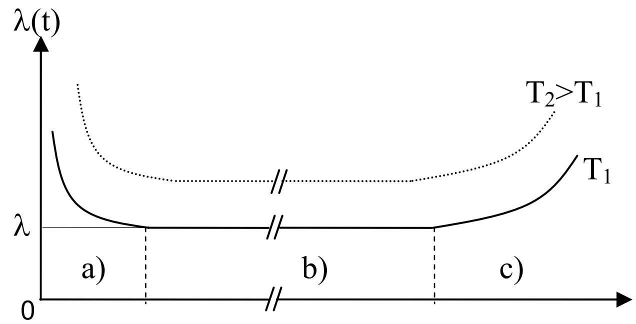

Figure 3: The bathtub curve: schematic curve for the failure rate of a large population of identical and independent items. The dashed line represents a curve with higher temperature stress.

The failure rate of a *large population* of *statistically identical and independent items* exhibits often a typical bathtub curve (Fig. 3) with the following three phases:

a) *Early failures:* $\lambda(t)$ decreases (in general) rapidly with time; failures in this phase are attributable to *randomly* distributed weaknesses in materials, components, or production processes.

b) *Failures with constant (or nearly so) failure rate:* $\lambda(t)$ is approximately constant; while the failure-free operating time λ is *exponentially distributed for* $\lambda(t)=\lambda$, the number of failures in this period is *Poisson distributed with parameter* $m= \lambda t$.

c) *Wearout failures:* $\lambda(t)$ increases with time; failures in this period are attributable to aging, wearout, fatigue, etc.

2.4 Availability

Availability (A) is a general term often used for the stationary and steady-state value of the point and average availability. *Point availability* P*A(t)* is a *characteristic* of an item expressed by the *probability* that the item will perform its *required function* under *given conditions* at a stated *instant of time t.* From a qualitative point of view, *point availability* can be defined as the ability of an item to perform its required function under given conditions *at a stated instant of time.*

Availability calculations are generally difficult, as *logistical support* and *human factors* should be considered in addition to reliability and maintainability. *Ideal* human and logistical support conditions are therefore often assumed, leading to the *intrinsic availability.* Further assumptions for calculations are continuous operation and *complete renewal for the repaired* element in the reliability block diagram (assumed as-good-as-new after repair).

Any availability analysis is based on failure rate λ and repair rate μ of the involved equipment, respectively mean time to failure MTTF=1/λ and mean time to repair MTTR = 1/ μ when failure free operating times and repair times are exponentially distributed.

In this case and assuming continuous operation and no preventive maintenance actions the asymptotic availability A of an item can be directly calculated using the constant failure and repair rates:

$$A = \frac{\mu}{\lambda + \mu} = \frac{MTTF}{MTTF + MTTR} \qquad (6)$$

Asymptotic unavailability U is then U = 1 - A and if $\mu >> \lambda$ holds, approximated by U = λ x MTTR.

In reality, MTTR can be a complex aggregation of several time consuming factors such as failure detection and isolation time, administrative delay, logistic delay, technical delay, and the actual repair time.

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3. RELIABILITY ANALYSIS

The analysis of reliability is of particular importance during the design and development of components and systems in order to detect and eliminate weaknesses as early as possible. Activities in this phase comprise *failure rate* and *failure mode* and *causes-to-effects* analysis, verification of the compliance with reliability design guidelines, and the accomplishment of preliminary design reviews. Investigating the failure rate of a system leads to the calculation of the *predicted reliability*, i.e. that reliability which can be calculated from the structure of the system and the failure rate of its elements.

In this section four methods for comprise *failure rate* and *failure mode* and *causes-to-effects* analysis are explained in brief.

3.1 Reliability Block Diagram

A reliability block diagram RBD [4] is an event diagram and answers the question: which elements of the considered item are necessary for the fulfillment of a clearly defined required function and which can fail without affecting it? The elements necessary for the required function are connected in series, while elements that can fail with no effect on the required function are connected in parallel and represent a redundancy. From the operating point of view, one can distinguish between active, warm, and standby redundancy. For active (also called hot) redundancies with identical elements, both elements are subject to the same load and have identical failure rates. The redundant element in standby (cold) redundancies is not loaded and its failure rate is often assumed to be zero. In warm redundancies the redundant element is partly loaded and its failure rate is generally lower than the one of the operating element.

In setting up a RBD, the ordering of series elements is arbitrary. For a given system, each required function has its own RBD. By definition only two states (good or failed) and only one failure mode (e.g. open or short for an electronic component) can be considered for each element. RBDs are often confused with functional block diagrams or the hardware structure of a system. The following examples illustrate the character of RBDs, Fig. 4.

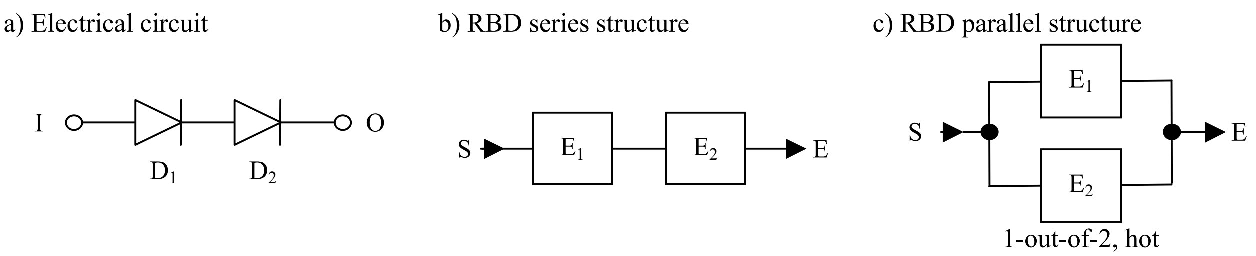

Figure 4: Example of two diodes electrically in series a); required function: diode characteristic between I and O; b) RBDs for assumed failure mode: open c) RBDs for assumed failure mode: short

Simple RBDs can be calculated analytically. For complex RBS Monte Carlo simulation is often used. When performing a Monte Carlo simulation, a random series of simulations is performed on the RBD. These simulations are test runs through the system - from the start node S through the end node E - to determine if the system completes its task or fails. During each iteration or test, the properties of each element are used to decide whether that element is operating or not, and eventually it is determined if the system is operating. For each test run, the number of successful states is tracked. The results of the Monte Carlo simulation are then the statistics over the whole series of tests.

3.2. Markov process

Many physical phenomena observed in everyday life are based on changes that occur randomly in time. Examples are the arrivals of calls in a telephone exchange, radioactive decay, or the occurrences of failures in technical equipment. Markov processes [5] can mathematically describe these phenomena. They are characterized by the property that for any time point t their future depends on t and the state occupied at t, but not on the history up to time t, hence a behavior without memory. Time-homogeneous Markov processes, THMP, describe processes where the dependence on time t also disappears, so that the future of the process, i.e. the next state depends only on the current state and its state transition probabilities. THMP are often used to describe the behavior of repairable systems consisting of components with time independent (constant) failure and repair rates.

A given system is considered, at any instant in time, to exist in one of several possible states. A state transition diagram defines the operational and failed system states and the transitions between these states. After certain properties are

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assigned to states and the transitions between states, these diagrams contain sufficient information for developing equations describing the system behavior. Fig. 5a) depicts the RBD of a 1-out-of-2 repairable, hot redundancy with two identical elements E_1 and E_2. In the state transition diagram depicted in Fig. 5b), Z_0 and Z_1 are up states (system operational) and Z_2 is the down state (system failed).

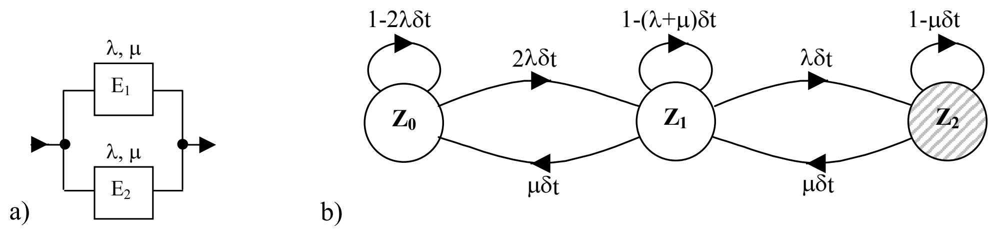

Figure 5: a) Reliability block diagram b) diagram of state transition probabilities in (t, t + δt] for availability analysis for a 1-out-of-2 hot redundancy with identical elements $E_1 = E_2$, constant failure rates λ and repair rates μ, one repair crew, arbitrary t, δt ↓ 0, Markov processes.

Provided that failure rate λ and repair rate μ are time independent, the system can be described by a system of differential equations for the state probabilities $P_0(t)$, $P_1(t)$ and $P_2(t)$, with $P_i(t)$ = probability {process in Z_i at time t}, i = 0, 1, 2. From the analytical solution of the differential equations the parameters of interest can be obtained, e.g. steady state availability. Computational support based on numerical calculation of differential equations, i.e. Runge-Kutta approximations are used to analyze more complex systems consisting of a larger number of elements.

While RBDs are graphical representations of a system's logical structure in terms of sub-systems and /or components, Markov processes are more useful to describe the system states and transition between states. RBDs are somewhat restricted to describe relatively simple (hardware) systems where e.g. perfect switching between redundant elements can be assumed. Markov analysis in this sense is more flexible and can also be used in cases where no RBD can be given or in applications where switching is necessary for powering down failed elements and powering up redundant or repaired elements.

3.3 Fault Mode and Effects Analysis FMEA

Failure rate analysis basically do not account for the *mode* and *effect* (consequence) of a failure. To understand the mechanism of system failures and in order to identify potential weaknesses of a fail-safe concept it is necessary to perform a *failure mode analysis*, at least where redundancy appears and for critical parts of the item considered. Such an analysis includes *failures* and *defects,* i.e. *faults,* and is termed FMEA (Fault Modes and Effects Analysis) or alternatively FMECA (Fault Modes, Effects, and Criticality Analysis) if the *fault severity* is considered.

FMEA/FMECA consists of the systematic analysis of fault *modes,* their *causes, effects,* and *criticality.* All possible fault modes for the item considered, their causes and consequences are systematically investigated. For critical faults, the possibilities to avoid the fault and/or to minimize its consequence are analyzed and corresponding corrective (or preventive) actions are initiated. The criticality describes and quantifies the severity of the consequence of a fault and is designated by categories or levels which are function of the risk for damage or loss of performance.

The FMEA/FMECA is performed *bottom-up* by the designer in cooperation with the reliability engineer. The procedure is well established in *international standards* [6]. It is easy to understand but can become time-consuming for complex equipment and systems. For this reason it is recommended to concentrate efforts to critical parts of the item considered, in particular where redundancy appears.

3.4 Fault Tree Analysis FTA

A further possibility to investigate failure-causes-to-effects relationships is the *Fault Tree Analysis* (FTA) [7]. The FTA is a *top-down* procedure in which the undesired event, for example a critical failure at system level, is represented by AND, OR, and NOT combinations of causes at lower levels. An example of *Fault Tree* for a LED switched by two redundant transistors is given in Fig. 6.

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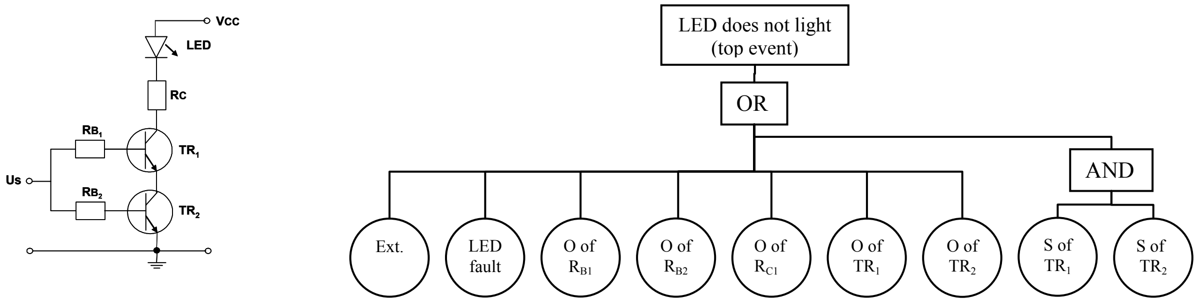

Figure 6: Fault Tree of a LED switching circuit with two redundant transistors TR_1 and TR_2, their base resistors R_{B1}, R_{B1}, and collector resistor R_C. O = open, S = short circuit, Ext. = external cause.

From a *complete and correct fault tree* it is possible to calculate the reliability function and the point availability of the corresponding system in the case of *parallel* (active) *redundancy* and *independent elements.*
Compared to the FMEA/FMECA, the FTA can take *external influences* (human and/or environmental) better into account, and handle situations where *more than one primary fault* (multiple faults) has to occur in order to cause the undesired event at system level. However, it does not necessarily go through all possible *fault modes.* Combination of FMEA/FMECA with FTA can be used to create *cause and effect diagram,* also called *Ishikawa* or *Fishbone* diagram*,* showing the relationship between identified causes and their single or *multiple consequences.*

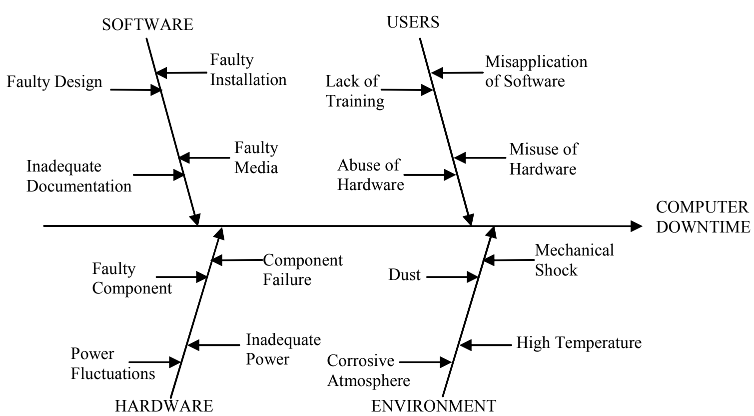

Figure 7: Example of cause and effect diagram

4. FAILURE RATE ASSESSMENT

The usefulness of the above presented reliability analysis methods is largely dependent on trusted failure rate data. The assessment of failure rates is therefore a key issue in reliability engineering. One has to be aware, that this is a difficult task because of the multitude and variety of electronic and optical components, the manifold of possible failure mechanisms, and the pace of technological progress. Three generic methods for failure rate assessment are presented in this section: collection and analysis of failure data of *reliability testing*, *physics of failure* analysis and extrapolation, and *empirical prediction models* based on the analysis of reliability field and test data.
Reliability testing for electronic or optic components which today have failure rates in the range of 10^{-10} to 10^{-7} h^{-1} can only be done in reasonable time by accelerated testing, i.e. tests in which usually an applied single operating condition, e.g. temperature, exceeds that encountered in the field application - but is still below technological or specification limits - and generates a higher than normal stress, e.g. mechanical stress due to the mismatch of the coefficients of thermal expansion of two bonded materials [8], [9]. The goal is to achieve genuine acceleration, i.e. shorten the time to failure without altering the involved failure mechanism or introducing new ones. The required acceleration model then enables the extrapolation of test results to the expected field stress. However such extrapolative predictions generated by accelerated testing models can raise serious concerns [10]. A main obstacle is the extrapolation of results gained with

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single-stress tests under carefully controlled laboratory conditions to the field application, i.e. an uncontrolled environment with combined stresses and extrinsic influences.

The *physics-of-failure* method describes the physical, chemical or other process mechanism which leads to failure. A large number of failure mechanisms have been investigated and for some physical explanations of degradation effects are proposed [11]-[13]. A top down physics-of-failure approach first identifies and quantifies the operational and environmental conditions acting on a component or system in terms of voltage, current, power, temperature, humidity, vibration etc. The profound analysis of the thermal, electrical, mechanical, or chemical material properties enable the description of material behaviour and degradation in response to the applied stress and thus the potential failure mechanism can be identified and modelled.

Empirical failure rate prediction models represent a statistical interpretation of failure data collected from field and accelerated tests [14]-[18]. These models provide equations for the calculation of a predicted failure rate λ. Data input consists of component specific parameters such as component type, technology, packaging material etc., operational parameters, e.g. temperature, applied voltage etc., as well as of parameters reflecting environmental impact. Such prediction models are based on the assumption that the failure rate of a large population of statistically identical and independent items can be often represented by a bathtub curve, see Fig. 3. Empirical models describe the phase b) in which the failure rate $\lambda_{(t)}$ is assumed to be approximately constant and which is between a phase of early failures I and a wear out phase III. The assumption of a constant failure rate is not in contradiction to the fact that failures are caused by failure mechanisms. It rather expresses that none of the various underlying failure mechanisms is dominant for some time period. During this equilibrium the random occurrence of failures can be statistically described by a constant rate.

The three methods introduced above each have their respective merits and are therefore used where their specific strength can be employed and the expenses can be justified [19]. However, especially empirical prediction models were under constant criticism mainly because of the high sensitivity on input data assumptions and the variability of prediction results between the different models [20], [21]. Since no convincing alternative was found efforts were undertaken by the IEEE in order to give guidance on how to use prediction models in a comprehensive reliability assessment. This lead to the IEEE standard 1413 with the objective to identify required elements for an understandable, credible reliability prediction, which will provide the users of the prediction sufficient information to evaluate the effective use of the prediction results [22], [23]. A reliability prediction according to this standard shall have sufficient information concerning inputs, assumptions, and uncertainty, such that the risk associated with using the prediction results would be understood.

Despite the debatable accuracy and other obvious disadvantages for the forecasting of field reliability *failure rate prediction models* provide useful results for the comparative evaluation of intrinsic failure rates. The effort and cost for the generation of reliability test data is considered to be considerably higher. Even though the physics of failure methodology would be suitable from a technical point of view it does not come into consideration due to its high complexity, cost and the weak applicability for complex systems.

Empirical failure rate prediction models emerged from the investigation of failures and efforts for their statistical description in military electronics applications. The earliest standard to appear was MIL-HDBK-217, *Reliability Prediction of Electronic Equipment*, which was developed by the United States Department of Defense (DOD) in the 1960s. Since then, MIL-HDBK-217 has been updated several times, with the most recent being revision F Notice 2, released in February 1995. Although the DOD has discontinued updates of MIL-HDBK-217, this standard is still widely used in military and commercial applications throughout the world. Other models mainly for telecommunication electronics were developed and some were standardized.

The five most important models MIL-HDBK-217 [14], Telcordia SR332 [15], IEC 61709[16], IEC TR 62380 [17], and FIDES [18] are briefly characterized in table 1.

Table 1: Main features of failure rate prediction models

Model	MIL-HDBK-217F N2	Telcordia SR 332	IEC 61709	IEC TR 62380	FIDES
a) Originator	US Dept. of Defense	Emerged from MIL-HDBK217	Emerged from DIN standard	France Telecom RDF2000	Airbus Industries, Thales
b) International Standard	no	no	yes	yes	no
c) last update / continuation	1995 / no	2001, not clear	1996, not clear	2000, yes	2004, yes
d) Base failure rates	yes	yes	no	yes	yes
e) Temperature cycles considered	no	no	no	yes	yes
f) Lifetime models	no	no	no	yes	no
g) range of use	Military, all industries	Mainly Telecom	All industries	Mainly Telecom	Avionics, Military

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Only models IEC TR 62380 and Telcordia SR 332 cover optical components in some depth. However, the models are very basic consisting of a base failure rate and a multiplier accounting for temperature influence, mostly following an Arrhenius law (see section 5).
IEC TR 62380 in addition provides life expectancy models for various types of light emitting diodes and optocouplers, Fig. 8. In particular it is the only model which provides a comprehensive consideration of temperature and temperature cycles and it is the only model including the assessment of the lifetime of components with a lifetime limitation. Tables 2 to 4 give an overview of base failure rates λ_0 of the Telcordia SR-332 and the IEC TR 62380 model.

Table 2: Base failure rates, Telcordia SR-332, ambient temperature 40°C

Device Type	Failure Rate [FIT] controlled (uncontrolled) environment
Fiber Optic Laser Module*	1000 (1500)
Fiber Optic LED Module*	240 (1100)
Fiber Optic Detector Module*	500 (1400)
Fiber Optic Coupler/Splitter	180 (725)
WDM passive	550 (1500)
Optical Isolator	110
Optical Filter	1500
Single LED/LCD Display	3
Phototransistor, -Detector	60, 15
Photodiode, - Detector	15, 10
Light sensitive Resistor	20

*a module is a small packaged assembly including a laser diode/LED/detector and means for electrical connection and optical couplings

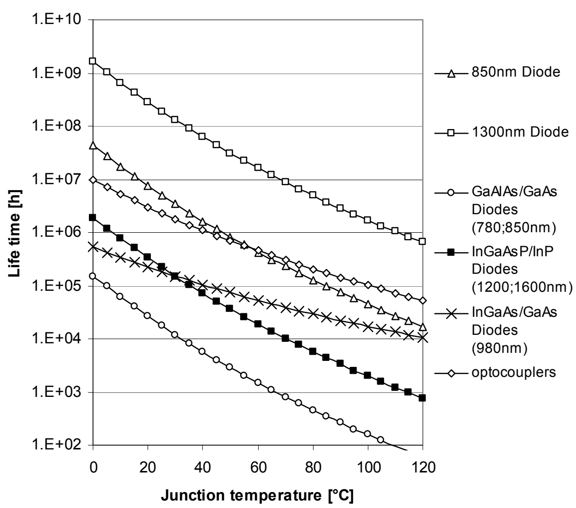

Figure 8: Life time of LEDs as function of junction temperature, IEC TR 62380

Table 3: Base failure rates of passive and miscellaneous optic components, IEC TR 62380

Component	λ_0 [FIT]
Attenuators: Bulk / fusion splice/ fusion splice >10dB / pasted	2 / 2 / 10 / 10
Fusing-stretching couplers: 1 to 2 / 1 to n with n <6	25 / 50
Integrated optical couplers 1 to n	60
Multiplexer and Demultiplexer Fusing-stretching 1 to 2 / 1 to n / micro-optic	25 / 50 / 60
Connectors, 1 optical contact	5
Jumper or optical cord, 2 optical contacts and fiber	10
Optical fiber (cable), per 100km or section (any length)	500
Doped optical fiber, Si matrix (5 to 30m)	1
LiNbO3 modulator	1000
Isolator	10
Accordable filter	
Bragg array filter	
Optical commutator el.mech. with mirror or integrated with prism	200
VCSEL 840nm	300

Table 4: Base failure rates optical modules, IEC TR 62380

Material	Module type	λ_0 [FIT]
GaAlAs/GaAs, 0.8μm	Elementary emitter modules	3000
InGaAs/InP 1.2-1.6μm	Elementary emitter modules without (with) electronics	40(60)
InGaAs/InP 1.2-1.6μm	Emitter/receiver module, with Laser PIN and electronics	80
InGaAs/InP 1.2-1.6μm	Integrated modulator laser module	100
InGaAs/InP 1.48μm	Pump laser module, p≤100mW / p>100mW	200/850
InGaAs/GaAs 0.98μm	Pump laser module	1000
Si 0.7-1.1 μm / InGaAs 1.2-1.6μm	PIN Diodes (PIN modules + electronics)	5 / 10 (30)
Si / Ge / InGaAs	APD Diodes (APD modules + electronics)	20/40/80 (100)
Elementary fibered LED module (+driver)		100(130)
Emitter/Receiver module, fibered LED + PIN (+APD) + electronics		180(200)
Optocouplers		10-100

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5. QUALIFICATION AND RELIABILITY TESTING

Components, materials, and assemblies have a great impact on the quality and reliability of the equipment and systems in which they are used. Their *selection and qualification* has to be considered with care, especially when new technologies are introduced, or important redesigns or process changes are undertaken. Besides cost and availability on the market, important selection criteria are the *intended application, technology, quality, long-term behaviour* of relevant parameters, and *reliability.*

A *qualification test* includes *characterization* at different stresses (for instance electrical and thermal for electronic and optical components), *environmental tests, reliability tests,* and *failure analysis.*

The purpose of a *qualification test* is to verify the *suitability* of a given item (material, component, assembly, equipment, system) for a stated application. Qualification tests are often a part of *a release procedure.* For instance, prototype release for a manufacturer and release for acceptance in a *preferred list (qualified parts list)* for a user.

The aim of a *reliability test* for electronic components is to obtain information about the failure rate, long-term behaviour of critical parameters, and the effectiveness of screening to be performed at the incoming inspection. The test consists in general of a *dynamic burn-in* with electrical measurements and *failure analysis* at appropriate time points, also including some components which have not failed to check for degradation. The number of devices under test can be estimated from the *predicted failure rate.*

With the failure rate λ of electronic and optic components in the range between 10^{-10} and $10^{-7}h^{-1}$, and that of assemblies in the range of 10^{-7} to $10^{-5}h^{-1}$ reliability testing usually has to be accelerated, see section 4. The *acceleration factor A, i.e.* the quantitative relationship between degree of activation and extent of stress is determined via specific tests. Many electronic and optic component *failure mechanisms* are activated through an increase in *temperature.* Calculating the acceleration factor *A,* the *Arrhenius model* can often be applied over a reasonably large temperature range (for instance about 0 to 150°C for ICs). The *Arrhenius model* is based on the Arrhenius rate law [24], which states that the rate λ of a simple (first-order) chemical/physical reaction depends on temperature T and activation energy. Assuming that the event considered occurs when the reaction has reached a given *threshold,* and the reaction time dependence is given by a function *r(t),* then the relationship between the times t_1 and t_2 - necessary to reach a given level of the reaction at two temperatures T_1 and T_2 - can be expressed as $\nu_1 \, r(t_1) = \nu_2 \, r(t_2)$. Furthermore, assuming $r(t) \sim t$, i.e. a linear time dependence, it follows that $\nu_1 \cdot t_1 = \nu_2 \cdot t_2$. By transferring this deterministic model to the failure rates λ_1 and λ_2 or to $MTTF_1$ and $MTTF_2$ at temperatures T_1 and T_2, it is possible to define an acceleration factor $A=MTTF_1/MTTF_2$, or $A=\lambda_2/\lambda_1$ expressed by

$$A = e^{\frac{E_a}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} \qquad (7)$$

where E_a *(in eV) is* the activation energy, *k* is the Boltzmann constant ($k=8.6\ 10^{-5}$eV/K), and T the absolute temperature in Kelvin. Eq. 8 can be reversed to give an *estimate* E'_a for the activation energy E_a based on $MTTF'_1$ and $MTTF'_2$ obtained from two life tests at temperatures T_1 and T_2. To verify the model, at *least three tests* at T_1, T_2 and T_3 are necessary. Activation energy is highly dependent upon the particular *failure mechanism* involved. High E_a values lead to high acceleration factors. For constant failure rates λ, the acceleration factor λ_2/λ_1 can be used as a multiplier in the conversion of the cumulative operating time from stress T_2 to stress T_1.

Another model for time compression resulting from an increase in temperature was proposed by Eyring [24], [25]. The generalized Eyring model led to accepted acceleration models for failure mechanisms like electromigration (8a), corrosion (8b), and voltage stress (8c):

$$A = \left(\frac{j_2}{j_1}\right)^m e^{\frac{E_a}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} \quad (8a) \qquad A = \left(\frac{RH_2}{RH_1}\right)^n e^{\frac{E_a}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} \quad (8b) \qquad A = e^{\left(C_0+\frac{E_a}{kT}+C_1\cdot\frac{V}{V_{max}}\right)} \quad (8c)$$

where j=current density, RH=relative humidity, and V=voltage, respectively.

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6. EXAMPLES

6.1 Optical Cross Connect

Availability analysis of an optical cross connect OXC capable of switching 16 wavelength channels is performed using Monte Carlo Simulation [26]. The OXC is based on 4 pieces of 4×4 InP laser amplifier gate space-division switches. Each switch consists of 24 laser amplifiers whose combination determines its failure rate depending on the system requirements [26].

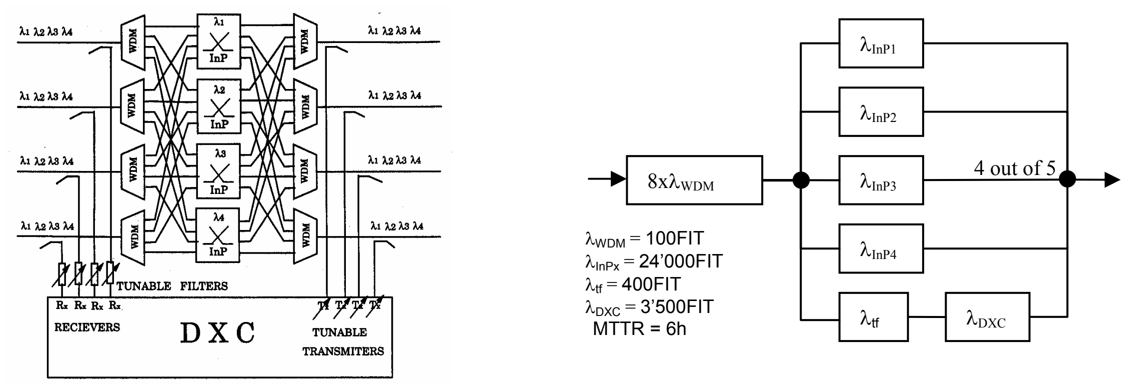

Figure 9: OXC system architecture (left) and resulting reliability block diagram (right)

Each of the four input and output fibers is a wavelength–multiplexed link carrying four wavelength channels. The optical signal on each input fiber is first divided by a beam splitter in two parts. The first one is connected to the wavelength division demultiplexer WDM that distributes the four wavelength channels to the respective switch. The second one is passed through tunable filters TF to the digital cross connect DXC. The DXC contains four receivers and four tunable transmitters and can be used for regeneration of the optical signals or as the opto-electrical interface in the case of originating or terminating traffic. Furthermore it represents a redundancy for failures of one of the four switches.

Based on the failure rates and MTTR given in Fig. 9, the steady state unavailability results as $5 \cdot 10^{-6}$, equal to 2.6 minutes per year, or a corresponding MTTF of 137 years. Sensitivity analysis, i.e. analysis of system availability performance with varying failure and repair rates of components, shows that the availability of the OXC can be best improved by using more reliable WDMs, because they are a purely series element in the RBD, or in other words a single point of failure.

6.2 Optical network availability analysis

Common requirements are that a connection in an optical telecommunication network is available 99% to 99.999% (five 9s) of the time. Five 9s correspond to a connection down time of about 5 minutes per year. Physical connection availability is a key factor for the establishment of different service priority classes offered by providers commonly designated as platinum, gold, silver etc. which are related to restoration speed and down time.

In order to meet the availability requirements networks are designed survivable, i.e. they are able to continue providing service in the case of a single failure [27]. The involved techniques of protection and restoration use pre-assigned or dynamically assigned spare capacity within the network enabling the rerouting of the affected traffic around the failure.

Complex repairable structures are often represented by reliability block diagrams. For network connection availability analysis the blocks represent spans S of the connection and are characterized by their respective constant failure rate λ and constant repair rate μ. The term span is used to describe the physical connection between two adjacent nodes. A span consists of the fiber optic cable and a number of optical amplifiers (OA) depending on the length of the span. We have assumed that bidirectional OAs with a failure rate λ_{OA} are located every 50 kilometers on a span, thus an optical amplifier spacing constant $C_{OA} = 0.02$ per kilometer. The failure rate of a span λ_S is therefore its length L_s multiplied by the sum of cable failure rate per kilometer λ_{cable} and optical amplifier failure rate per kilometer:

$$\lambda_S = L_s \times (\lambda_{cable} + C_{OA} \times \lambda_{OA}) \qquad (9)$$

Path protection is the mechanism that automatically switches the traffic from the working path through a predetermined and (node-) disjoint path connecting start and end node in case of any span or node failure. Path protection can be

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implemented as 1+1, 1:1, or 1:N. In the case of 1+1 , also designated as 1+1 Automatic Protection Switching (APS), traffic is transmitted simultaneously on both paths, but one path is selected for transmission usually based on the quality of the signals. In case of failure the receiver simply chooses the signal of the protection facility. 1+1 APS is therefore very fast and requires no signalling between source and destination nodes.

Because working path W and protection path P are diverse and spare capacity is not shared within the network for 1+1 APS, the availability of a connection is the product of the sum of unavailabilities of spans i along the working path and the sum of unavailabilities of spans j along the protection path ($i \neq j$):

$$U_{conn}^{APS} = \sum_{i \in W} U_i * \sum_{j \in P} U_j \qquad (10)$$

Unavailability figures can be translated to handier units such as down time per year (hour/year) and loss of traffic per year (Gb/year).

If $EDC_{s,t}$ represents the expected down time per year for a connection between nodes s and t, then

$$EDC_{s,t} = U_{conn}^{s,t} * 365 * 24 , \qquad s,t \in N \qquad (11)$$

where N is the set of nodes in the network. Once we have $EDP_{s,t}$ for each connection, we can define the average connection downtime in a network, i.e. average expected downtime per year of all connections, AEDC (hour/year).

$$AEDC = \frac{1}{|N|(|N|-1)} \cdot \sum_{(s,t) \in N^2 | s \neq t} EDP_{s,t} \qquad (12)$$

The availability of all connections of a pan-European network consisting of 28 nodes and 41 spans is analyzed based on formulas (9) to (12). The total length of network is 25640km, the average length of span is 625km. Node failures are not considered.

Calculations are performed assuming a low and a high failure rate for λ_{cable} for the fiber optical cable. The two values of 114FIT/km and 570FIT/km are in a range observed in the field, i.e. failure rates comprise also extrinsic impacts (e.g. dig-outs) and therefore are higher than the intrinsic failure rate of fiber optical cables which are in the range of a few FIT/km, see also Table 4. The lower failure rate can be assigned to a physically well protected cable in a duct, the higher failure rate to a cable exposed to higher extrinsic stress, e.g. aerial optical cables. In addition, two values for the $MTTR_S$ of spans are chosen. An $MTTR_S$ of 24h can be considered as an average value in long haul networks. The shorter $MTTR_S$ of 5h is assumed to result from the on-line monitoring of optical parameters for each fiber span due to faster failure localization. Moreover it can be assumed that degradation of fibers and optical amplifiers along a span can be observed before failure and preventive maintenance will be initiated timely. Thus, the following scenarios are investigated:

Table 5 Reference reliability parameters, C_{OA}=0.02 km^{-1} and λ_{OA}=2500 FIT for all scenarios a)-d)

	a)	b)	c)	d)
λ_{cable}	114FIT/km	114FIT/km	570FIT/km	570FIT/km
$MTTR_S$	5h (monitoring)	24h (no monitoring)	5h (monitoring)	24h (no monitoring)

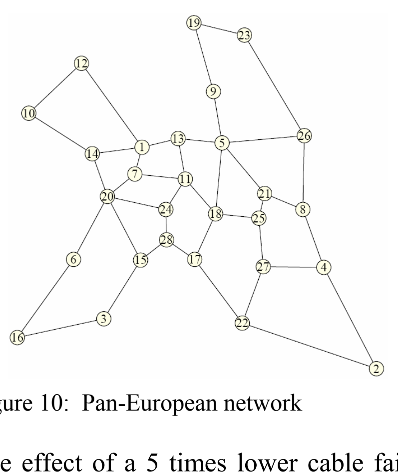

Figure 10: Pan-European network

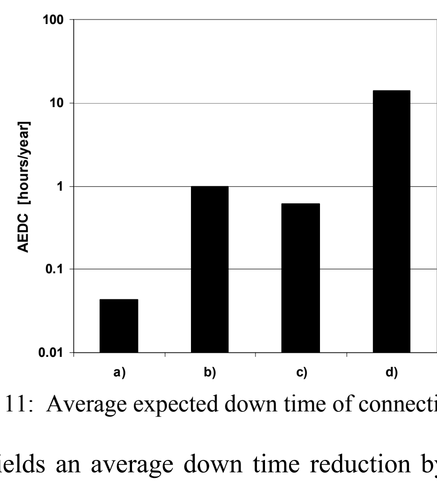

Figure 11: Average expected down time of connection

As a result, the effect of a 5 times lower cable failure rate yields an average down time reduction by a factor of 14, whereas a 5 times lower $MTTR_S$, i.e. the benefit of monitoring, reduces average down time by a factor of 23.

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6.3 Fiber Bragg grating sensors for infrastructure monitoring

In Winterthur, Switzerland, a stay cable bridge of length 120m, the Storchenbrücke, with a new suspension scheme was built in 1996 [28],[29]. It was for the first time that on a major bridge two cables were made of 241 CFRP wires of diameter 5mm. The fiber Bragg grating FBG based sensor system is operational since April 1996.

For each monitored cable a fiber with seven FBG was used as shown in Fig. 12. The fiber sensors were adhered with epoxy adhesive to the surface. Only the FBG A1, A2 and A3, are used to record strain of the cable. The others are attached to unstrained CFRP wires and serve for temperature compensation and self monitoring as explained below. The FBG D1 and D2 are attached unstrained to the wires whereas F1 and F2 are adhered in a pre-strained state to monitor possible creep.

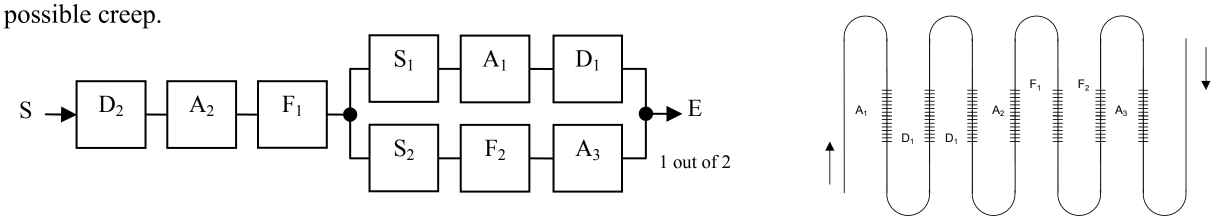

Figure 12: Reliability block diagram of the FBG system on the Storchenbrücke, maximum requirements, access from both sides (left), and meander structure of sensor fiber accessible from both sides (right).

First, the best epoxy adhesive (out of selected samples) was identified by an accelerated aging test. However, any documented field behavior at that time was not known. So far, i.e., since nearly 10 years, none of the FBG failed. Of 14 FBG 10 are strained and did not fail during 9.6 years. The cumulative operating time is T_k=14·9.6·365·24h=1'177'300h. Since the number of failures n in this time is zero the MTTF=T_k/n is calculated setting n to 0.5 yielding roughly 2Mio. hours as MTTF or 500 FIT as failure rate for a sensor. The failure rate of the splices on both ends of a fiber is taken as λ_{sp}=10 FIT from Table 3.

The *maximum requirement* function is defined as: $(A_1 \cup A_2 \cup A_3) \cap (D_1 \cup D_2) \cap (F_1 \cup F_2)$ for each cable, i.e. at least one strain sensor (A_i), one temperature sensor (D_i), and one pre-strained (and temperature) sensor for diagnostic purpose (F_i) must be functional. The corresponding RBD in Fig. 12 considers the fact that access to the FBG is possible from both sides of the sensor fiber, which is reflected in the series structure of D_2, A_2, and F_1 through which the light has to be transmitted in any case. A less stringent requirement – *minimum requirement* - is $(A_1 \cup A_2 \cup A_3) \cap (D_1 \cup D_2 \cup F_1 \cup F_2)$, which leads to simpler RBDs of both, the case with access to both sides and that with access to only one side of the sensor fiber.

The consequences of the above definitions of required functions and variations in failure rates of components A, D, and F by a factor of 2 and 10 on system reliability R(t) and on the resulting $MTTF_s$ are shown in Fig. 13 and Table 6. The vertical distance of curves b) and d) or curves f) and g) represents the impact of the light access on both sides of the sensor fiber. The benefit in terms of MTTFs is an increase by factors of 1.3 and 1.5, respectively. The impact of lower failure rates under otherwise identical requirements and access conditions is represented by the vertical distances of curve f) to curves e) and c) with $\lambda_s/2$ respectively $\lambda_s/10$ for A2, D2, F1 instead of λ_s. Here the benefit in terms of MTTFs is an increase by a factor of 1.5 with $\lambda_s/2$ respectively a factor of 2.5 with $\lambda_s/10$ for the most critical components A2, D2, and F1.

No failure occurred in 130 cumulated FBG operation years at the Storchenbrücke. As shown, high reliability over decades can be achieved by a combination of hardware redundancy, redundancy in the measurement process, i.e. light access from both sides of the fiber system, and reliable components with realizable failure rates in the range of 100 FIT.

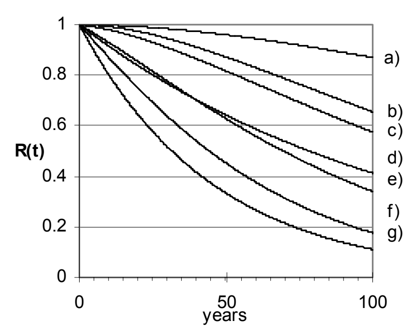

Figure 13: Reliability R(t) for Storchenbrücke

Table 6: Resulting $MTTF_s$ for cases a) to g)

Require-ment	Access	Failure rates*	$MTTF_s$ [h]
a) min	2 sides	$\lambda_s/2$ for all D, A, F, λ_{sp}	$3 \cdot 10^6$
b) min	2 sides	λ_s, λ_{sp}	$1.5 \cdot 10^6$
c) max	2 sides	$\lambda_s/10$ for A2, D2, F1, λ_{sp}	$1.3 \cdot 10^6$
d) min	1side	λ_s, λ_{sp}	$1 \cdot 10^6$
e) max	2 sides	$\lambda_s/2$ for A2, D2, F1, λ_{sp}	$0.8 \cdot 10^6$
f) max	2 sides	λ_s, λ_{sp}	$0.5 \cdot 10^6$
g) max	1 side	λ_s, λ_{sp}	$0.4 \cdot 10^6$

*λ_s for all elements A, D, F is 500 FIT, λ_{sp} for splices S is 10 FIT

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6.4 Reliability of fiber and fiber sensors

The top down approach as shown in example 6.3 allows estimating the long term performance of planned sensor systems. Its relevance and validation, however, depends on the FIT values of the individual components. To make the most accurate estimation it is necessary to investigate failure mechanisms in a bottom up approach, i.e., for the individual components [30]-[32]. If the failure mechanisms are known and understood the temporal behavior can be modeled and lifetime estimation is possible, i.e. FIT values can be given. Fig. 14 summarizes causes for fiber degradation and failure. There are mechanisms that attack the fiber, the coating, interfaces like fiber coating interface or the linkage of the fiber to the object or alter the FBG.

Stress corrosion of optical fibers due to crack growth under load can lead to mechanical failure. The currently accepted power law lifetime model requires many fiber tests to obtain accurate model parameters for lifetime estimation being it under static or cyclic load, Fig. 15a. Even under conditions close to zero-stress, optical fibers suffer and fracture strength decreases, which can be modeled with help of an Arrhenius law, Fig. 15b. However, for modern fibers static strain up to 2% is acceptable over lifetime of civil engineering structures, given that during sensor fabrication and installation no additional surface cracks were initiated.

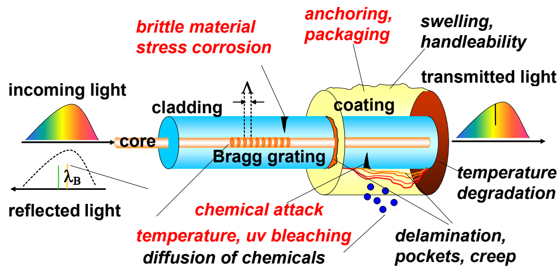

Figure 14: Failure mechanisms of optical fibers.

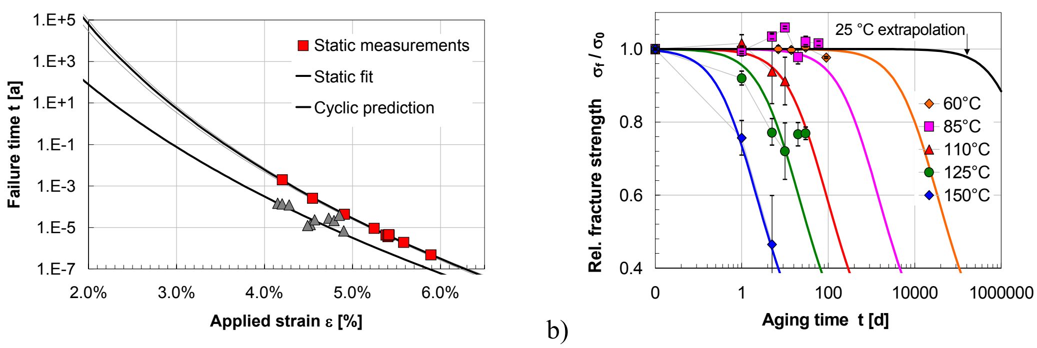

Figure 15: Fiber life time estimation by model extrapolation after accelerated aging tests: a) aging by stress, and b) aging at low strain but high relative humidity (85% r.H.) and increased temperature.

FBGs fabricated in pristine fibers often show insufficient fracture strength for sensor applications because the fibers have to be stripped and re-coated. Their fracture strength distribution often is bi-modal in contrast to the uni-modal Weibull-distribution of pristine fibers, Fig. 16a, and lifetime is significantly reduced, Fig. 16b. By high-strength proof testing, bad samples can be removed and lifetime can be increased, Fig. 16b. Single shot FBGs, fabricated directly on the draw tower, were shown to have fracture strength close to pristine fiber.

FBGs have to be pre-annealed at a temperature higher than operation temperature. If not, their refractive index modulation and increase induced during UV-illumination in fabrication can decay with time leading to a reflectivity decrease and a wavelength shift, which reduce measurement accuracy. With annealing experiments as shown in Fig. 17a (necessary for each grating type) decay behavior can be predicted and proper pre-annealing allows the reduction of wavelength drift to an acceptable value within the required lifetime, Fig. 17b.

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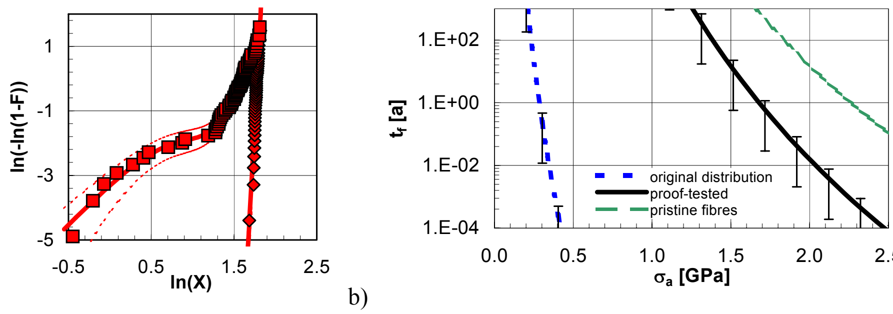

Figure 16: Weibull-distribution (cumulative density F versus normalized fracture load X) of fibers (◊, uni-modal distribution) and FBGs manufactured by stripping-illuminating-recoating (□, bi-modal distribution) (a) and expected life time under stress for FBGs as delivered, proof-tested FBGs (bad samples eliminated), and pristine fiber (b).

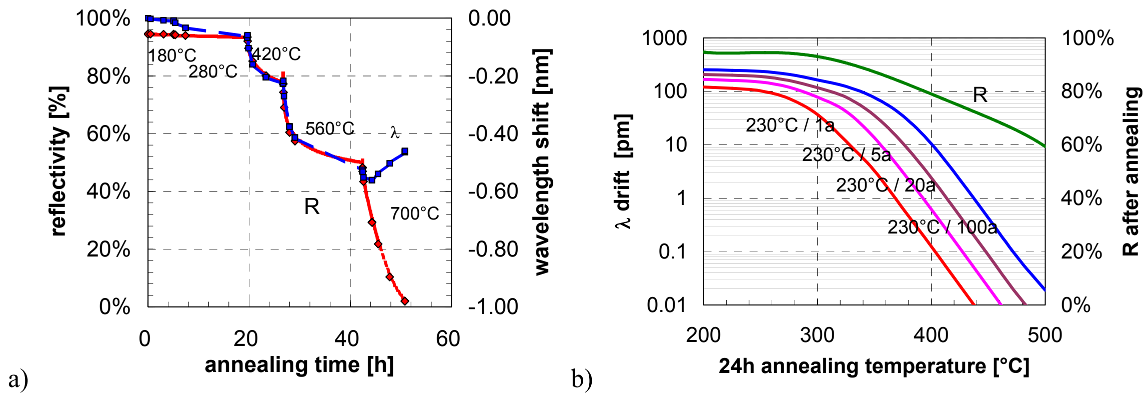

Figure 17: Decay of FBG with increasing temperature (a) and annealing temperature during 24 h for FBGs with corresponding wavelength drift at high (230 °C) operation temperature (b).

7. CONCLUSION

The use of fiber optic networks in communications has exploded since the discovery of its practicality. Optical components are key elements in today's telecommunication and sensor industry. With the emergence of all-optical telecommunication networks they will replace or redundantize electronic components due to better performance to cost ratio. While intrinsic reliability characteristics and lifetime behaviour - mainly of passive optical components such as fibers and sensors - has been studied intensively, reliability prediction and physics of failure models are still fragmentary especially for active optical components. As pointed out in this paper, the assessment of failure rates is crucial for all kinds of reliability and availability analysis. It is therefore essential to develop a comprehensive and profound reliability data handbook dedicated to optical components.

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