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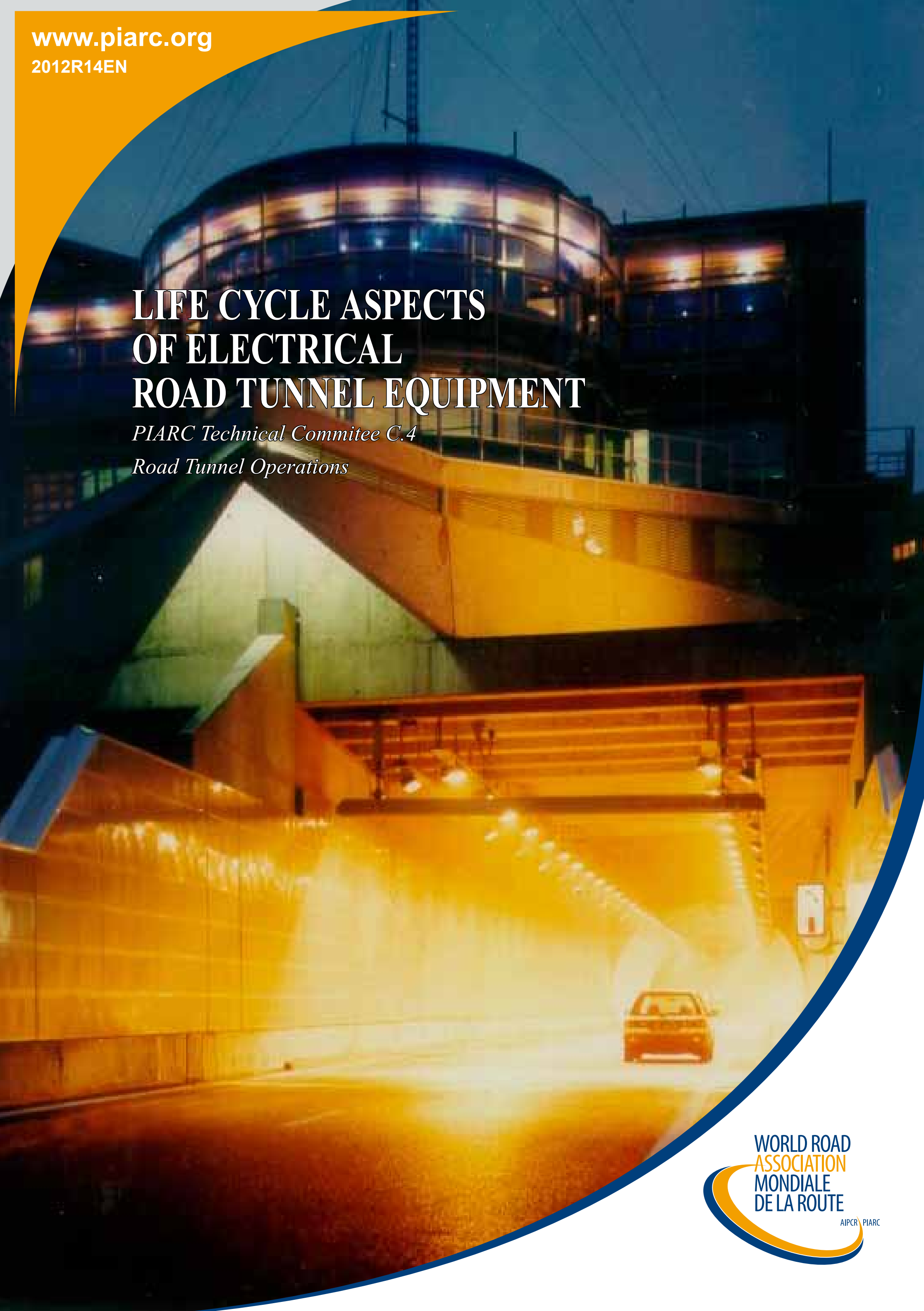

LIFE CYCLE ASPECTS OF ELECTRICAL ROAD TUNNEL EQUIPMENT

PIARC Technical Commitee C.4

Road Tunnel Operations

WORLD ROAD ASSOCIATION
MONDIALE DE LA ROUTE
AIPCR PIARC

STATEMENTS

The World Road Association (PIARC) is a nonprofit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2008 – 2011 approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.

Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organizations or agencies.

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CONTENTS

SUMMARY

Life Cycle Cost Aspects (LCC-Aspects) have become an important task for private tunnel owners, as well as government agencies. Well-founded knowledge about life cycles serves to optimise investment costs during the early stages of designing a system. In addition, it is helpful in organizing the periodical maintenance of the technical equipment.

This report describes how LCC-Aspects support the design of equipment as well as maintenance concepts. Having in mind that investment decisions are often technology-driven and that equipment costs have increased dramatically in the past years, this report helps to understand the life cycle process and deals with the impact of the ageing of material.

An international survey was conducted in order to gain an insight on how tunnel owners behave today regarding system maintenance and component replacement. Twenty seven (27) answers from ten countries worldwide showed that average lifetime of equipment varies between 10 to 25 years, depending on the system. Comparing the results, it was found that there are big differences in equipment lifetimes, which is not surprising: electronic systems, monitoring equipment like SCADA[1]-systems have a limited lifetime while mechanical and energy supply/ cabling systems have longer life expectations, which reach 20 years and more. Surprisingly low is the life span of illumination equipment – the impact of the tunnel atmosphere will probably deteriorate the material quicker than expected. The rest of the typical tunnel systems like safety and signing equipment are positioned in the middle of the scale, with average lifetime of approximately 15 years.

This report gives some theoretical background on the LCC-Aspects, which could be of some help for further investigations. A special focus is placed on the surrounding conditions, which have a high impact on the ageing process. As such keeping temperatures low in technical centres is basically a *"good investment"*. For two typical tunnel systems – illumination and SCADA – further details are given.

This report shows how useful it is to consider factors that influence life expectancies of systems and components such as temperature, humidity, mechanical stress and environment. The influence of temperature is often underestimated. Using the Arrhenius equation, it can be shown that ageing is highly affected by the ambient temperature. Particular attention therefore has to be paid to environmental temperature in equipment and control rooms.

[1] Supervisory Control And Data Acquisition systems

PURPOSE

In recent years, Life Cycle Cost Aspects (LCC-Aspects) have become an important tool for private tunnel owners, as well as government agencies. On the one hand, well-founded knowledge about life cycles serves to optimise investment costs during the early stages of designing a system, on the other hand,it is also helpful in organizing the periodical maintenance of the technical equipment.

This report shall outline how LCC-Aspects support the design of equipment as well as maintenance concepts. In order to study these relationships, the following these are tested:

- investment decisions are often technology-driven and do not take into account life cycle aspects in a sufficient way;
- equipment costs have risen dramatically in the past years: more and more complex systems are going to be used in tunnels;
- knowing life cycles helps to reduce maintenance costs and improves safety;
- knowing life cycles requires understanding of ageing processes;
- understanding the ageing processes of materials, devices, components helps selecting the systems in a cost-effective way.

GOAL

The report discusses a methodology how to use LCC-aspects in design and maintenance. It is aimed to reach following goals:

- show how equipment ages,
- investigate typical life cycles of tunnel equipment,
- show influence of temperature conditions on life cycles,
- show influence of mechanical stress on life cycles,
- show importance of selection of system components on life cycles,
- show influence of maintenance strategies on life cycles,
- show influence of life cycles on replacement costs.

LIMITATIONS OF THE STUDY

There is no detailed cost analysis given in the study. The report only shows in an exemplary way how the expected lifetime of equipment influences the tunnel operation and redesign costs.

Further, the focus is directed on some typical aspects of technical equipment used in tunnels, whereas some findings are of a rather general nature. Because not all tunnel systems can be dealt with, the subject is discussed on the base of a few typical examples.

1. TERMINOLOGY

To facilitate international communication and comparison a minimal set of terms is desirable. Such a terminology is proposed and defined (in the following table).

For reference, the ISO 6707-1, Building and civil engineering – Vocabulary – Part 1: General terms can be used.

DESCRIPTION	DEFINITION
Ageing Process	The third or last portion of the bathtub curve and identifies the end of the system, equipment or component end of useful life.
Arrhenius-Equation	Formula for the temperature dependence of the rate constant, and therefore, rate of chemical reaction used to model the temperature effect on the rated life of electrical equipment.
Availability	Ability of an item to be in a state to perform a required function under given conditions at a given instant of time or during a given external resources are provided.
Bathtub Curve	A widely used reliability engineering curve to describe failure rates over time. The curve is comprised of three parts: Early Failures – Constant Failures – Wear-out Failures.
Burn-in-Period	The process by which system components are exercised prior to being placed in service (and often, prior to the system being completely assembled from those components). The intent is to detect those particular components that would fail as a result of the initial, high-failure rate portion of the bathtub curve of component reliability.
Cabling/Wiring	Two or more wires running side by side and bonded, twisted or braided together to form a single assembly. A current carrying conductor used to power electrical equipment or transmit data signals from point to point.
CEN	European Committee for Standardization
Closed Circuit Television Systems (CCTV)	Video surveillance equipment including automatic incident detection (AID) cameras installed in the tunnel, centrally located video monitors located at a central location, pan/tilt/zoom equipment, video switchers, video recording equipment (VCR), AID software, AID processing equipment and communication network transmitting video signals between cameras and monitors.
Control Centre	A location where tunnel-operating personnel monitor the Traffic Incident Management System. Control Centre is generally staffed 24 hours per day, 7 days per week. Operators observe traffic conditions and implement required responses including coordination with outside agencies.
Corrective Maintenance	Maintenance performed to restore systems, equipment or components to proper operating conditions.

DESCRIPTION	DEFINITION
Energy Supply	Power distribution system including service equipment, transformers, low voltage control systems and associated cables/wiring used to power electrical, ventilation, lighting, communication/control systems and traffic control and surveillance systems for vehicular tunnels.
Failure Rate	The frequency with which an engineered system or component fails. The failure rate of a system usually depends on time, with the rate varying over the life cycle of the system.
IEEE	Institute of Electrical and Electronic Engineers
IEC	International Electrotechnical Commission
Illumination	Normal and emergency egress (life safety) lighting systems to allow motorists to travel safely through vehicular tunnels.
Infant Mortality	Premature failure of systems, equipment or components. The first portion of the bathtub curve.
ISO	International Organization for Standardization
Life Cycle (LC)	The notion that a fair, holistic assessment requires the evaluation of raw material production, manufacture, distribution, use, environment and disposal including all intervening transportation steps necessary or caused by the product's existence.
Life Cycle Costs (LCC)	The total discounted cost of installing, operating, maintaining and disposing of systems, equipment or components over a period of time.
Life Safety Systems	Protection, monitoring and occupancy systems installed in tunnels that are necessary to minimize danger to life caused by vehicle incidents and fire, including smoke, fumes, or panic. A system whose failure or malfunction may result in death or serious injury.
Maintainability	Ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources.
Maturity	The second or centre portion of the bathtub curve constant failure rate.
Mean Time Between Failures (MTBF)	The arithmetic mean (average) time between failures of a system or system component.
Mean Time To Failure (MTTF)	Average time between failures with the modelling assumption that the failed system is not repaired. This method is used for non-repairable products or components associated with systems.
Mean Time To Repair (MTTR)	The average time that it takes to repair a failed system or component.
Preventive Maintenance	Maintenance performed at predetermined intervals or in accordance with prescribed criteria (manufacturer's recommendations) and intended to reduce the probability of failure or degradation of system, equipment or component operation.

DESCRIPTION	DEFINITION
RAMS	Reliability-Availability-Maintainability-Safety. ISO 50126 is an international standard, used mainly for railway/signalling applications.
Reliability	Ability of a system or component to perform and maintain its required function under any given conditions for a given time interval.
Remote Control	Control systems to operate tunnel ventilation, power distribution, lighting and traffic control and surveillance systems from a central location or from a location away from the tunnel.
Safety	Safety is related in this report to safety equipment in tunnels, (fire detection, emergency telephones, air quality detection) that helps safe driving in normal and emergency situations
Scheduled/Planned Maintenance	Preventive maintenance performed in accordance with an established time schedule or established number of operations.
Service life	Period of time after installation during which a facility or its component parts meets or exceeds the performance requirements
Service life planning	The design process of preparing the brief and the design for the building and its parts to achieve the design life, for example in order to reduce the costs of building ownership, facilitate maintenance and refurbishment
Signing	Signs that are designed to have one or more informational, signals or warning messages to motorists. These messages may be displayed or deleted as required. Signs may be changed manually either locally or by remote control or by automatic controls that can sense the conditions that require the special pre-programmed message or messages.
SCADA	Supervisory Control and Data Acquisition Systems used to control and monitor the mechanical, electrical and traffic control systems using a computer based system from a central location.
Technique Rooms	Mechanical and electrical equipment rooms used for electrical distribution, ventilation, drainage and traffic surveillance and control equipment at tunnel facilities.
Useful Life	The expected life or the acceptable period of use in service for systems, equipment or components where it is economically feasible to maintain.
Ventilation	Mechanical fans used to maintain the environment within tunnels, to remove smoke and vehicle pollutants
Whole life costs (WLC)	All significant and relevant initial and future costs of an asset, throughout its life cycle, while fulfilling the performance requirements

2. INTERNATIONAL REQUIREMENTS

2.1. HIERARCHY OF STANDARDS AND GUIDELINES

The different levels for directives and standards are shown as follows.

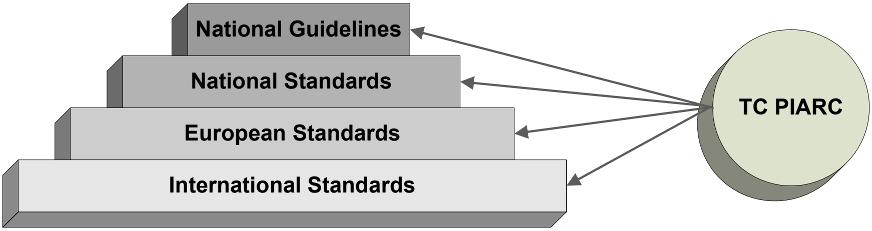

FIGURE 1 - TYPICAL LEVELS OF STANDARDISATION

The standardization can be pictured in form of a pyramid, including national guidelines, national standards, European standards and international standards.

- National Guidelines are specifically related to national requirements and are normally very detailed (e.g. RVS Austria, NFPA USA).
- National standards are legally binding norms and codes (e.g. DIN Germany, Ö-Norm Austria, AASHTO USA).
- There are "Inter-country/interstate" standards (e.g. European standards CEN, Federal Highway Standards FHWA USA).
- International standards are for worldwide application (e.g. ISO, IEC, IEEE).

2.2. THE EUROPEAN DIRECTIVE 2004/54/EC

The directive defines minimum requirements for construction and operation in European tunnels. The member countries of the European Union are obliged to put these requirements in their legislation within a defined period.

The directive was one of the first international quasi-standard for road tunnel safety and is applied not only in Europe.

2.3. THE ISO-STANDARD *"RAMS"*

The RAMS-Standard is a common norm/standard dealing with probability-related aspects of life cycles.

The application of the standard RAMS for a technical system means defining the requirements of the quality and life expectancy for subsystems and components.

All four elements of the RAMS standard (reliability, availability, maintainability, safety) are applicable to the technical requirements of systems used in road tunnels.

2.4. THE ISO-STANDARD 15686 ON SERVICE LIFE PLANNING

The standard is basically made and intended for buildings; however, it is also applicable for electrical equipment in tunnels.

The standard ISO 15686 establishes a systematic framework for undertaking service life planning of planned building or construction works throughout its life cycle. It also compares the remaining life cycle for existing buildings or construction works.

The ISO 15686 consists of the following parts:

Part 1: General principles
Part 2: Service life prediction procedures
Part 3: Performance audits and reviews
Part 4: Data requirements
Part 5: Life cycle costing
Part 6: Procedures for considering environmental impacts
Part 7: Condition assessment and feed-back of relevant durability data from practice
Part 8: Reference Service Life
Part 9: Inclusion of requirements of service life assessment and service life declaration in product standards
Part 10: Serviceability

2.4.1. General principles

The design brief limits acceptable life cycle cost. The service life of technical equipment in tunnels depends on the service life of each component. Service life planning is a process of estimation of future events. If the estimated service life of any component is less than the design life the functions have to be adequately maintained (e.g. by replacement or maintenance).

The service life planning should consider:

- the likely performance of components,
- the life cycle cost and environmental impact,
- operation and maintenance costs,

- the need for repairs, replacements, dismantling, removal, re-use and disposal,
- the construction of the whole system, installation and the maintenance of components.

The service life planning should be integrated into the building design process, so the estimated service life is a key-factor in the planning process.

The estimated service life depends on the data sources as shown in the following figure:

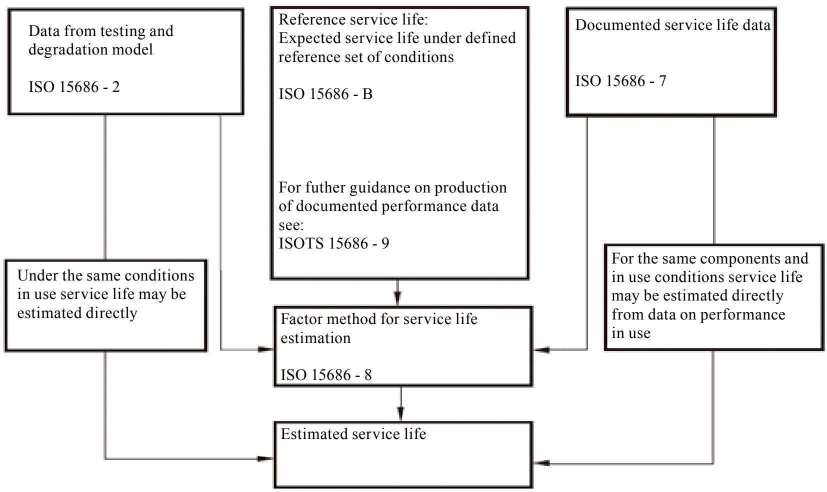

FIGURE 2 - APPROACHES TO SERVICE LIFE ESTIMATION IN ISO 15686

The quality as well as the reliability of this estimation depends on the data used to generate the service life estimation. In annex of part 1 the service life planning during a design process is described. The expression *"useful life"* – as used in this report – broadens the originally used expression "service life" with the aspect of economy.

2.4.2. Life cycle costing

In part 5 of this standard the life cycle cost (LCC) and the whole life cost (WLC) are described. The difference between these two approaches is that the WLC includes additional externalities, non- construction costs and income streams to LCC.

Life cycle cost includes the cost of construction, of operation, of maintenance and the cost of end-of-life. The LCC should also include consideration of special risks. LCC analysis may be used during following key stages:

- project investment and planning,
- design and construction,
- during operation,
- disposal.

The analysis is based on the client requirements and may be revised and clarified throughout the project life cycle. The LCC should contain the sum of the independent parts and the interaction between them. LCC analysis may be used to evaluate if higher acquisition costs are a good investment to lowering lifetime costs.

2.5. REFERENCES TO MAINTENANCE AND LIFE CYCLES

References to standards (extract):

ISO 15686	Buildings and constructed assets - Service life planning
IEC 60706	Maintainability of equipment
IEC 61709	Electronic components - Reliability - Reference conditions for failure rates and stress models for conversion
IEC 61508	Functional Safety
ISO 50126	RAMS: Reliability, Availability, Maintainability and Safety
EN 60300-3-3	Dependability management - Part 3-3: Application guide - Life cycle costing
EN 13306	Maintenance terminology
DIN 31051	Fundamentals of maintenance

References to PIARC-reports

PIARC 05.13.B-2005	Good Practice for the Operation and Maintenance of Road Tunnels
PIARC 05.06.B-1999	Reduction of Operating Costs of Road Tunnels
PIARC 2008R15	Urban road tunnels - Recommendations to managers and operating bodies for design, management, operation and maintenance

Beside these documents, the fundamental principle of planned maintenance (see PIARC.05.06.B-1999, Reduction of Operating Costs of Road Tunnels) is common practice.

3. MAINTENANCE AND LIFE CYCLES

3.1. INTRODUCTION INTO THE THEORY OF RELIABILITY AND AVAILABILITY

As a natural consequence, installations suffer break downs over time due to ageing, so that the maintainability of the system can get compromised. Maintainability describes all activities which aim to keep or restore the operability of a unit. When maintaining parts of a system, attention has to be paid, that the functioning of the overall system is ensured.

In order to optimise maintenance and to be better able to determine the ideal time for replacement, guidelines or a decision tool are required. Such decision-making aids take their origin in failure rates of typical installations as detailed in the following chapters. Failure rates can be used in a simple deterministic based maintenance strategy or in more advanced probabilistic maintenance strategies. Failure rates can be obtained from manufacturers or have to be monitored from structures in service.

In the following, the theory of failure rates as a help to determine maintenance and replacement strategies is briefly introduced.

The reliability of systems is illustrated as a function of operational time. It not only declines over time, but is also depending on the environmental conditions i.e. temperature, pollution, vibration, etc.

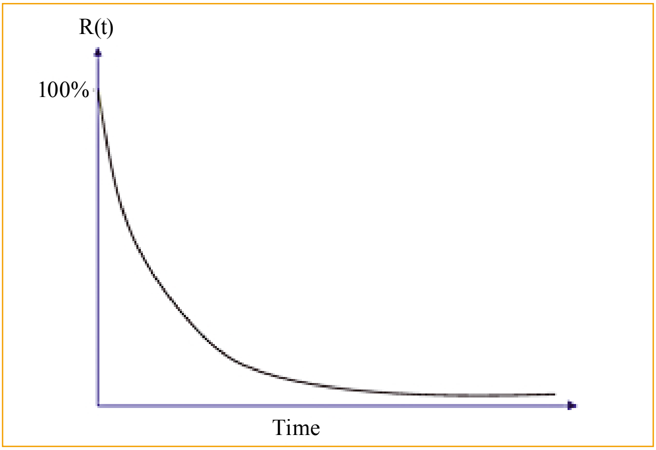

FIGURE 3 - RELIABILITY IN FUNCTION OF TIME

Reliability is expressed as R(t) and represents the probability of a system working without failures under given conditions over a certain period of time. In other words, reliability indicates the probability that a system does not fail in accomplishing its specific task. A failure arises when the considered unit stops fulfilling its purpose. The failure rate plays a decisive role in reliability analyses and describes the number of failures over a given time.

Reliability is represented by a logarithmic curve *(figure 3)* and expressed as follows:

$$R(t) = e^{-(\lambda_1+\lambda_2+\ldots+\lambda_n)t}$$

R Reliability [1]
λ Failure Rate [1/s]
n Number of units with different failure rates [1]
t Time [s]

In this equation λ stands for the failure rate (number of failures during a specified period) and n for the number of elements to be considered. It gets clear, that the overall reliability is dependent on the failure rates of all elements in the system. One key to keep a system in a reliable state is to design redundancies and include them into the operational process. If some components of a system should fail, such backups have the potential to heighten the reliability of a system because there are alternative paths for accomplishing a function.

The mean value of all periods where the system is functioning faultlessly (without failures) is usually called *"Mean Time To Failure"* (MTTF). Once the components break down they need to be repaired in order to resume their given task. The mean value of all repair times is named *"Mean Time To Repair"* (MTTR), which is of course depending on the repair organization (capability, staff size, mobilization, availability of replacement parts, etc.). These two expressions are further used to express the availability of a system, which is the probability that the considered system is performing as planned at a certain point of time, under given working conditions.

The availability of a system is defined as the quotient of the mean value of the time where the system is working as planned and the mean time between failures (MTBF = MTTF + MTTR)

$$A = \frac{MTTF}{MTTF + MTTR}$$

A Availability [1]
MTTF Mean Time To Failure [s]
MTTR Mean Time To Repair [s]

With the help of this equation it gets obvious that the system availability increases, if the MTTF can be prolonged while the MTTR is held at a constant level. The overall system availability is expressed in probabilistic terms, indicating the probability ($A < 1$) that the system is available at a specific time. Because every component of a system is susceptible to failure, the overall system availability is always less than 1. On the left side of *figure 4, following page,* the availability of a component which is not repairable is illustrated. Once the unit has failed, it needs to be replaced.

On the right-hand side of following figure, the same situation is shown for systems where the failed components can be repaired. This fact results in an *"up-and-down"* pattern of the operating state. The line is indicating the overall availability, which was determined from the relationship of MTTF and MTTR as illustrated above. It never reaches the state of *"total availability"* (as when the system is functioning faultlessly in *"up-periods"*) due to mathematical reasons.

In other words, the availability depends on the number of failures, the time between the failures and the time it usually takes to restore the normal operating state of the affected components.

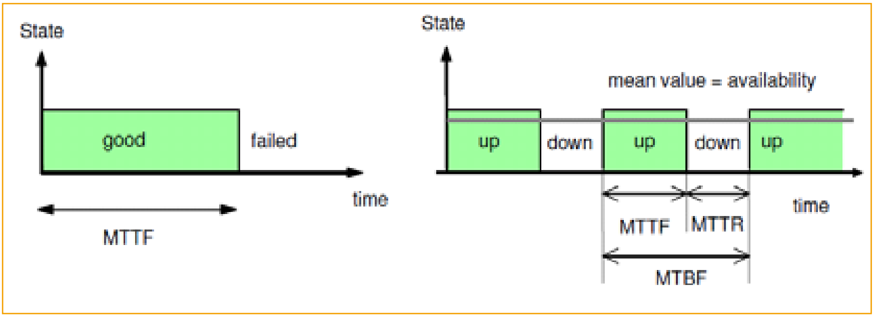

FIGURE 4 – RELIABILITY AND AVAILABILITY

The failure rate (λ) can easily be determined by life cycle investigations of a certain sample of identical items.

Using the example of a lighting system, the failure rate shall be ascertained from the life cycle information of a number of lamps. For a given time interval (e.g. 24 hours) the number of failed lamps is counted. As mentioned above, the failure rate is expressed as:

$$\lambda = \frac{\text{number of failed items during the interval}}{\text{number of remaining good items at the beginning of the interval}}$$

If the failure rate is depicted as a graph, following picture emerges *(figure 5)*.

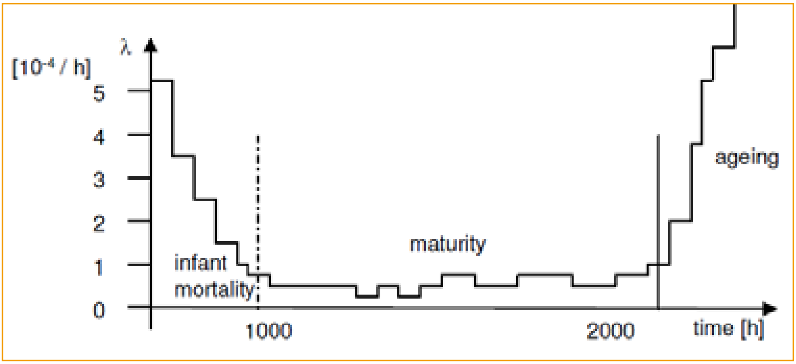

FIGURE 5 - EXPERIMENTAL FAILURE RATE

This graph is commonly known as *"bathtub curve"* and shows 3 typical sections.

In the first section called *"infant mortality"*, failures occur due to material defects, deficiencies or manufacturing problems. Some manufacturers perform special burn-in programs prior to delivery in order to minimize these early life-cycle failures.

The next section characterises the "maturity" and features an almost constant failure rate at a low level. For this area the relation is:

$$\lambda = \frac{1}{MTTF} \text{ or } \frac{1}{MTBF} \text{ for repairable systems}$$

λ Failure Rate
MTTF Mean Time To Failure
MTBF Mean Time Between Failures

The last section of the bathtub curve named *"ageing"* illustrates the end of a life-cycle, where the failures increase rapidly.

The bathtub curve starts again after replacement of a system component.

3.2. LIFE CYCLES AND MAINTENANCE STRATEGIES

In the following, other aspects such as life cycle of systems and good practice in maintenance strategies are considered.

3.2.1. Influence of Life Cycle Knowledge on Maintenance Strategies

The knowledge of a typical life cycle, as depicted in *figure 4*, assists in defining appropriate maintenance strategies.

After the early failure period – typically the warranty period – the failure rate stabilises during the service period. In this maturity phase, preventive maintenance is carried out according to a maintenance plan *(figure 6)*. As an example, this might incorporate the replacement of components whose life span is known because of the manufacturer's recommendations.

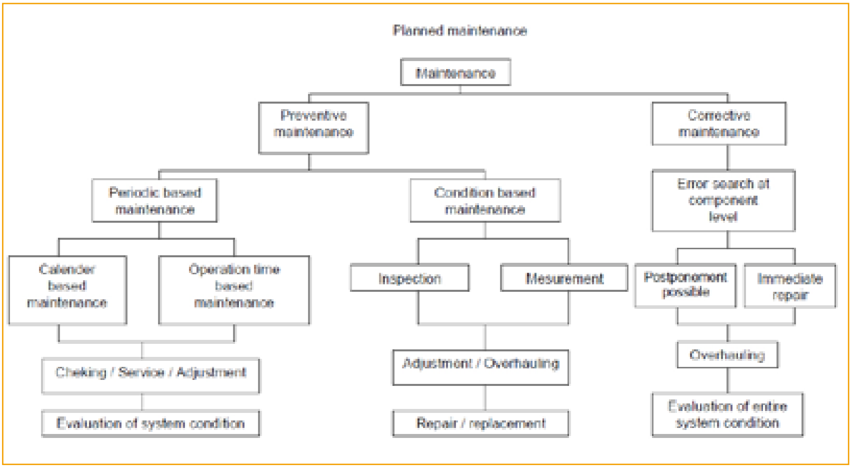

FIGURE 6 – SCHEDULED OR PLANNED MAINTENANCE

3.2.2. Maintenance Strategies

Besides the knowledge on life cycles, the maintenance strategy is also depending on the following factors:

- technical performance of the system;
- the environmental influences;
- the available funding.

With reference to a road tunnel, a selection of different environmental influences is outlined in the *figure 7, following page*:

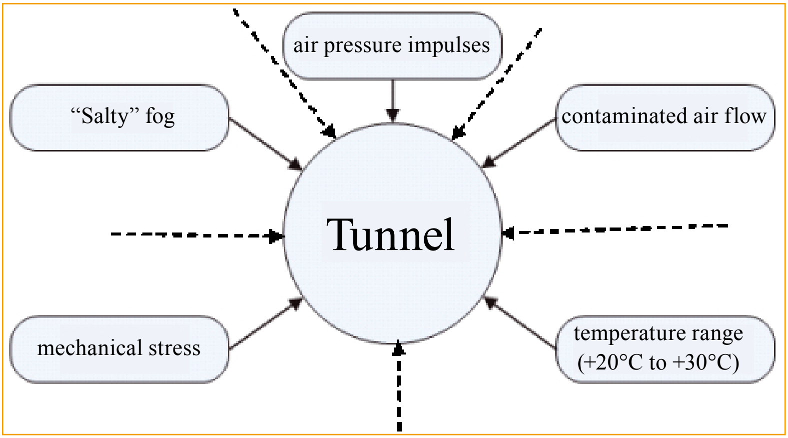

FIGURE 7 - A FEW IMPORTANT ENVIRONMENTAL INFLUENCES IN TUNNELS (incomplete list)

The once defined maintenance strategies as e.g. suggested by manufacturers need to be evaluated and periodically adapted based on the local environmental conditions.

For certain components, no preventive maintenance is recommended, for instance if the defect of a single item has no influence on the overall system performance (single lamp replacement).

In road tunnels systems are affected by the environmental conditions, especially by salty fogs due to winter services. Under these conditions it may be advantageous to replace the complete system instead of periodically changing components. This decision can be made after the tunnel is in operation by performing a risk analysis.

It is of utmost importance that we can get more stringent and detailed characterizations of the environment in the tunnels to get the expected useful lifetime of the equipment from the contractor/supplier.

4. THE INTERNATIONAL LIFE CYCLE SURVEY

In 2008 an international survey was conducted within PIARC-countries in order to evaluate the average lifetime of typical technical systems associated with road tunnels. The questionnaire was based on the following criteria:

- Questions about the average lifetime of 26 systems in road tunnels,
- Possible answers: 5, 10, 15, 20, 25, 30, 35 years.

The following systems were included in the survey:

	SYSTEM	DESCRIPTION
1	SCADA SYSTEMS	SCADA Systems general Traffic SCADA systems Operation Centre equipment
2	ILLUMINATION	Lamps Luminaries Lamp control units Monitoring systems
3	VENTILATION	Jet fans Axial fans Monitoring systems CO/Opacity measuring instruments Dampers
4	SIGNING	Active signs Lane use signals
5	SAFETY EQUIPMENT	Fire detection Systems Video equipment Radio systems Emergency stations
6	ENERGY SUPPLY	High/Low voltage equipment Transformers Distribution panels Uninterrupted power supplies Batteries
7	CABLING	High voltage cables Communication cables Fibre cables

FIGURE 8 - SYSTEMS USED FOR THE SURVEY

The result allowed an analysis based on a significant sample: 27 questionnaires from 10 different countries were received and could be evaluated. The participating countries were: Austria, Belgium, Finland, France, Japan, Spain, Sweden, Switzerland, UK, USA.

The typical life cycle of main tunnel systems and components are shown in *figure 9, following page*.

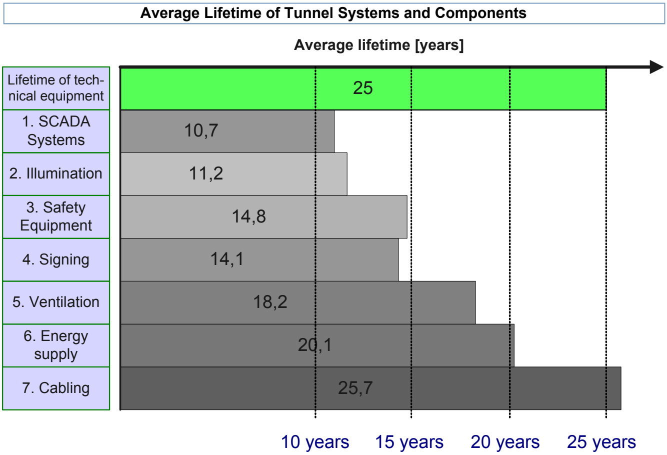

FIGURE 9 - AVERAGE LIFETIME OF DIFFERENT TUNNEL SYSTEMS

The chart demonstrates that the typical lifetime varies between 10 and 25 years. “Lifetime of technical equipment” is referring thereby to the electromechanical equipment only.

The standard deviations illustrate a variety of impact to installations that differ from case to case depending upon basic design quality, level of maintenance, physical impact (temperature, mechanical stress, environmental conditions).

4.1. DISCUSSION OF THE SURVEY RESULTS

Comparing the results, we find big differences in equipment lifetimes, which are not surprising: Electronic systems, monitoring equipment like SCADA-systems have a limited lifetime. Mechanical and energy supply/cabling systems have higher life expectations, which reach 20 years and more. Surprisingly low is the life span of illumination equipment – the impact of the tunnel atmosphere will probably deteriorate the material quicker than expected. The rest of the typical tunnel systems like safety or signing equipment is positioned in the middle of the scale, with average lifetime of approximatively 15 years.

It is interesting to compare the lifetime differences between the countries, considered for a specific system. The difference of the standard deviation is between 5 and 8 years for the following equipment:

- ventilation: fans, respective controls, dampers ;
- safety equipment: emergency stations, fire detection systems;
- energy supply: all systems except uninterrupted power supplies;
- cabling: all type of cabling.

In all these systems the differences of the active system life period varies with more than 5 years – this is not surprising for equipment with a relatively long life span like cables, ventilation; however, also for safety systems the differences are relatively high. For all other systems the deviations (standard deviation) are between 3 and 5 years.

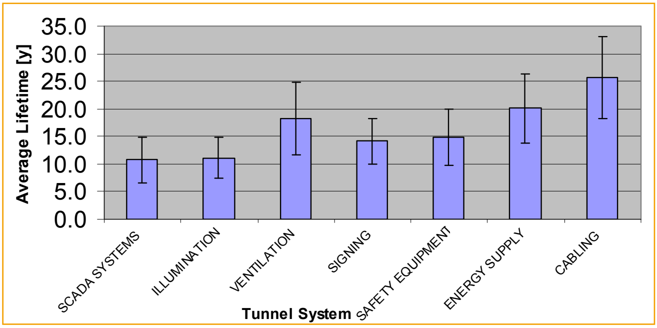

FIGURE 10 - STANDARD DEVIATIONS IN YEARS, MAX/MIN DEVIATIONS

We conclude that due to the broad variety of this survey this practical data has a sufficient statistical value to be used for life time planning.

4.2. REPLACEMENT COSTS OF TUNNEL SYSTEMS BASED ON SURVEY DATA

The statistical data is used to calculate the average cost per annum, based on the initial investment cost and the average lifetime. The calculation is illustrated through the example of three typical tunnels from three different countries.

Replacement costs per anno for a tunnel (about 2km) in Switzerland, 1 tube

	Mean Life Cycles	Costs [million US$]	Relative Costs [%]	Costs/year [US$]
SCADA SYSTEMS	10.7	2.9	15%	270'000
ILLUMINATION	11.1	2.3	12%	207'000
VENTILATION	18.2	2.5	13%	137'000
SIGNAGE	14.1	3.8	20%	269'000
SAFETY EQUIPMENT	14.8	3.5	18%	237'000
ENERGY SUPPLY	20.1	1.7	9%	85'000
CABLING	25.7	2.4	13%	93'000
Total Costs		**19.1**		**1'298'000**

Replacement costs per anno for a tunnel (about 2,7km) in Austria, 2 tube

	Mean Life Cycles	Costs [million US$]	Relative Costs [%]	Costs/year [US$]
SCADA SYSTEMS	10.7	1.2	7%	107'000
ILLUMINATION	11.1	2.0	13%	177'000
VENTILATION	18.2	1.5	9%	81'000
SIGNAGE	14.1	1.9	12%	135'000
SAFETY EQUIPMENT	14.8	3.6	23%	241'000
ENERGY SUPPLY	20.1	2.7	17%	134'000
CABLING	25.7	2.9	18%	112'000
Total Costs		**15.6**		**987'000**

Replacement costs per anno for a tunnel (about 3,2km) in USA, 2 tube

	Mean Life Cycles	Costs [million US$]	Relative Costs [%]	Costs/year [US$]
SCADA SYSTEMS	10.7	1.6	8%	148'000
ILLUMINATION	11.1	3.7	19%	330'000
VENTILATION	18.2	5.3	28%	290'000
SIGNAGE	14.1	2.6	14%	187'000
SAFETY EQUIPMENT	14.8	2.1	11%	139'000
ENERGY SUPPLY	20.1	4.4	23%	218'000
CABLING	25.7	2.9	15%	113'000
Total Costs		**22.5**		**1'425'000**

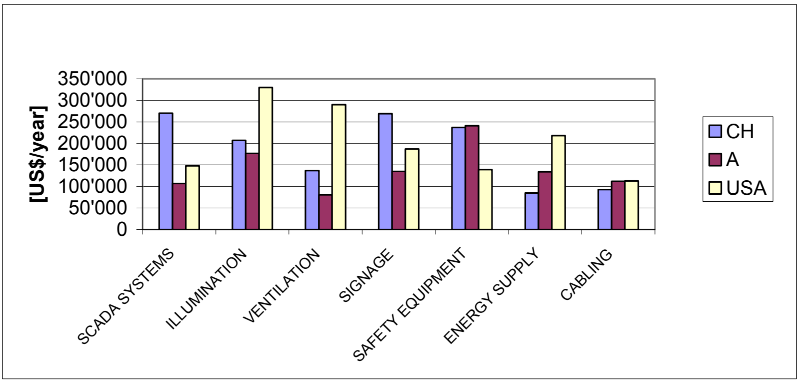

FIGURE 11 – AVERAGE REPLACEMENT COSTS PER ANNUM FOR 3 TYPICAL TUNNELS BASED ON – AVERAGE LIFE CYCLES COLLECTED IN THE SURVEY

4.3. REPLACEMENT STRATEGY BASED ON SURVEY DATA

Based on the calculations of the average costs and the expected maintenance costs during service and traffic costs, different replacements strategies can be prepared and assessed.

The 3 examples in section 4.2 are used as the basis to illustrate how replacement strategies can be prepared. In principle there are 2 basically different strategies

Strategy 1: Installations are replaced successively according to break down.
Strategy 2: Replacement occurs according to a plan that originates in the expected service life and the traffic restrictions related to the specific replacement.

Strategy 2 includes again 2 alternatives as an illustration on how to use service life data in this stage of the process:

Strategies	Strategy 2.1				Strategy 2.2			
Years	10	15	20	25	10	15	20	25
1 SCADA systems	x		x		x		x	
2 Illumination	x		x		x		x	
3 Ventilation	x		x			x		
4 Signing	x		x			x		
5 Safety equipment			x				x	
6 Energy supply			x				x	
7 Cabling			x					x

FIGURE 12 - DIFFERENT REPLACEMENT STRATEGIES ACCORDING TO EXPECTED SERVICE LIFE

The comparison between the different strategies can be based on e.g. the net present method where interest rates are taken into account similar to the method used within the field of economics.

It has to be kept in mind, that the ascertainment of an optimal strategy is a matter of a combined consideration of cost benefit and safety evaluation.

In the above mentioned case study, the comparison using a 5% interest rate shows that strategy 2 is economically more efficient than strategy 1. Furthermore, strategy 2.2 is the optimal strategy compared to 2.1, though it interrupts the normal operation of the tunnel more often. But still, it includes a lower risk of unforeseen breakdowns before the expected service life is fulfilled.

Strategy 1, however, uses the service life of the single system to its optimum. If the service life of a system is longer than the expected average service life, strategy 1 might be the optimal maintenance strategy, although safety considerations have to be taken into account – can an unexpected breakdown with a possible impact on safety be accepted?

Close coordination with other necessary tunnel renovations have to be considered in order to optimize available funding and maintenance schedule.

4.4. RELATION BETWEEN MAINTENANCE AND LIFE CYCLES

The schedule of maintenance measures is often regulated by national guidelines (e.g. RVS 13.03.41 in Austria). Additionally there are manufacturers' guidelines and common practice which are used to establish maintenance schedules. Experience demonstrates that preventive maintenance is vital to the useful life cycle for systems and components. It also has the potential of prolonging the MTTF of components which in turn enhances the overall availability of the system.

An important factor when refurbishing tunnels, are the resulting costs developing from a diversion of traffic. Tunnel cleaning cycles therefore may be used to perform maintenance works simultaneously. Such a strategy has the advantage, that the absence of traffic allows an effective and safe maintenance procedure.

Based on experience, the condition of certain systems and components can be categorized and adapted to the maintenance schedule. Many systems can be checked by collecting specific intrinsic data or visual observation (vibration value of a fan to verify bearing condition, lighting density of illumination).

Further systems parameters may be evaluated and used to determine the current condition. These parameters deliver valuable data to define the applicable maintenance measures. The following guidelines provide a foundation to extend the useful life of equipment.

Electrical and mechanical equipment situated in the tunnel are exposed to an aggressive atmosphere which causes corrosion and wearing-out of bearings. Therefore, recommended maintenance has to be performed periodically in order to extend the useful life of systems (lubrication of bearings, cleaning).

Constant supervision of the control centre and equipment room temperature, dust and humidity, has an important impact on availability (e.g. MTTF, down-time) of certain subsystems, components, elements of the SCADA-systems. However, there are processes which lead to replacement beyond the control of tunnel owners, e.g. software technology changes, platform changes, end of manufacturer's support, availability of spare parts. Even if appropriate maintenance programs are implemented, the intrinsic system life may not be prolonged.

5. MAIN FACTORS INFLUENCING THE AGEING PROCESS

5.1. OPERATING TEMPERATURE

It is necessary to review and evaluate causes of ageing or reduction in life cycle, regardless of maintenance procedures and performance. Especially the operating temperature is one of the main causes for accelerated ageing, which is discussed herein below in detail.

In the field of chemistry, the ageing process and the respective simulation is often described and investigated using the Arrhenius equation.

FIGURE 13 - SVANTE ARRHENIUS (1859-1927)

The principle is based on the observation that a chemical reaction accelerates with increasing temperature. It was found that a temperature increase of around 10°C results in a doubling of the reaction speed. This doubling rule is a good benchmark; in practice it is between 1.6 and 2. This is equivalent to a life cycle reduction relative to the ambient temperature by this factor of 1.6 to 2.

This ageing process, as described above for chemical reactions, can also be used to estimate the life expectancy of systems and components of technical equipment in tunnels accordingly.

An increase or decrease of the reaction rate can be described with the following equation - the Arrhenius equation:

$$r = \frac{dq}{dt} = A * \exp^{\left(-\frac{E}{kT}\right)}$$

r Reaction rate [1/s]
q Chemical (ageing) reaction [1]

t	Time [s]
A	Material constant (available from international data bases) [1]
E	Activation energy (available from international data bases) [eV]
k	Boltzmann constant [eV/K]
T	Absolute temperature [K]

5.1.1. The 10 degree Celsius rule

The formula can be used to establish a 10-degree rule to determine the ageing acceleration factor, and will thus be simplified as follows (ratio of reaction rates): factors > 1 indicate that the ageing effect is accelerated for this factor at the elevated temperature and therefore the life cycle is shortened accordingly.

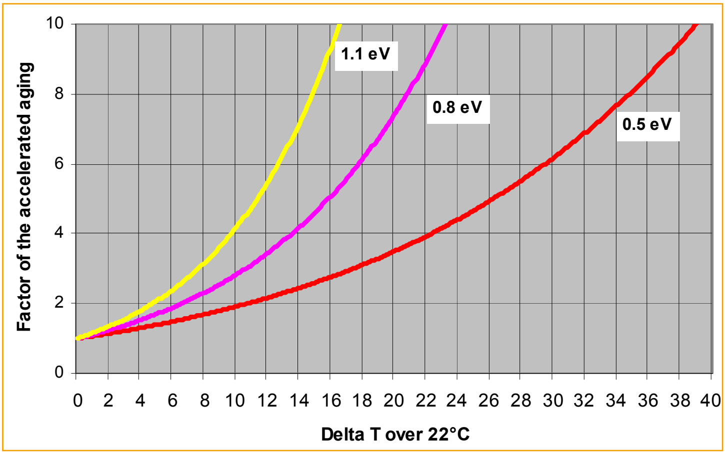

FIGURE 14 – ACCELERATED AGEING AS A FUNCTION OF THE DIFFERENCE BETWEEN ACTUAL OPERATION TEMPERATURE AND 22 DEGREES. THE DIFFERENT ACTIVATION ENERGIES REPRESENT DIFFERENT MATERIALS.

At an activation energy of 0.5 eV, a temperature increase of 10 degrees (from 22 to 32 degrees) quickens the ageing process by a factor 2. With an activation energy of 0.8 eV, a temperature rise of 10 degrees results in an accelerated ageing process of almost a factor 3.

Thus, it gets obvious, that the activation energy is an important element, and further, that it is also dependent on other extrinsic factors. The sensitivity of the activation energy is therefore crucial in achieving a quantitative assessment. Good to know that there are international databases available, for such data.

TECHNICAL COMPONENT	ACTIVATION ENERGY E[EV]
High Tension Cable Insulation	0.5
Low Density Polyethylene Cable (LDPE)	0.94 (at 6kV/mm) 0.82 (at 20kV/mm)
Cross-Linked Polyethylene Cable, 250kV Insulation (XLPE)	0.9-1.0
High Density Polyethylene Cable (HDPE)	0.7
Electronic Component (integrated circuit)	0.7

FIGURE 15 - TYPICAL VALUES FOR ACTIVATION ENERGIES

Most of the technical equipment is located in equipment rooms, control centres and special areas within control buildings. It is therefore essential to constantly control the temperature of these rooms. The design temperature of equipment, which normally ranges from 0° and 40°C, does not account for the ageing process. This temperature range is just a figure from the manufacturer applied to the warranty period.

Often temperatures > 30°C are observed, which should be avoided. As shown above, the life time of several systems is directly linked with ambient temperature.

Other environmental conditions also have to be considered: dust, salty fog, tire and exhaust particles, pollutants, humidity.

5.2. MECHANICAL STRESS

Mechanical stress is another key factor with respect to accelerated ageing: Wind loads generated by trucks, vibration during operation of e.g. vibrating fans due to a lack of maintenance or old bearings, expansion and contraction due to temperature changes. (Mechanical stress during installation is not considered here; however, these stresses should be carefully evaluated prior to installation; for example electric cable pulling tension calculations and bending radii).

These factors have to be carefully considered and incorporated into the maintenance procedures. As there are no general rules to be adapted, each system has to be analysed individually.

A typical example for mechanical stresses and other influencing factors on energy cables is given below. Are these stresses higher than expected, this will lead to a phase of forced ageing.

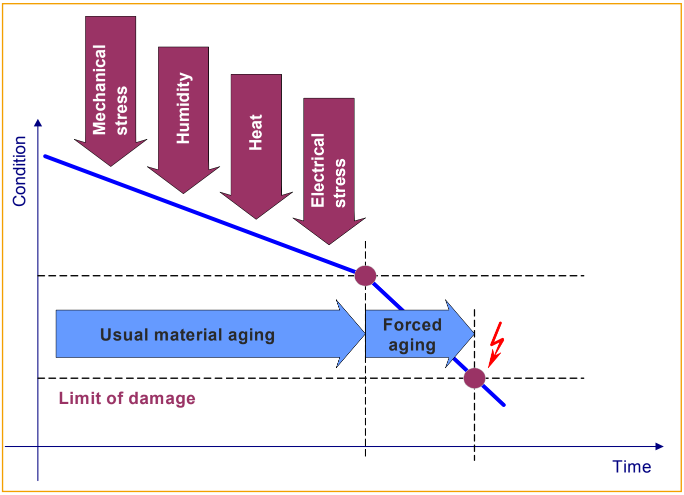

FIGURE 16 - DIFFERENT STRESSES SHOWN FOR ENERGY CABLE

5.3. GALVANIC CORROSION

There are other important influences on the life cycles, which highly jeopardize mechanical systems and are not especially addressed in this report, e.g. galvanic corrosion. The tunnel equipment is exposed to an atmosphere, which could cause corrosion. Hence, there are materials used with high corrosion resistance, like stainless steel; however, screws, bolts, washers, etc. have often not the same standard and lead to galvanic elements.

This subject will not especially be addressed here; however, it should not be neglected in the overall LCC-Aspect analysis.

6. TYPICAL SYSTEMS AND THEIR LIFE CYCLES

In the previous sections, the focus has been directed on the theoretical approach and principles of ageing, maintenance and average service life.

To illustrate the practical use of the theory, two typical tunnel systems are investigated in this section   SCADA (Supervisory Control and Data Acquisition) and lighting systems. These examples are intended to illustrate, how design and decisions taken in the design phase influence maintenance and visa versa.

6.1. SCADA-COMPONENTS, COMPUTERS (PC'S)

A crucial issue during the design phase is to decide on a quality level of e.g. PC´s. Should one invest in an expensive long life PC or a cheaper one with a shorter service life?

In order to get a well-founded decision, attention has to be paid to a series of technical aspects, such as the possibility of cooling of PC's. The cooling of active control components is often neglected, which makes it all the more essential, that following points are assessed:

- expansion of a control centre, thereby increasing concentration,
- increased density of active rack components,
- no adequate method of cooling,
- too narrow rack organization, space allocation,
- no suitable choice of the hardware design.

Although active ventilation should be applied whenever possible, a natural circulation of air, used as an active third-ventilation has to be taken into account. Through this, possible disadvantages of an additional critical component "fan" and the additional entry of dirt, dust and moisture may be avoided.

Industrial PC's are an option worthwhile to be evaluated. These devices are specifically designed for industrial applications and are optimized to customer requirements. Models with or without fans are available as well as devices especially designed for higher temperatures.

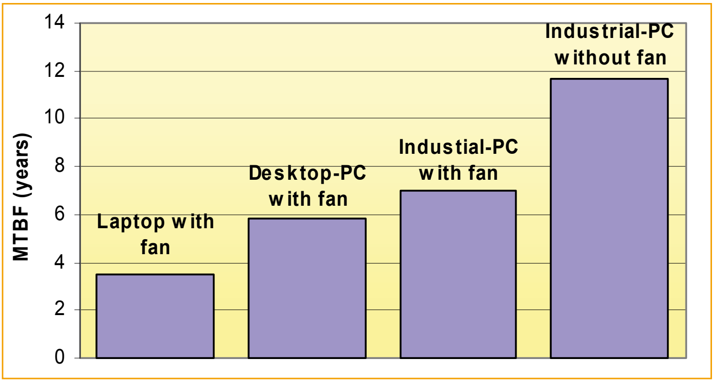

FIGURE 17 - COMPARISON OF DIFFERENT LIFE SPANS

The useful life time of components of SCADA systems cannot be judged as a whole, a consideration of the main operational hardware is necessary. However, it can be stated, that without special attention the useful life time of such equipment is reached already after 3 to 5 years. If there are special stress, factors like high ambient temperature, humidity, vibration, gases applying, the life period decreases accordingly.

Example:
The head of a hard disk drive has an expected lifetime of 6.4 years when steadily operated with 3 kHz at an ambient temperature of 25 ° C (1.27eV activation energy). The temperature rise of 10° C accelerates the ageing process by a factor 4.

6.2. ILLUMINATION

The lamp is part of the tunnel lighting system, consisting of control equipment, lamps and luminaries. The statements by manufacturers regarding lifetime of lamps in tunnels based on the observation that optimum operating conditions for the lamp apply. Only luminaries especially developed for tunnels are designed for the required operating conditions. Therefore, the lamp has to cope with thermal, mechanical, electronic influences and environmental aspects such as humidity or pollutants.

Regarding the lifetime of light sources, there are different terms used on the market depending on the lamp type and the manufacturer. The lifespan of a lamp is an essential quality element of the product and is here defined as the period until the light flux has reached the level of 70-80 %.

The following graph shows experienced values in tunnels and also illustrates the possibility of reaching long life spans if special lamps are installed. As seen in the plot, the introduction of long living fluorescent lamps bears the potential to prolong the life cycle of lighting systems significantly.

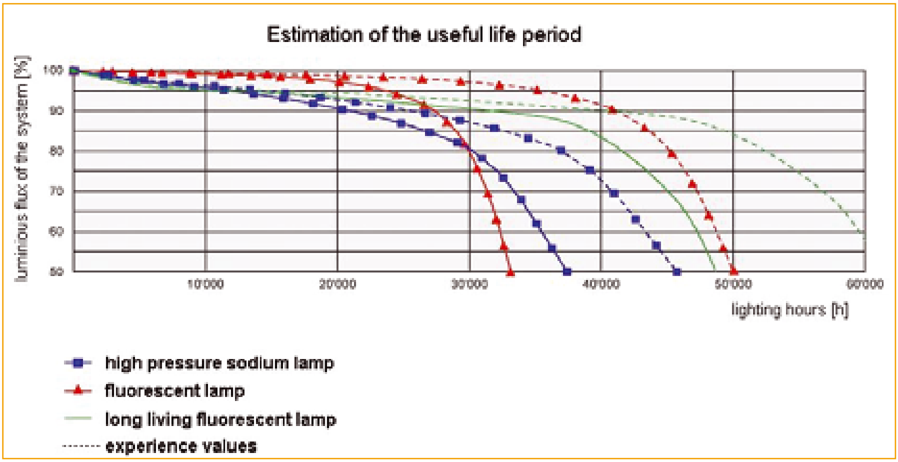

FIGURE 18 - COMPARISON OF LIFE PERIODS OF TYPICAL TUNNEL LAMPS

The new lighting technology using LED (light emitting diodes) is introduced in different outdoor applications starting ca. 2007/2008. This technology will change standard street (and tunnel) lighting in a way that was not experienced in the last decades. LED-lamps are claimed to deliver higher life times at lower energy consumption with comparable or even better lighting quality and performance. However, at the stage of finalizing this report (2010), it is still too early to provide qualified statements on the effectiveness and life cycle cost of LED-lamps.

7. CONCLUSIONS AND RECOMMENDATIONS

The 2008 international life cycle survey showed that the useful life of standard equipment varies between 10 and 25 years, while the average life span lies at approximately 15 years. But still, some systems and components have life spans of 10 years and below, which makes it all the more essential to consider the useful life periods. The factors that exert a considerable influence on the system need to be established, so that life cycles can be extended.

A careful planning of the service life and the useful life period is essential. The analysis of the different life stages could be done according to the graph presented in *figure 19*.

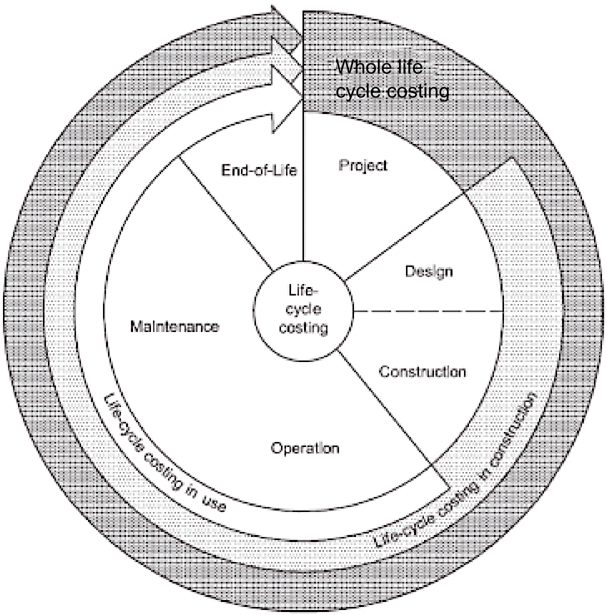

FIGURE 19 - ANALYSIS OF DIFFERENT STAGES OF THE LIFE CYCLE (ISO 15686-5)

The following adapted bathtub curve is widely used as a general guideline for considering the life phases of systems *(figure 20)*. Note, that early decisions on e.g. the selection of products and their quality, but also varying maintenance strategies have an influence on the extension of the life cycle at the end of the useful life period. The importance of this fact is depicted through several failure rates with different rising points at the end of the life cycle.

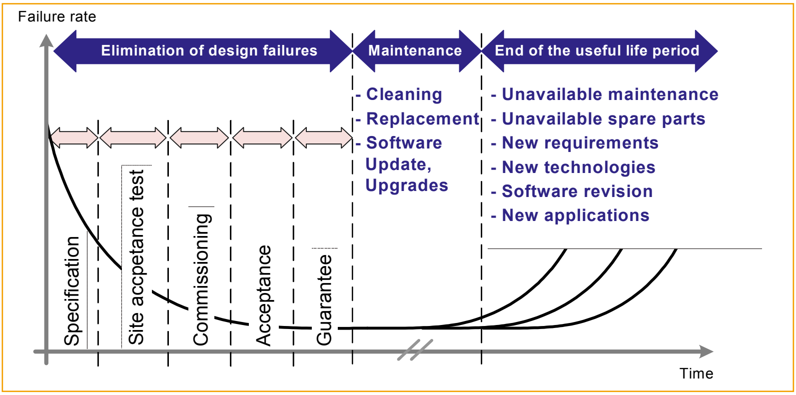

FIGURE 20 - ADAPTED BATHTUB CURVE FOR TECHNICAL EQUIPMENT INCORPORATING SOFTWARE

It is useful to consider special factors that influence life expectancies of systems and components such as temperature, humidity, mechanical stress and environment. The influence of temperature is often underestimated. Using the Arrhenius equation, it can be shown that ageing is highly affected by the ambient temperature. Particular attention therefore has to be paid to environmental temperature in equipment and control rooms.

Experience demonstrates that preventive maintenance is vital to the useful life cycle of systems and components. The schedule for maintenance measures is often regulated by national guidelines. Additionally, there are manufacturer s guidelines and common practice used to establish a maintenance schedule.

Sufficient and/or well distributed funding is a key factor to useful life cycles and protection of investment costs.

8. ABBREVIATIONS

RVS	Richtlinien für Verkehr und Strassen (Austrian guidelines for traffic, roads, tunnels)
DIN	Deutsches Institut für Normung (German Institute for Normalization)
ÖNORM	Österreichisches Normungs-Institut (Austrian Standards Institute)
ÖVE	Österreichischer Verband für Elektrotechnik (Austrian Association for Electrotech-nique)
CEN	Comité Européen de Normalisation (European Committee for Standardization)
ISO	International Standardization Organization
IEC	International Electrotechnical Commission
NFPA	National Fire Protection Association
TC	Technical Committees of PIARC
AASHTO	American Association of State Highway and Transportation Officials
IEEE	Institute of Electronic and Electrical Engineers
FHWA	Federal HighWay Administration

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