RELIABILITY OF INSTRUMENTATION SYSTEMS FOR SAFEGUARDING AND CONTROL

Edited by J.P. JANSEN and L. BOULLART

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Proceedings of the IFAC Workshop
The Hague, The Netherlands
12–14 May 1986

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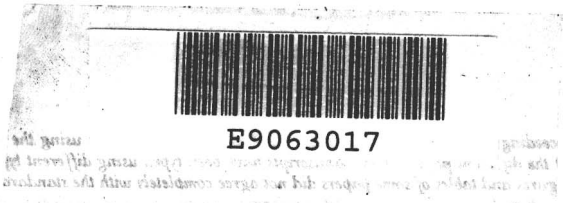

Published for the
INTERNATIONAL FEDERATION OF AUTOMATIC CONTROL
by
PERGAMON PRESS
OXFORD · NEW YORK · BEIJING · FRANKFURT
SÃO PAULO · SYDNEY · TOKYO · TORONTO

U.K. Pergamon Press, Headington Hill Hall, Oxford OX3 0BW, England

U.S.A. Pergamon Press, Maxwell House, Fairview Park, Elmsford, New York 10523, U.S.A.

PEOPLE'S REPUBLIC OF CHINA Pergamon Press, Room 4037, Qianmen Hotel, Beijing, People's Republic of China

FEDERAL REPUBLIC OF GERMANY Pergamon Press, Hammerweg 6, D-6242 Kronberg, Federal Republic of Germany

BRAZIL Pergamon Editora, Rua Eça de Queiros, 346, CEP 04011, Paraiso, São Paulo, Brazil

AUSTRALIA Pergamon Press Australia, P.O. Box 544, Potts Point, N.S.W. 2011, Australia

JAPAN Pergamon Press, 8th Floor, Matsuoka Central Building, 1-7-1 Nishishinjuku, Shinjuku-ku, Tokyo 160, Japan

CANADA Pergamon Press Canada, Suite No. 271, 253 College Street, Toronto, Ontario, Canada M5T 1R5

First edition 1987

British Library Cataloguing in Publication Data

Reliability of instrumentation systems for safeguarding & control:
proceedings of the IFAC workshop, The Hague, The Netherlands, 12-14 May 1986.
1. Engineering instruments
I. Jansen, J. P. II. Boullart, L. III. International Federation of Automatic Control
620'.0044 TA165
ISBN 0-08-034063-6

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IFAC

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RELIABILITY OF INSTRUMENTATION SYSTEMS FOR SAFEGUARDING AND CONTROL

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Royal Institution of Engineers in the Netherlands (KIvI)

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FOREWORD

This volume contains the papers and the major discussions presented at the IFAC Workshop on Reliability of Instrumentation Systems for Safeguarding and Control.

This Workshop, which was sponsored by the IFAC Applications Committee (APCOM), was the first of its kind.

It was organised as a cooperation between the Netherlands Association of Engineers and the Royal Institute of Engineers in the Netherlands.

The aim of the Workshop was to present and discuss the various reliability aspects of modern instrumentation systems for industrial processes. The programme was divided into a number of sessions covering the following topics: System design, Reliability modelling, Field data and maintenance and Human factors.

In addition, invited tutorial papers were given to introduce the subject in more general terms. Due to some dramatic events in industrial processes in the weeks before the Workshop, the awareness of the reliability problems in general and hence instrumentation systems is steadily increasing. This was felt during the informal talks throughout the Workshop.

Although a significant amount of literature is available, this has tended to emphasize more the mathematical and analytical aspects. Many presentations emphasized that the practical aspects of reliability and availability and its assessment are in many circumstances still a large problem. Software and Human reliability aspects are only slightly covered areas. Reliability engineering is a science where a large number of disciplines strongly interact. As most participants came from industry, it reflects the high impact and need in today's industrial life. This was also highlighted by the fact that the special "Industrial Problem Session" organized on one of the evenings was attended by almost all participants.

The aim was to provide a platform to discuss "real life" problems without the necessity to write a full paper. Nevertheless papers and notes were presented and are recorded in these proceedings under the session headed: "Industrial Problems".

We would like to thank the Netherlands Association of Engineers (NIRIA) for their constant support and assistance in making this first Workshop a successful one, the International Program Committee for their effort in the selection of papers and the members of the National Organizing Committee for their support in the organisation.

We hope that by the publication of these papers, which came from specialists of 12 different countries, reliability engineering will find its way into the design, engineering and management of industrial instrumentation systems.

J P Jansen
L Boullart

CONTENTS

INTRODUCTION TO RELIABILITY MODELING

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Abstract. Reliability predictions refer to the future behaviour of items and therefore can only be expressed as probabilities. With wearout failures the lifetimes of devices are normally distributed and with random ones they are exponentially distributed. The latter distribution is determined by the failure rate λ, which is independent on time but dependent on operational and environmental conditions (MIL HDBK 217).

Also the reliability of equipments which are composed by parts can be described by a failure rate. The failure effect analysis indicates whether the failures are detectable or not detectable, whether they are safe or unsafe. By means of failure detection, combined with repair and restauration, fault tolerant equipments can be realized. Their availability depends upon failure rate, failure detecting rate and repair rate.

In order to establish high reliable systems the principles of redundancy, diversity and physical and electrical separation are used as preventive measures against random and common mode failures. By this way the availability of the systems is higher than that of the components. It can be numerically predicted by means of a fault tree analysis.

Keywords. Failure rate; failure effect analysis; fault tree analysis; Markov processes; quality control; reliability theory; system failure and recovery.

INTRODUCTION

Recent intrumentation and control systems have not only to fulfill the operational conditions; they have to fulfill them reliably, a goal which is not achieved by chance but only by a careful design /1-6/. The paper deals with some aspects useful for the design of parts, equipments (composed by parts) and systems (composed by equipments). It explains some models suitable for a numerical prediction of failure probability and unavailability. As those quantities describe the future behaviour of items they can only be expressed as probabilities. Therefore this introductory lecture will start with a short chapter about probability distributions. It is followed then by three others in which reliability models of parts, units and systems are discussed.

1 LIFETIME DISTRIBUTIONS

1.1 Definitions

In order to define some terms needed in the reliability theory the following experiment is considered: A lifetime test is started with a number of n_0 items operating at time $t = 0$; after the time t the number $n(t)$ is still working; the number $n_0-n(t)$ has failed. If the fractional number $n(t)/n_0$ is graphically represented with respect to time, then a curve is obtained like that in Fig. 1.1a. At the beginning all items were operating, at the end all failed. At a given time t the ratio $n(t)/n_0$ will have survived. Its lifetime is equal to or longer than the corresponding time t.

This ratio can be used as an estimate of future behaviour based on the outcomes of a previous series of events. The ratio $n(t)/n_0$ is interpreted as the probability $p(t)$ that an item will reach or exceed the lifetime t. It is called reliability: The reliability $R(t)$ of an item is the probability that the item will perform a required function under a specified condition for a stated period of time t,

$$R(t) = \frac{n(t)}{n_0} = p(\text{lifetime } X \geq t) \; . \qquad (1.1)$$

The complement of the reliability is the failure probability $F(t)$. This is the probability that the lifetime of an item is shorter than or equal to a given time t:

$$F(t) = 1 - R(t) = \frac{n_0-n(t)}{n_0} = p(\text{lifetime } X \leq t) \; . \qquad (1.2)$$

The failure probability (Fig. 1.1b), but not the reliability, is a cumulative probability distribution function, which can range in value from zero to unity.

If the failure probability function is differentiated with respect to time then the probability density function $f(t)$ is obtained (Fig. 1.1c)

$$f(t) = \frac{dF(t)}{dt} = -\frac{dR(t)}{dt} \; . \qquad (1.3)$$

This function divided by the reliability $R(t)$ gives the hazard function or failure rate function $z(t)$ (Fig. 1.1d)

$$z(t) = \frac{f(t)}{R(t)} = -\frac{1}{R(t)}\frac{dR(t)}{dt} \; . \qquad (1.4)$$

As characteristic marks of probability distributions the median and the mean are used. The median t_{50} is the lifetime of the middle item; the mean lifetime $\bar{t}$ is given by

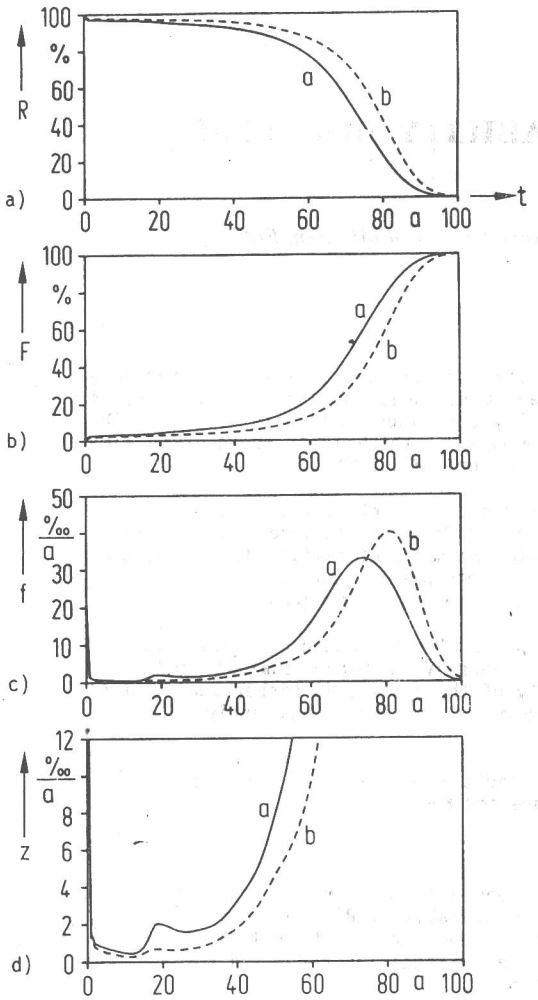

Fig. 1.1 Lifetime Distribution of the People in Western Germany /5/
R reliability, F failure probability,
f failure probability density function,
z failure rate function, a male, b female

$$\bar{t} = \int_0^\infty t \cdot f(t)\, dt,$$

which after some steps yields

$$\bar{t} = \int_0^\infty R(t)dt. \qquad (1.5)$$

Fig. 1.1 shows the lifetime distribution of the people in Western Germany. Curve a refers to males, curve b to females. Owing to the infant mortality the "reliability" decreases within the first year of life, remains fairly constant over a longer period of time and begins to fall down at an age of 50. At any age the mortality of men is higher than that of women. The probability density function f(t) has its maximum at 70, respectively 80 years. The failure rate function z(t) clearly indicates the "early failures". Furthermore it has an unexpected peak for boys at the age of about 20 years. This is due to "annatural" accidents mostly caused by cars and sports. Yet the death rate is low, that of the infants is not reached until an age of about 60 years.

Half of the population gets an age of 71 (men), resp. 77 (women) years, while the mean lifetimes of 67 and 73 years are a bit shorter.

In the following three distributions are briefly discussed which are important in engineering. These are

- the normal distribution, describing the lifetime of items with wear out failures,
- the exponential distribution effected by random failures and
- the Weibull distribution applicable for both, the wear out and random failure mode.

1.2 Normal Distribution

Wear out failures occur as a result of deterioration processes or mechanical wear. The lifetimes of items which have failed by wear outs correspond to the normal or Gaußian distribution. The failure probability F(t) is defined as

$$F(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_{v=-\infty}^{t} e^{-\frac{1}{2}\left(\frac{v-\bar{t}}{\sigma}\right)^2} dv. \qquad (1.6)$$

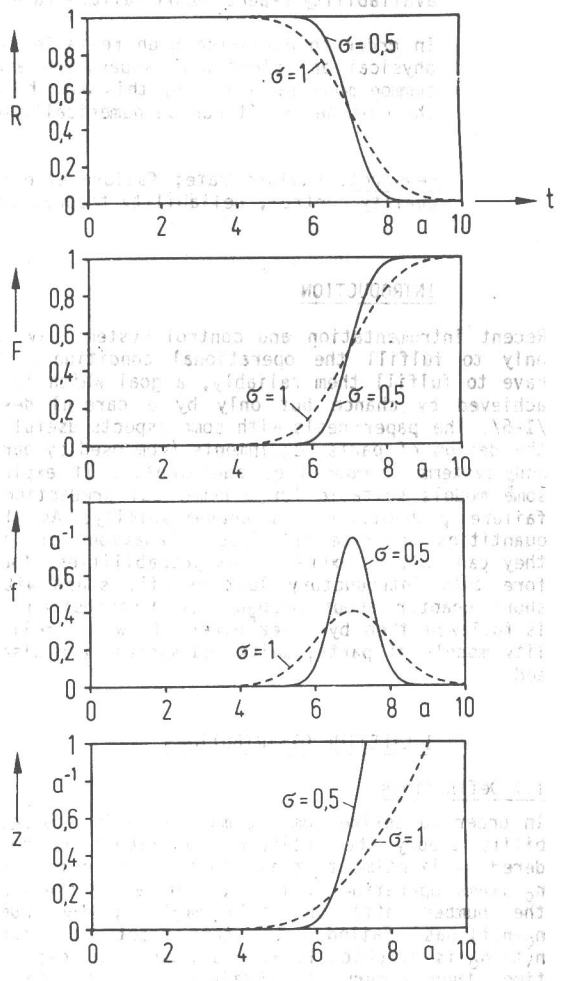

Fig. 1.2 Normal Distribution

It is determined by 2 parameters. The one is the mean lifetime $\bar{t}$ and the other is the standard deviation σ (Fig. 1.2). The graph of the probability density function is a bell-shaped curve with a maximum at $t = \bar{t}$. The most likely lifetime t_{max} has the same value as the median t_{50} and the mean lifetime $\bar{t}$. The standard deviation σ is a shape parame-

ter. It expresses how far the different lifetimes are grouped around the mean.

With the normal distribution the reliability, the probability of success, does not decrease at the beginning of an item's application. There is a period of time in which items do not fail and in which the reliability remains unity. In this region the failure probability and the failure rate are zero. If the latter starts increasing, it increases rather fast and in a short period of time all items will fail.

An example of items with normally distributed lifetimes are candles, light-bulbs or tires. The useful lifetime of these items is limited by wear out. If the items are replaced before entering the region with decreasing reliability, then an operation without breakdowns is possible. Therefore a preventative maintenance is assumed to be very useful.

1.3 Exponential Distribution

Another group of failures are the random ones, which are predictable only in a probabilistic or statistical sense. Such failures predominate in electronic devices. Their lifetimes are exponentially distributed with the reliability R(t) and the failure probability F(t) (Fig. 1.3)

$$R(t) = e^{-\lambda t} \tag{1.7}$$

$$F(t) = 1 - e^{-\lambda t} \tag{1.8}$$

$$\approx 1 - (1 - \lambda t) = \lambda t \quad \text{if } \lambda t \ll 1. \tag{1.9}$$

Differentiating of Eq. (1.8) yields the probability density function f(t)

$$f(t) = \lambda e^{-\lambda t} \tag{1.10}$$

and the failure rate function z(t) is obtained by dividing Eq. (1.10) by the reliability R(t)

$$z(t) = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda. \tag{1.11}$$

The failure rate function has a time independent constant value λ. It is called "failure rate" and it is the only parameter determining the exponential distribution.

The time independent failure rate is connected with another important property of the exponential distribution. It has no memory. This results from the fact that the distribution is related to the Poisson resp. Markov process. Asking for the probability that an item will reach the lifetime t, given it has reached the lifetime t_1 with $t_1 < t$ it can be shown that this conditional failure probability $F(t|t_1)$ is obtained by

$$F(t|t_1) = \frac{F(t)-F(t_1)}{1-F(t_1)} = \frac{1-e^{-\lambda t}-(1-e^{-\lambda t_1})}{1-(1-e^{-\lambda t_1})} = F(t-t_1). \tag{1.12}$$

The corresponding conditional failure density function $f(t|t_1)$ then becomes

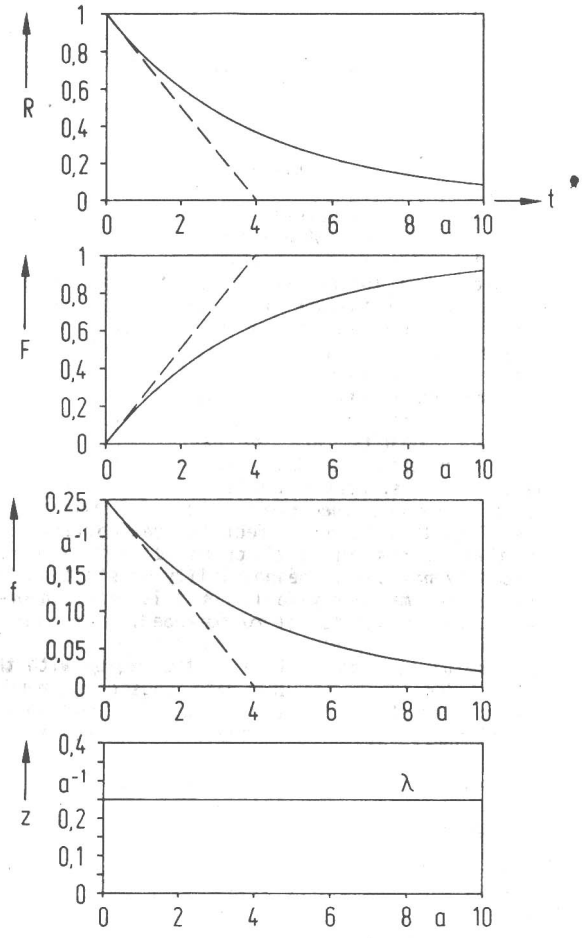

Fig. 1.3 Exponential Distribution

$$f(t|t_1) = \frac{dF(t|t_1)}{dt} = \frac{f(t)}{1-F(t_1)} = \frac{e^{-\lambda t}}{1-(1-e^{-\lambda t_1})} = \lambda e^{-\lambda(t-t_1)} = f(t-t_1). \tag{1.13}$$

That means that the functions $F(t|t_1)$ and $f(t|t_1)$ are the original functions F(t) and f(t) but shifted for the time t_1. Has an item survived until the time t_1 then its failure probability starts at this time with $F(t=t_1|t_1) = 0$. The history before t_1 is no longer relevant.

For these reasons a preventative maintenance does not improve the reliability. It is not only not useful, but can even deteriorate the performance. This shall be explained by means of the bath-tub curve in the following section.

1.4 Bath-tub curve

It may be replied that the time independent failure rate is only a mathematical idealization which does not represent the real situation. It should be better to describe the failure rate with respect to time by a curve like that of Fig. 1.4, the well-known bath-tub curve. That is true, but not a serious argument.

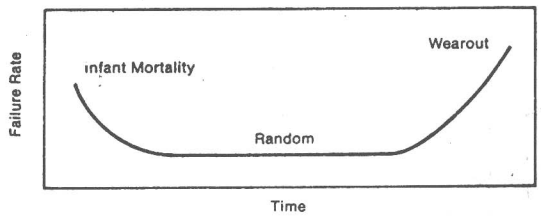

Fig. 1.4 Bath-tub Failure Rate Curve

The resulting characteristic can be seen falling into three distinct phases representing the infant mortality, the random failures and the wear out failures. The infant mortality is concerned with the early-life failure of a part. These failures are usually associated with material or manufacturing defects. The failure rate decreases rapidly and stabilizes when the weak units have died out. That may occur after some hundred hours for discrete semiconductors and after some months for integrated circuits. Are the parts used in larger control systems then the preoperational tests generally last so many hours that the early failures happened before the actual start of the plant. Therefore they do not affect the reliability. But in these cases in which operated parts get replaced by new ones, the possiblity exists that the new devices may early fail. For this reason a preventative renewal is not recommended.

The useful portion of life is the region with the time independent failure rate caused by random events. The low failure rate depends upon operational and environmental stresses. It remains constant for a period up to 30 - 50 years. Then the wear out failures occur and the failure rate increases rapidly. The end of the useful life is reached.

In most industrial applications the parts are not applied for such a long time. After about 10 or 20 years the devices do no longer represent the state of the art and have to be replaced before the wear out failures become essential. The end of the bath-tub is not be reached. Only the period with the time independent failure rate is important for industrial applications.

1.5 Weibull Distribution

The Weibull distribution (Fig. 1.5) can be used to describe all three regions of the bath-tub curve. The distribution has two parameters,

- the scale parameter or characteristic life time T
- the shape paramter a.

The reliability functions are given by

$$R(t) = e^{-(t/T)^a} \tag{1.14}$$

$$F(t) = 1 - e^{-(t/T)^a} \tag{1.15}$$

$$f(t) = \frac{at^{a-1}}{T^a}\, e^{-(t/T)^a} \tag{1.16}$$

$$z(t) = \frac{at^{a-1}}{T^a}\,. \tag{1.17}$$

In the region $0 < a < 1$ the failure rate decreases and the infant mortality can be described. With $a = 1$ the Weibull distribution corresponds to the exponential distribution for $\lambda = 1/T$. With $a > 1$ the failure rate increases. The wear out failures are characterized as with the normal distribution.

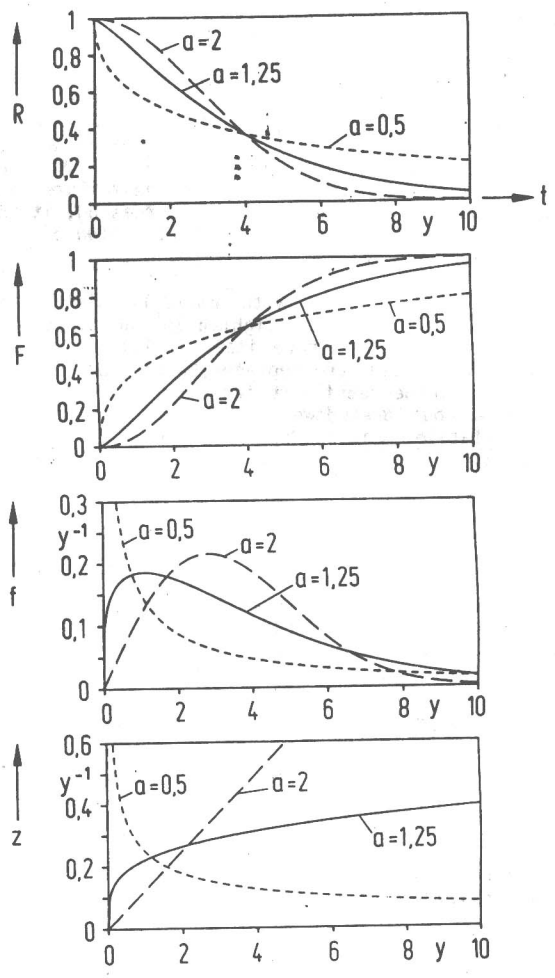

Fig. 1.5 Weibull Distribution

In the region $3 \leq a \leq 5$ the Weibull distribution approaches the normal distribution especially well.

2 PART FAILURE RATES

2.1 Random and Systematic Failures

We refer to the useful life phase of the parts which is connected with a constant time independent failure rate function. The corresponding life times are exponentially distributed. This model describes not only the behaviour of electronic and electric components such as diodes, transistors, IC's, resistors, inductive devices, capacitors but also that of mechanical parts such as wrapped, soldered, crimped or welded joints, relays and switches.

The failure rate includes only random catastrophic failures (sudden and complete), but not deterministic or systematic ones which occur if an item is not handled under the specified conditions. Such a misuse includes

- the application of a device in environmental stresses beyond those intended
- the human errors resulting in an improper installation, operation, maintenance and transportation and
- the use in a service never intended for the device.

If a transistor fails e.g., because it is operated with too large power or at too large an ambient

temperature then the failure is not a random event but caused by the unskillness of the operator. Such failures are not included within the failure rate. They are found nearly as numerous as the random ones. Fig. 2.1 gives the result of an investigation of failed integrated circuits. 47 % of the failures are due to material and manufacturing weakness, but 49 % are caused by the customers' misuse.

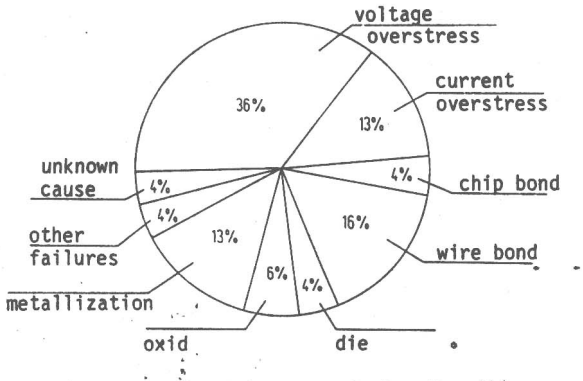

Fig. 2.1 Failures of integrated circuits /4/

2.2 Failure Rate Data

Mostly the failure rates are obtained by analysing data from the field use of operated systems. Manufacturers and particularly the customers of automatic control systems have detailed operation-, failure- and repair-listings. These inform about the appliances installed and the used parts. The failed and repaired devices are reported, too. These are large samples in a mathematical sense and an estimate $\hat{\lambda}$ for the failure rate may be obtained by the number k of failed devices divided by the product NT, N representing the number of parts operated and T the operating time,

$$\hat{\lambda} = \frac{k}{NT} . \qquad (2.1)$$

The probably most detailed failure rate data bank is the Military Handbook MIL HDBK 217 published by the United States Department of Defense /6/. In this report the lifetimes of the equipment used by the US forces - army, navy, air force - and the National Aeronautics and Space Administration are collected and interpreted. The edition A of this handbook was published more than 20 years ago in 1962, the edition D in 1982. In the handbook the failure rates are modeled as the product of a base failure rate λ_b and a number of adjustment factors that relate to the manufacturing process and to the anticipated stresses. Such factors are e.g.

- the quality factor π_Q, accounting for effects of different quality levels
- the learning factor π_L
- the temperature factor π_T, accounting for effects of temperature
- the electrical stress factors π_V, π_R, π_{S2}, accounting for voltage and power ratings
- the environmental factor π_E, accounting for environmental effects others than temperature; it is related to application categories.
- the application factor π_A, accounting for effect of application in terms of circuit function
- the complexity factor π_C, accounting for effect of multiple devices in a single package.

The different failure rates are tabulated in the MIL HDBK. They allow to predict the failure rate of a discrete semiconductor e.g. as

$$\lambda = \lambda_b \cdot \pi_Q \cdot \pi_E \cdot \pi_A \cdot \pi_R \cdot \pi_{S2} \cdot \pi_C \cdot 10^{-6}\ h^{-1}, \qquad (2.2)$$

where the base failure rate λ_b depends upon the temperature. The failure rate of monolithic bipolar and MOS digital SSI/MSI-devices (less than 100 gates) follows from

$$\lambda = \pi_Q [C_1 \pi_T \pi_V + (C_2 + C_3) \pi_E] \pi_L \cdot 10^{-6}\ h^{-1}, \qquad (2.3)$$

In this equation C_1 and C_2 are circuit complexity failure rates based upon gate count and C_3 is the package complexity failure rate.

Some of these factors affecting the part failure rate and particularly relating to the natural enemies of electronic part such as heat, excess voltage and environmental stress are discussed in the following sections.

2.3 Quality System

The manufacturing of a typical integrated circuit requires 35 - 40 processing steps that must be performed with sufficient accuracy to ensure both the reliability and the reasonable cost of the product. Thus the first key to quality is a good process control. In order to ensure the anticipated low failure rate a lot of tests are carried out during and after the production process. The objectives are

- the elimination of early failures
- the elimination of weak or potentially weak devices randomly present in a lot of components
- the elimination of lots having too large a proportion of unstable products.

Beginning 20 years ago, test procedures and very strong and comprehensive screening specifications were developed. Among the US-specification the MIL-STD-883 is applied to IC's and the MIL-STD-750 to discrete semiconductors. Within the European CECC-System the IC's are processed according to CECC-90000 and the discretes according to CECC-50000 /7, 8/. Both systems include the following tests

- Internal Visual Inspection of the device prior to sealing to screen out defects such as insufficient metallization or oxide and bond defects and to detect the presence of foreign material.
- High Temperature Storage without electrical power applied to stabilize electrical characteristics.
- Temperature Cycling to check the thermal compatability of dissimilar materials (die attachment on mounting base).
- Constant Acceleration to detect mechanically weak devices, particularly loose connections.
- Leak Test (gross leak and fine leak) to detect faulty seals and to assure package hermeticity.
- Burn-in, operating a device at an elevated temperature with electrical biases applied, to detect excessive parametric drift and to eliminate early failures.
- External Visual Inspection to assure that mechanical characteristics and visual aspects are within specifications.
- Final Electrical Quality Conformance to assure that devices are within electrical paramter limits.

Among these the burn-in is the most effective procedure as Table 2.1 shows:

TABLE 2.1 Effectiveness of Screening Tests of hermetically sealed IC's /9/

High Temperature Storage	0 - 15 %
Temperature Cycling	5 - 15 %
Constant Acceleration	0 - 5 %
Burn-in	60 - 80 %
Hermetic Seal	5 - 15 %

In many cases it is technically feasible to produce components which are virtually infinitely reliable. The costs of such parts and of equipment constructed from them would, however, be prohibitive unless - as it is the case with aerospace equipment - any failure cannot be tolerated under any circumstances. On the other hand in applications easily repairable an extremely high price due to high screening costs is less acceptable than a lower commercial grade reliability. Therefore many parts are covered by specifications that have several quality levels. Hereby the highest reliability - the lowest failure rate - is related to the highest price and vice versa. Table 2.2 shows some quality levels and the corresponding relative failure rates. A transistor e.g. can be delivered in 5 different grades. The transistors encapsulated or sealed with organic materials have the lowest quality level P1. That failure rate is a 100 times higher than the failure rate of JAN-TXV-quality.

TABLE 2.2 Quality levels and relative quality factors

parts and spec.	quality levels and rel. factors								
integrated circuits (MIL-M-38510, MIL-STD-883)	S	B	B-0	B-1	B-2	C	C-1	D	D-1
	1	2	4	6	13	16	26	35	70
discrete semiconductors (MIL-S-19500, MIL-STD-750)	JANTXV		JANTX		JAN	Lower		Plastic	
	1		2		10	50		100	
resistors (MIL-STD-199, MIL-STD-202)	S	R	P	M	NE	Lower			
	1	3.3	10	33	165	500			
capacitors (MIL-STD-199, MIL-STD-202)	S	R	P	M	L	NE	Lower		
	1	3.3	10	33	50	100	333		

The quality levels refer to devices processed and screened in accordance with supervised US-government specifications. European companies do not or do not exclusively manufacture according to this US-standards but to their own quality control systems. If the models of the MIL-HDBK are applied to these European products then it is necessary to know the quality level of these devices manufactured not in accordance with MIL-standards. To answer this question our Munich institute carried out some investigations and analyses /10/. It was found out that the quality of European commercial parts comes up to level C for IC's, to level JAN (an US-trademark) for discrete semiconductors and to level M ("established reliability" ER) for resistors and capacitors.

2.4 Learning Factor

With the introduction of a new product line difficulties may occur until conditions and controls have stabilized. In the first lot more weak devices may be fount than in the later ones. This fact is taken into consideration for IC's by a learning factor π_L which is 10 under any of the following conditions

- new device in initial production
- where major changes in design or process have occured
- where there has been an extended interruption in production or a change in line personnel.

The factor of 10 can be expected to apply for as much as six months of continuous production /6/.

2.5 Temperature Aspects

As the velocity of many chemical reactions increases with rising temperature the failure rate grows up with temperature, too. With the thermal activation energy E_a (eV), the Boltzmanns constant K ($8{,}63 \cdot 10^{-5}$ eV/K), and a proportional factor B the failure rate depends upon the temperature T (K) according to the Arrhenius equation as

$$\lambda = B\, e^{-\frac{E_a}{kT}} . \qquad (2.4)$$

Herein the activation energy is the energy which is required for a particular reaction to take place. Each failure mechanism has its own activation energy which is characteristic of that mechanism. It is 0,3 eV for oxide defects e.g. and 1,4 eV for ion migration. With a temperature rise from 25 to 100 °C the failure rate increases by a factor of 10 for E_a = 0,3 eV and by a factor of 100 000 for E_a = 1,4 eV.

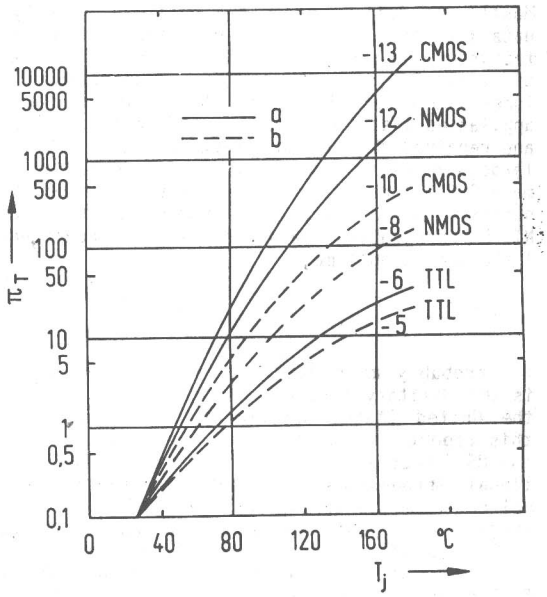

Fig. 2.2 Temperature Factor π_T with respect to Junction Temperature T_j /6/
a nonhermetic package, b hermetic package

The temperature dependence of the failure rate is a very serious effect (Fig. 2.2). In order to avoid these failures caused by temperature and to ensure a reliable operation

- a reduced power consumption
- a improved extensive heat sinking or
- an air conditioned operating area

can become necessary.

On the other hand the Arrhenius model is used for accelerated life testing. A high temperature test of a short duration is correlated to many hours of operation at lower temperatures. If λ_j is the failure rate at junction temperature T_j, then an acceleration factor F may be calculated as

$$F = \frac{\lambda_2}{\lambda_1} = e^{-\frac{E_a}{k}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)} \quad . \qquad (2.5)$$

2.6 Electrical Stress

In addition to temperature, also electrical quantities such as voltage, current or power affect the part failure rate. In order to lengthen the useful life the operation of parts is recommended not with maximum acceptable ratings but with reduced stress conditions. Such a derating will improve the reliability and diminish the failure rate.

To give an example of this effect Fig. 2.3 shows the voltage factor π_V increasing with rising voltage. The failure rate of an IC is proportional to this factor. With a power supply of 15 V a CMOS IC may fail 10 times as much as if it is operated at 5 V.

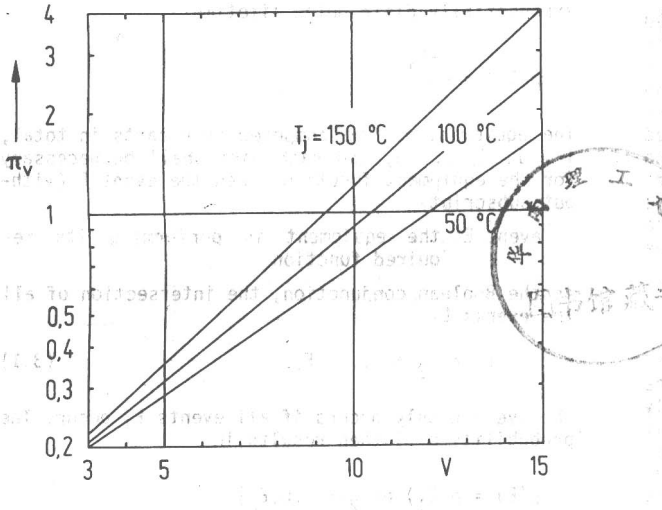

Fig. 2.3 Voltage Stress Factor π_V of CMOS IC's /6/

A serious problem is the electrostatic discharge (ESD) damage, which some reliability engineers have termed "the new contaminant of the age of microelectronics". It occurs in both MOS and bipolar devices. It can cause an immediate or delayed damage to circuits. In many cases no damage can be measured until months have passed and the equipment has failed in the field. Remember that a person walking across a carpet can seperate a charge generating a voltage up to 1000 to 6000 V. In fact, a voltage as low as 100 V is reported to be capable of damaging semiconductor devices. Most of the customer induced failures by voltage overstress (Fig. 2.1) are assumed to have occured by ESD. This happened inspite of input protective devices (e.g. diodes) on the IC to prevent the discharge from rupturing the gate oxide. Other provisions to protect against ESD are

- a proper floor finish
- grounding of furniture
- application of special sprays and
- control of humidity in the work area.

Another kind of damage is caused by current stress. The main effect is electromigration of metallization patterns. The rate of migration is proportional to current density and the failure rate increases approximately with the square of current density.

Derating is an effective procedure for improving reliability, but it has its limitations. The semiconductors must not be derated to such low power that more parts for signal processing are needed. Under these circumstances the reliablity would be reduced due to the larger number of components. Furthermore the signal to noise ratio must not fall below a given level in order to avoid disturbancies by electromagnetic interferences. And last not least mechanical parts such as relay contacts or moving shafts need a periodic operation to remain in good working condition.

2.7 Environmental Stress

The parts' reliability is affected by environmental stresses, too. Unsafe conditions are

- high temperatures
- temperature changes
- water condensations
- agressive gases in the ambient air and
- shocks, vibrations and accelerations.

The MIL HDBK summarizes all these effects by an environmental factor defined for various working areas. The industrial equipment use is encompassed by the areas

- G_B, Ground, Benign: Nonmobile, laboratory environment readily accesible to maintenance; includes laboratory instruments and test equipment, medical electronic equipment, business and scientific computer complexes.

- G_F, Ground, Fixed: Conditions less than ideal such as installation in permanent racks with adequate cooling air and possible installation in unheated buildings; includes permanent installation of air traffic control, radar and communications facilities.

- G_M, Ground, Mobile: Equipment installed on wheeled or tracked vehicles; includes mobile communication equipment.

The different parts such as diodes, transistors, bipolar or MOS IC's, optoelectronic devices have their specific environmental factors. To give an order of magnitude the failure rate in the ground, mobile area is about 10 times higher than in the ground, benign application. An IC installed within the control room of an electrical power station will be more reliable than the same one used for brake control of a car.

2.8 Summary

As discussed in the foregoing sections the part failure rate has not a given value but depends upon both the manufacturers quality system and the customers operation conditions. Especially the thermal, electrical and environmental stresses have to be considered. Fig. 2.4 shows the ranges which the failure rates are found in. The industrial application G_F is marked by a circle.

In the last years the complexity of IC's has been increased, the price has been decreased and nevertheless the reliablity has been enlarged. Thus it is recommendable to use IC's instead of discrete semiconductors not only with respect to the price but also with respect to a small failure rate. If the 1982 edition of the MIL HDBK is compared to the 1979 publication lower failure rates are found. They have been reduced e.g. by the following factors:

Si-diodes	5
Si-NPN-transistors	7
TTL-IC, 50 gates; P1	10
TTL-IC, 5000 gates, P1	50

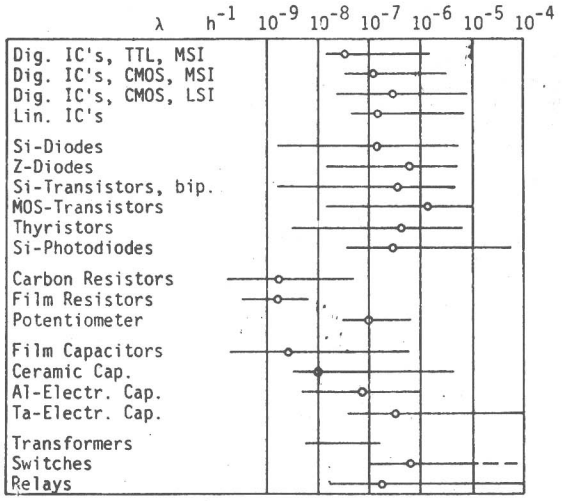

Fig. 2.4 Failure Rates

The failure rate data have been obtained from field use of passed systems. As those data are used for reliablity predictions of future systems an uncertainty exists until the new parts become tried and true. With improved reliability of the latest devices it can be expected that the anticipated "theoretical" failure rates give an upper limit and a "conservative" estimate of the real behaviour. The prediction is the more accurate the higher the degree of similarity is between the new and the operated devices both in hardware design and in the anticipated environments.

3 EQUIPMENT FAILURE RATES

The equipment designer will take into account the failure rate of the individual parts. He will apply them to compose modules and the modules will result in an equipment performing its required function. One of the properties of the equipment is its reliability. The objectives of this chapter are to deal with some characteristic quantities determining the reliablity and availability.

3.1 Failure Rates from Field Experience

Data collected from the field use of operating equipment are assumed to be the most proved and substancial. As with the parts equation (2.1) may be used to find an equipment failure rate.

The failure rate is rather high at the beginning of the production process of a new designed appliance and decreases the more the better the production process has been understood (Fig. 3.1). There is a "learning factor" as with the IC's. Another similarity is found with respect of the environmental stresses /11/. Resistance thermometers e.g. fail in a chemical plant twice as much as in an electrical power station. The failure rate is enlarged by aggressive or corrosive gases and liquids. With mobile application it is increased by a factor of three compared with the installation in permanent racks.

Such failure rates based on experience are not available for new designed appliances. In these cases it can be extrapolated from used equipment to the newly designed, if similar parts and modules in a similar environment are used. If that is not possible then theoretical analysis become necessary.

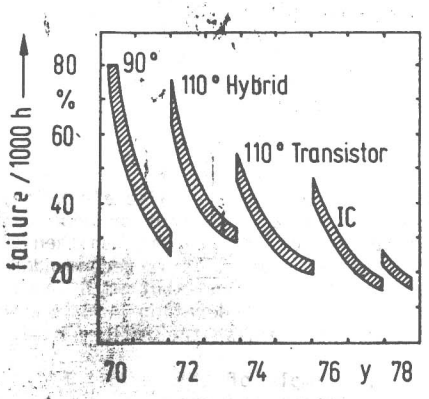

Fig. 3.1 Manufacturing of TV-sets; Learning Effect

3.2 Parts Counting Method

Let be E_i the event, that the part i with failure rate λ_i is performing its required function. The probability $p(E_i)$ that the event E_i occurs is with exponentially distributed lifetimes

$$p(E_i) = e^{-\lambda_i t}.$$

The equipment may be composed by n parts in total, i = 1, 2, ... n, and each part shall be necessary for the equipment function. Then the event E (without subscript)

event E: the equipment is performing its required function

is the Boolean conjunction, the intersection of all the events E_i

$$E = E_1 \wedge E_2 \wedge \ldots \wedge E_n. \qquad (3.1)$$

The event E only occurs if all events E_i occur. The probability p(E) then results in

$$p(E) = p(E_1)\cdot p(E_2)\cdot \ldots p(E_n)$$

$$= e^{-\lambda_1 t} \cdot e^{-\lambda_2 t} \cdot \ldots e^{-\lambda_n t} = e^{-\Sigma\lambda_i t} = e^{-\lambda t} \qquad (3.2)$$

where $$\lambda = \sum_{i=1}^{n} \lambda_i \qquad (3.3)$$

represents the anticipated failure rate λ of the equipment.

Equation (3.3) is often used as it is easy to handle. Like in book-keeping the part failure rates only have to be summed up and an equipment failure rate is achieved. Yet the problem arises that the number calculated by Eq. (3.3) is not a confidental statement. The assumption "all parts are necessary that the equipment performs its required function" does not always apply. In most cases an appliance will fulfill its mission though one of the parts (or some) has failed. It is even extremely difficult to design an equipment in such a manner that it will fail with each part fault.

In this situation it is very important to know whether or not a given fault affects the equipment function. To answer this question a failure effect analysis has to be carried out.