EUROPEAN POWER SUPPLY MANUFACTURERS ASSOCIATION

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RELIABILITY

Guidelines to Understanding Reliability Prediction

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This report gives an extensive overview of reliability issues, definitions and prediction methods currently used in the industry. It defines different methods and looks for correlations between these methods in order to make it easier to compare reliability statements from different manufacturers' that may use different prediction methods and databases for failure rates.

The report finds however such comparison very difficult and risky unless the conditions for the reliability statements are scrutinized and analysed in detail.

Furthermore the report provides a thorough aid to understanding the problems involved in reliability calculations and hopefully guides users of power supplies to ask power manufacturers the right questions when choosing a vendor.

The European Power Supply Manufacturers Association was established in 1995, to represent the European power supply industry.

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1 Introduction

1.1 The Origin and Structure of this Guide

This guide was produced by EPSMA to help customers understand reliability predictions and the different calculation methods and life tests.

There is an uncertainty among customers over the usefulness of, and the exact methods used for the calculation of reliability data. Manufacturers use various prediction methods and the reliability data of the circuit elements used can come from a variety of published sources or manufacturer's data. This can have a significant impact on the reliability figure quoted and can lead to confusion especially when a similar product from different manufacturers appear to have different reliability.

In view of this EPSMA decided to produce this document with the following aim:

"A document which introduces reliability predictions and compares results from different MTBF calculation methodologies and contrast the results obtained using these methods. The guide should support customers to ask the right questions and make them aware of the implications when different calculation methods are used."

To aid the transition to the following chapters, section 1.2 includes a brief introduction to reliability.

Chapter 2 is an overview of reliability assessment methods of reliability models and life testing.

The following Chapter 3 explains failure rate prediction in detail based on the method of IEC 61709.

Chapter 4 gives an outline of the observations of an EPSMA member using life testing in accordance with MIL-HDBK-781 test plan VIII-D over a period of 8 years. It also outlines Accelerated Life Testing.

Chapter 5 is an extract from an EPSMA members report comparing their theoretical predictions with failures as recorded by 'failed' units returned from customers

EPSMA members use a number of prediction methods and these are compared in Chapter 6 both by prime application and their pros and cons. Chapter 7 shows the result of comparing predicted reliability (*MTBF*) of the same products using different methods.

Chapter 8 lists questions and answers and Chapter 9 draws some conclusions from the report.

Appendix A contains detailed definitions of the terms used in reliability engineering, exponential distribution models and relationships between measures.

1.2 A Brief Introduction to Reliability

Reliability is an area in which there are many misconceptions due to a misunderstanding or misuse of the basic language. It is therefore important to get an understanding of the basic concepts and terminology. Some of these basic concepts are described in this section.

What is failure rate (λ)?

Every product has a failure rate, λ which is the number of units failing per unit time. This failure rate changes throughout the life of the product that gives us the familiar bathtub curve, shown in figure 1.1, that shows the failure rate / operating time for a population of any product. It is the manufacturer's aim to ensure that product in the "infant mortality period" does not get to the customer. This leaves a product with a useful life period during which failures occur randomly i.e. λ is constant, and finally a wear out period, usually beyond the products useful life, where λ is increasing.

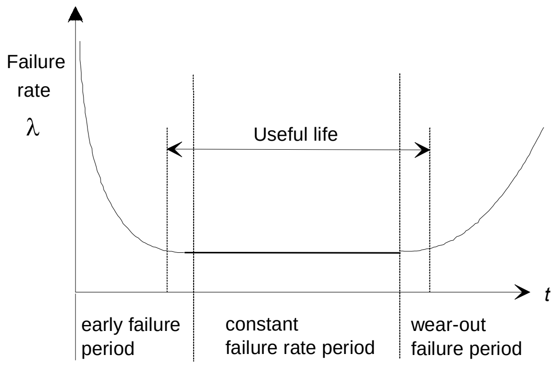

Figure 1.1 - The Bathtub Curve

What is reliability?

A practical definition of reliability is "the probability that a piece of equipment operating under specified conditions shall perform satisfactorily for a given period of time". The reliability is a number between 0 and 1.

What is *MTBF, MTTF*?

Strictly speaking, *MTBF* (mean operating time between failures) applies to equipment that is going to be repaired and returned to service, *MTTF* (mean time to failure) applies to parts that will be thrown away on failing. During the 'useful life period' assuming a constant failure rate, *MTBF* is the inverse of the failure rate and we can use the terms interchangeably, i.e.

$$MTBF = \frac{1}{\lambda}$$

Many people misunderstand *MTBF* and wrongly assume that the *MTBF* figure indicates a minimum, guaranteed, time between failures. If failures occur randomly then they can be described by an exponential distribution

$$R(t) = e^{-\lambda t} = e^{\frac{-t}{MTBF}}$$

After a certain time, *t* which is equal to the *MTBF* the reliability, *R*(t) becomes

$$R(t) = e^{-1} = 0.37$$

This can be interpreted in a number of ways

(a) If a large number of units are considered, only 37% of their operating times will be longer than the *MTBF* figure.

(b) For a single unit, the probability that it will work for as long as its *MTBF* figure, is only about 37%.

(c) We can say that the unit will work for as long as its *MTBF* figure with a 37% Confidence Level.

(d) In order to put these numbers into context, let us consider a power supply with a *MTBF* of 500,000 hours, (a failure rate of 0.2%/1000 hours), or as the advertising would put it "an *MTBF* of 57 years!"

(e) From the equation for *R*(t) we calculate that at 3 years (26,280 hours) the reliability is approximately 0.95, i.e., if such a unit is used 24 hours a day for 3 years, the probability of it surviving that time is about 95%. The same calculation for a ten year period will give *R*(t) of about 84%.

Now let us consider a customer who has 700 such units. Since we can expect, on average, 0.2% of units to fail per 1000 hours, the number of failures per year is: $\frac{0.2}{100}\times\frac{1}{1000}\times 700\times 24\times 365 = 12.26$

What is Service life, mission life, useful life?

Note that there is no direct connection or correlation between service life and failure rate. It is possible to design a very reliable product with a short life. A typical example is a missile for example: it has to be very, very reliable (*MTBF* of several million hours), but its service life is only 0.06 hours (4 minutes)! 25 year old humans have an *MTBF* of about 800 years, (λ about 0.1%/year), but not many have a comparable "service life". Just because something has a good *MTBF*, it does not necessarily have a long service life as well.

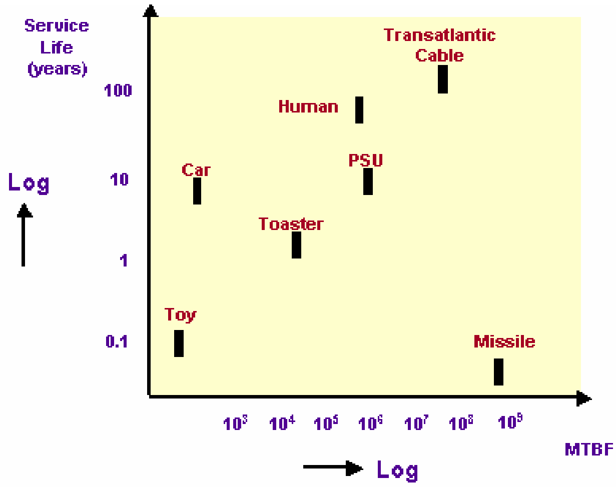

Figure 1.2 - Some examples of Service Life vs. *MTBF*

What is reliability prediction?

Reliability prediction describes the process used to estimate the constant failure rate during the useful life of a product. This however is not possible because predictions assume that:

- The design is perfect, the stresses known, everything is within ratings at all times, so that only random failures occur
- Every failure of every part will cause the equipment to fail.
- The database is valid

These assumptions are sometimes wrong. The design can be less than perfect, not every failure of every part will cause the equipment to fail, and the database is likely to be at least 15 years out-of-date. However, none of this matters much, if the predictions are used to compare different topologies or approaches rather than to establish an absolute figure for reliability. This is what predictions were originally designed for.

Some prediction manuals allow the substitution of use of vendor reliability data where such data is known instead of the recommended database data. Such data is very dependant on the environment under which it was measured and so, predictions based on such data could no longer be depended on for comparison purposes.

These and other issues will be covered in more detail in the following chapters.

2 Overview of reliability assessment methods

Reliability of a power product can be predicted from knowledge of the reliability of all of its components. Prediction of reliability can begin at the outset of design of a new product as soon as an estimate of component count can be made. This is known as ‘parts count’ reliability prediction. When the product has been designed and component stresses can be measured or calculated then a more accurate ‘parts stress’ reliability prediction can be made.

Reliability can also be predicted by life tests to determine reliability by testing a large number of the product at their specified temperature. The prediction can be determined sooner by increasing the stress on the product by increasing its operating temperature above the nominal operating temperature. This is known as accelerated life testing. Predictions by these methods take account of the number of units and their operating hours of survival before failure.

From either method the reliability under different specified end-user operating conditions can be predicted.

In practice when a product is first released, the customer demand for samples may mean that there has been insufficient time to perform extensive life testing. In these circumstances a customer would expect reliability prediction by calculation and that field-testing would be progressing so that eventually there would be practical evidence to support the initial calculated predictions. Some prediction methods take account of life test data from burn-in, lab testing and field test data to improve the prediction obtained by parts stress calculations.

The following chapter explains reliability prediction from both parts count and parts stress methods. Subsequent chapters look at life testing and compare the results of both prediction and life tests.

3 Failure rate prediction

3.1 General

Reliability predictions are conducted during the concept and definition phase, the design and development phase and the operation and maintenance phase, at various system levels and degrees of detail, in order to evaluate, determine and improve the dependability measures of an item. Successful reliability prediction generally requires developing a reliability model of the system considering its structure. The level of detail of the model will depend on the level of design detail available at the time. Several prediction methods are available depending on the problem (e.g. reliability block diagrams, fault tree analysis, state-space method).

During the conceptual and early design phase a failure rate prediction is a method that is applicable mostly, to estimate equipment and system failure rate. Following models for predicting the failure rate of items are given:

- failure rate prediction at reference conditions (parts count method)
- failure rate prediction at operating conditions (parts stress method)

3.2 Application

Failure rate predictions are useful for several important activities in the design phase of electronic equipment in addition to many other important procedures to ensure reliability.

Examples of these activities are:

- to assess whether reliability goals can be reached,
- to identify potential design weaknesses,
- to compare alternative designs,
- to evaluate designs and to analyse life-cycle costs,
- to provide data for system reliability and availability analysis,
- to plan logistic support strategies,
- to establish objectives for reliability tests.

3.3 Assumptions and limitations

Failure rate predictions are based on the following assumptions:

- The prediction model uses a simple reliability series system of all components, in other words, a failure of any component is assumed to lead to a system failure.
- Component failure rates needed for the prediction are assumed to be constant for the time period considered. This is known to be realistic for electronic components after burn-in.
- Component failures are independent.
- No distinction is made between complete failures and drift failures
- Components are faultless and are used within their specifications.
- Design and manufacturing process of the item under consideration are faultless.
- Process weaknesses have been eliminated, or if not, screened by burn-in.

Limitations of failure rate predictions are:

- Provide only information whether reliability goals can be reached.
- Results are dependent on the trustworthiness of failure rate data.
- The assumption of constant component failure rates may not always be true. In such cases this method can lead to pessimistic results.
- Failure rate data may not exist for new component types.
- In general redundancies cannot be modelled.
- Other stresses as considered may predominate and influence the reliability.
- Improper design and process weaknesses can cause major deviations.

3.4 Prediction models

The failure rate of the system is calculated by summing up the failure rates of each component in each category (based on probability theory). This applies under the assumption that a failure of any component is assumed to lead to a system failure.

The following models assume that the component failure rate under reference or operating conditions is constant. Justification for use of a constant failure rate assumption should be given. This may take the form of analyses of likely failure mechanisms, related failure distributions, etc.

3.5 Failure rate prediction at reference conditions (Parts count)

The failure rate for equipment under reference conditions is calculated as follows:

$$\lambda_{S,i} = \sum_{i=1}^{n} \left(\lambda_{ref}\right)_i \quad ,$$

where

λ_{ref}	is the failure rate under reference conditions;
n	is the number of components

The reference conditions adopted are typical for the majority of applications of components in equipment. Reference conditions include statements about

- operating phase,
- failure criterion,
- operation mode (e.g. continuous, intermittent),
- climatic and mechanical stresses,
- electrical stresses.

It is assumed that the failure rate used under reference conditions is specific to the component, i.e. it includes the effects of complexity, technology of the casing, different manufacturers and the manufacturing process etc.

Data sources used should be the latest available that are applicable to the product and its specific use conditions. Ideally, as said before, failure rate data should be obtained from the field.

Under these circumstances failure rate predictions at reference conditions used at an early stage of design of equipment should result in realistic predictions.

3.6 Failure rate prediction at operating conditions (Part Stress)

Components in equipment may not always operate under the reference conditions. In such cases, the real operational conditions will result in failure rates different from those given for reference conditions. Therefore, models for stress factors, by which failure rates under reference conditions can be converted to values applying for operating conditions (actual ambient temperature and actual electrical stress on the components), and vice versa, may be required.

The failure rate for equipment under operating conditions is calculated as follows:

$$\lambda = \sum_{i=1}^{n} \left(\lambda_{ref} \times \pi_U \times \pi_I \times \pi_T\right)_i$$

where

λ_{ref} is the failure rate under reference conditions;
π_U is the voltage dependence factor;
π_I is the current dependence factor;
π_T is the temperature dependence factor;
n is the number of components

In the standard IEC 61709, clause 7 specific stress models and values for component categories are given for the π-factors and should be used for converting reference failure rates to field operational failure rates. The stress models are empirical and allow fitting of observed data.

However, if more specific models are applicable for particular component types then these models should be used and their usage noted.

Conversion of failure rates is only possible within the specified functional limits of the components.

3.7 The failure rate prediction process

The failure rate prediction process consists of the following steps:

- Define the equipment to be analyzed
- understand system by analysing equipment structure
- determine operational conditions: operating temperature, rated stress;
- determine the actual electrical stresses for each component;
- select the reference failure rate for each component from the database;
- in the case of a Failure rate prediction at operating conditions calculate the failure rate under operating conditions for each component using the relevant stress models;
- sum up the component failure rates;
- document the results and the assumptions.

The following data is needed

- description of equipment including structural information;
- all components categories and the number of components in each category;
- failure rates at reference conditions for all components;
- relevant stress factors for the components;

3.8 Failure rate data

Failure rate data of components are published in several well-known Reliability Handbooks. Usually the data published is component data obtained from equipment in specific applications e.g. telephone exchanges. In some cases the source of the data is unspecified and is not principally obtained from field data. Due to this reason failure rate predictions often differ significantly from field observations and can often lead to false consequences.

It is therefore advisable to use current reliable sources of field data whenever it is available and applicable as long as they are valid for the product. Data required to quantify the prediction model is obtained from sources such as company warranty records, customer maintenance records, component suppliers, or expert elicitation from design or field service engineers. If field failure rate data has been collected then the conditions (environmental and functional stresses) for which the values are valid shall also be stated.

The failure rates stated should be understood as expected values for the stated time interval and the entirety of lots and apply to operation under the stated conditions; i.e. it is to be expected that in future use under the given conditions the stated values will, on average, be obtained.

Confidence limits for expected values are not reasonable because they will only be determined for estimated failure rates based on samples (life tests).

When comparing the expected values from reliable failure rate database with specifications in data sheets or other information released by component manufacturers, the following shall be considered:

- If a manufacturer's stated values originate from accelerated tests with high stresses and have been converted to normal levels of stress for a long period through undifferentiated use of conversion factors, they may deviate from the values observed in operation.
- Due to the different procedures used to determine failure rates by the manufacturer (e.g. worst case toleranced components) and by the user (e.g. function maintained despite parameter changes, fault propagation law), more favourable values may be obtained.

3.9 Failure rate prediction based on IEC 61709

The standard IEC 61709 [1)] "Electronic components – Reliability, Reference conditions for failure rates and stress models for conversion" allows developing a database of failure rates and extrapolating the same for other operating conditions using stress models provided.

The standard IEC 61709

- gives guidance on obtaining accurate failure rate data for components used on electronic equipment, so that we can precisely predict reliability of systems.
- specifies reference conditions for obtaining failure rate data, so that data from different sources can be compared on a consistent basis.
- describes stress models as a basis for conversion of the failure rate data from reference conditions to the actual operating conditions.

Benefit of using IEC 61709:

- The adopted reference conditions are typical for the majority of applications of components in equipment; this allows realistic reliability predictions in the early design phase (parts count)
- The stress models are generic for the different component types; they represent a good fit of observed data for the component types; this simplifies the prediction approach.
- Will lead to harmonization of different data sources; this supports communication between parties.

If failure rate data are given in accordance with this standard then no additional information on specified conditions is required.

The stated stress models contain constants that were defined according to the state of the art. These are averages of typical component values taken from tests or specified by various manufacturers.

A factor for the effect of environmental application conditions is basically not used in IEC 61709 because the influence of the environmental application conditions on the component depends essentially on the design of equipment. Thus, such an effect may be considered within the reliability prediction of equipment using an overall environmental application factor.

Figure 3.1 provides as an example for the use of IEC 61709 for developing a failure rate database and for carrying out failure rate predictions.

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[1] IEC 61709 has been adopted as European standard EN 61709

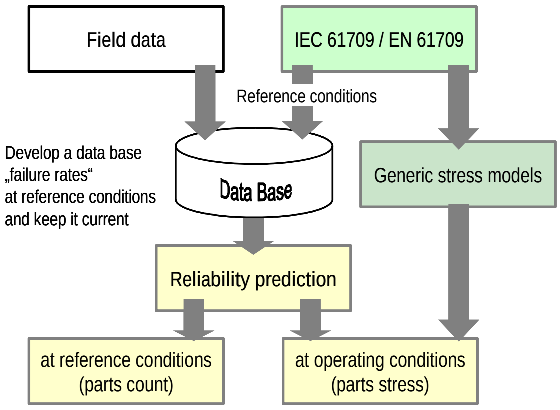


Figure 3.1 – Prediction methods

Two concrete examples for using IEC 61709 as basis for the development of a reliable failure rate database are the company handbooks IRPH 2003 [2] and SN 29500 [3].

4 Reliability Tests - Accelerated Life Testing

As mentioned earlier, life testing can be used to provide evidence to support predictions calculated from reliability models. This testing can be performed either by testing a quantity of units at their likely operating environment (e.g. 25°C) or at an elevated temperature to accelerate the failure mechanism. The latter method is known as accelerated life testing and it is based on failures being attributed to chemical reactions within electronic components. The mechanism is described by S. Arrhenius and it can be used to predict how much *MTTF* will be reduced from its value at 25°C, for example, and how tests at higher temperatures can accelerate failure and reduce test time. This chapter will look briefly at life testing at 25°C and using the principles of S. Arrhenius to predict *MTTF* at other temperatures and to accelerate life testing.

To test the reliability of a product at 25°C, a reasonable number of about 100 units would be subjected to continuous testing (not cycled) in accordance with say MIL-HDBK-781 test plan VIII-D at nominal input and maximum load for about 1 year. (Discrimination ratio = 2. Decision risk = 30% each).

If there are any failures the test time is extended. For example with two failures the test is continued to twice the minimum length of time. Preferably the test would be continued indefinitely even if there were no failures, until the space or the jigs are needed for another product. Every failure would be analysed for the root cause and if that resulted in a component or design change all the test subjects would be modified to incorporate the change and the test would be restarted.

In the experience of one power supply manufacturer over eight years only two products failed during life testing. These were due to a mosfet and a capacitor not meeting specification. The mosfet increased temperature after several months and was found to be from a faulty batch that had voids under the chip. The capacitors were found to have micro cracks when supplied and these led to short circuits over time.

The *MTTF* demonstrated by life tests under representative operating conditions is often found to be many times longer than the calculated value and it has the benefit of providing operational evidence of reliability.

If predictions are required for higher temperatures then the tests at 25°C can be used with an acceleration factor to predict the reduced *MTTF* at elevated temperatures. Alternatively if units are tested at temperatures higher than 25°C then an acceleration factor again applies. In this situation the time to failure is ‘accelerated’ by the increased stress of higher temperatures and the test time to calculate *MTTF* at 25°C can be reduced.

The Acceleration Factor *AF* is calculated from the formula below. In practice an assumption has to be made on a value for E, the activation energy per molecule. This depends on the failure mechanism and can vary. Different

[2] Italtel: IRPH 2003 - Italtel Reliability Prediction Handbook
[3] Siemens: SN 29500 - Failure rates of components

data sources shows E from less than about 0.3eV (gate oxide defect in a semiconductor) to more than 1.1eV (contact electro-migration).

Acceleration Factor $AF = \frac{tf_1}{tf_2} = \exp\left(\frac{E}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right)$

tf_1 = time to failure at temperature T_1

tf_2 = time to failure at temperature T_2

T_1, T_2 = temperature in degrees Kelvin (°K)

E = activation energy per molecule (eV)

k = Boltzmann's constant (8.617×10^{-5} (eV/°K))

5 Overview of Combined Prediction and Life Tests

The two previous chapters looked at reliability prediction from a model and prediction based on tests at specified operating conditions or accelerated by the stress of higher temperatures. Both these methods are useful indicators of reliability and can be specified separately in data sheets.

When a product is established in service in end user equipment, a study of causes of failures and time to failure provides another indication of reliability.

The following example quoted by a PSU manufacturer resulted from a study of their deliveries and claims databases:

"When studying failure rates for different periods you will see that the failure rate will vary. Also the failure pattern will vary. For one period you may not have any or very few failures, and then there may be a very high failure rate for some period and then you may again have a period of very few failures. And if you get a problem later, it will probably be another component that causes you that problem.

Normally one expects that the failure rate higher early in a products life and that there will be a reliability growth during the products life. In reality it is not that simple.

The diagrams below show the predicted failure rate and the observed failure rate of three different product types labelled as 'A', 'B' and 'C'. (Information on how the observed failure rate was obtained is shown at the end of this chapter).

The high failure rate of **Product A**, Figure 5.1, below, during 1995 was due to one poor batch of one component. The whole batch was taken back and was registered as poor components. The failure rate for that year was calculated from a relatively small number (approx. 5k). For all other years the number of delivered units is higher than 150k.

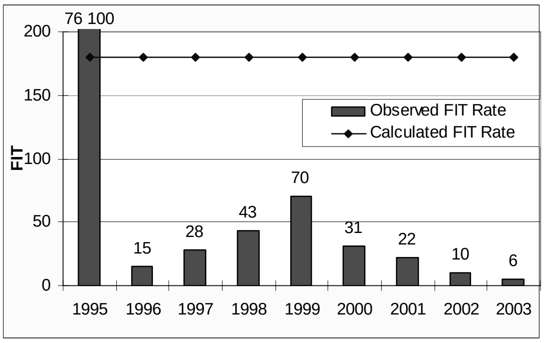


Figure 5.1 - Product A

Product B, Figure 5.2 below, has been manufactured in more than 500k each year. One can see that the failure rate is very low, though it has increased during 2003. Most of the failures during 2003 are "No failure found", which illustrates another problem with failure reporting. There may be an intermittent failure in the product, or e.g. the customer has not been able to solder the product properly. Then, when the product is replaced with another, the circuit suddenly starts to work however the product is still considered to be faulty.

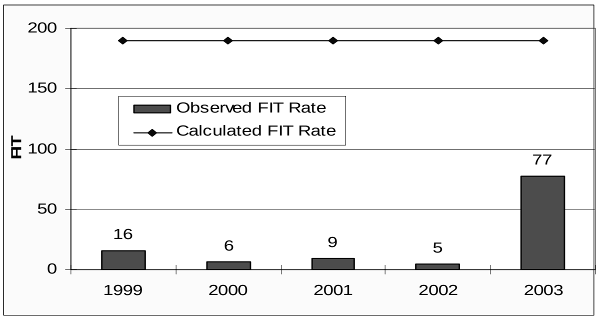


Figure 5.2 -Product B

Product C, **Figure 5.3** below, has been manufactured in more than 100k per year, except for 1995, where the numbers was 32k. The design has not changed, but during 2000 one component type was replaced by another type. However, they will both still have the same predicted failure rate as they have the same basic data and are from the same component category. The failure mode that was dominant during the years 1998-2000 has gradually disappeared as the weak population of the components of the old component has disappeared (the same change has been performed for all three modules in this study). This is an example of reliability growth.

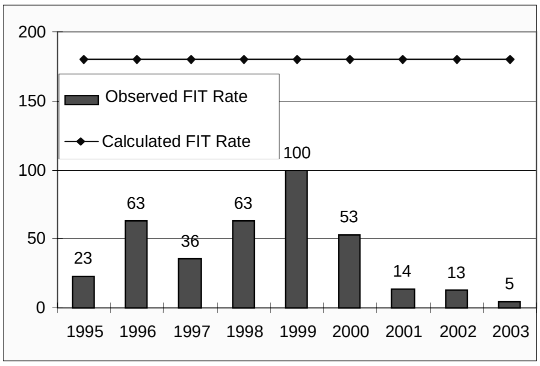


Figure 5.3 - Product C

In conclusion we normally see that the observed failure rate is much lower than the predicted rate. For shorter periods it may happen that the observed rate is higher than the predicted, due to special events, such as a bad component batch. A batch with only one tenth of one per cent weak components will destroy the *MTBF* (*MTTF*) figures.

One may expect that the failure rate will "oscillate" more than 1 order of magnitude during its life.

Field failures are difficult to track, and the reporting rate may be low. This is the parameter that most severely affects the calculation of "real" FIT Rates."

A reliability calculation method using field data is shown in Appendix A4.

6 Reliability Prediction Methods used by EPSMA Members

A survey of *MTBF* prediction methods was carried out with 16 EPSMA member companies and a summary is in the following Table 6.1. It shows a range of practices across the industry with some manufacturers using several methods to meet 'industry standards' or customer needs.

Table 6.1 - RELIABILITY PREDICTION METHODS USED BY EPSMA MEMBERS

Method	Number of EPSMA Users*	% of EPSMA Users*
MIL-HDBK-217F Parts count only	1	6
MIL-HDBK-217F Parts stress only	6	38
MIL-HDBK-217F Both Parts count and Parts stress	2	13
Bellcore TR332	3	19
Telcordia SR332	3	19
Bellcore TR332 and Telcordia SR332	2	13
Siemens SN29500	1	6
British Telecom HRD4 and HRD5	2	13
Field Returns	1	6
Life Testing	4	25
RAC Prism and Relex tools used with several of these methods.		

* The survey represents 16 EPSMA Companies/Divisions

The different methods have various applications, merits and limitations and some of these are listed in the following Table 6.2.

Table 6.2 - COMPARISON OF FEATURES OF RELIABILITY PREDICTION METHODS

Reliability Prediction Model	Application	Limitations
MIL-HDBK-217F	It provides failure rate data and stress models for parts count and parts stress predictions. It provides models for many component and assembly types and fourteen environments ranging from ground benign to canon launch. It is well known for international military and commercial applications and has been widely accepted. It provides predictions for ambient of 0ºC to 125ºC.	The component database omits newer commercial components and has not been updated since 1995 and there are apparently no plans for further updates. It penalises non-military components, and predicts failure rates of some components as worse than actual performance.
Telcordia SR332/ Bellcore TR332	Updated to SR332 in May 2001. It provides three prediction methods incorporating parts count, lab test data and field failure tracking. It provides models for many component and assembly types and five environments applicable to telecommunications applications.	Predictions are limited to ambient of 30 ºC to 65 ºC.

Reliability Prediction Model	Application	Limitations
British Telecom HRD4 and HRD5	Similar to Telcordia SR332	Predictions are limited to ambient of 0ºC to 55ºC.
Siemens SN29500 (based on IEC 61709 concept)	SN 29500 provides frequently updated failure rate data at reference conditions and stress models necessary for parts count and parts stress predictions. The reference conditions adopted are typical for the majority of applications of components in equipment. Under these circumstances parts count analysis should result in realistic predictions. The stress models described in this standard are used as a basis for conversion of the failure rate data at reference conditions to the actual operating conditions in the case that operating conditions differ significant from reference conditions.	Field failure rate data are determined from components used in Siemens products while also taking test results from external sources into account.

7 A Comparison of Reliability Calculations

An aim of this guide was to provide examples showing reliability predictions using different methods and the assumptions made in applying these methods. As can be seen from Table 7.1 below, the differences due to variation in data sources and model parameters is significant.

For example the *MTTF* at room temperature (25ºC) of a small 1Watt DC-DC converter with 10 components ranged from 95 years to 11895 years - a variation of 125:1. When it was agreed that the major cause was an inappropriate assumption to consider the potted product a 'hybrid assembly' re-calculation showed the variation to range from 1205 years to 11895 years - a variation of 9.9:1.

(Latest MIL-HDBK-217F and Telcordia SR332 Parts stress respectively).

The *MTTF* at 40ºC of a 100W AC-DC PSU with 156 components appeared to be moderated by the high component count and it ranged from 78.4 years to 177.4 years - a variation of 2.3:1.

(MIL-HDBK-217F and Siemens SN29500 (based on IEC61709), respectively).

These differences have been investigated and some considerations and major contributors include the following:

1. Inappropriate assumptions of the class of packaging (e.g. company C below assumed hybrid factor for a potted 10-component DC-DC converter. This produced a pessimistic result reducing *MTTF* by a factor of 127.6)
2. Different failure rates for each component type. (The combined FIT (Failures in 10^9 component hours) of 5 capacitors in a 10-component DC-DC converter was 92 FIT using MIL-HDBK-217F and 8 using Telcordia SR332).
3. Different temperature dependence factor π_T. (During the development of IEC 61709 the temperature dependence curves of components from different data sources were compared. An example for a CMOS IC is given in Figure 7.1. It shows for example that at 50°C the temperature dependence factor $\pi T = 0.5$ using MIL HDBK 217 and $\pi_T = 2.0$ using Bellcore TR332 (Telcordia SR332). The ratio between these is a factor of 4 and assuming the other stress factors and base failure rate are the same then Bellcore TR332 would result in four times greater failures.)
4. In products with a small component count the *MTBF* can be dominated by the prediction from few components and very sensitive to differences between methods. For example if the *MTBF* is dominated by the capacitors, as in point 2 above, then the *MTBF* could vary in that case by up to 92:8 = 11.5:1.

In practice the stress factors and base failure rate of each component type can differ between methods and the final outcome needs detailed analysis. In the example the actual *MTTF* of the10-component DC-DC converter exceeded 416 years (Ignoring the erroneous 17.8 and 95 years). With an *MTTF* as long as 416 years it seems academic to be concerned with the difference between that and 11895 years though it does show how much predictions can vary and the importance of determining the underlying assumptions.

A selected prediction method can be used to assist design for reliability by comparing predictions from the same method, however as the example shows, a comparison between methods is complex.

Table 7.1 - A Comparison of Reliability Calculations (*MTTF* in both hours and years)

Reliability Prediction Model[1]	Company	1 Watt DC-DC Converter[2]				100W AC-DC PSU[3]	
		25ºC		85ºC		40ºC	
		Hours	Years[4]	Hours	Years[4]	Hours	Years[4]
MIL-HDBK-217F (EXAR 7.0)	A	31,596,574	3606.9			686,771	78.4
MIL-HDBK-217F Notice 2	B	832,000	95.0	86,000	9.8		
MIL-HDBK-217F Notice 1	C	156,000	17.8	124,000	14.2		
Telcordia SR332 Parts count	D	89,380,000	10203.2	29,260,000	3340.2		
Telcordia SR332 Parts stress	D	104,200,000	11895.0	57,160,000	6525.1		
Siemens SN29500 (IEC61709)	A	80,978,217	9244.1			1,554,055	177.4
HRD5 Parts stress	B	2,465,000	281.4	849,000	96.9		
HRD4 Parts count	B	1,132,000	129.2	1,132,000	129.2		
MIL-HDBK-217F (EXAR 7.0)	A	31,596,574	3606.9			686,771	78.4
Telcordia SR332 Parts count	E					1,418,000	162.0

[1] Reliability Prediction Model is based on parts stress analysis except where stated otherwise.

[2] 1 Watt DC-DC Converter prediction assumes ground benign environment, hybrid assembly, 5 ceramic capacitors, 2 transistors, 1 diode (resistor and transformer not included in the calculations).

[3] 100W AC-DC PSU prediction assumes ground benign environment, 156 components including, 37 capacitors, 9 transistors, 18 diodes, 71 resistors, 2 power semiconductors, 1 relay switch, 2 opto's, 2 analogue IC's, 1 standard IC, electrical connections, 1 connector socket and 12 'other' components.

[4] Years based on 1 year = 365 days x 24 hours = 8760hrs/yr.

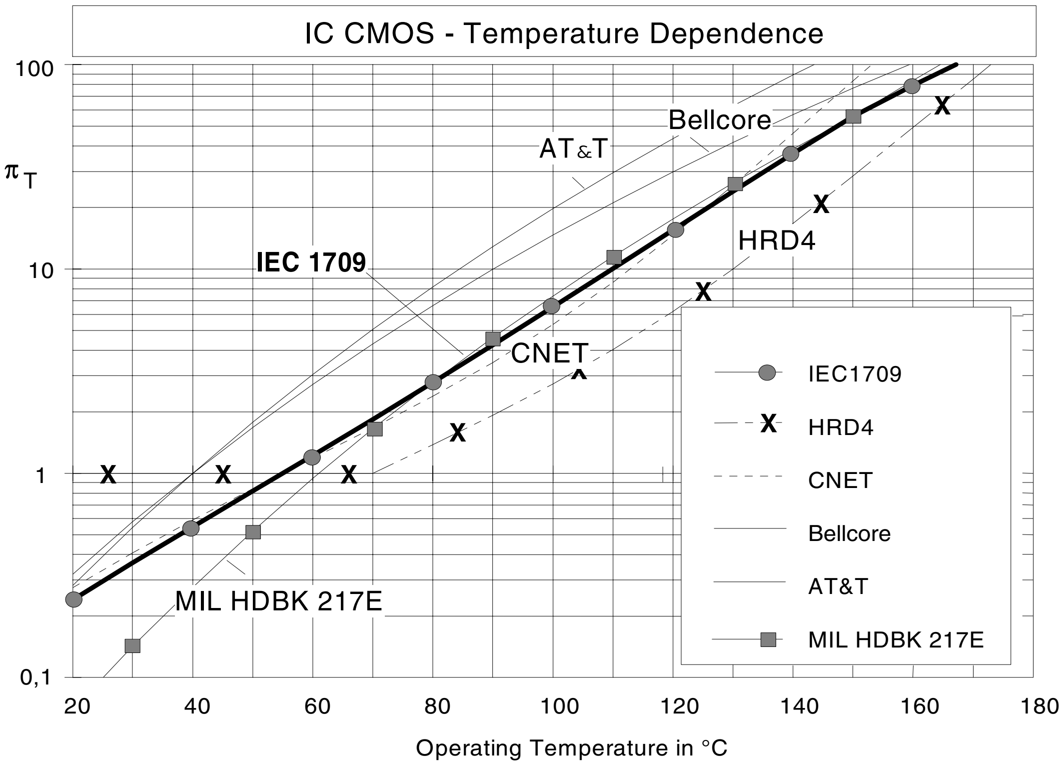


Figure 7.1 - Comparison of the temperature dependence for CMOS IC (Sept. '90)

8 Reliability Questions and Answers

This chapter attempts to summarise many of the topics brought up in this report in the form of a table of Questions and Answers. It is hoped that these will help clarify the issues.

Table 8.1 – Frequently Asked Questions and Answers

	Question	Answers
1	What is the use of reliability predictions?	Reliability predictions can be used for assessment of whether reliability goals e.g. *MTBF* can be reached, identification of potential design weaknesses, evaluation of alternative designs and life-cycle costs, the provision of data for system reliability and availability analysis, logistic support strategy planning and to establish objectives for reliability tests.
2	What causes the discrepancy between the reliability prediction and the field failure report?	Predicted reliability is based on: - Constant failure rate - Random failures - Predefined electrical and temperature stress - Predefined nature of use etc. Field failure may include failure due to: - Unexpected use - Epidemic weakness (wrong process, wrong component) - Insufficient derating
3	What are the conditions that have a significant effect on the reliability?	Important factors affecting reliability include: - Temperature stress - Electrical and mechanical stress - End use environment - Duty cycle - Quality of components
4	What is the *MTBF* of items?	In the case of exponential distributed lifetimes the *MTBF* is the time that approx. 37% of items will run without random failure Statements about *MTBF* prediction should at least include the definition of: - Evaluation method (prediction/life testing) - Operational and environmental conditions (e.g. temperature, current, voltage) - Failure criteria - Period of validity
5	What is the difference between observed, predicted and demonstrated *MTBF*?	- Observed = field failure experienced - Predicted = estimated reliability based on reliability models and predefined conditions - Demonstrated = statistical estimation based on life tests or accelerated reliability testing
6	How does HALT/HASS affect the predicted reliability?	Testing improves the reliability by detecting and eliminating weaknesses. HALT is used to find weaknesses of the product under development and improve the reliability of the design. HASS does the same to the production process.
7	How do the manufacturing, packing and transport affect the reliability/predicted reliability?	Manufacturing, packing and transport are not taken into account in reliability predictions and it is important that they adequate for the product. Manufacturing process defects, and packing not suitable to protect the product from stresses in transportation may impair reliability.

	Question	Answers
8	Can *MTBF* figures from different vendors be compared?	As shown in chapter 8 many factors affect the result and the vendors' assumptions need to be understood. Factors to be questioned include - Prediction methods - Predefined conditions - Quality level of components - The source and assumptions for the base failure rate of each component type
9	At which stage is the reliability known?	Reliability can be predicted before construction as soon as a unit has been designed. To know the reliability of an item with high confidence, one must wait until a number of items fails and apply statistics to calculate *MTBF*. Accelerated reliability testing is a way to shorten the time needed to *demonstrate* the reliability.
10	How many field failures can be expected during the warranty period if *MTBF* is known?	If lifetimes are exponential distributed and all devices are exposed to the same stress and environmental conditions used in predicting the *MTBF* the mean number of field failures excluding other than random failures can be estimated by: $\mu = n \times \left(1 - \exp\left(-\frac{t_w}{T}\right)\right) \approx \frac{n \times t_w}{T} = n\lambda t_w$ where n = quantity of devices under operation t_w = warranty period in years, hours etc. T = *MTBF* or *MTTF* in years, hours etc.
11	Do we have less service visits when using power supplies in parallel as a) 4+1 redundancy b) 1+1 redundancy	Presume, that the temperature increase under full stress is 30°C, and that the failure rate will doubled for each 10 ºC. a) Adding one unit will decrease the temperature stress by 6°C. This will initially result in 0.66 times the required service visits due to increasing the reliability of the units. On the other hand, adding one more unit adds 25% of the remaining service visits, but still the number of service visits is decreased by 17.5%. b) Adding one unit will decrease the temperature stress by 15°C. This will initially result in 0.35 times the required service visits due to increasing the reliability of the units. On the other hand, adding one more unit adds 100% of the remaining service visits, but still the number of service visits is decreased by 29.3%.
12	Do we have less system failures when using power supplies in parallel as 4+1 redundancy	Yes, dramatically. If the *MTBF* of a single power supply is 100.000 hrs, then without redundancy the system failure is expected in every 25.000 hrs. Adding one power supply means that a failure of a single power supply will not cause a system failure and it will increase the time to system failure.

Note: Items 11 and 12 assumes that some precautions has been taken for current sharing control of the paralleled devices otherwise an increased stress on one or more devices and even so called “current hogging” may result.

9 Conclusion

This report has briefly looked at reliability engineering, its terms and formulae, and how to predict reliability and demonstrate it with tests and field data.

We have seen from chapter 3 that reliability predictions are conducted during the concept and definition phase, the design and development phase and the operation and maintenance phase, in order to evaluate, determine and improve the dependability measures of an item.

Failure rate predictions are useful for several important activities in the design and operation of electronic equipment. These include assessment of whether reliability goals can be reached, identification of potential design weaknesses, evaluation of alternative designs and life-cycle costs, the provision of data for system reliability and availability analysis, logistic support strategy planning and to establish objectives for reliability tests.

The report has shown that, in the experience of power module manufacturers, reliability predictions tend to be pessimistic in comparison with actual test data and field data.

A Survey of sixteen EPSMA member companies showed many different prediction methods in use reflecting their views of an 'industry standard' or their customers needs.

This report has shown that direct comparison between different prediction methods will not be possible.

Reliability predictions of the same product were predicted using the tools and methods of different power supply manufacturers. This showed in the case of a product with only ten electronic components that *MTTF* predictions varied by up to 11.5:1. The differences were examined and shown to arise from a number of factors including the effect of different capacitor failure predictions in a product where these dominated the *MTBF* prediction.

Many of the topics brought up in this report are summarised in table 8 Reliability Q & A's.

10 Bibliography

MIL-HDBK-217F	Military Handbook, Reliability prediction of electronic equipment (1991)
MIL-HDBK-217F Notice 1	Military Handbook, Reliability prediction of electronic equipment (1992)
MIL-HDBK-217F Notice 2	Military Handbook, Reliability prediction of electronic equipment (1995)
MIL-HDBK-781 A	Handbook for reliability test methods, plans, and environments for engineering, development qualification, and production; Department of Defence (1996).
Telcordia SR332	Reliability prediction procedure for electronic equipment (2001)
Bellcore TR332	Reliability prediction procedure for electronic equipment
Siemens SN29500	Failure rates of components, expected values (2004), based on IEC 61709
IEC 61709 (1996)	ELECTRONIC COMPONENTS – Reliability, Reference conditions for failure rates and stress models for conversion
Italtel: IRPH 2003	Italtel Reliability Prediction Handbook (2003)
HRD5 Parts stress	Handbook of Reliability Data for Components used in Telecommunication Systems.
HRD4 Parts count	Handbook of Reliability Data for Components used in Telecommunication Systems

Annex A Reliability measures

A.1 Terms used in the reliability field

This chapter shall promote a common understanding about terms used in the reliability field. Terms and their definitions are adopted from the International Standard IEC 60050(191).

A.1.1 Reliability (performance)

Definition

The ability of an item to perform a required function under given conditions for a given time interval.

NOTE 1: It is generally assumed that the item is in a state to perform this required function at the beginning of the time interval.

NOTE 2: The term "reliability" is also used as a measure of reliability performance (see A.1.2).

A.1.2 Reliability

Symbol: $R(t_1,t_2)$

Definition

The probability that an item can perform a required function under given conditions for a given time interval (t_1, t_2)

NOTE 1: It is generally assumed that the item is in a state to perform this required function at the beginning of the time interval.

NOTE 2: The term "reliability" is also used to denote the reliability performance quantified by this probability (see A.1.1).

The general expression for reliability $R(t)$ is given by

$$R(t) = \exp\left(-\int_0^t \lambda(x)\,dx\right)$$

where $\lambda(t)$ denotes the (instantaneous) failure rate.

A.1.3 Probability of failure

Symbol: $F(t)$

Definition

A function giving, for every value of t, the probability that the random variable X be less than or equal to t: $F(t) = P(X \leq t)$

[According to ISO 3534-1]

The general expression for probability of failure is given by

$$F(t) = 1 - R(t) = 1 - \exp\left(-\int_0^t \lambda(x)\,dx\right)$$

where $\lambda(t)$ denotes the (instantaneous) failure rate.

A.1.4 (instantaneous) Failure rate

Symbol: $\lambda(t)$

Definition

The limit, if this exists, of a ratio of the conditional probability that the instant of time, T, of a failure of an item falls within a given time interval, $(t, t+\Delta t)$ *and the length of this interval,* Δt *, when* Δt *tends to zero, given that the item is in an up state at the beginning of the time interval.*

NOTE: In this definition *T* may also denote the time to failure or the time to first failure, as the case may be.

Failure rates have the dimension one over time, e.g.:

- Failures/year,
- Failures/hours,
- FIT (Failures in Time), i.e. the number of failures in 10^9 component hours. (10^{-9} Failures/hours)
- Failures/cycles

Example: λ=1.5/year = (1.5/8760) h^{-1} = 1.71233×10^{-4} h^{-1} = 171233 FIT

Time dependence of the failure rate

The time dependence of the failure rate for a given population of items of the same type often exhibits at least one of the following three periods which produce a bathtub curve (see Figure A.1).

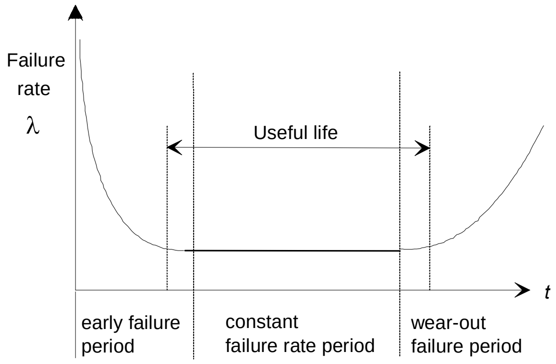


Figure A.1 - Time dependence of the failure rate

These three periods can be explained as in the following. However, the time dependence curve for any single item type could be significantly different. When interpreting reliability figures it is important to determine the physical reality of failure modes and distributions.

- Early failure period: At the start of the operating period, sometimes a higher failure rate is observed which decreases with time. Early failures occur due to manufacturing processes and material weaknesses that do not result in failures in tests (before shipping).
- Constant failure rate period: After the early failure period, the failures occur with varying failure causes that result in an effective constant failure rate during the useful life.
- Wear-out failure period: The final period that shows an increasing rate of failures due to the dominating effects of wear-out, ageing or fatigue.

The time points which separate these three operating periods cannot be determined exactly.

Failure rate data for electronic components

The characteristic preferred for reliability data of electronic components is the failure rate. Failure rate data for components of electronics in general refer commonly to the phase with constant failure rate. It is recognized that the constant failure rate assumption is sometimes not justified but such an assumption provides suitable values for comparative analysis.

For items which are operated into the wear-out failure period (e.g. wear-out of relays) the failure rate is averaged for the time interval specified in the data sheet (e.g. the time interval that 90% of the items survive).

The numerical value of how many failures occur within the time interval in question in relation to the number of items at the start of this time interval is to be observed on average under given environmental and functional stresses. Stated failure rates only apply under the conditions given.

The failure rate of an electronic component depends on many influences, such as time range (operating phase), failure criterion, duration of stress, operating mode (continuous or intermittent), ambient temperature, humidity, electrical stress, cyclical switching rate of relays and switches, mechanical stress, air pressure and special stresses).

A failure rate value alone, without knowledge of the conditions under which it was observed or is to be expected, provides no real information. For this reason, the values of the relevant factors of influence should always be given when stating a failure rate. It is possible to state how the failure rate depends on some of these influences (ambient temperature, electrical stress, switching rate of relays and switches). This dependence applies only within the specified limit values of the components.

<u>Point estimates for failure rates from test results or from the field</u>

Estimated values of the failure rates can be derived either from life tests or from field data. The rules according to which such estimates are derived depend on the statistical distribution function applying, i.e. whether "constant failure rate period" (exponential distribution) or "early and wear-out failure period" (e.g. Weibull distribution) exist. If the distribution over time of the failures is known, and estimated values of the failure rate have been calculated, the result should be interpreted statistically.

If observed failure data for n items are available from tests or from field data with a constant failure rate λ then the estimated value is given by

$$\hat{\lambda} = \frac{r}{T^*}$$

where

r	number of failures
n	items under test (at the beginning)
$T^* = n \times t$	accumulated test time when failed items are replaced during test
$T^* = (n-r)t + \sum_{j=1}^{r} t_j$	accumulated test time when failed items are not replaced during test
t	test time

If no failures are observed during the test, the point estimate is zero. However estimates can be made of the upper one-sided confidence limit on the failure rate.

To obtain confidence limits for failure rates subjected to time or failure terminated tests, it is necessary to know whether failed items are replaced during test or are not replaced (see IEC 60605-4).

A.1.5 Mean failure rate

Symbol: $\overline{\lambda}(t_1, t_2)$

<u>Definition</u>

The mean of the instantaneous failure rate over a given time interval (t_1, t_2).

NOTE: The mean failure rate relates to instantaneous failure rate $\lambda(t)$ as $\overline{\lambda}(t_1, t_2) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \lambda(x) dx$

A.1.6 Mean Time To Failure; *MTTF*

Symbol: *MTTF* (abbreviation)

Definition

The expectation of the time to failure

The general expression for *MTTF* is given by

$E\{t\} = MTTF = \int_0^\infty x\, f(x)\, dx = \int_0^\infty R(x) dx$, where $R(t)$ denotes the reliability (performance).

When the failure rate $\lambda(t)$ is constant with time the *times to failure* are exponentially distributed. This leads to

$$MTTF = \int_0^\infty R(x) dx = \int_0^\infty \exp(-\lambda\, x)\, dx = \frac{1}{\lambda}.$$

MTTF is a measure used for non-repaired items.

MTTF is sometimes misunderstood to be the life of the product instead of the expectation of the times to failure. For example, if an item has an *MTTF* of 100 000 hours, it does not mean that the item will last that long. It means that, on the average, one of the items will fail for every 100 000 item-hours of operation.

If the *times to failure* are exponentially distributed, then on average 63.2 % of the items will have failed after 100 000 hours of operation.

Specifying a single value, such an *MTTF*, is not sufficient for items that will have time dependent failure rates (e.g. wear-out failures, early-life failures).

A.1.7 Mean Operating Time Between Failures; *MTBF*

Symbol: *MTBF* (abbreviation)

Definition

The expectation of the operating time between failures

The general expression for *MTBF* is given by

$E\{t\} = MTBF = \int_0^\infty x\, f(x)\, dx = \int_0^\infty R(x) dx$, where $R(t)$ denotes the reliability (performance).

When the failure rate $\lambda(t)$ is constant with times the operating times between failures are exponentially distributed. This leads to

$$MTBF = \int_0^\infty R(x)\, dx = \int_0^\infty \exp(-\lambda x)\, dx = \frac{1}{\lambda}.$$

MTBF is a measure used for items which are in fact repaired after a failure.

If the *times between failures* are exponentially distributed, then on average 63.2 % of them are lower or equal than the *MTBF*.

Specifying a single value, such an *MTBF*, is not sufficient for items that will have time dependent failure rates (e.g. wear-out failures, early-life failures).

A.1.8 Mean Time To Restoration; Mean Time To Recovery; *MTTR*

Symbol: *MTTR* (abbreviation)

<u>Definition</u>

The expectation of the time to restoration

Note: The use of "Mean Time To Repair" is deprecated

MTTR is a factor expressing the mean active corrective maintenance time required to restore an item to an expected performance level. This includes for example trouble-shooting, dismantling, replacement, restoration, functional testing, but shall not include waiting times for resources.

A.1.9 Mean Down Time; *MDT*

Symbol: *MDT* (abbreviation)

<u>Definition</u>

The expectation of the down time

MDT is the total down time of an item. This includes

- Mean Time To Restoration *MTTR* (mean active maintenance time),
- Logistic Delay Time (*LDT*)
  (waiting for recourses (e.g. spares, test equipment, skilled personnel), travelling, transportation, etc.) and
- Administrative Delay Time (*ADL*)
  (personnel assignment priority, organizational constraint, transportation delay, labour strike, etc.)

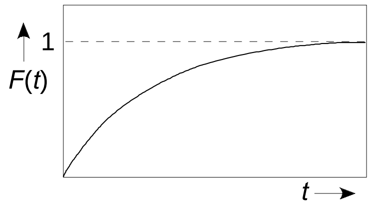
A.2 Exponential distribution

The exponential distribution is used to model the failure behaviour of items having a constant failure rate.

- Probability of failure, distribution function

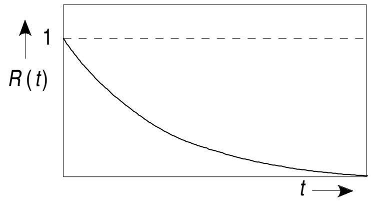
  $F(t) = 1 - \exp(-\lambda t), \qquad \lambda > 0$

  Parameter λ (failure rate)



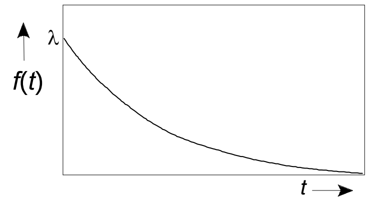
- Reliability

  $R(t) = \exp(-\lambda t), \qquad \lambda > 0$



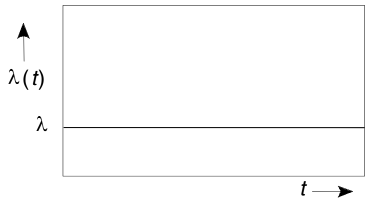
- Probability density function

  $f(t) = \frac{dF(t)}{dt} = \lambda \exp(-\lambda t)$



- Failure rate

  $\lambda(t) = \frac{f(t)}{1 - F(t)} = \lambda = const$



- Expectation, mean

  $E(t) = \mu = \int_0^\infty x\, f(x) dx = \int_0^\infty R(x) dx = \frac{1}{\lambda} = T$

  The Mean *T* of the exponential distribution is called

  – <u>for non-repaired items</u>:
  MTTF (Mean Time To Failure).
  With exponentially distributed *times to failure*, on average 63.2 % of the items will have failed after *T = MTTF* hours of operation.

  With $F(t) = 1 - \exp(-\lambda t)$ follows: $F(t = T) = 1 - \exp(-\lambda T) = 1 - \exp\left(-\frac{T}{T}\right) = 1 - \frac{1}{e} \approx 0.632.$

  – <u>for repaired items</u>:
  MTBF (Mean operating Time Between Failures)
  On average 63.2 % of *operating times between failures* are lower then *T=MTTF*.

A.3 Relationship between measures

	$F(t)$	$R(t)$	$f(t)$	$\lambda(t)$	
$F(t) =$	$F(t)$	$1 - R(t)$	$\int_0^t f(x)dx$	$1 - \exp\left(-\int_0^t \lambda(x)dx\right)$	Probability of failure
$R(t) =$	$1\text{-}F(t)$	$R(t)$	$\int_t^\infty f(x)dx$	$\exp\left(-\int_0^t \lambda(x)dx\right)$	Reliability
$f(t) =$	$\frac{dF(t)}{dt}$	$\frac{dR(t)}{dt}$	$f(t)$	$\lambda(t)\exp\left(-\int_0^t \lambda(x)dx\right)$	Probability density function
$\lambda(t) =$	$\frac{\frac{dF(t)}{dt}}{1 - F(t)}$	$\frac{d(\ln R(t))}{dt}$	$\frac{f(t)}{\int_t^\infty f(x)dx}$	$\lambda(t)$	Failure rate

A.4 How to calculate time in use from delivery data.

To calculate time in use for a product we need to know how long the product has been in the field. This discussion is valid for products that are not normally a standalone product, but will be a part of another product that will be sold to the end customer. (Most manufacturers of this type of product lose track of the product when it has left their warehouse).

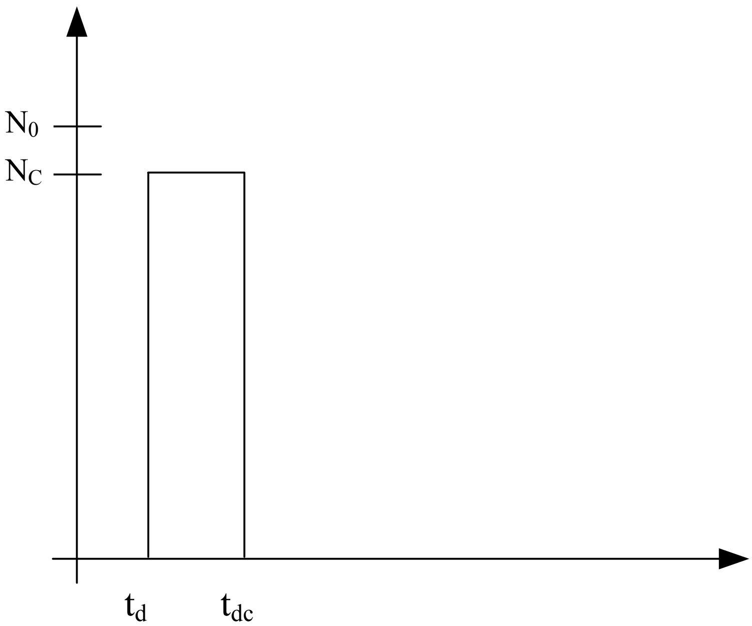
We now look at time in use for only one order (delivery).

The time in use for one order is called t_{del} below.

This means that the delivery date has to be used in some way to establish the first day (as an average) that the products in the delivery reached the field. There will be a certain delay, as the manufacturing process of the end product will take some time, and this product will also be in stock for some while, until it reach the end customer and the "field". All of those products will not be sold, and during the manufacturing process there will be some yield losses.

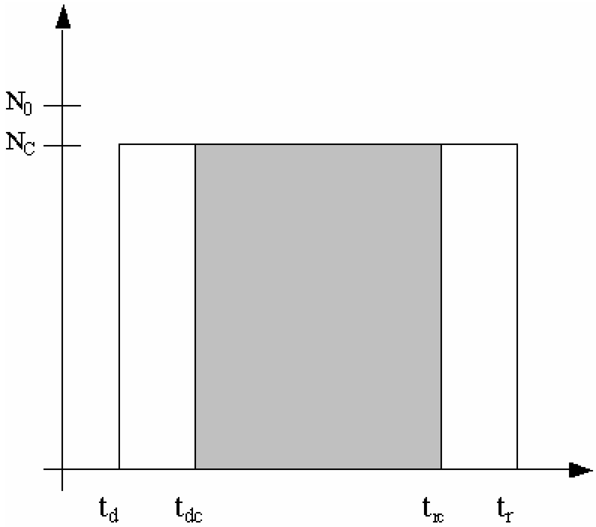
We now define a number of parameters for this order (delivery):

N_0	the number in the original order
N_c	the "corrected" number of products reaching the field ($N_c = k* N_0$, where k is a number between 0 and 1)
t_d	the delivery date
t_{dc}	the corrected delivery date ($t_{dc} = t_d +$ average time to field)
k_d	the proportion of a 24-hour day a system is used. (k_d is a number between 0 and 1)
k_r	The estimated ratio between the number of real failures and reported failures (k_r is a number between 0 and 1)



We have now established a starting date, which is a certain time later than the delivery date. How long it will take from the delivery date till the product reaches the field use is of course difficult to know. There is some indications of that a typical time to field is in the range of 90 to 150 days, but this time will probably differ for different manufacturers, and the type of customer.

To calculate the time in use, it seems we simply subtract the corrected starting date from today's date. This would however not be correct, as we have a "blind time" because we haven't got the failure reports. This time is as difficult to establish as the time to field, but typically this seems to be slightly longer (150- 210 days). Some customers seem to report as soon there is a failure, but very often the report is delayed for various reasons. Therefore one has to look into which could be the typical time for this product, depending on the type of product and the type of customers it is sold to.



The date t_r is the time of interest (that is the date of failure), but as it will take some time to get the failures reported, we need to correct for that. The time in use for the products in this order seems now to be:

$$t_{del} = k_d N_c (t_{rc} - t_{dc})$$

This should be correct if all failures would be reported, but as some of them probably won't be, we also have to correct for that. We have now the formula:

$$t_{del} = k_r k_d N_c (t_{rc} - t_{dc})$$

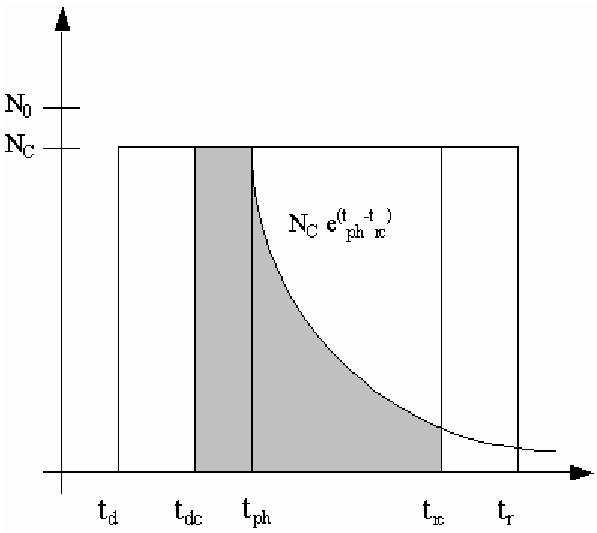
Hence, we have now introduced two new parameters:

t_r the date of failure

t_{rc} the date corrected for the report delay i.e. $t_{rc} = t_r$ - *(average report delay),*

However; this will probably overestimate the time in use, as after a while the products in the field will be replaced by new products, or will be taken out of service because some other part of the end product has failed.

There will be a low probability for this in the beginning of the end-products life, but it will then increase. We can estimate a time for this to happen. This is called t_{ph} (for phase out date, which is the estimated date for the phase out to start). Of course we do not know when the products starts being phased out, so even for this parameter we have to use common sense (or if there is some other indication to be used). For consumer products this time is probably rather short (in the range of 1 year), but longer for professional products (maybe in the range of 3 years). We do not either know how the phase out will take place, but it seem reasonable to think that the phase out can be estimated to be exponential, with a typical phase out rate (called characteristic life, t_{ch}). See picture:



The time in use for one order is the shaded area. We now have two cases, either is $t_{rc} \le t_{ph}$ or $t_{rc} > t_{ph}$. In the first case we still have the simple equation we arrived with earlier:

$$t_{del} = k_r k_d Nc(t_{rc} - t_{dc})$$

But in the latter case we will have:

$$t_{del} = k_r k_d Nc((t_{ph} - t_{dc}) + t_{ch}(1- e^{\frac{(t_{ph}-t_{rc})}{t_{ch}}}))$$

Integrating the exponential part of the curve will give the last term in the equation. We have of course to sum over all deliveries to find out the time in use for one product.

To calculate time in use we now arrive with the following equation:

$$t_{in\_use} = \sum_{all\ deliveries} t_{del}$$

From this we calculate reliability using this field data as follows

λ= (Number of failures)/$t_{\text{in use}}$

and MTTF = $1/\lambda$

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