THE ORGANISATION AND STATISTICAL ANALYSIS OF AN ELECTRONIC COMPONENT FIELD FAILURE DATABASE

by

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to MUM & DAD

ABSTRACT

This Thesis is concerned with the establishment of a Database for electronic component reliability data.

Previous research on the reliability of electronic components has mostly originated from accelerated life test studies. However, this Database contains information on field failure data. In addition, the Database was designed specifically for the purpose of exploration of the data in order to establish the potential factors which may contribute to the reliability of electronic components.

The administration of such a Database must be adequately controlled in order to make any statistical analysis valid, and therefore this Thesis includes those procedures which ensure the validity and integrity of the data stored in the Database.

The analysis of the data has employed simple exploratory techniques in order to identify those component types which consistently cause problems in electronic systems. Moreover, such techniques help to identify the observed failure distribution for those component types which have sufficient data.

A more complex statistical model has also been applied to this data, namely the Proportional Hazards Model. This has been used as a non-parametric model incorporating those factors which may have a significant effect in the failure distribution of any particular electronic component.

To conclude, the achievements are predominantly the establishment of a robust Database designed specifically for exploratory data analysis, the management of

such a Database to ensure data integrity, and finally the statistical analysis of the data stored in the Database.

This Database is therefore unique with respect to the current state of field failure analysis of electronic components and may, in the future, form the basis of new approaches to analyzing electronic component field reliability data.

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SYMBOLS AND NOMENCLATURE

α	Weibull scale parameter
β	Weibull shape parameter
β_i	Explanatory factors of PHM
δ	Smallest extreme value scale parameter
λ	Failure Rate
λ	Smallest extreme value location parameter
π factors	Factors used in MIL HDBK 217
χ^2	Distribution
AGREE	Advisory Group on the Reliability of Electronic Equipment
bfr	Base failure rate
BSI	British Standards Institution
BT	British Telecom
CODASYL	Conference for System Languages
DBMS	Database Management System
DIA	Danish Engineering Academy
DSL	Data Sub-Language
E	Activation energy
EDA	Exploratory Data Analysis
ETI	Elapsed Time Indicator
EuReData	European Reliability Databank Association

FIT	Failure Unit in 10^9 component hours
f(t)	Probability density function
F(t)	Cumulative density function
fm	Failure mechanism
GB	Ground Benign
GM	Ground Mobile
HDBK	Handbook
HRD	Handbook of Reliability Data
HF	High no of failures
HCF	High no of component hours
h(t)	Hazard function
H(t)	Cumulative hazard function
IC	Integrated Circuit
IEC	International Electrotechnical Commission
iid	Independant identically distributed
k	Boltzmans constant
k	Reverse rank
LCH	Low no of component hours
LF	Low no of failures
LINUS	Logical Enquiry and Update System
LUT	Loughborough University of Technology
MIL	Military
MOD	Ministry of Defence
MOS	Metal Oxide Semiconductor
MRDS	Multics Relational Data Store

NFF	No Fault Found
PCB	Printed Circuit Board
pdf	Probability Density Function
PHM	Proportional Hazards Modelling
PL/1	Programming language 1
R(t)	Survivor function
r	No of failures
SAE	Society of Automotive Engineers
SQL	Structured Query Language
TC	Technical Committee
T	Temperature
t	time
USAF	United States Air Force
z	Covariates for PHM

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APPENDICES

1. INTRODUCTION AND BACKGROUND

1.1. Introduction to Reliability

The reliability of electronic equipment has received increasing attention during the past twenty years, as technology has advanced. As a consequence of this, reliability analysis has been applied to a number of different fields, for example, navigation at sea and in the air, communications, atomic energy, computers and many others.

The reliability of electronic systems became more noticeably important during World War II as equipment was required to withstand different environmental stresses, e.g.desert heat, humidity and extreme cold etc. Results of American Surveys conducted of wartime equipment showed that most electronic equipment was operative for only about one third of the time, thus indicating the need for further research on the reliability of military systems.

In 1952 the Advisory Group on the Reliability of Electronic Equipment (AGREE) was established by the American Government. After 5 years of study, a reliability clause was introduced into the specifications for equipment purchased for military use [1]. This procedure was also eventually introduced by the civil airlines.

However, it is not only the military who are concerned with reliability. Over the last 20 years the consumer electronic industry has escalated, and as world competition for manufactured goods continues to grow there is increased emphasis on product quality and, in particular reliability [2].
With this increased emphasis on reliability, there is a need for engineers and manufacturers concerned with the design of electronic systems to understand the factors that influence reliability.

Dummer illustrated, in his book "An Elementary Guide to Reliability" [2], the importance of reliability in a lighthearted way.

1.2. The Reliability of Electronic Components

The design and construction of an electronic system involves the utilisation of large numbers of similar components. For example, any one particular system can have a number of printed circuit boards (PCB's) which in turn have numerous attached components. Figure 1.1 below shows an example of such a system. In general, if a PCB fails, it is replaced by another identical PCB so that the system is operational as soon as possible. The failed board is then tested and the failed component found and replaced. The board is then available and is usually kept as a spare. Thus, in general, electronic systems and printed circuit boards are known as repairable systems, while electronic components are generally known as non-repairable items.

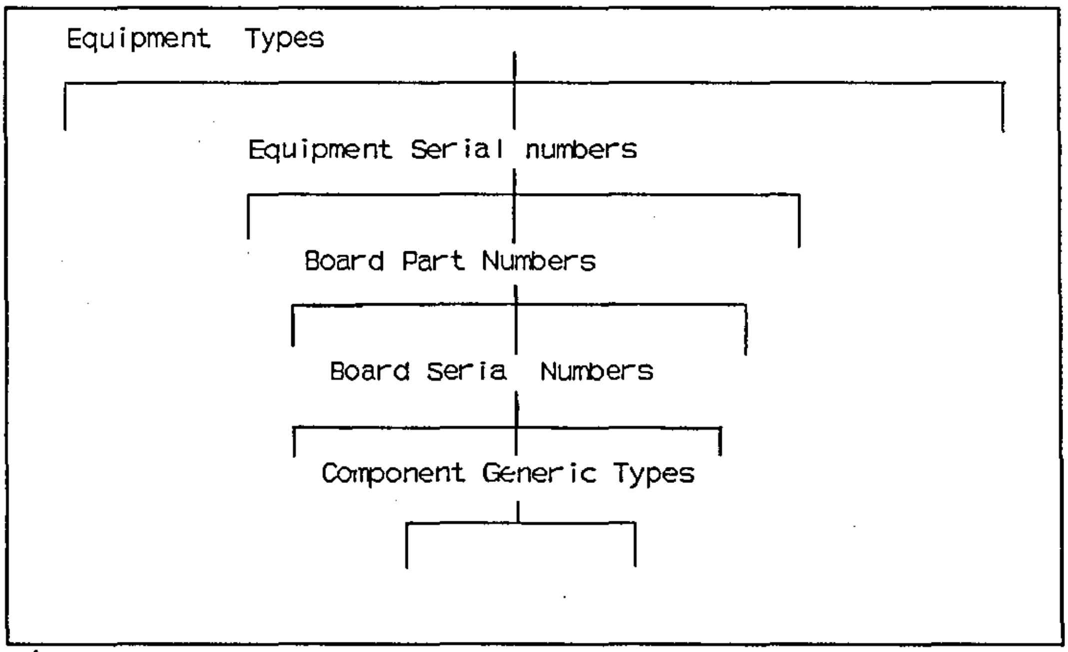

Figure 1.1
Hierarchy of Parts from Electronic Systems

Much work has been conducted on the reliability of electronic components. However, much of this work has come from laboratory generated data. This means that components have been subjected to different types of environmental testing and the resultant data extrapolated backwards to estimate the life under field conditions. Data generated in this way have the advantages that any failures occur under controlled conditions and known stress levels. However, they have the disadvantage that components may face further stresses in real field experience. In addition, it is rarely possible to test in the laboratory as many components as in the field or for so long [3]. It is therefore evident that the ideal situation would be to both generate data from controlled environmental tests and to collect field data in order to draw conclusions using both techniques on the reliability of electronic components [4].

To date, most studies of electronic components have made the assumption that failures occur randomly in time. This means that the instantaneous hazard rate of components is constant. Mathematically, this implies the distribution of times to failure is an exponential distribution. This distribution will be discussed in more detail in Chapter 2.

This assumption is based on the philosophy that the hazard rate of electronic components follow the 'bath tub curve' [5], [6], [7], shown below.

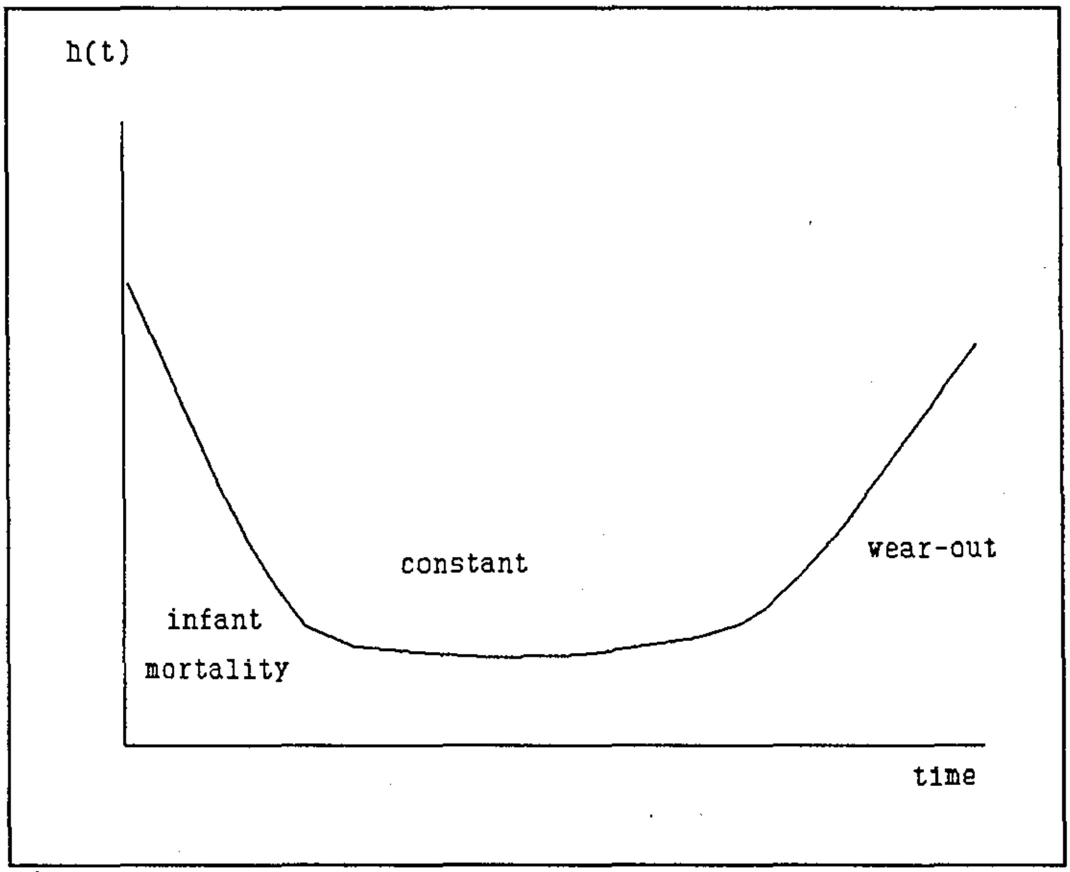

Figure 1.2
The Bath-Tub Curve

This curve shows that when a component is first put into use, any inherently weak components fail fairly soon. The early hazard rate may therefore be relatively high, but starts to fall. There is then a period in which the hazard rate is constant and failures are occurring randomly in time. This constant hazard rate period is known as the useful life of the component. The final stage is known as the wear-out stage where the hazard rate starts to increase as components wear-out. Examples of components which have been shown to exhibit this increasing hazard rate include potentiometers, switches and electrolytic capacitors. Further discussions of the constant hazard rate are contained in chapters 2, 6 and 7.

1.3. Some Features of Electronic Components

The life of an electronic component is a function of many variables, not only within the design and manufacture of the component, but also within the design and manufacture of the equipment the component is operating in [8]. When assessing the reliability of components it is therefore important to take into account all the factors which may affect the component's life distribution [3].

1.3.1. Circuit Reference Position

On each design or part number of a printed circuit board are locations where a component is positioned. This is known as the circuit reference position of that component. This means that any component can be identified by its position. Circuit reference position is important when looking at failure data of electronic components because it may highlight whether the components are being over-stressed by faulty design, e.g. heat source.

1.3.2. Encapsulation

Encapsulation refers to the material which an electronic component is surrounded by to protect it from the environment in which it is operating. For example, Integrated Circuits (IC) are generally either plastic encapsulated or hermetically sealed. Plastic encapsulated devices are cheaper and therefore tend to be used in domestic, commercial and industrial equipments. However, they are not suitable for high temperature operation or in high humidity environments and thus they are not often used in military or aerospace applications [9]. There is therefore an interest in how different encapsulations affect the reliability of electronic components. Chapter 3 will deal with the different types of encapsulation in more detail.

1.3.3. Mounting Technology

This refers to how the component is attached to the printed circuit board [9]. As with encapsulation there are many methods for component attachment and much research has been carried out on the merits of different mounting technologies. For example, many components may be either conventionally through-hole mounted or alternatively surface mounted (this is where there are no leads on the component and it is mounted directly to the surface of the board) [10]. In through-hole mounted components only the pins need be exposed to the full soldering temperature whereas in surface mounted components involving wave soldering the whole component is subjected to high temperature. This may therefore result in the two types of mounted components having different failure patterns. Chapter 3 will also deal with the different types of mounting in more detail.

1.3.4. Screened Level

Quality is an important factor in component reliability, since, in general, electronic components do not exhibit a wear-out mechanism except for those which are defective. Thus, screening levels have been standardised to enable a cost effective choice between cost and reliability to be made. The British Standard (BS) and CECC systems use the same screened levels. Screening tests include temperature cycling, burn-in, visual inspection, leakage tests, electrical testing etc. of components [11]. A BS9000 screened component would therefore have been subjected to a combination of such environmental tests.

Not all components are required to be screened and in general only military components have to be screened to the BS9000 level. Companies sometimes have their own screening procedures and standards. It is therefore of interest to investigate the reliability of screened components using both BS9000 and other standards compared to the reliability of non screened components.

1.3.5. Environment

This refers to the environment in which the system is operating. For example, a military equipment which is being carried around in a tank in the field will be experiencing different stresses to a computer sitting in an air-conditioned office. It is therefore important to know the differences in reliability of the same component type in different environments.

1.4. An Outline of the Field Failure Project

This thesis is based on a project being carried out at Loughborough University of Technology (LUT), under the leadership of Prof. D. S. Campbell, entitled "The Field Failure Study of Electronic Components". The broad aim of this study is to determine, over a period of several years, those component types which consistently cause failure in equipments [12].

As one of the initial phases of the project a pilot study was conducted at the Danish Engineering Academy (DIA) where field failure data was collected from two major Danish companies. This pilot study together with research on particular electronic components under test conditions at LUT helped formulate the basis of certain aspects for the current study [13].

In addition, parallel studies are being carried out at LUT on different aspects of component reliability, in particular, environmental testing, and failure analysis and mechanism investigations [14], [15]. These studies were instigated from the results achieved by the pilot studies at both LUT and the DIA. Moreover, these studies together with the results of the Field Failure project will both aid improvements in design of electronic components and assemblies and increase our knowledge of how electronic components fail in systems.

Further discussion about the organisation and aims of this project will be dealt with in Chapter 3.

1.5. Scope of Thesis

The scope of this thesis is concerned with the field failure of electronic components with respect to some of the factors discussed above, without making any 'a priori' assumptions on the distributional form of the times to failure. Its aims include the description of the process of data collection and the establishment of a robust database for storage and subsequent exploratory data analysis. In addition, the application of standard reliability techniques are discussed together with results from the database. It will introduce Proportional Hazards Modelling, as a tool for analyzing electronic component field data and its corresponding covariates and discuss the benefits of such an approach to the reliability of electronic components.

1.6. Organisation of Thesis

Chapter 2 will discuss some of the previous work on the reliability of electronic components together with details of statistical models which may be applied to the failure of electronic devices.

Chapter 3 includes more detailed discussion of the field failure project together with information on the organisational structure of the project and details of the specific data requirements.

Chapters 4 and 5 discuss the formation of the database and the validation procedures employed to ensure data integrity.

Chapter 6 highlights some results of initial explorations of the database. In particular, the FIT (failures in 10^9 component hours) for all components types in the database, including discussion and implications. This chapter also addresses the problems associated with particular aspects of the data collected.

Chapter 7 shows applications of hazard plotting as a technique for identifying the failure distributions of particular electronic components. In addition, this chapter shows some results on 3 different component types, together with the likely explanations for the results achieved.

Proportional Hazards Modelling is discussed and applied in Chapter 8. This technique has, in recent years become more widely applied to reliability data. However, not many of these applications have been directly concerned with the field experiences of electronic components. This chapter, therefore, discusses the adaption of PHM to electronic component data and includes some preliminary results achieved by employing this technique.

Chapter 9 concludes the thesis by outlining the main achievements of this extensive study and highlights the direction of further work in this area.

1.7. Summary

This chapter has introduced the concept of electronic component reliability and specifically has introduced the field failure study being carried out at Loughborough University of Technology. It has also given a brief introduction to some of the different factors which can affect the reliability of electronic components. In addition, chapter 1 highlights the scope of the thesis and provides a brief synopsis of the material discussed in the remaining eight chapters.

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2. REVIEW OF RELIABILITY MODELLING

2.1. Introduction

Chapter 1 gave a brief introduction to electronic reliability with particular emphasis on electronic components together with descriptions of some of the associated factors. This chapter will discuss some of the methods for quantifying reliability and is divided into two sections.

The first section describes the most common statistical distributions which are applied to reliability data and references some of the justifications for applying these particular distributions. The second section discusses some of the most important component reliability databases which are in current use.

First, however, we must define some of the reliability terms which will be continually referred to throughout this thesis and the relationship between them [1]:-

> $f(t)$ is the probability density function (pdf) of time to failure.

It is the mathematical model for the population histogram containing relative frequencies. The properties of a pdf are that each frequency should be greater than or equal to zero and the area under the curve must equal one (or the sum of the relative frequencies is unity).

$F(t)$ is the cumulative distribution, mathematically:

$$F(t) = \int f(u)du \qquad (2.1)$$

Both f(t) and F(t) are alternative ways of representing a distribution and the relationship between them is given by:

$$f(t) = dF(t)/dt \tag{2.2}$$

In reliability, F(t) is interpreted as the probability of failing by time t.

Another important function in reliability is The Reliability Function or Survivor Function, and is given by:

$$R(t) = 1 - F(t) \tag{2.3}$$

This is interpreted as the probability of surviving beyond time t.

From equation 3, the Hazard Function h(t) is defined as:

$$h(t) = f(t)/R(t) \tag{2.4}$$

This is the instantaneous hazard rate at time t, ie the conditional probability of failure in (t,t+dt) given that the item survived up to time t. In reliability, we are often interested in whether the component's hazard rate increases or decreases with time. The 'bath-tub curve' discussed in the previous chapter is an example of a hazard function where the hazard rate firstly falls, then becomes constant and then starts to increase with time.

Finally, there is the Cumulative Hazard Function of a distribution:

$$H(t) = \int h(t)dt \tag{2.5}$$

H(t) is a linear function and in reliability, is a more convenient function to work with. For example, for hazard plotting (discussed in Chapter 7) it is easier to work with cumulative hazard paper than with cumulative probability paper.

2.2 Statistical Models

Having discussed the main functions applicable in reliability, we can now consider some of the distributions which apply to reliability problems.

2.2.1 The Exponential Distribution

The exponential distribution, as mentioned in the previous chapter, describes the situation wherein the hazard rate is constant. The pdf is given by:

$$f(t) = \lambda e^{-\lambda t} \qquad t \geq 0 \qquad (2.6)$$

where λ is the failure rate

Thus

$$R(t) = e^{-\lambda t} \qquad t \geq 0 \qquad (2.7)$$

and consequently

$$h(t) = \lambda \qquad (2.8)$$

This means that the probability of failure is a constant and failure occurs at random time intervals.

The exponential distribution is a very important distribution and provides the basis for many (if not all) of the currently used reliability prediction techniques for electronic components (some of which are discussed in Section 3). It is obviously a very simple model to apply since its main property is 'lack of memory', ie a failure of a component at time t is independent and has no relationship with any previous failures.

The basis for applying this distribution comes from the 'bath-tub curve' shown in Figure 1.2. It is thought that the decreasing hazard rate lasts typically for periods up to several hundred hours and is often hidden from customers since it generally occurs during the testing and commissioning period (or burn-in period). These early life failures are generally thought to be caused by inherently defective or poor quality components which were not detected in earlier tests.

The increasing hazard rate identified by the 'bath-tub curve' is thought not to apply to most electronic components, (with the exception of potentiometers, switches and electrolytic capacitors), in particular semiconductor devices, since it is believed that wear out is seldom a characteristic of electronic components. Thus, from these evaluations the constant hazard rate was regarded as valid [2].

However, the validity of this assumption has been, and continues to be, a discussion topic among reliability engineers and statisticians. Many reliability engineers have observed that semiconductor devices exhibit a decreasing hazard rate over the observed time period, thus indicating a non constant hazard rate [3].

Studies at the DIA rejected the use of the 'bath-tub curve' altogether and introduced a replacement named the 'S curve'[4]. Instead of the three phases of life as in the 'bath-tub curve', this work introduced 3 different conditions for failure, namely, infant-mortality, freaks and strong components. This model was established using accelerated life test data together with a knowledge of statistics.

Wong in 1988 introduced another curve which was called the Roller-Coaster curve to replace the bath-tub curve [5]. This curve is based on the idea that a piece of electronic equipment decreases with age during its useful life and the shape of this hazard rate curve is analogous to a Roller Coaster. The humps exhibited on such a curve are said to be due to freak failures and small flaws left over from major flaw groups caused by limitations in inspection and test.

From these, and other conflicting opinions, it is obvious that an investigation of the validity of the constant hazard rate model using field data will be of considerable value. Indeed, one of the aims of this thesis is to identify whether there is justification for applying the exponential distribution to the failure of electronic components.

2.2.2 The Weibull Distribution

The Weibull distribution is one of the most versatile and widely used distributions in the field of reliability. It is named after Waloddi Weibull, a Swedish scientist, who used it to describe the breaking strength of materials and life properties of ball bearings [6].

One of the reasons for its popularity is that by altering the shape parameter different shapes are observed which makes it extremely flexible in fitting data [7]. This discussion is concerned with the 2 parameter Weibull distribution since we are assuming that systems begin at time $t=0$.

The 2 parameter weibull pdf is given by :

$$f(t) = (\beta/\alpha^{\beta})t^{\beta-1}e^{-(t/\alpha)^{\beta}} \qquad t>0 \qquad (2.9)$$

where β is called the shape parameter and α is the scale parameter or characteristic life time [1]. Figure 2.1 shows that the value of β determines the shape of the distribution and α determines the spread.

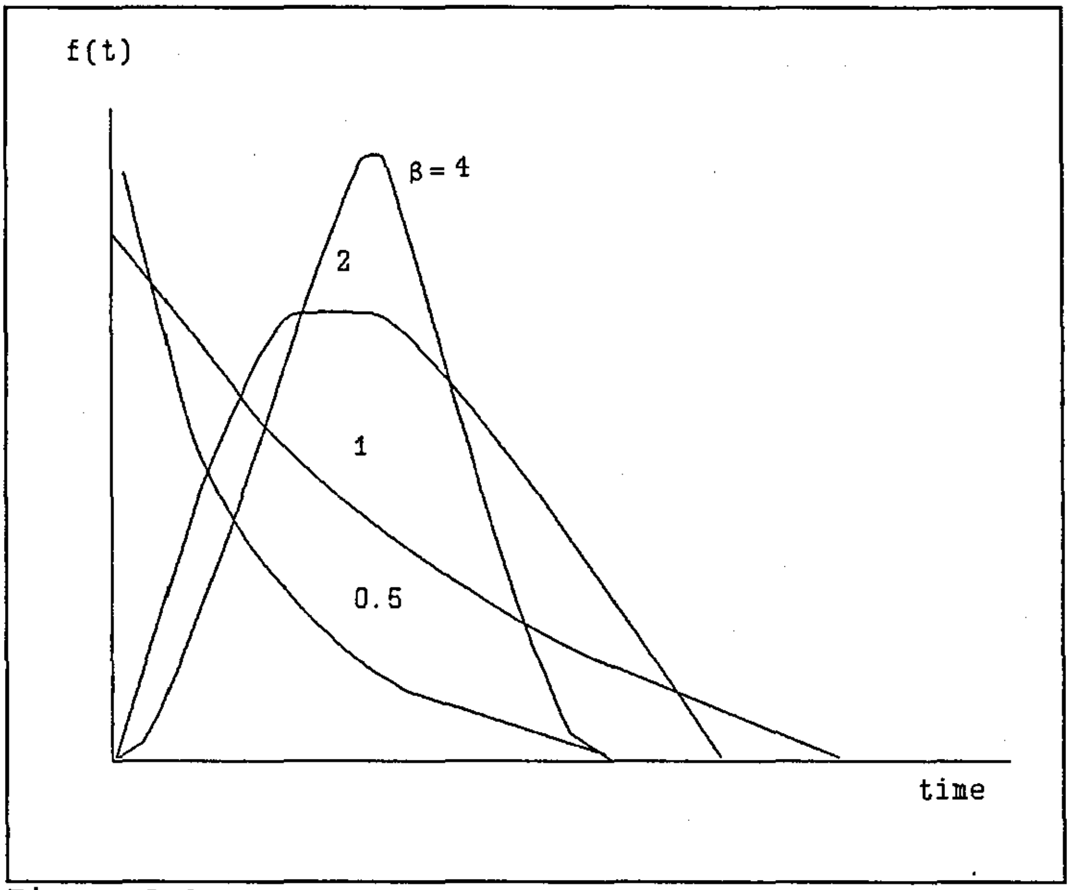

Figure 2.1
Weibull Probability Distribution Function

A special case of the Weibull distribution is the exponential which occurs when $\beta = 1$.

In addition, the Weibull distribution is close to a normal when $3 \leq \beta \leq 4$ and close to the smallest extreme value distribution when $\beta \geq 10$. Thus for much life data, the Weibull is more suitable than the exponential, normal and extreme value distributions.

The Weibull cumulative distribution is

$$F(t) = 1 - \exp -(t/\alpha)^{\beta} \qquad t>0 \qquad (2.10)$$

The reliability function can be shown to be

$$R(t) = \exp -(t/\alpha)^{\beta} \qquad t>0 \qquad (2.11)$$

Thus the Weibull hazard function is

$$h(t) = (\beta/\alpha)(t/\alpha)^{\beta-1} \qquad t>0 \qquad (2.12)$$

and is illustrated in Figure 2.2.

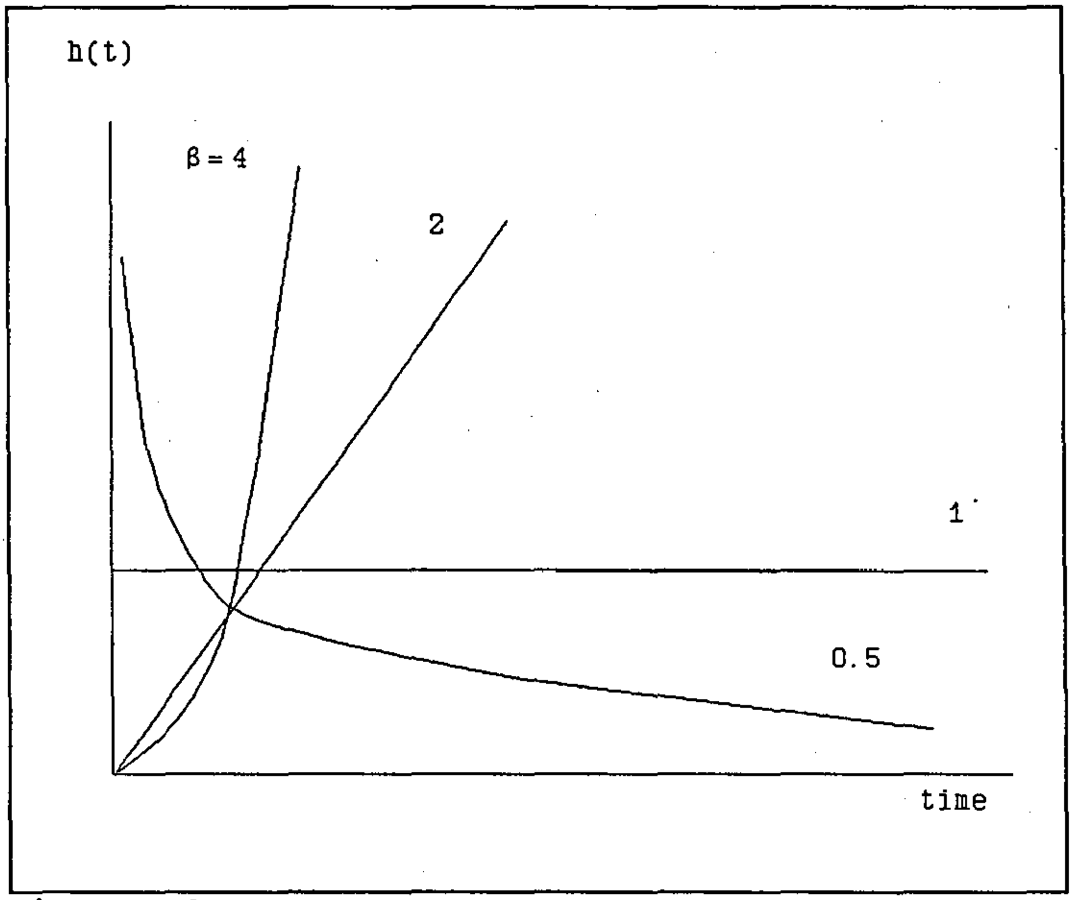

Figure 2.2
Weibull Hazard Function

As can be seen in Figure 2.2 when $\beta < 1$ we have a decreasing hazard rate, when $\beta = 1$ a constant hazard rate and $\beta > 1$ an increasing hazard rate. This ability to describe the changes of failure probabilities has contributed to the popularity of the Weibull distribution for life data analysis.

2.2.3 Other Relevant Distributions

The normal distribution empirically fits many types of data and is a very well known and understood distribution. However, due to its strictly increasing hazard function, it may be appropriate for modelling products with wear-out mechanisms only, eg light bulbs. For this reason the normal distribution is only occasionally used for reliability data.

The lognormal distribution which is evidently related to the normal, is only used for certain specific types of life data, for example, solder joint fatigue and electrical insulator life, and is also used for the distribution of repair times of equipments. However, since electronic components are non-repairable we will not discuss this distribution further.

The smallest extreme value distribution is of some interest because it is related to the Weibull distribution. This distribution may be suitable for 'weakest-link' products.

The hazard function of the smallest extreme value is given by:

$$h(t) = (1/\delta)\exp\left[(t-\lambda)/\delta\right] \quad -\infty<t<\infty \quad (2.13)$$

where λ is the location parameter and
δ is the scale parameter

and is shown in Figure 2.3. This distribution adequately describes human mortality in old age ie people wear out with an exponentially increasing failure rate.

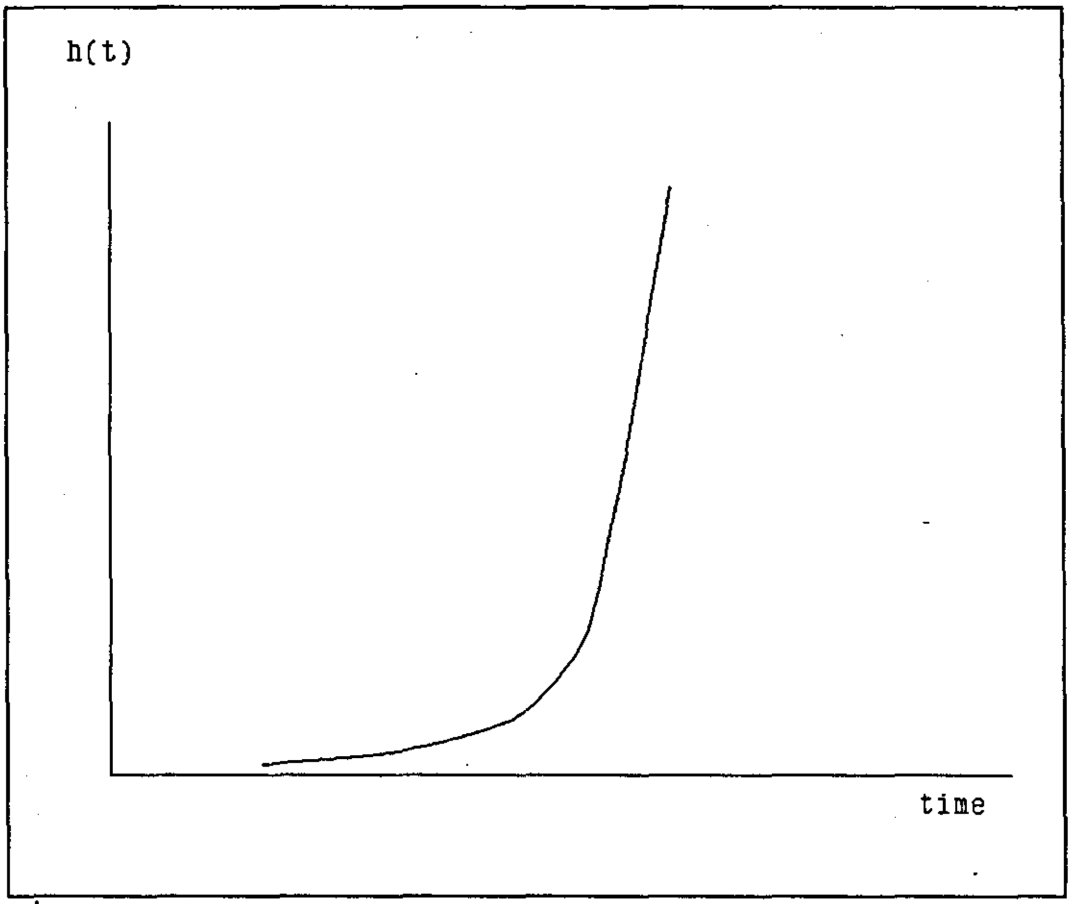

Figure 2.3
Extreme Value Hazard Function

There are many other statistical distributions but those described above are the most applicable to reliability data [1].

2.2.5 The Proportional Hazards Model (PHM)

In the previous sections different types of distributions applicable to reliability data were discussed. This section discusses a distribution-free approach to analyzing reliability data.

The proportional hazards model is a particularly flexible model, which is not only semi-parametric, but can be used to isolate the effects of many factors on the hazard function of an electronic component [8]. As discussed in Chapter 1 there are many factors which have potential impact on electronic component reliability, and PHM can incorporate and quantify some of these factors as explanatory variables or covariates. The proportional hazards model is structured upon the hazard function. It is assumed for each component type that the associated hazard function can be decomposed into the product of a base-line hazard function, common to all components of a certain type, and an exponential term incorporating the effect of the values of the explanatory factors specific to each individual component, ie

$$h_0(t;z_1,z_2,\dots,z_n) = h_0(t)\exp(\beta_1 z_1 + \beta_2 z_2 + \dots + \beta_n z_n) \qquad 2.14$$

where z_i's are the values of the explanatory factors
and $h_0(t)$ is the base-line hazard function

The z values can be either measured values, for example, percentage time an equipment is switched on, or indicator variables representing, for example, two encapsulation methods or two environments etc. The β's are unknown parameters of the model and represent the effect on the overall hazard of the explanatory factors. These β's are required to be estimated and tested to see whether each explanatory variable has an effect on the variation in observed times to failure. These explanatory variables are assumed to have a multiplicative effect on the base-line hazard function. Thus the hazard functions for components, say, with different encapsulations are proportional to each other. An example is shown in Figure 2.4 below. Figure 2.4 illustrates graphically the proportionality of the hazard functions. For example, from Figure 2.4, for all time t the hazard experienced by plastic encapsulated components is twice that experienced by hermetically sealed components.

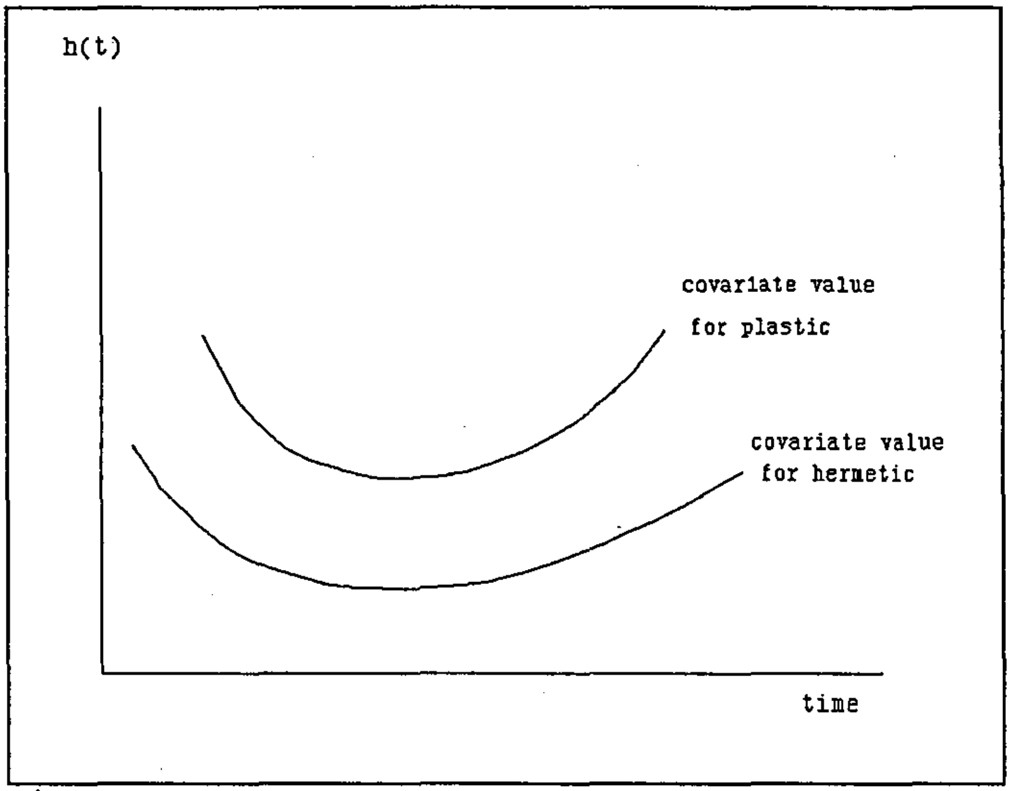

Figure 2.4
Hazard Functions for 2 different Covariates

The base-line hazard function $h_0(t)$ represents the hazard the component would experience if the explanatory factors all take the base-line value of zero.

There are two ways of modelling the base-line hazard; either by assuming a particular distribution or allowing the base-line hazard to be distribution-free. Obviously, in the current context, where there is dispute as to what distribution electronic components follow, it is important to adopt the distribution-free approach. Thus, the base-line hazard function is subsequently estimated from the data and can be used to check the appropriateness of standard distributional forms.

It is also fairly obvious then, from the discussion above, that the application of PHM to the reliability of electronic components would be of great value.

PHM owes its origin to a seminal paper given by Professor D. R. Cox in 1972. At first, PHM was mainly applied in the biomedical field, but in recent years the number of applications to reliability data has been increasing [9]. Dr D Wightman's Phd thesis on the application of PHM to reliability data, lists some of the published papers which concern applications to reliability data [10]. However, in the field of electronic component reliability, there have been very few applications.

Dale in 1983 published a paper which gave an example of the application of PHM to non-repairable systems [11]. However, the data which he used was generated from accelerated life test and consequently had controlled explanatory variables. In fact, the sample size was small ie 40 events and the components were electrical parts rather than electronic components. Similarly, Landers and Kolarik, in 1986, published a paper comparing PHM and MIL HDBK 217 [12]. However, this application not only assumed a constant hazard function for the base-line hazard but used data obtained from MIL 217. This paper, is therefore, of limited value since it does not attempt to verify any of the main comments on MIL 217, namely the constant hazard rate assumption and the accuracy of the models employed together with their associated data. Ascher published 'The use of Regression Techniques for Matching Models to the Real World' in [13]. However, the application was based on a hypothetical type of transistor 2NXXXX. In fact Ascher states 'the entire problem has sprung from the mind of the writer'. This example highlighted the potential use of PHM in the reliability analysis of transistors but real data would obviously have been of greater interest.

To date, the three papers discussed above are the only published applications of PHM to non-repairable electronic components. In fact, there are no publications on the application of PHM to electronic component field data using this distribution-free approach.

Chapter 8 will provide further details on the theory of PHM and in particular will consider the application of this model to electronic component field data. In addition, some results will be shown and some conclusions drawn.

2.3. Electronic Component Reliability Databases

2.3.1 The Arrhenius Model

Many of the physical processes that cause the degradation of electronic components are strongly temperature dependent. This temperature dependence may be described by the relationship [14]:

$$\lambda_b = Ae^{(-E/kT)} \qquad (2.15)$$

where E is the activation energy for the process
k is Boltzmann's constant
T is absolute temperature
A is a constant
λ_b is the base failure rate

Equation 2.15 describes the rate of many processes responsible for the degradation and failure of electronic components, including drift, diffusion, creep etc. Further information on this topic can be found in [15].
Figure 2.5 below shows how λ_b may change with temperature for a particular failure mechanism.

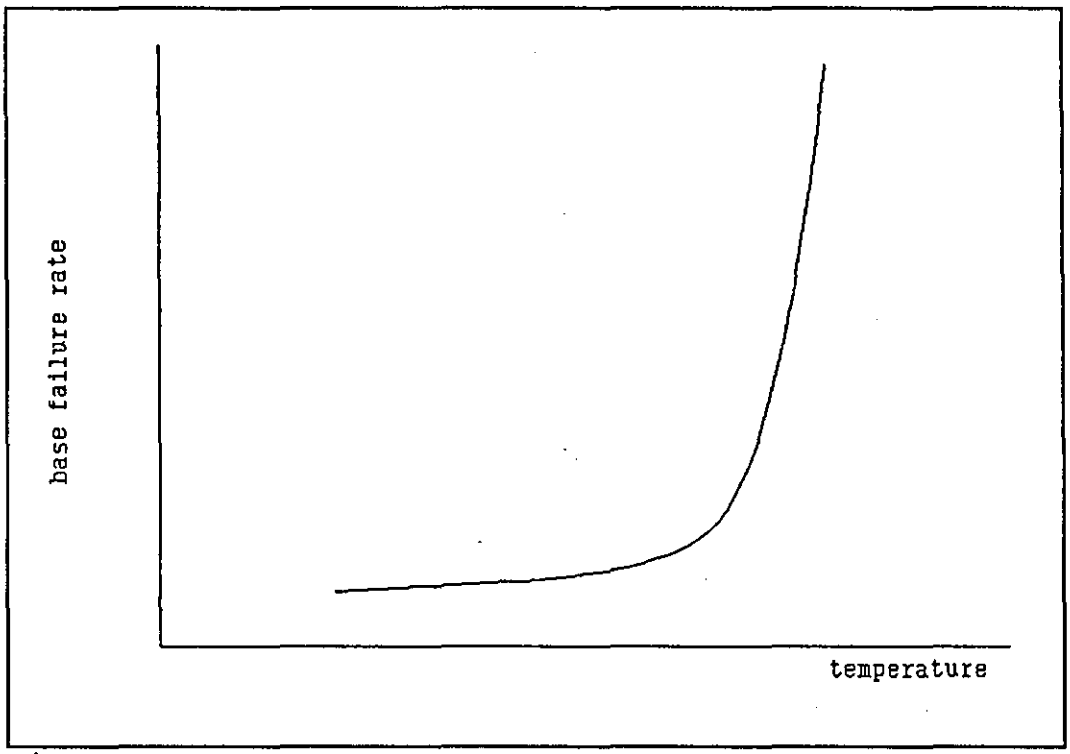

Figure 2.5
The Relationship between the Failure Rate and Temperature

This model forms the basis for most accelerated life test studies and consequently provides some of the data found in MIL HDBK 217E (discussed in the next section). For example, Figure 2.6 shows some results from an accelerated test at 3 different temperatures. Extrapolating from the fitted line gives the failure rate at the operating temperature.

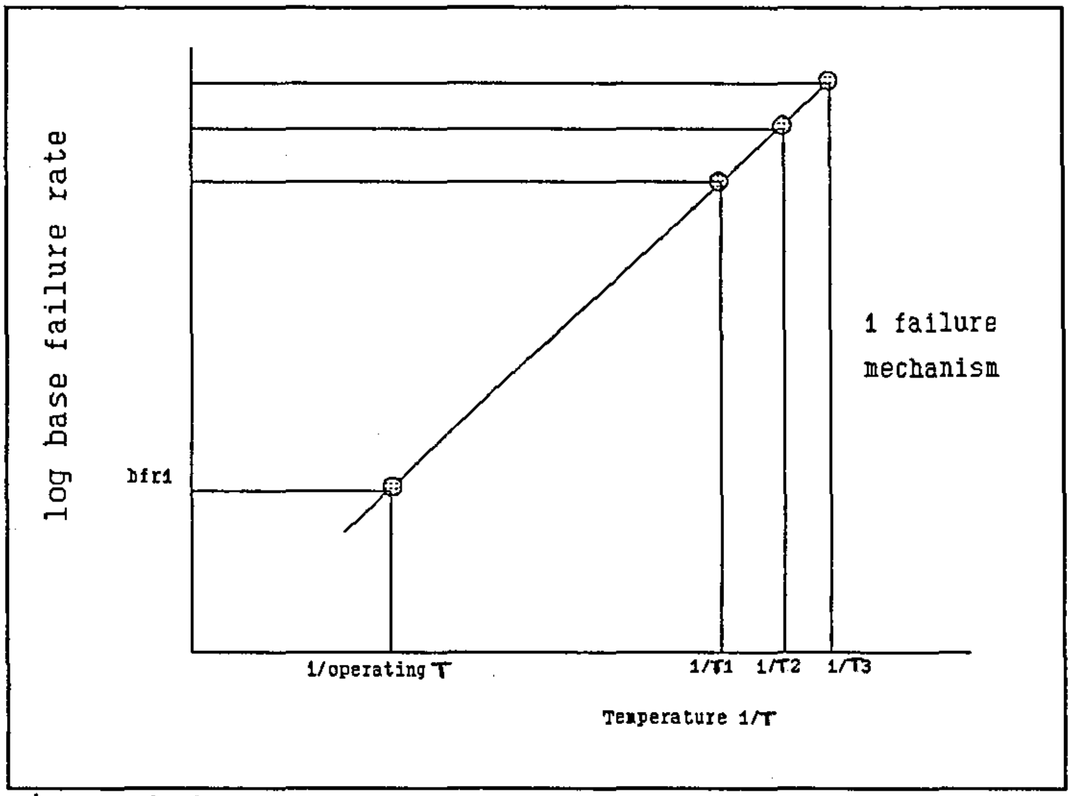

Figure 2.6
Arrhenius Relationship for 1 Failure Mechanism

However, this is only valid for one particular failure mechanism. In practice, there may be many failure mechanisms associated with this particular component type, each with a different activation energy. Figure 2.7 below shows an example of this problem. In this test the observed failures were thought to be caused by one failure mechanism, thus the predicted failure rate was bfr1 (λ_0). However, there were in fact, say, two failure mechanisms associated with this component type. From the plot, failure mechanism 1 (fm1) is dominant at high temperatures and failure mechanism 2 (fm2) is dominant at low temperatures. Therefore, the overall failure rate curve can be seen in Figure 2.7. The true failure rate therefore is much higher than the original predicted assuming one failure mechanism (fm1).

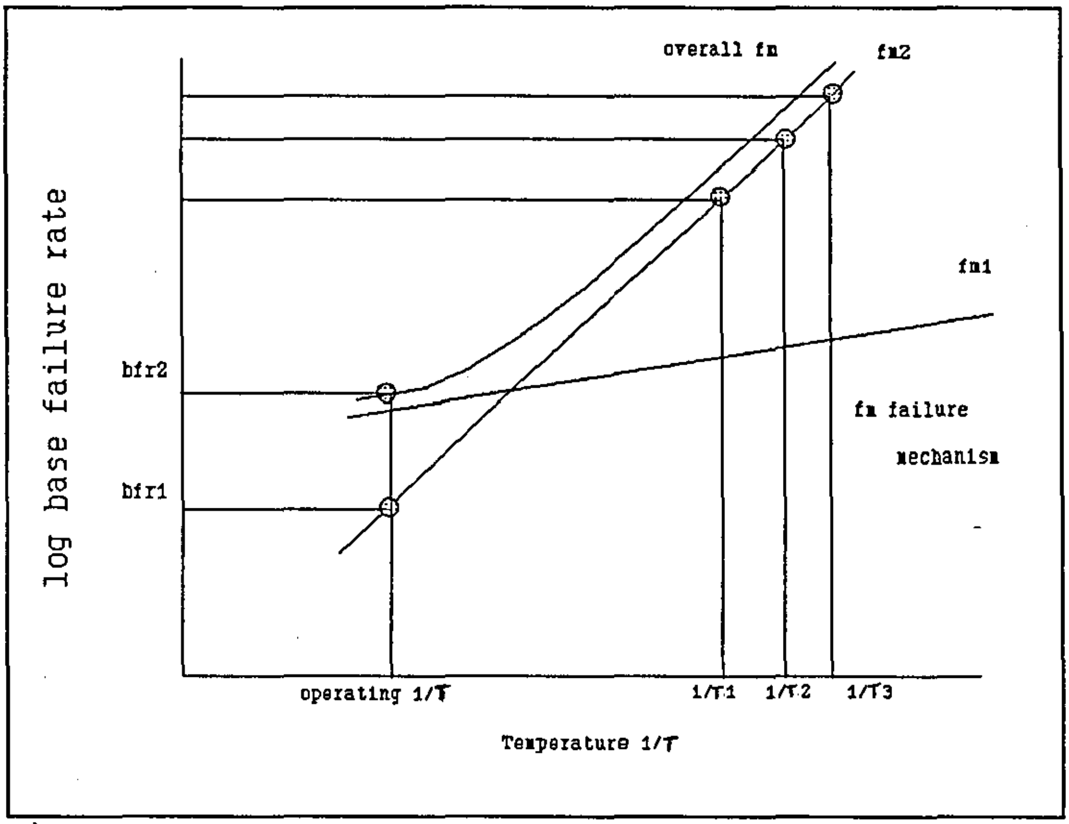

Figure 2.7
Arrhenius Relationship for 2 Failure Mechanisms

This example demonstrates the problems of using accelerated life test data for prediction since, in general, it is not known whether those failure mechanisms that will occur in the field are the same as those occurring in life tests.

Although the Arrhenius equation models the physical relationship between temperature and on the failure mechanism of electronic components, the application of this model often produces misleading results [16],[17].

2.3.2. MIL HDBK 217E

The most widely applied reliability prediction methods are those developed by USAF Rome Air Development Center and the latest version published as US MIL HDBK 217E (reliability prediction for electronic systems) [18]. This reliability handbook was originally published in 1968 and was innovative in its time. In 1968, there were very few guidelines for reliability prediction, certainly not as detailed as MIL 217, therefore the publication of MIL 217 was welcomed with enthusiasm and praise by reliability engineers.

The models implemented in MIL 217 are based upon the Arrhenius equation discussed in the previous section. MIL 217 assumes independent, identically exponentially distributed times to failure for all components and therefore all the models assume a constant hazard rate for each component type. As discussed earlier this may not be a valid assumption. However, making this assumption makes system reliability prediction simple since an additive approach can be used.

The general MIL 217 failure rate model for an electronic component is of the form:

$$\lambda_p = \lambda_b \pi_Q \pi_E \pi_A \ldots\ldots \tag{2.16}$$

where λ_b is the base failure rate related to temperature and π_Q, π_E, and π_A are factors which take account of the quality level of the component, the system environment, application stress etc. This model is used to give estimates of the failure rates of individual electronic components and by summing the failure rates for all the components in a system, an estimate of system reliability may be obtained.

However, in recent years the number of critics of MIL 217 has been growing, mainly due to the inaccuracies of the predicted failure rates and the growing awareness of the importance of reliability. The following list of comments have been compiled from published articles on the subject together with discussions with engineers working in the reliability field.

Comments on some of the problems associated with MIL 217

1. The assumption is that all electronic components exhibit a constant failure rate which, although making calculations simple has not been validated.
2. The data used in MIL 217 is from accelerated life tests which has several shortcomings:
   (a) The number of failure mechanisms in most electronic devices is greater than one, and extrapolation from life tests cannot take account of this [19]. Consequently the dependence on temperature is often smaller than predicted from accelerated life tests [16].
   (b) The conditions under which components fail in testing are different from those conditions experienced in the field [20].
3. The values used for the π factors are dubious [21].
4. Failure rate predictions from MIL 217 have been shown to be both pessimistic or optimistic when compared to field experience [21].
5. The models assume that all devices are prone to failure. However, O'Connor states that this is not true, since the only devices that are likely to fail under the correct operating conditions are defective components. In addition, most electronic components have no inherent wear-out failure mechanism [22].
6. Apart from those problems above, Durr [23] states that if a parts count (a simplified method of parts stress)

is carried out independently by several engineers
on the same equipment using the same information,
the results can vary by up to a factor of six .

Due to these problems many companies are starting to establish their own company databases to make more accurate estimates of how their components/systems perform in the field.

However, although reliability engineers have lost some confidence in the accuracy of the predictions in MIL 217 it is still used for reference. MIL 217 has changed very little in terms of the methods used to achieve the predictions, perhaps it is out of date and it is time to introduce a new approach to the investigation of the reliability of electronic components and systems, but without losing the experience and knowledge of MIL HDBK 217.

In fact, in the past, companies which provided electronic equipment to the MOD were required to use MIL 217 in their specifications. However, various authors [24], [25] have stated that MIL 217 and similar prediction methods should no longer be at the top of the list of reliability requirements in specifications.

It is obvious from the above discussion that the studies mentioned in this thesis will be of great interest to the electronic reliability community as a whole.

Although MIL HDBK 217 is the most widely used data bank for electronic component reliability there are several other commercially available databases.

The Handbook of Reliability Data (the latest edition HRD4) [26] is produced by British Telecom with the cooperation of the telecommunications industry. The main purpose of this handbook is to provide a common basis for system reliability prediction in the fields of civil applications and in particular telecommunications.

The handbook contains lists of component failure rate predictions quoted in Failure unITS (FIT) ie the number of failures in 10^9 component hours. 'MIL

217' type failure rate models are also shown thus allowing the effect of different factors to be quantified. These factors include quality level and the effect of integrated circuit junction temperature.

The data used to produce these FIT are obtained partly from performance in service in the UK inland telecommunications Network. However, in HRD4, the failure rates given have associated grading to indicate the type of data source the information came from. Not all the data used in HRD4 comes from the BT database, some of the data comes from other less dependable sources. In addition, the data used applies only to one particular environment, ie ground benign and therefore caution must be used when making predictions about systems operating in different environments. The models employed in HRD4 make the fundamental assumption of constant hazard rate, which, as discussed earlier, has not been validated.

Although the data from HRD4 has particular problems, British Telecom have a large department which is concerned with collecting data, accelerated life test studies, failure mechanism studies and the collection of field returns for failure analysis. However, the results achieved are not totally dependable since the traceability of the data used is questionable.

The European Reliability Data Bank Association (EuReData) was formed in 1973 and in the first instance aimed to solve the problems encountered by all organisations in setting up and managing reliability data banks. It was formally constituted as EuReData in 1979 with the support of the Commission of the European Communities.

Its main objectives include the promotion of reliability data exchange between organisations and the establishment of a forum for the exchange of reliability data bank operating experiences.

Members of EuReData include commercial companies, educational establishments, government departments etc. which are directly involved with planning or operating reliability or incident databases. Project groups are established to cater for specific fields of interest, for example, nuclear safety and reliability. A project group on the field reliability of electronic components has been proposed by Prof. Moltoft of the DIA. The main objective of this group will be to set up a European electronic component reliability database based on field data. The viability of such a database is currently being assessed.

The main advantage of the Euredata organisation is the cooperation and sharing of knowledge between European Countries on reliability. In addition, every 3 years a conference is held where papers are presented on current databases and reliability issues of interest.

Within the Society of Automotive Engineering (SAE) is an Electronic Reliability Subcommittee [27]. One of the objectives of this committee is to provide a reliability prediction tool as a substitute for or supplement to the use of MIL HDBK 217 for electronic components used in automotive applications. This departure from MIL 217 is mainly due to the fact that most of the data contained in MIL 217 is based on electronics used in military applications.

A paper by members of this subcommittee [28] outlines the techniques developed for reliability prediction of electronic components in the automotive industry. The models employed are multiplicative and of the form used in MIL 217. In fact, they also make the assumption that automotive electronics follow an exponential distribution. However, the generation of these prediction models involved the use of field data on electronic components and in addition, stepwise multiple linear regression techniques were applied to obtain values for the π factors. The field data used, however, was sparse and, in general, obtained from the manufacturer's warranty period. In addition, the regression technique used considered failure data only and non-failed information was not incorporated.

Although there are some obvious problems with these prediction methods, it appears that the SAE are moving away from dependence on MIL HDBK 217 and are instigating new approaches to reliability prediction of electronic components.

As part of the British Standards Institute (BSI) there is a panel which deals with standards for Reliability and Maintainability and is called QMS/2/3/7. Some of the members of this panel are experts in specific areas of reliability and maintainability. In this field of interest the BSI are working with the International Electrotechnical Commission (IEC), Technical Committee 56 (TC56). There are 12 working groups within IEC TC56, each is a particular specialised area of reliability and maintainability. Each expert in a particular area of reliability and maintainability attends the relevant TC 56 working group meetings where standards are devised together with experts from all over the world. Working group 7 is the forum for producing standards on the reliability and maintainability of electronic components.

There are several further reliability prediction methods [29],[30],[31], however, those described above are the most widely known and applied. In fact, most large electronics companies have established their own databases and consequently use their own data for prediction and increase their knowledge of the reliability of electronic components.

2.4. Summary

This chapter has introduced some of the fundamental concepts in reliability together with discussions on the most important statistical distributions for modelling reliability problems. Proportional Hazards Modelling has been introduced as a semi-parametric model for analyzing electronic component field data and their corresponding characteristics. Literature searches on the application of this model to electronic components have shown that there are only 3 publications on this subject. The limitations of the results achieved from these publications have been discussed, therefore providing further evidence for interest of the application of this technique to electronic component field data.

Existing electronic component reliability databases have also been the subject of this chapter. In particular, the most widely known database MIL HDBK 217 has been discussed and criticisms of this data for reliability prediction shown. Other databases have been introduced together with commenting on their advantages and disadvantages.

The discussion on the problems concerning the use of the currently available commercial databases has shown that the achievements of this study will benefit those involved in the reliability of electronic components.

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3. THE ORGANISATION OF THE FIELD FAILURE STUDY

3.1 Introduction and Background

As discussed in the previous chapters, the analysis of field failure data is more representative of the reliability of electronic components than the analysis of accelerated life test data. There are no problems of extrapolation and the conditions which the components are working under are not artificially controlled and therefore, field failure data should allow an accurate assessment of the reliability of electronic components.

In order to investigate the failure behaviour of electronic components when used in equipments in the field [1], a study centred at LUT and sponsored by MOD was initiated in 1984. The aim of this study was to identify component types which are a major cause of failure in electronic equipments, the conditions under which failure occurs and the nature of the failure mechanisms. The intention of this study was to build up a structured component failure database over a period of time [2].

A field failure study took place at the Danish Engineering Academy (DIA). The DIA collected field failure data from two major Danish Companies and established a database for storage and processing of the data. However, the Danish project was concerned with system reliability and in particular the point processes of the systems. Further studies had been conducted at LUT. These activities were concerned mainly with laboratory testing of electronic components, for example, the estimation of failure rate from parametric drift measurements [3], the applicability of the bath-tub curve for component failure rates [4], the reliability of thick film resistors [5] and optocouplers [6]. These studies helped to form the basis for the current field failure study of electronic components.

In order to set up a database of field failure information, the data had to be assessed and collected. By the end of August 1984, discussions had been held with many companies regarding access to their field failure data and any available data was assessed for its dependability. Dependability, in this context, means that the data must conform to the specified data input requirements. These requirements are discussed in subsequent sections. However, a minimum requirement for such data to be of use was specified in the first instance and requires that a dataset contains accurate, traceable information on the generic description of a component, its operating environment and the times to failure of these components. It became obvious that such data may not be instantly available since the data recorded by systems manufacturers is not always structured to contain component failure information in the detail required.

Following this assessment LUT finally entered into detailed discussion with the research centres of three major British Electronic Companies, in order to investigate further the feasibility of collecting dependable field failure data. These companies include:

PLESSEY
GEC/MARCONI
STC

3.2 Organisational Structure

In 1985, contracts were let by the MOD to Plessey, STC and GEC/Marconi to provide dependable data to LUT and to collaborate with LUT in this joint project. In addition, LUT placed a sub-contract with the DIA to act as a data provider and to pass on some of the experience attained from their pilot study. Figure 3.1 shows the organisational structure of the project. This Figure illustrates the relationships between LUT and those participating organisations.

The named British companies transfer the data to LUT, however, this data is collected from the data sources within the companies. Figure 3.1 shows an example of 3 data sources providing data to each of the 3 British companies. Such data sources are, in general, the manufacturing and operating companies within a larger group. For example, ICL may be a data source for STC.

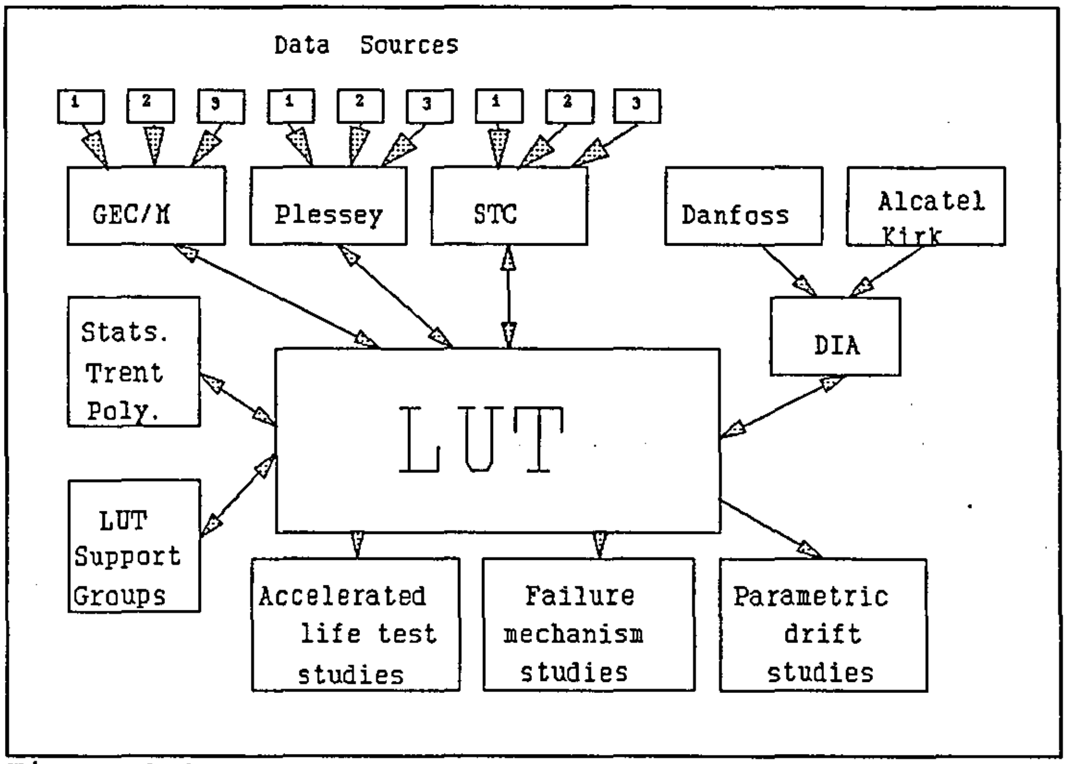

Figure 3.1
Organisational Structure of The Field Failure Project

After assessing the dependability of the data available from the data sources within each company, the data is processed and subsequently transferred to LUT. The DIA performs a similar function for the Danish companies. In addition, to the data providers, a contract was let by the MOD to Nottingham Polytechnic (formerly Trent Poly.) for their assistance in the statistical analysis of the field failure data. Parallel studies at LUT are concerned with accelerated life testing, failure mechanism and parametric drift studies. It is expected that results produced from the analysis of the field failure data will indicate which component types require further testing and failure analysis. The LUT support groups involved include the computer centre for both software and hardware and advice on the storage of the data and the Physics Department for use of the Surface Analysis Facilities for the Failure Mechanism Studies.

3.3 Data Requirements

Although, as discussed previously, field failure data is more useful than environmental test data when analyzing the reliability of electronic components, there may be many problems associated with the collection of such information. As discussed in a paper entitled "Planning and Conducting Field-tracking Studies" by S J Amster et al [7], the most important requirement for a successful field tracking study is a clear statement of the purpose of such a study. However, before any data requirements can be imposed an indication of what type of analysis is to be carried out on the data must be given. For example, when calculating constant failure rates, the total number of components and the total observed time for components is required ie parts count. However, to identify the statistical distribution for a particular component type requires each individual component's time to failure together with a censoring time for all non failed components. Obviously the data requirements differ between these two types of analysis and it is therefore important to establish what type of analysis will be carried out on the data before proceeding to set up any data collection procedures.

The main aim of this study is to identify those components which consistently cause failure in equipments. What, therefore, is the minimum data requirements to fulfil this aim? Firstly, we must identify what type of analysis is likely to be carried on this data. As discussed in the previous two chapters, both the identification of the statistical distributions of the time to failure of electronic components and the variables which may affect the reliability of these components are of great interest. From this we can identify the minimum data requirements [8], [2] as:-

1. Data is required not only on component failures, but, on those components which have not failed and are at risk in the field.
2. Traceability of the observed systems and printed circuit boards is necessary. This means that, not only the total number of systems and boards in the field should be known, but, the individual times to failure and corresponding censoring times for non failed components must also be known.
3. A detailed description of component generic types and their encapsulation method, mounting technology and substrate is required.
4. The identification of both equipments and PCBs i.e. types and serial numbers. is necessary.
5. Finally, the equipment operational environment must be identifiable.

In order for this data to be dependable further restrictions are necessary. The installation date and subsequent commissioning (switch-on) time of an equipment is crucial, (known as time-zero). No 'in-house' or accelerated test data is acceptable [9]. Any historical data is required to have been collected since 1980 in order to ensure the database only contains up to date technology. In addition, we have full company backup so that if there are any problems with the data, discussions with the data providers will help to provide a solution.

These data requirements enable the data to be dependable and trackable and thus will allow the statistical techniques mentioned in chapter 2 to be subsequently applied. From this analysis the aims of the project can be achieved.

3.4 The Confidentiality of Information

For such a study to progress, an extremely important element of collecting data from competitive companies must be addressed. Such an element is confidentiality.

The origins of any data transferred to LUT, are known only to the data provider and LUT. This is obviously crucial because of the risk of industrial espionage.

In addition, the sponsors of this project ie The MOD are also the customers of equipments produced by the companies involved in this study. Thus, it is important that The MOD do not know the origins of any specific piece of information. If the MOD were aware of, say, the number of failures of a particular equipment purchased by them, they may decide to drop the supplier of this equipment. However, this is not a threat to the project because the MOD sees only pooled and desensitised results from the project. Indeed, if there was any likelihood of this scenario occurring, the companies would simply, terminate any data transfer to LUT.

This project is not used by the MOD for the assessment of those electronic companies supplying military equipment.

3.5 Data Format

3.5.1 Introduction

To establish the details of what data was required to be collected, a working group was set up in 1985. This working party included representatives from those involved in the acquisition, transfer and processing of the data and therefore had members from each company, Trent Polytechnic, the DIA and was chaired by LUT. The author was also an active member on this working group.

The data format was arrived at after considerations of the minimum information necessary for analysis. This data format consists of 3 levels, namely:-

1. Equipment information
2. Printed Circuit Board Information
3. Failure characteristics

Figure 3.2 shows the data format from the breakdown of this hierarchy of data. Section 1 in Figure 3.2 indicates all the data required concerning an equipment type. Section 2 highlights the data items concerning the life history of boards and components and finally, section 3 shows the data items corresponding to the failure characteristics of a component.

After the establishment of the data input format, decisions regarding the selection of equipment types to be followed in the field had to be made. The criterion for equipment selection was, as discussed in the previous section, based on the dependability of the data available.

In order to identify suitable data sources, a check list based on the data requirements, as shown in Figure 3.2, was devised and the operating companies were required to indicate whether this data was available for each system. The columns on Figure 3.2 show the use of this checklist. For each data item, a company would indicate whether that data item was either easily available, available with some work or virtually impossible to obtain. The results from these completed check lists indicated that not all the data sources approached could meet the data requirements, and consequently the company coordinators had to often assess many different data sources within their organisations before final selection could be made.

	COMPANY			
	A	B	C	D
1.1 EQUIPMENT				
Company (prefix)				
Equipment Type				
Serial Number				
1.2 ENVIRONMENT				
Environment (MIL 217 Definition)				
1.3 EQUIPMENT DATES				
Up and running date				
end date				
percentage usage				
2.1 CIRCUIT BOARD DESCRIPTION				
Primary function				
Company design (part no)				
Board serial number				
2.2 CIRCUIT BOARD HISTORY				
Up and running date of board in system				
Manufacturing date of board				
Previous use				
Storage				
2.3 COMPONENT DETAIL				
Component type				
Screened level				
Circuit reference position				
Manufacturer				
Batch no				
3.1 FAILURE CHARACTERISTICS				
Failure Mode of equipment				
Operating time of system to failure				
Operating time of board to failure (this time around)				
Failure mode of component				
Failure mechanism				

Figure 3.2
Preferred Data Input

After the initial equipment selection had been finalised, the working group addressed the practical problems associated with the detailed coding of the data.

The type and manner of internal data recording procedures differ between sources. The working group, therefore, had to formulate a standard for the coding of some of the data items. Those data items which caused most discussion include:-

(1) Component generic coding and additional characteristics.
(2) The calculation of dates and times.
(3) Previous use and storage.
(4) Screened level of a component.
(5) Equipment environment.

3.5.2 Component Generic Type

The coding of a component type is based on material and construction and therefore allows the component field failure behaviour to be linked to specific failure mechanisms. Table 3.1 shows an example of some of the codings for particular devices.

The detailed generic codings enables the standardisation of data across different data sources. However, this detailed coding means, in practice that the company coordinators are involved in extensive translation from parts lists to this format. Although slowing the rate of data transfer the benefits of such standardisation far outweigh this slight time delay.

In addition to the component coding, further information regarding the device is required, i.e. details of the encapsulation, mounting and substrate. Again, these needed to be coded. Table 3.2 shows an example of the resultant codes. A further data item concludes the component description, that is, the component part number. This is only essential for integrated circuits (IC's), transistors and hybrids. Due to advancing technology IC's are becoming more complex. To identify a particular IC, a part number must be used since there many different types of IC's within the same family. The coding of IC's is discussed further in Chapter 6. Hybrids, although sold as units or components are in reality subsystems. They can either be thick film printed on alumina with resistors or thin film deposited on glass using resistors, capacitors or other components. If a recurrent failure of a hybrid arises then by collecting the part number of the particular hybrid will help to identify where the real problem lies by carrying out the failure analysis of this component. The part number for a transistor provides further information concerning the size of a transistor and therefore will provide more precise information about a transistor. This is necessary for failure analysis of the device.

TABLE 3.1

COMPONENT TYPE CODINGS

CODE	DESCRIPTION
A1A	Transformers
A1B	Air cored transformers
A1C	Pulse transformers
B1A	Coil activated relay
B1B	Coil activated/mercury wetted relay
B2A	Reed relay
C1A	Aluminium foil capacitors
C1B	Aluminium foil (solid electrolyte) capacitor
C1B	Aluminium foil capacitors with solid electrolyte
C2A	Mica metallised capacitor
C2B	Mica foil capacitor
C5C	Paper/plastic/foil capacitor
C5D	Paper/plastic (metallised) capacitor
ClG	Tantalum foil capacitor
D1B	Varactor diode
D1C	Avalanche/zener diode
D2A	Schottky barrier diode
E1A	Photosensitive diode
H	Hybrid circuit
I1xx	Bipolar IC (TTL.DTL.ECL.TIL)
I2xx	MOS IC (NMOS.PMOS.CMOS)
I3xx	Bipolar/MOS IC
I4xx	JFET IC
I5xx	MESFET IC
K1A	Rectangular connector

K1B	Edge connector
K1C	Cylindrical connector
K1D	Spade connector
K1E	Coaxial connector
K2A	Optical fibre connector
K3A	Feed through (insulator) connector
K3B	Feed through (filter) connector
L1A	Air cored inductor
L1B	Loaded inductor
M1A	Wave guide transmission line
M6A	Microwave Cavity
M7A	Microwave switch
N2A	Varistor nonlinear resistor
P1B	Carbon film variable resistor
P2A	Metal oxide variable resistor
Q1A	Crystal oscillator
R1A	Carbon resistor
R2A	Metal oxide resistor
R3A	Wirewound resistor
R3C	Metal film resistor
R6A	Network of thick film resistors
S1A	Push button switch
S6A	Microswitch
T1A	Bipolar transistor
T1B	Darlington pair
T2A	JFET transistor
T3A	MOSFET enhancement transistor
T3B	MOSFET depletion transistor
U1B	Loudspeaker
U4A	ETI
U4B	Digital ETI

TABLE 3.2

CODING FOR ENCAPSULATION, MOUNTING AND SUBSTRATE

ENCAPSULATION DESCRIPTION		CODE
	Unencapsulated	1A
	Non-hermetically capped	1B
	Plastic, transfer moulded	2A
	Plastic, conformal coating	2B
	Hermetically sealed, glass-ceramic	3A
	Hermetically sealed, solder	3B
	Hermetically sealed, welded	3C
	Hermetically sealed, not known	3_ [1]

MOUNTING DESCRIPTION		CODE
(a) Non-soldered		
	Wire wrapped without solder	A
	Crimped	B
	Conductive resin	C
	Socketed	D
	Chassis mounted	N

[1] _ signifies a space character.

MOUNTING DESCRIPTION		CODE
(b) Soldered		
	Beam lead	E
	Surface mounted	F
	Flip chip	G
	TAB	H
	Radial wired	I
	Axial wired	J
	Dual in line	K
	Wire wrapped with solder	L
	Quad in line	M
	Flat pack	O
	Single in line	P

PRINTED CIRCUIT BOARD/SUBSTRATE		CODE
(a) Thick film		
	Alumina substrate	1
	Porcelainised steel substrate	2
(b) Printed wiring circuitry		
	Single sided	3
	Double sided without plated through holes	4
	Double sided with plated through holes	5
	Multi layer	6
	Single sided flexible	7
	Double sided flexible without plated through holes	8
	Double sided flexible with plated through holes	9
(c) Panel mounting		A

3.5.3 The Calculation of Dates and Times

The calculation of the up and running date of both the system and the PCB can differ between data sources. To overcome this difficulty codes were devised to indicate how these dates were calculated. The letter indicator preceding the up and running date of a system indicates the status of the up and running date and is coded as follows:-

A	Actual, recorded
B	Calculated from end of commissioning
C	Calculated from start of commissioning
D	Calculated from delivery date
E	Calculated up and running date for shipboard equipment

Similarly, the operating time to failure of a system or PCB can be calculated in different ways, depending on whether an elapsed time indicator (ETI) is attached to the equipment. The indicators in use are:-

A	Known accurate time, ETI adjusted
B	Calculated from ETI reading
C	Estimate, no ETI reading available
D	Other

In the case of identifier D, this occurs when the calculation of operating time to failure does not correspond to any of the other indicators defined. If D is used then the calculation method applied must be specified when transferring the data. A soft information document has been devised to include such auxiliary information, this document is described further in section 3.5.7., page 60.

These indicators highlight the relative accuracy of the data and ensures the integrity of the data used in any statistical analysis.

3.5.4 Previous Use and Storage of a PCB

The previous use of a PCB is vital information in tracking the life history of a board and its components. This information is coded as a letter indicating the number of previous repairs for a particular board serial number and the number of days it was previously used in other equipments. This data highlights the repair loop for PCB's. In addition, the data on storage of a PCB is also coded as a letter indicating the storage conditions and the number of days the PCB has been stored under these conditions.

3.5.5 Screened Level

As discussed in Chapter 1, screening indicates what level of testing has been carried out on a component. There are many different types of screening and a comparison of the relative effectiveness of these different types would be of great interest, (particularly to the military who spend vast sums of money on component screening). With this in mind, codings for different levels of screening were devised and are shown below:-

9	Certified BS9000/CECC
8	Presumed BS9000/CECC
7	Established reliability
X	Other imposed screening
Y	Commercial part

3.5.6 Environment

The environment the system is operating under can affect the reliability of electronic components and therefore, coding of environment is important. The coding used is the same as in MIL HDBK 217 and is shown in Table 3.3 below. For example, from Table 3.3 a code of 01 would indicate that such systems are operating in ground benign conditions. An example of such a system would be desk top computer.

TABLE 3.3

ENVIRONMENT TYPE CODING

ENVIRONMENT	CODE	DESCRIPTION
Ground, Benign	01	Non-mobile, laboratory environment readily accessible to maintenance; includes laboratory instruments and test equipment, medical electronic equipment, business and scientific computer complexes.
Ground, Fixed	∅2	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, and missile silo ground support equipment.
Ground, Mobile	∅3	Equipment installed on wheeled or tracked vehicles; includes tactical missile ground support equipment, mobile communication equipment, tactical fire direction systems.
Space, Flight	∅4	Earth orbital. Approaches benign ground conditions. Vehicle neither under powered flight nor in atmospheric re-entry; includes satellites and shuttles.
Manpack	∅5	Portable electronic equipment being manually transported while in operation; includes portable field communications equipment and laser designations and rangefinders.
Naval, Sheltered	∅6	Sheltered or below deck conditions, protected from weather; includes surface ships communication, computer, and sonar equipment.

3.5.7 The Total Data Transferred

A working document defining the data format and corresponding codings was established by LUT [10]. This document provides the rules for coding and highlights those data items which are considered essential information. It was decided that, because there are some items which may be difficult to collect data on, a set of data items which must be collected would be termed as essential data meaning that any data set must contain information on these fields.

A 'soft information' document is required when a data set is sent to LUT. This document gives further information about the data. For example, it discusses the repair and maintenance policies of the equipment and should also discuss how the percentage usage (or duty-cycle) figure for an equipment is calculated. This discussion on usage should also indicate the on-off cycling rate of an equipment. Thus, if a system has a usage of say 30% does this mean that it is operational continuously for 1 week in three or is it switched on 8 hours a day? This is obviously an important piece of information since the duty cycling rate can affect the reliability of some electronic components. In addition, as discussed in section 3.5.3, when using the indicator D for operating time to failure, details concerning the calculation method of this date must be specified in the soft information document.

Any information not contained in the main data set should be given in the soft information document. It is therefore evident that this document, although a supplement to the data, is of the utmost importance when analyzing the data.

The working group continues to meet about every 3 months and although the data format was finalised about 3 years ago, minor amendments are occasionally made, e.g. the addition of new component codings. The working group is now (Aug 1989) mainly concerned with the results of the data analysis, the building up of the database and the solution to any data problems which may be encountered.

3.6 Data Transfer

In Figure 3.1, the organisation of the project was shown, Figure 3.3 displays the data transfer procedure to LUT as an expansion of part of Figure 3.1 and illustrates the flow of data from the companies to LUT. The communication medium for the three British companies is magnetic tape while the DIA communicate via IBM compatible floppy disks [8]. The validation process shown in this figure is discussed at length in Chapter 5 together with discussion on the security aspects of the database.

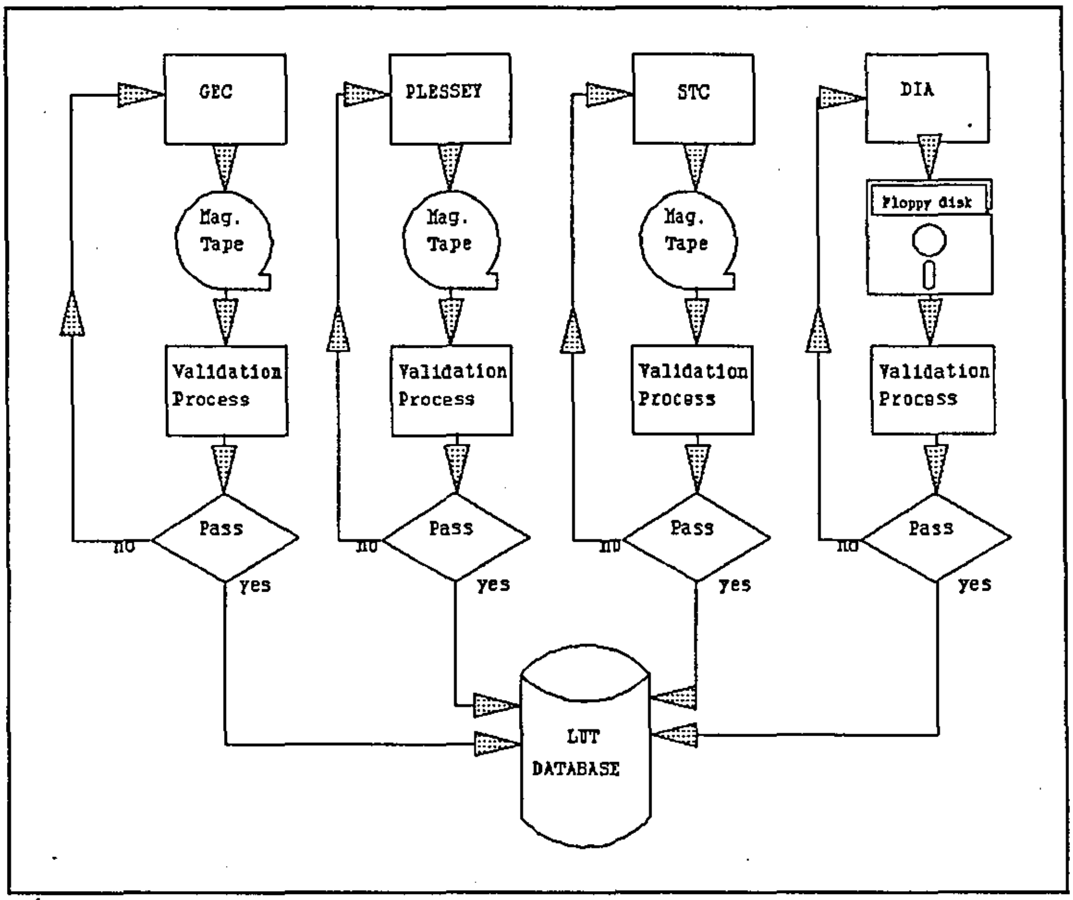

Figure 3.3
Data Transfer Flowchart

3.7 Conclusions

The construction of the finalised data format has been arrived at by the efforts of a working party of both engineers and statisticians whose main aim is to collect dependable data on the field experiences of electronic components.

Although this exhaustive study has been conducted with the expectations of producing a database which has integrity and no 'a priori' assumptions built in, there are factors affecting electronic components which are not included in this detailed data format, e.g. human factors. Such influences have not been considered in the construction of this database due to the difficulty of quantifying and collecting such information.

The database not only contains detailed information on the field failure of electronic components but in addition it contains some of the most dependable data ever collected. Moreover the fact that competitive electronic companies are collaborating on such a project makes it all the more unique.

3.8 Summary

This chapter has introduced the LUT Study and given some of the historical background to the project.

The organisation of this project has been illustrated and discussed with respect to the functions that each of the participants perform.

The requirement of dependable, as interpreted by the study, and traceable data has been introduced together with the minimum data requirements, imposed by LUT, which ensure this dependability and traceability.

The full data format, devised by a working group of engineers and statisticians has been described with examples of particular codings.

A working document has been introduced as an aid to the data provider and a soft information document was devised to enhance the understanding of a particular data set. In addition, the transfer procedures for the data have been illustrated and discussed.

On the whole, this chapter has shown how the project has developed from an idea to the realisation of the collection of specified failure data from dependable data sources.

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4. THE FORMATION OF THE ELECTRONIC COMPONENT DATABASE

4.1 Introduction

The previous chapter discussed the data items which are required to be collected in order to achieve the aims of the field failure of electronic components project. However, it is not enough to create and issue a working document of the details of such items, decisions on how to store and access the collected data must be made. This chapter introduces the concept of a database and illustrates how the decisions on the storage of the data were made by describing the different types of database and their associated advantages/disadvantages. In addition, the final database design together with its associated advantages is discussed.

Firstly, however, we must ask the question, what is a database system? "A database is a well organised collection of data and one should be able to process, update and make additions to the contents of a database in a simple and flexible way. It should also be easy to make different kinds of unplanned as well as planned retrievals of data from the database." [1] But why do we need to structure the storage of our data?

As illustrated in the previous chapters, the collection of data is a very complex process, therefore it is obviously extremely important to consider the implications for the storage and accessability of this data. Indeed the following points highlight why a structured database is necessary:

1. Since we are collecting data from diverse sources, the centralised control of the data is important.
2. The amount of redundancy can be reduced.

Eliminating redundancy is important in order to reduce storage capacity, provide efficient retrievals and a reduction in coding.

3. Inconsistency in the data can be avoided. Chapter 5 discusses the validation procedures carried out on the data and includes discussions on the use of the database structure to detect inconsistencies in the data.
4. Standards can be enforced.
5. Security restrictions can be applied. Obviously a project collecting data from competitive companies requires adequate security measures. Chapter 5 discusses some of these security measures.
6. Data integrity can be maintained. As discussed earlier, data integrity is of the utmost importance in achieving credible results from any statistical analysis. A database can ensure such integrity is maintained through employing validation and consistency checks.
7. The data can be shared. This means that the data is stored once and anyone (who has authority) can access the data. Thus, in the future, the companies involved may be able to access the central database and will not need to keep their own databases.

4.2 Different Types of Database Systems

4.2.1 Introduction

As explained above a database is the structured organisation of data. When accessing a database the user requires an external view of the data. A Data Base Management System (DBMS) provides this external view. A DBMS is an intermediary link between the physical database, the computer and the operating system and also between the different kinds of users, for example, programmers, end users and administrators. This mediating function performs such tasks as retrieving data, adding data, updating etc. in accordance with instructions from the users. A DBMS therefore supports the database system.

The generalised DBMSs which are available on the market today are often based upon one of the following three main approaches to database systems, ie

1. Hierarchical
2. Network
3. Relational

4.2.2 The Hierarchical Database

Figure 4.1 shows an example of a hierarchical view of a suppliers and parts database. In this view the data is represented as a simple tree structure, with parts superior to suppliers. This relationship is known as one-to-many, ie each part may have any number of suppliers. Figure 4.1 illustrates an example of a simple parts and suppliers hierarchical data structure. For example there are two suppliers of part 1 (P1), 3 suppliers of part 2 (P2) and so on.

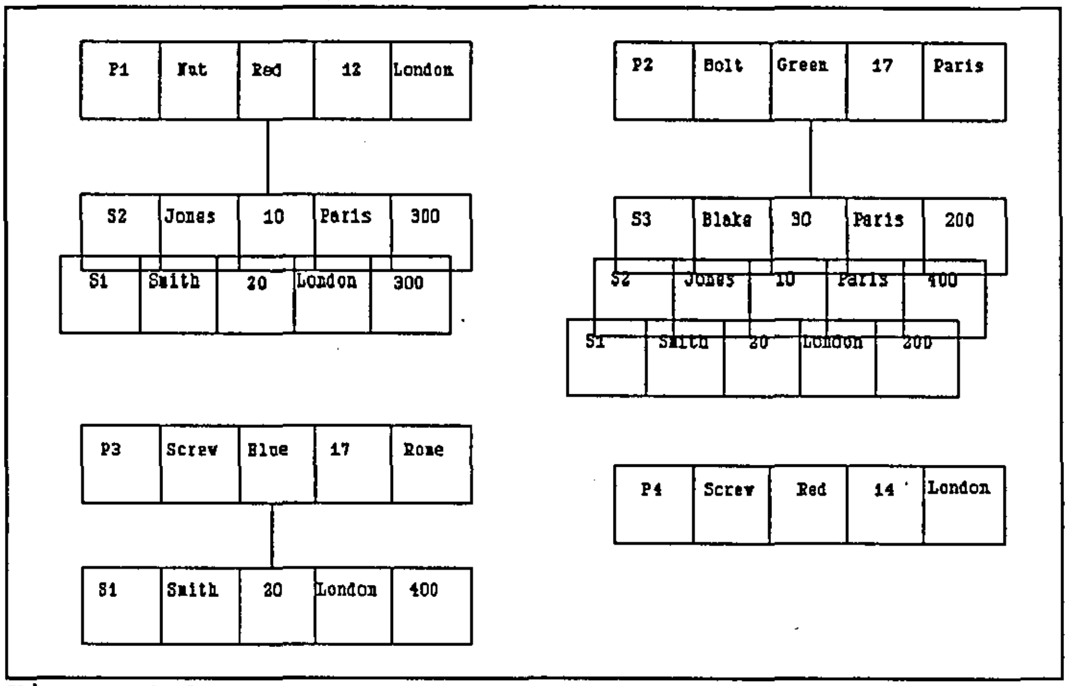

Figure 4.1
Example of Hierarchical Database

The record type at the top of a tree is usually known as the "root" (in Figure 4.1 the part is the root) . This example is one of the simplest possible hierarchical structures which has a root and a single dependant record type (in Figure 4.1 suppliers is the dependant record). In general, the root may have any number of dependants, each of these may have any number of lower-level dependants etc. to any number of levels.

This example can be likened to one single file containing records arranged in 4 individual trees. In this file there are two types of records ie one for parts and one for suppliers and in addition, the file contains links connecting occurrences of these two types of records. It is fundamental to the hierarchical view of the data that any given record occurrence takes on its full significance only when seen in context. In fact, no dependent record occurrence can exist without its superior.

The procedures for accessing the data stored using this hierarchical structure are extremely complex. For example, comparing the following queries:

Q1 Find the supplier number for all suppliers who supply part P2.

Q2 Find the part numbers for all parts supplied by supplier S2.

These queries appear very similar but they require two different search procedures. Indeed, due to the fact that parts are treated as superiors and suppliers are dependents there is a loss of symmetry. This asymmetry is a major drawback of the hierarchical approach, because it leads to unnecessary complications for the user.

Because of this problem users are required to write programs which are more complicated than they need be. In fact, as more types of record are introduced the more complex the hierarchy becomes. Although hierarchies are obviously a natural way to model truly hierarchical data structures the problem of asymmetry in retrieval still arises.

In the case of update operations, hierarchical structures possess further undesirable properties. For example, inserting a new supplier, say S4, this is not possible without introducing a special dummy part or until a supplier supplies a particular part. Similarly, if we want to delete a part which is the only part supplied by some supplier then the supplier is also deleted since all dependent occurrences are automatically deleted.
Because of these problems, hierarchical databases are infrequently used. Indeed this approach is a very outdated approach which requires a user to be an expert programmer.

Some of the longest established databases are hierarchical, but this is because the hierarchical database was the first of what we now call database systems [2].

4.2.3 The Network Approach

Figure 4.2 shows a network view of the suppliers and parts database. As in the hierarchical approach, the data is represented by records and links. However,a network is a more general structure than a hierarchy because a given record occurrence may have any number of immediate superiors as well as any number of dependents; this is known as a many-to-many relationship. In addition to the record types represented by the suppliers and parts themselves, there is a third type which is called a connector. A connector represents the association (shipment) between one supplier and one part, and contains data describing this association.

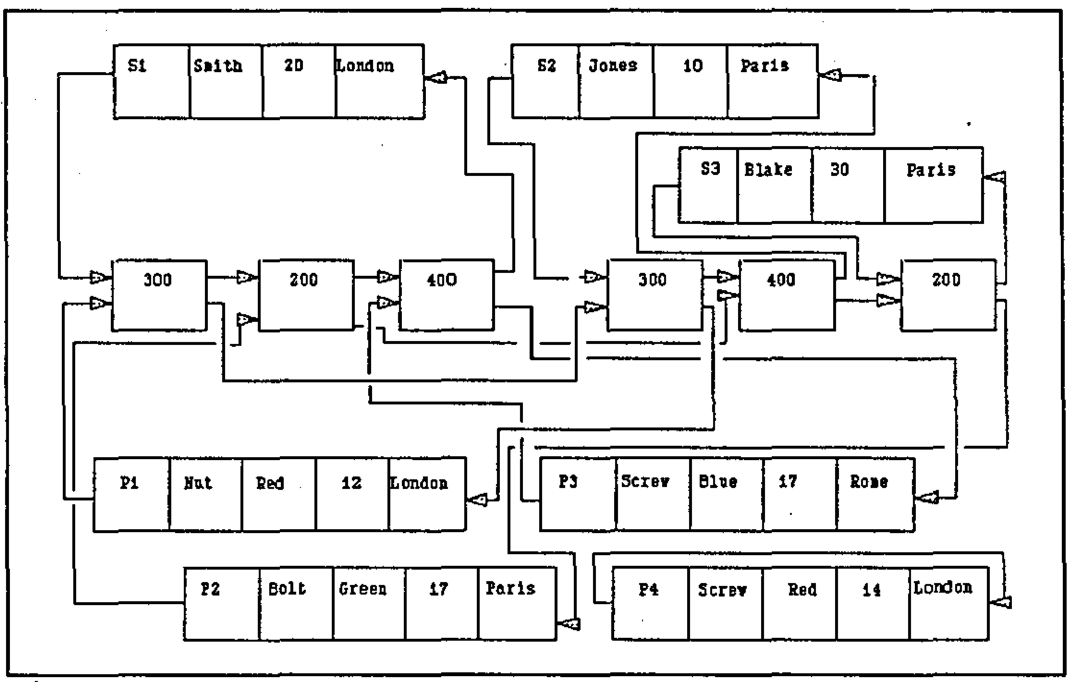

Figure 4.2
Example of Network Database

The internal structure of this file is even more complex than the hierarchical case. Although the network structure is more symmetric than the hierarchical structure, the procedures for accessing the data are even more complicated.

Updates are fairly straightforward unlike in the hierarchical structure. However, the major disadvantage of the network approach is the complexity, both in the data structure itself and in the data manipulation.

There are several commercially available systems which are based on the network approach and include UNIVAC's DMS1100 and IBM's DBCOMP among others. These are based on specifications provided by CODASYL. CODASYL means COnference for SYstems Languages. The CODASYL model was initially the most common for large data processing databases with most manufacturers supporting it [3],[4].

A network database is suitable for large applications and for applications where static relationships among data are important. However, it is not suitable for ad-hoc querying of data or small applications.

4.2.4 The Relational Approach

In a relational database all the information is stored in two dimensional tables and no explicit links exist between the tables. Tables are manipulated using a query language based on Relational Algebra.

Figure 4.3 shows an example of the parts-suppliers database in relational form, and includes shipments.

SUPPLIERS

S No	SNAME	STATUS	CITY
S1	Smith	20	London
S2	Jones	10	Paris
S3	Blake	30	Paris

PARTS

P No	PNAME	COLOUR	WEIGHT	CITY
P1	Nut	Red	12	London
P2	Bolt	Green	17	Paris
P3	Screw	Blue	17	Rome
P4	Screw	Red	14	London

SHIPMENTS

S No	P No	QTY
S1	P1	300
S1	P2	200
S1	P3	400
S2	P1	300
S2	P2	400
S3	P2	200

Figure 4.3
Example of Relational Database

The data is organised into 3 tables namely suppliers, shipments and parts. The supplier table contains for each supplier, a supplier number and name, a status code and a location. The parts table contains, for each part, a part number and name, the colour and weight of the part and the location where the part is stored. Finally, the shipment table contains, for each shipment, a supplier number, a part number and the quantity shipped.

Assumptions are made concerning each of these three tables [5]. Firstly, we assume that each supplier has a unique supplier number, name, status value and location. Secondly, we assume that each part has a unique part number and exactly one name, colour and weight and location. Finally, we assume that at any given time no more than one shipment exists for a given supplier and part combination.

It is clear, that the relational structure is easy to understand. However, the manipulation language is just as important as the simplicity of the data represented. If we consider two sample queries:

Q1 Find the supplier number for all suppliers who supply part P2

Q2 Find the part numbers for all parts supplied by supplier S2.

By looking at the shipment table we can see that this is a simple operation. To find the solution to Q1 we scan for all parts P2 and find the corresponding supplier numbers (S1,S2,S3). Similarly for Q2 we can scan for all supplier numbers S2 for the corresponding part numbers (P1,P2). These two queries are symmetric, in fact one is the inverse of the other.

Inserting, updating and modifying a table can be carried out simply without having to create dummy items or writing complex programs [6].

This section has introduced briefly the three main types of database systems, but more detailed information can be found in most database texts, for example [7], [8]. Both the hierarchical and the network approach represent relationships by means of links and consequently introduce complications for the user when accessing such a database. The relational approach, however, represents the data using the natural relationships between data and enables accessing the database to be carried out without complex programming. In addition it enables an exploratory approach to extracting the data.

Having introduced and described the three different approaches, the remainder of this thesis is concerned with an application of the relational database.

4.3 The Advantages of the Relational Approach

The relational approach was largely pioneered by the work of E. F. Codd in the early 1970's [9], [10] and is firmly based on sound mathematical ideas from set theory. The major appeal of this approach is its simplicity since tables are a very simple and natural way of regarding data.

This model is made up of a collection of 2 dimensional tables, all records in a single table are of the same type and the relationships between records are not held by connectors or pointers but by holding common data values in related tables.

The relational approach does not just use any sort of table. These tables conform to a 'set of rules';

1. Each box in a table contains one value.
2. Within a column the box values are of the same type.
3. Each column has a distinct name.
4. Each row is unique.
5. A relational database contains at least one relation (table).

In addition, there is a specialised set of terms associated with this approach. Figure 4.4 illustrates this terminology by means of an example. From this Figure a table is known as a relation thus the example in Figure 4.3 consists of 3 relations, suppliers, parts and shipments. Each row in a relation is known, not as a record, but as a tuple. The name of a column of data is an attribute, for example, 'suppliers name' is an attribute and the value "Smith" is known as the attribute value.

PRESIDENTS DATABASE

NAME	PARTY	HOME-STATE
Eisenhower	Republican	Kansas
Kennedy	Democrat	Massachusetts
Johnson	Democrat	Texas
Nixon	Republican	California

COMPARISON OF TERMINOLOGY

DEFINITION	ILLUSTRATION	RELATIONAL TERMINOLOGY	GENERAL TERMINOLOGY
A file. A collection of organised data	The set of data given above.	relation	file
A record. A representative "row" of data.	"Kennedy, Democrat MAssachusetts"	tuple	record
The name of a data field within a record; a column of information.	"HOME_STATE"	attribute	field or data item
Content of data field within a record.	"Texas"	attribute value	value of field or data item
The set of all values a data field may assume	The name of the 50 states.	domain	file
User's definition the data base.	Created by user & administrator.	data submodel	not used
Total definition of the data base.	Created by the administrator.	data model	data format

Figure 4.4
Comparison of Terminology

Figure 4.4 shows the comparison of general terminology and relational terminology using an example database ie Presidents Database. Generally the table representing the Presidents Database would be termed a file, but in relational terminology it is known as a relation. Similarly, a record is known as a tuple and a field is known as an attribute. The definition of the database or data format in relational terminology is known as a data model. Thus Figure 4.4 shows the definitions for relational terminology.

Manipulating a relational database uses a language based on relational algebra and set theory. Figure 4.5 illustrates a library containing books and borrowers. Sample questions from this relational database could include the following examples. These questions will be answered simply by using relational algebra together with a query langauge. The sample output is also shown.

BORROWERS

borrower_no	borrower_name	department	status
1234	John Smith	Elec. Eng	Staff
1345	Jane Black	Physics	Student
1507	Joe Bloggs	History	Staff

BORROWED_BOOKS

accession_no	borrower_no	due_back
22651604	1234	1/10/90
12345678	1345	5/9/89

BOOKS

accession_no	title	author	publisher	class
22651604	Database Analysis and Design	Hugh Robinson	Chartwell-Bratt	001.6442
27918101	Databases and Data models	Bo Sundgren	Chartwell-Bratt	001.6442
13301201	An Introduction to Databases	C. J. Date	Addison-Wesley	001.6442
123456789	Successful Dieting	J. Marshall	Sample	123.456

Figure 4.5
Example Relational Database

Q1: Does the library contain the book entitled "Database Analysis and Design" by Hugh

Robinson and what is its accession number
and class mark?

QL1: Select books.accession_no and books.class
from books where
title = "Database Analysis and Design" and
author = "Hugh Robinson"

A1:

accession_no	class
22651604	001.6442

If there was no such book contained in the library the empty set is retrieved together with a message "no record found which satisfies the query".

Q2: Is this book already borrowed, if so when is it due to be returned?

QL2: Select borrowed_books.accession_no and
borrowed_books.due_back
from borrowed_books
where accession_no = "22651604"

A2:

accession_no	due_back
22651604	1/10/90

Q3: Are there any overdue books and what are the borrower details?

QL3: Select borrowed_books.accession_no and
borrowed_books.borrower_no and borrowers
from borrowed_books and borrowers
where due_back < today's date and

borrowed_books.borrower_no = borrowers.
borrower_no

A3: accession_no borrower_no
12345678 1345
name etc
Jane Black

This answer illustrates the joining of two relations where the specified condition is fulfilled. Having found the borrower_no, this number is joined to the borrower relation to find the details of the borrower.

Q4: How many books does John Smith have borrowed from the library at the moment?

QL4: count (select borrowed_books
from borrowed_books and borrower
where borrowed_books.borrower_no =
borrower.borrower_no and
borrower.borrower_name = "John Smith")

A4: count = 1

Again this is an example of a join between two relations, however, in this example we are counting the number of records (tuples) which satisfy the condition.

Q5: How many books are on loan out of the total contained in the library?

QL5: count (select borrowed_books.accession_no
from borrowed_books
intersect
select books.accession_no from books)

A5: count = 2

This query applies set algebra. The set of all accession_nos which are in both specified relations is returned. Figure 4.6 illustrates the solution to this query by using a Venn Diagram. The set of borrowed books is a subset of the books relation.

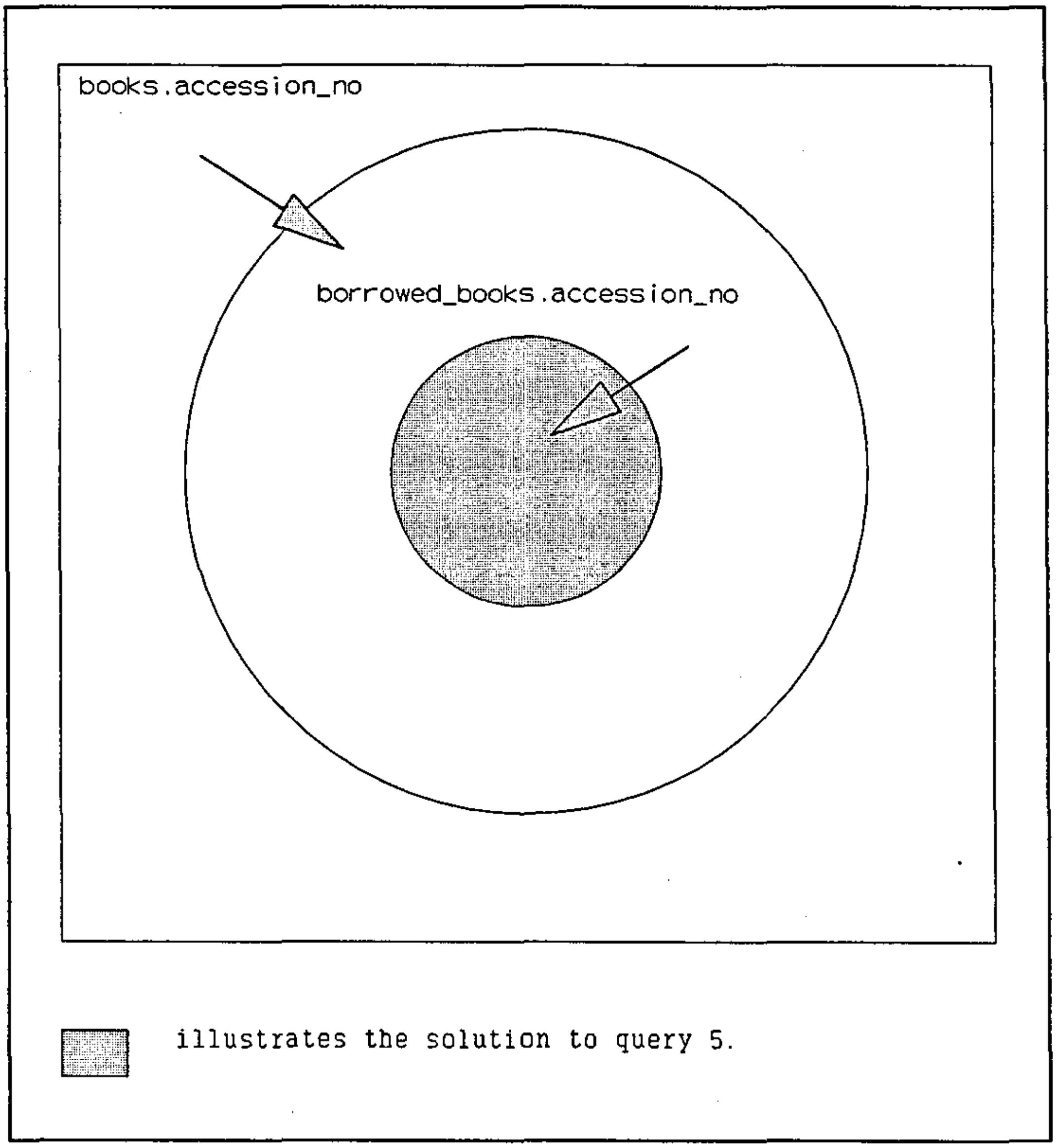

Figure 4.6
Venn Diagram of Subset

Q6: How many borrowers do not have any books out at the moment?

QL6: count (select borrower.borrower_no
from borrower
differ
select borrowed_books.borrower_no
from borrowed_books)

A6: count = 1

Similarly, this query uses set algebra. However, in this example, we are looking at the complement, ie the set of all borrowers who are not contained in the set of borrowed books. Figure 4.7 illustrates the solution by using a Venn Diagram.

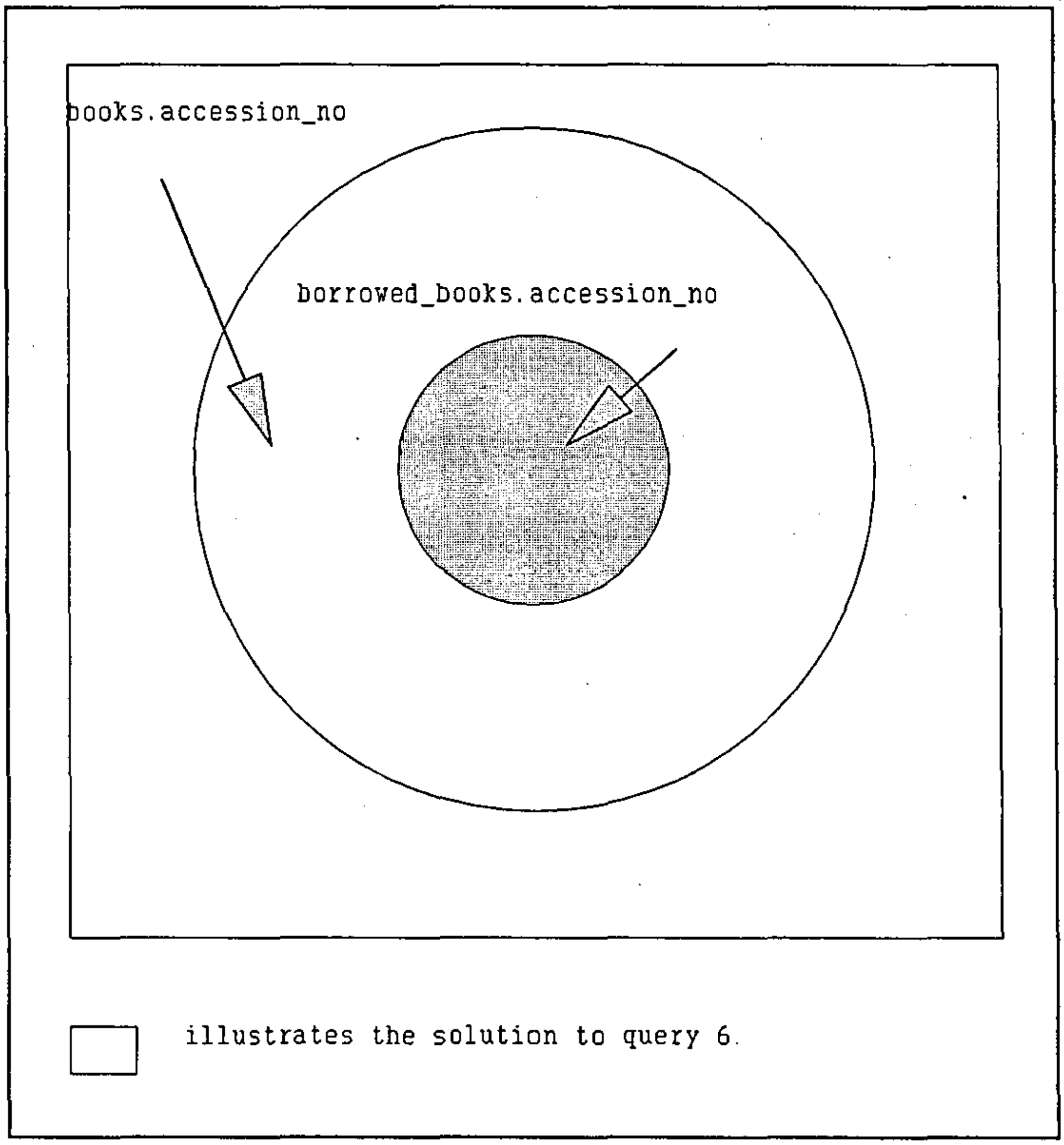

Figure 4.7
Venn Diagram of Complement

These queries illustrate the simplicity of retrieving information from a relational database. Updating, deleting and appending data are similarly straightforward to implement.

From this discussion, it can be seen that there are some major advantages of using this relational approach, including:

1. It has a sound theoretical foundation based on set theory.
2. Simplicity.
3. The relations contain a natural structure of the data.
4. There is no requirement to know about the internal structure of storage since the DBMS deals with this, unlike the network approach.
5. The relationships between tables are represented explicitly.

There is however, one disadvantage. When a database becomes large, joining relations can slow down the retrieval process. This is not a great problem, since as technology advances, faster computers are becoming commercially available at a reasonable cost.

4.4 The Design and Implementation of the Electronic Component Reliability Database

4.4.1 Historical Background and Initial Ideas

Initially, it was thought, based on the pilot studies in Denmark, that the database could be contained on an IBM PC AT. However it soon became evident that this would be inadequate both with regard to the storage facilities required for the data and the availability of the necessary statistical software packages to run on this type of machine. It was therefore decided to use the Honeywell Multics mainframe based in the Computer Centre at LUT, for both data storage and statistical analysis.

While compiling the data format no consideration had been given to the actual storage of this data. In fact, when the data format was complete, the original concept was to store the data in 3 separate text files, as shown below.

File 1 - Failure Data

Company
Equipment Type
Equipment Serial Number
Environment
Equipment up and running Date
Primary Function of Board
Board Part No (co_design)
Up and running Date of Board
Manufacturing Date of board
Previous use/storage

Component Type
Screened level
Circuit Reference Position
Component Manufacturer
Batch No
Operating time of equipment to failure
Operating time of board to failure
Failure mode of component

File 2 - Population Data

Company
Equipment type
Equipment serial no
Environment
Equipment up and running date
End date
Usage
Primary function of board
Co_design
Board serial no
Previous use/storage

File 3 - Parts List

Company
Equipment Type
Co_design
Total list of components

Obviously, to access any of this data would involve vast amounts of programming. In addition, these files would quickly become very large, since file 2 requires information on every equipment and board in the field. For example, for one type of equipment, say, a television set, there could be millions of the same type in the field. Therefore, storing and retrieving this data would become impossible in this current format. It, thus became apparent that a structured database would be more appropriate.

The requirements of such a database were considered and included:

1. There was a need to minimise duplication in the data not only to improve the efficiency of storage and retrieval but to reduce some of the workload on the companies.
2. Invalid data items could be corrected simply.
3. In order to analyze the data, manipulation and exploration must be fairly simple.
4. The accuracy of the data in the database.
5. Security procedures.
6. Following equipments in the field is an ongoing situation therefore updating facilities are necessary.

The relational database approach was the most appropriate way of satisfying these requirements. In addition, to fulfilling these requirements, the database would not be an accounting system performing the same routines periodically, but one in which retrieval of data is flexible and exploration possible.

4.4.2 The Natural Hierarchical Structure of the Data

As can be seen in the previous section there are three data files, each of which are hierarchical in their structure. For example, an equipment is made up of boards which in turn are made up of many components. This hierarchical structure does not, at first glance, appear to naturally fit a relational structure.

4.4.3 The Evolution of the Database Design

The design of the database is crucial to the success of attaining the aims of the study.

The technique for designing a relational database is known as normalisation. A relation which satisfies the rules discussed at the beginning of section 4.3 is said to be normalised [9]. Normalisation in effect forces the designer to achieve the optimum design for a given set of data. Since the process of normalisation refers to utilising the natural groupings within the data, the first step in achieving an appropriate design involved splitting the data into its natural groupings. Table 4.1 shows the results of this breakdown. In Table 4.1, each relation has a unique key field (or several fields concatenated) indicated by "*". An element of data which is in a unique key field cannot be duplicated. For example, in the equipment identification relation, there is one unique company identifier for each equipment type in the field.

Relations 1 to 4 inclusive contain all the population information about equipments and boards and relation 5 is the link between them. Relation 6 shows the relationship between circuit boards and components and relations 7 and 8 contain all the failure data corresponding to a component failure.

Table 4.1
Relational Database Design
Step 1

1 EQUIPMENT DEFINITION

Co

Equipment type*

2 BOARD DEFINITION

Circuit board
primary function
Co_design*

3 EQUIPMENT I.D.

Equipment type*
Equipment serial no*
Environment

Up and running date
End date
Usage

4 BOARD I.D.

Co_design
Circuit board serial no*
Circuit board
up and running date
Previous use
Storage

5 EQUIPMENT_BOARD

Equipment serial np*
Co_design*

6 BOARD_COMPONENT_POP

Co_design*
Component type*
Number of components

7 FAIL I.D.

Record no
Equipment serial no*
Circuit board serial no*
Component type*

Circuit board
up and running date

Manufacturing date

Previous use

Storage

8 FAIL CHARACTERISTICS

Component type*
Screened level
Component manufacturer
Circuit reference
position
Batch no
Equipment Operating
Condition
Equipment failure
mode
Equipment operating
time to failure
Circuit board operating
time to failure
component failure
mode

* unique key

The design shown in Table 4.1 was found not to be correct for several reasons. Firstly, the unique key fields are incorrect, for example, in relation 1, by chance, the codes for equipment types may be the same for different companies. Concatenating the two fields would be more accurate. Secondly, there is some duplication of data between the failure and population relations.

The design required to be normalised further, the result of which is shown in Table 4.2.

Relations 1, 2 and 3 contain all the population information. In particular, relations 1 and 2 define a piece of equipment in terms of the types and number of boards and components which identify the equipment type. These two relations need never be altered unless an equipment or board is redesigned. Relation 3 describes, for a particular unique piece of equipment of a certain type and supplied by a specific company, when it was switched on and the end of the observation period. This relation also contains data on the environment in which this particular equipment operated. The final relation, FAIL, gives the details for a equipment failure report including the component type which failed and its associated failure characteristics. For example, when it failed, where on a board it failed, which board it was in etc.

Table 4.2
Relational Database Design
Final Design

1 EQUIPMENT STRUCTURE

Company*
Equipment type*
Co_design*
Number of boards
Circuit board
primary function

2 BOARD STRUCTURE

Company*
Co_design*
Component type*
Component part no*
Component additional
information*
No of components

3 EQUIPMENT I.D.

Company*
Equipment type*
Equipment serial no*
Up and running date
End date
Usage
Environment

4 FAIL

Company*
Record no*
Fail identifier*
Equipment type*
Equipment serial no
Co_design
Circuit board serial no
Circuit board
up and running date
Manufacturing date
Previous use
Storage
Component type
Component part no
Component additional
information
Component manufacturer
Circuit reference
position
Batch no
Screened level
Equipment operating
time to failure
Board operating
time to failure
etc.

* unique key

This, then, is the final database design which, although incorporating some duplication (company codes), has been normalised and abides by most of the rules of relational databases. Figure 4.8 illustrates the design in relational format. In each relation, the unique key fields are made up of several fields, for example, in the equipment identification relation, there is one unique record for a particular equipment serial number of particular type and company code in the field.

EQUIPMENT STRUCTURE

Company*	Equipment type*	Co_design*	No of boards*	Board primary function

BOARD STRUCTURE

Company*	Co_design*	Component type*	Component part no*	Component additional info*	No of Components

EQUIPMENT IDENTIFICATION

Company*	Equipment type*	Equipment serial no*	Up and running date	End date	Usage	Environment

FAILURE

Company*	Record no*	Fail id*	Equipment type*	Equipment serial no	Co_design	Board serial no	Board up and running date

Board manuf. date	Previous use	Storage	Component type	Component part no	Component additional info	Circuit reference position	Screened level	etc

* unique key fields

Figure 4.8
Final Database Design

The following examples demonstrate how, in practice, information can be retrieved from this database:

Q1: How many failed bipolar transistors are there in the database (T1A)?

QL1: count (select FAILURE from FAILURE
where component type = "T1A")

Q2: Are all bipolar transistors screened to
BS9000 specifications?

QL2: select screened level from FAILURE
where component type = "T1A" and screened
level ^= "9"

note : "9" is the coding for BS9000
screened components.

Q3: How many bipolar transistors are there in
board type Y?

QL3: sum (select no of components from BOARD
STRUCTURE where co_design = "Y" and
component type = "T1A")

Q4: How many pieces of equipment of type X are
there in the field and what is the total
operational time for equipments of this
type?

QL4: count (select (end date - up and running
date)) from EQUIP ID where equipment
type = "X")

These retrievals are fairly simple. More complex retrievals would involve joining relations using the keys. From table 4.2, the natural structure of the data has been used to provide this design.

This database design was achieved through the understanding of the data structure and the relationships between the data items.

4.4.4 Implementation

The database was implemented on the Multics Relational Data Store (MRDS) existing on the Honeywell Multics mainframe at the LUT Computer Centre. MRDS is a relational database and therefore has a supportive DBMS. Figure 4.9 shows a functional diagram of the process of creating and accessing a database using MRDS [11], [12]. Three basic steps are illustrated in Figure 4.5, ie:

1. Create the model and the corresponding unpopulated database.
2. Load the unpopulated database with data.
3. Access the populated database.

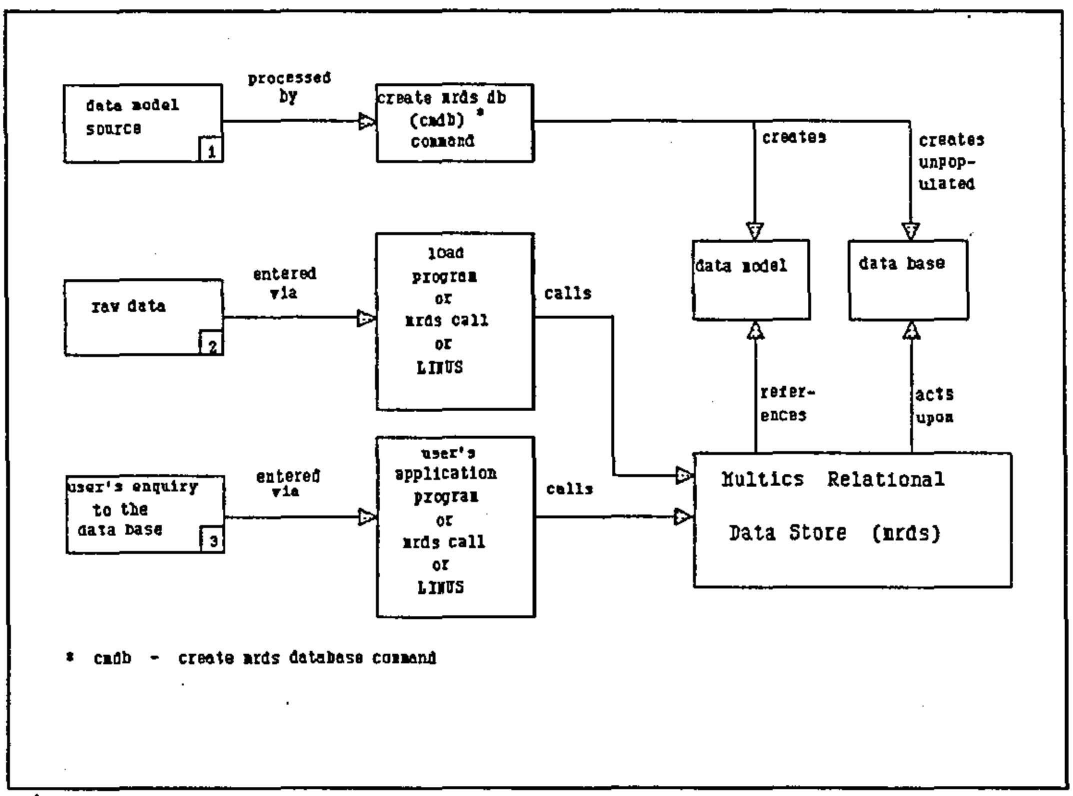

Figure 4.9
Functional Diagram
MRDS DBMS

Step 1 is a process which is generally carried out only once. However, steps 2 and 3 concern users accessing an established database.

From Figure 4.9, steps 2 and 3 introduce the different ways of storing and accessing the database, namely:

1. MRDS call.
2. Application programs utilising the data sub-language routines (dsl).
3. LINUS (Logical Inquiry and Update System)

Only items 2 and 3 are discussed in detail here, since direct calls to MRDS tend to be used for low level applications.

4.4.5 DSL Routines

These are subroutines which can be built in to any program. PL/1 is the most obvious language to write in because both the database system itself and the multics operating system are written in PL/1. The subroutines include facilities for retrieving, updating and deleting data from the database. They are advantageous for carrying out routine analysis. For example, each time a new data set is added to the database, a program to calculate failure rates for each component type, can be executed. Minimal effort is, therefore, required from the user after the software has been written. Such programs are complex to write and require extensive knowledge about how data is accessed by MRDS. However, once this knowledge has been attained the software can be written and maintained fairly easily.

4.4.6 LINUS

This is an enquiry language which can retrieve, update and delete information from the database. It is simple to use and requires very little knowledge about database systems or programming, but it does require knowledge about the particular database the user is accessing.

The query examples illustrated in previous sections were written in LINUS. All query languages for relational databases are similar and LINUS is not too dissimilar from SQL (called sequel). SQL is a 4th generation language written by IBM which is quickly becoming a standard for all relational databases. Appendix A discusses the further development of the database with particular reference to the use of SQL as a database language.

The advantage of LINUS over DSL routines is its simplicity. Its main use, in this database, is for exploration of the data. For example, to explore the relationship between time to first failure of a PCB of certain type and the time to second failure of the same type of boards, LINUS would be a simple tool to employ. Firstly, select all those board times to first failure of a given board part number and store the results in a data file. Secondly, select the times to second failures for the same board part numbers and store these in another file. Using any graphics package a scatter plot of time to first failure against time to second failure will help to indicate any relationship between the two variables. Note, to find from the database the number of times a board of a certain type has failed, the previous use field is queried. If the previous use indicator is "A" (no previous repairs) then the corresponding time is the time to first failure. Obviously, this type of exploration is quick and simple to employ.

4.5 The Advantages of the Database

The applications of this database are numerous due to the flexibility of the design and the ability to explore the database. The following points, however, indicate some of the main advantages that have been found in the operation of this database design:

1. It is efficient for storing the data since there is less duplication.
2. It is possible to retrieve all the information which is ever likely to required.
3. Updating is simple because:
   a. There is no need to update the structure information unless there is a redesign of an equipment or a board.
   b. Additional failure records are easily appended.
   c. Data on new equipments in the field are appended to all the population relations.
   d. An update of an equipment in the field requires only the end date of observation to be changed for a given equipment.
4. Exploration of the data for validation and statistical analysis is simple.

From this, the aims of the project can be achieved by utilising this database to its full capacity.

4.6 Alternative Views of the Database

Due to the flexibility of a relational database, different views of the data can be set up for specific purposes. Three such views could include:

1. Research View.
2. Commercial View.
3. Raw Data.

The research view of the data would include all the information on the characteristics of component types. The function of this view is for statistical analysis. For example:

1. Exploring the time structure of the data for a particular component type.
2. Making comparisons of BS9000 screened components with other screening methods.
3. Comparing different mounting technologies.
4. Exploring the relationship between first and subsequent failures of boards.

etc.

The commercial view of the data could perhaps consist of tables with calculated failure rates for the pooled data. This view, after enforcing security restrictions, could be used by the companies to see their own data and the pooled data in a summarised form. This ability to retrieve summarised information may encourage the data sources to provide data on further equipment types.

Finally, the raw database would be used by the database administrator for updating, controlling and validation of the raw data and obviously to provide the previously discussed (and other) views of the database.

4.7 Summary

This chapter has illustrated why a structured database is necessary and outlined the three different types of database systems, namely, hierarchical, network and relational.

The relational database was chosen for the project mainly because of its flexibility and ease of use. In addition, this chapter introduced the importance of database design and showed the evolution of the design which was determined for the purposes of storage and retrieval of the data collected on the field failure project.

The advantages and some of the uses of this database have been discussed together with the different ways of viewing the data.

In conclusion, this database was achieved by understanding, not only the principals of relational database systems, but more importantly, by understanding the concepts of the data and the potential statistical analysis to be carried out on the data.

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5. ADMINISTRATION AND CONTROL OF THE DATABASE

5.1 Introduction

This chapter is concerned with important administrative details of the database. Having decided what data is to be collected, how it is to be stored and accessed and how it is to be transferred to LUT, it is important to be able to maintain and control the database.

There are three main areas of administration which warrant discussion. These include:

1. Data Validation
2. Security
3. Software Control and Validation

The previous chapters discussed in detail the extensive work involved in setting up a database with dependable data for analysis purposes. It is, therefore, extremely important to establish procedures for controlling such a database in order to maintain this high level of accuracy and dependability of the data.

5.2 Data Validation

5.2.1 Introduction

A computer cannot detect errors in data being processed in the way an operator can. Validation checks are an attempt to build into a computer program powers of judgement so that incorrect items of data are detected and reported [1].

As was seen in the organisational diagram (Figure 3.1) in Chapter 3, the data passes through several stages of processing before being transferred to LUT. For example, the first stage of data collection could be a repair engineer filling out a failure report. This report will be sent to the company who manufactured the equipment, where all failure reports are stored. From here, data from these reports could be entered on to a computer and subsequently transferred to the central collection site within the company who process it again into the format required for transfer to LUT. In some instances the path the data takes may be even more complex than this example, but it illustrates that the number of people handling this data is numerous, and therefore, errors in the data are very likely to be introduced somewhere along this process. It is therefore obvious that the data must be checked for inaccuracies. Indeed, before the data is transferred to LUT, each of the companies involved, carry out their own validation procedures. It may then seem pointless to revalidate the data at LUT. However, experience has shown this not to be true. In fact, no data set sent to LUT, has ever passed the validation checks at the first attempt.

Figure 5.1 illustrates a flowchart of the validation procedures implemented when a data set arrives from a company [2]. There are 2 stages in the validation process, the first includes checks at data entry and the second procedure involves consistency checking.

From Figure 5.1, the data is firstly read from magnetic tape/disk and stored in text files on the computer. It is then checked for erroneous data ie incorrect coding due to data input errors, before passing on to the next stage of validation. If the data does not pass the first stage of validation then a validation report is produced and the company involved is contacted. If the errors are fairly small then the data can be edited by LUT and revalidated, with the company's involvement. However, if there are major errors then the data is sent back to the company together with the validation report.

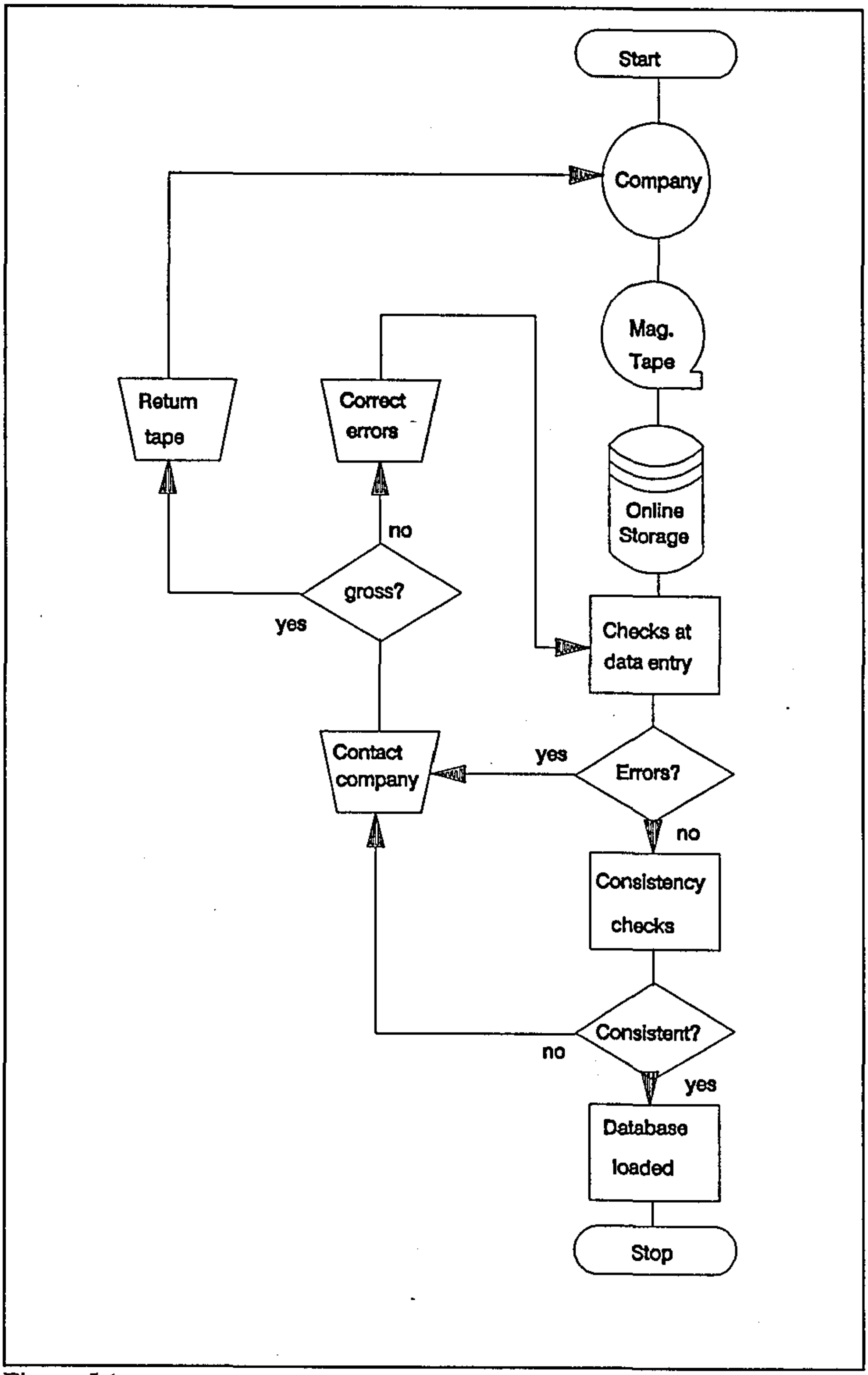

Figure 5.1
Flowchart of Validation Procedure

After the initial validation procedure, checks for consistency between the four data relations are employed (Figure 4.8). Any errors identified are discussed with the company and a decision as to whether the data should be returned to the company is made. Again, if there are minor errors then these can be edited at LUT through discussion with the company. If not, the consistency validation report is sent to the company together with the data requiring investigation and consequent correction.

When all the data has passed these two validation procedures it may be loaded on to the database. When a company has corrected erroneous data the data set can be resubmitted to LUT for revalidation and subsequent acceptance into the database.

In practice, this validation procedure takes, on average, about two days, depending on the complexity of the errors detected.

From Figure 5.1 and as discussed above, there are two stages of validation employed, ie

1. Checks at Data Entry
2. Consistency Checks

This section discusses in further detail these two stages and illustrates how they have been implemented on the system.

5.2.2 Checks at Data Entry

The first stage of the validation procedure is concerned with employing checks at data entry. These checks are used to detect problems which have occurred through errors in coding and transferring the data [3]. Such errors could be of the following type:-

1. Fields may be contain illegal characters. For example, numeric fields containing I instead of 1.
2. There may be duplicate records.
3. The coding of some of the data items could be wrong. As discussed in Chapter 3, a table of all valid component generic types exists. Therefore, if any data other than these occur in the component type field, an error is flagged. An example of this would be TIA instead of T1A. Obviously, this is a keying error.
4. Numeric values could be out of range. For example, an error will occur if the equipment operating time to failure is less than circuit board operating time to failure.
5. Data could be missing. For example, if screened level of a component is missing then an error would be flagged.
6. Invalid dates could cause an error. For example, if the month number is not between 1 and 12 then an error has occurred.
7. The length of fields or records may be wrong.

The above checks are only examples of those checks employed. In fact the errors mentioned above are examples of actual problems that have been encountered during the validation of incoming data sets.

The implementation of this first stage of validation is carried out after the data is read and stored in text files. A program has been written in PL/1 incorporating all the checks, such as those described above. One record is read and validated at a time, and if it passes then it is automatically stored in a preliminary database, using DSL subroutines to MRDS. If it fails then the error message is printed on the validation report and the next record is then read and validated, and so on.

The preliminary database is exactly the same design as the actual database and therefore the features of relational databases can be used to further validate the data, ie the second stage of validation.

5.2.3 Consistency Checks

The first stage of validation was mainly concerned with erroneous coding of the data. The second stage however, is concerned with the consistency of the data between the 4 relations shown in Figure 4.8.

These checks implement the database manipulation procedures, as discussed in the previous chapter, and use set theory to investigate inconsistencies. Examples of the types of checks incorporated are shown below together with the corresponding LINUS query and Venn Diagram:-

1. Are all the component types which have failed and are in the FAILURE relation also stored in the BOARD STRUCTURE relation ie the population of boards and components table?

   Query:Select component type from FAILURE
   differ
   select component type from BOARD STRUCTURE

Diagrammatically, this is shown in Figure 5.2.

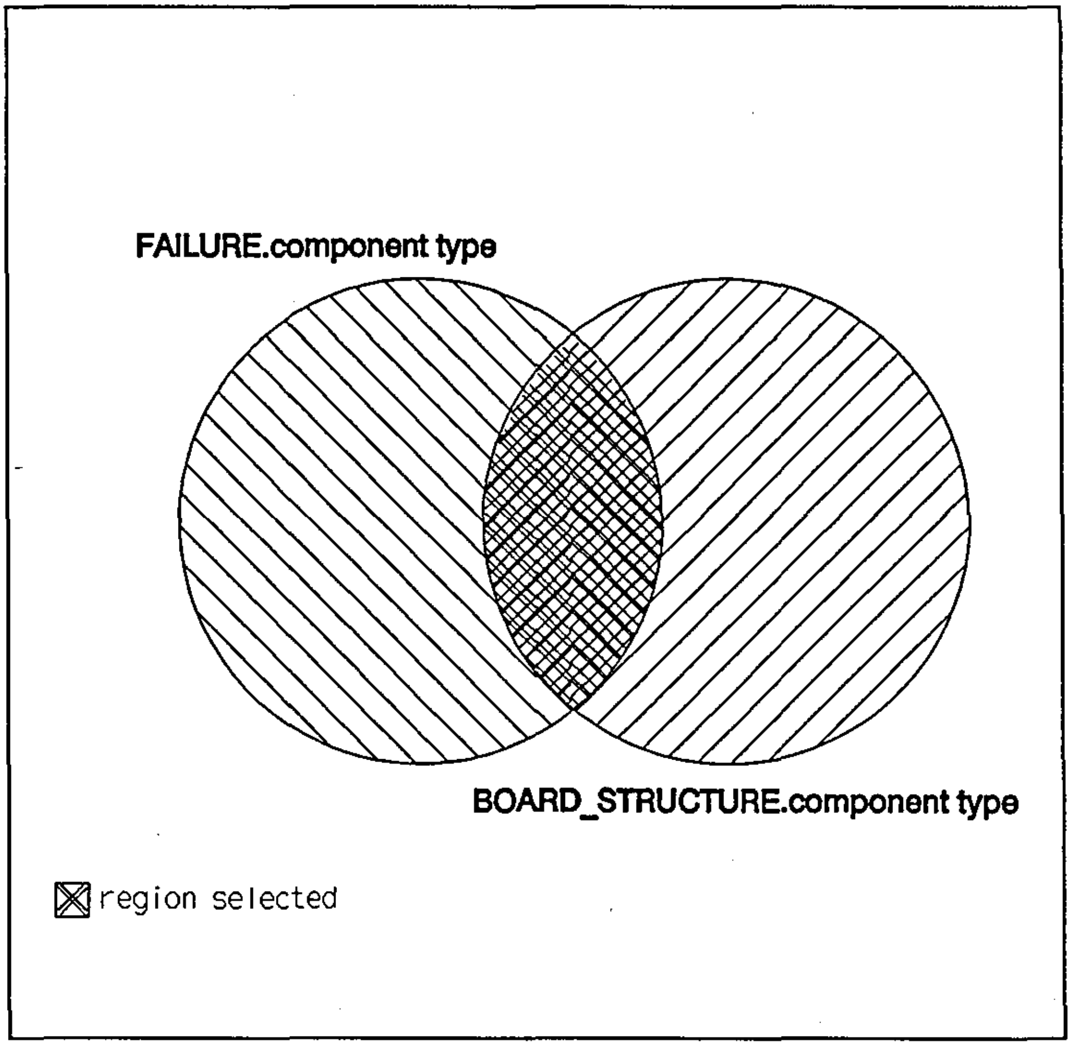

Figure 5.2
Venn Diagram of Solution to Query

If there are components which have failed and are not in the population (BOARD_STRUCTURE), then all those components are selected, and are shown in the shaded area of Figure 5.2. If, however, all failed components are in the population then no records will be found and the Venn diagram would be shown in Figure 5.3:

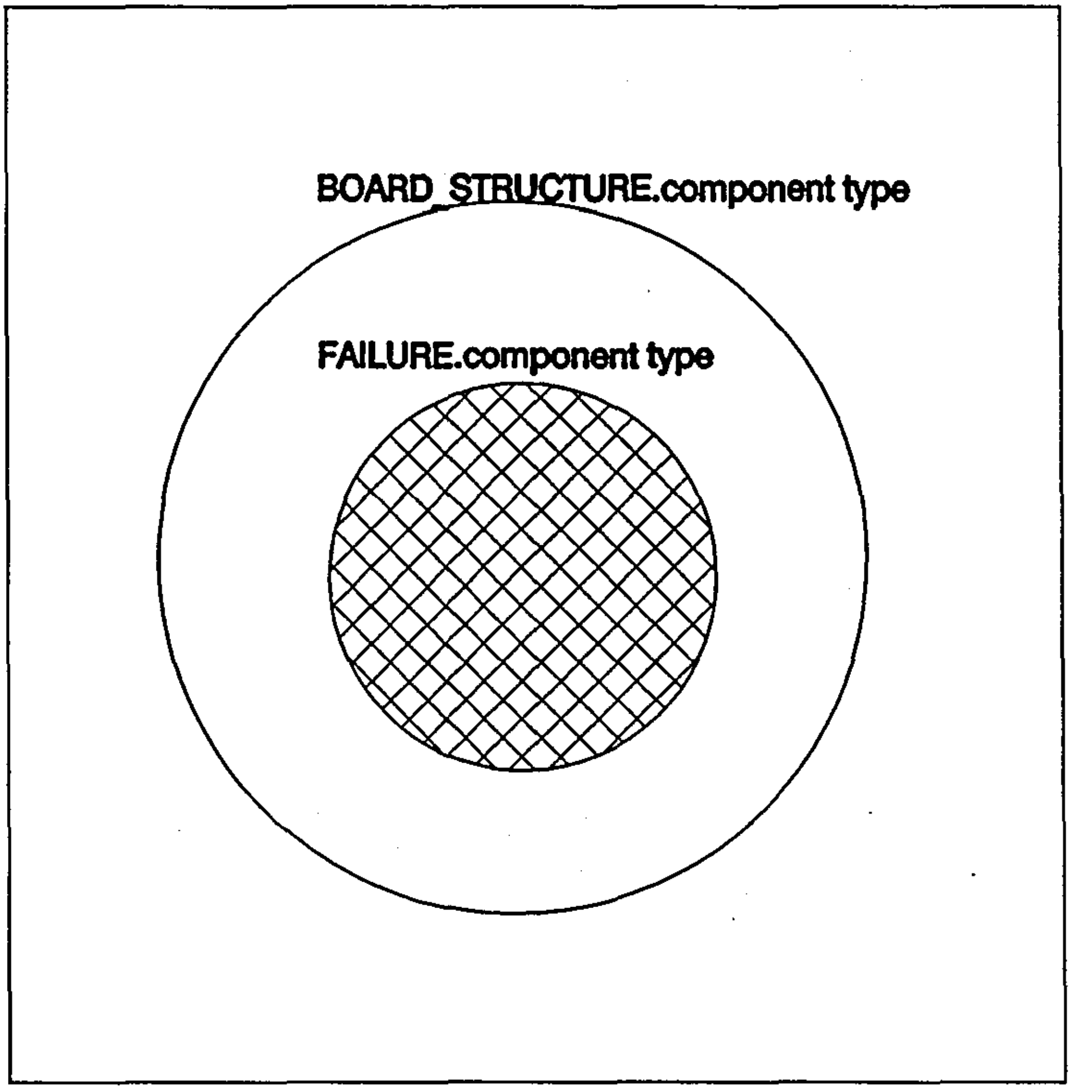

Figure 5.3
Venn Diagram of Valid Solution to Query

ie the set of failed components is a subset of the population of component types.

Similar validation tests of this nature include:

a. Are failed board part numbers a subset of the population of board part numbers?
b. Are failed equipment a subset of both the

EQUIPMENT_ID and EQUIPMENT_STRUCTURE relations.

etc.

2. Are the equipment operating times to failure for a particular equipment type and serial number during than the observation period for the same equipment type and serial number?

Query:Select FAILURE.equipment type,
FAILURE.equipment serial number,
FAILURE.equipment operating time,
EQUIPMENT_ID.up and running date,
EQUIPMENT_ID.end date,
EQUIPMENT_ID.usage from FAILURE,
EQUIPMENT_ID
where
FAILURE.equipment type =
EQUIPMENT_ID.equipment type and
FAILURE.equipment serial no
= EQUIPMENT_ID.equipment serial no and
FAILURE.operating time to failure >
((EQUIPMENT_ID.end date -
EQUIPMENT_ID.up and running
date)*100/EQUIPMENT_ID.usage)*24

This query calculates for a particular piece of equipment the observation period in hours and compares it with the operating time to failure. If the time to failure is greater than the observed time in the field then the equipment type and serial no is selected from the FAILURE relation. Since it is not reasonable for a failure to occur outside the period of observation of a particular equipment an error is flagged for this equipment. The corresponding details for this equipment can be selected from the database and sent to the company so that this error can be investigated and subsequently corrected.

As can be seen from these examples, these consistency checks use the manipulation procedures of the database. The full suite of consistency checks are written in PL/1 and use DSL subroutines to MRDS. From the results of the execution of this suite of programs, a validation report is issued and sent to the appropriate company for the investigation of the problems identified.

These two stages of validation have been operational since the database design was finalised and have proved to be successful in identifying erroneous data and thus ensuring the quality and integrity of the database.

The identification of erroneous data is an ongoing procedure. In fact new validation checks are continually being added as new data errors are found during the exploration of the database. In addition, as more experience and knowledge is gained about the data stored in the database it has been found that further validation checks are required. Thus the data validation procedures are continually being updated.

5.3 Security

The security of the database, both for protection against loss or corruption of data and for illegal access, is an extremely important aspect of administrating a database. As the database develops and further data is collected and stored, the security implications become more crucial.

The Computer Centre at LUT has a strategy for maintaining the security of all information stored on the Multics computer [4]. This strategy was developed by considering the two most likely causes of corruption or loss of files, namely, system crash and fire. The security strategy carried out consists of 4 dumping procedures:-

1. Complete system dumps. At any time there are 8 complete system dumps. These take place at different time intervals and are carried out approximately every:

   2 weeks, 1 month, 2 months, 3 months, 6 months, 9 months, 1 year, 2 years.

2. Hierarchical dumping. This entails storing information on magnetic tapes in directory order. Thus all the files in a particular directory are stored as one segment of tape. For example, if a user loses or deletes any information from their directory, then it can be located on the magnetic tape and restored to the user's directory very quickly.

3. Volume dumping. This consists of physically dumping information block by block onto magnetic tape. Thus if there is a system problem, for example a disk pack crash, then the information can be very quickly restored using the volume dumps.

4. Intervening incremental dumping. In addition to the above procedures, there are intervening incremental dumps of both hierarchical and volume dumps. This entails dumping onto a single tape, any files which may have changed since the last dump (hierarchical or volume). For example, suppose a disk pack crashes, the last complete volume dump together with an incremental dump will give a complete restore of all information.

All dumps are stored on magnetic tape. Some of these tapes are held in the Computer Centre with at least one complete system copy stored in a fire proof safe. In addition, there are some complete system dump tapes held in a separate building. Thus in the event of a fire in the Computer Centre, all the information would not be destroyed.

From this discussion, it can be seen that due to the security strategy carried out and devised by the Computer Centre, loss or corruption of the data is very unlikely.

Another aspect of security which must be discussed, is the access to the database by unauthorised persons ie 'hackers'.

It is generally considered that there is no computer which is completely safe from an expert 'hacker' and the Multics is no exception. However, security measures must still be implemented in order to make unauthorised access as difficult as possible to discourage any 'would-be hackers'.

The Honeywell Multics System is divided into directories, with each Department having a unique directory, as shown in Figure 5.4.

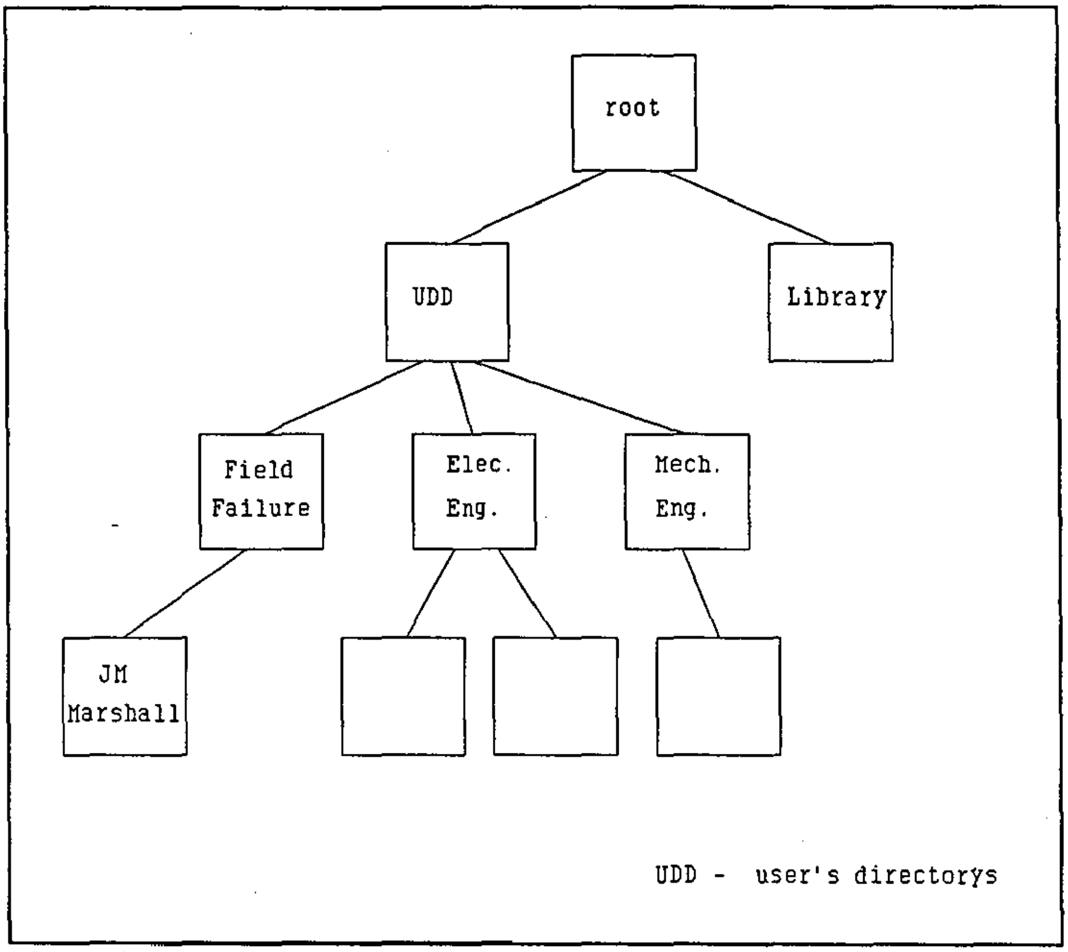

Figure 5.4
Hierarchy of Directories on Multics

Within each Department, each individual member of staff has their own directory, user identification and password. It is possible to move from one directory to another within the departmental directory and list the files stored. However, it is not possible to read, write or update any files in any other directory unless the appropriate access rights have been set.

The directory which contains all the data and software connected with this project is on the same level as a departmental directory. Not only is it impossible to change anything in this directory (without access rights), it is also impossible to see the names of any of the programs or files stored in it. In fact, it is unlikely that users of the system, apart from the systems programmers in the Computer Centre, are aware of the existence of this directory.

The chances of this directory being accessed by unauthorised users are therefore fairly small, but not impossible.

These security measures discussed above help to guard the database from corruption and therefore help to maintain the integrity and confidentiality of the data.

5.4 Software Control and Validation

Developing software for the validation procedures and statistical analysis is not as simple as just sitting at a computer terminal and typing in a program. Such software must be written according to requirement specifications. Software control and validation refers to this testing and maintenance and is the discussion topic of this section. In fact, all MOD contracts which involve the development of software are required to implement such procedures. Details of the requirements for software control and validation are shown in documents [5], [6].

Concentrating on the validation software, a requirement specification would, in a summarised form, consist of the format of the data input, the list of checks to be performed and the output required from the program. When this specification has been written, the structure of the software can be tackled. For example, a program can be split into modules:-

1. Declarations
    a. File declarations
    b. Database subroutines

c. Procedural

d. Variables

2. Open all files
3. Open the database for update
4. Validation checks to be performed
5. Print out of the relevant output
6. Close the database
7. Close all files.

Figure 5.5 shows a flowchart of the first stage of validation, following the above modules.

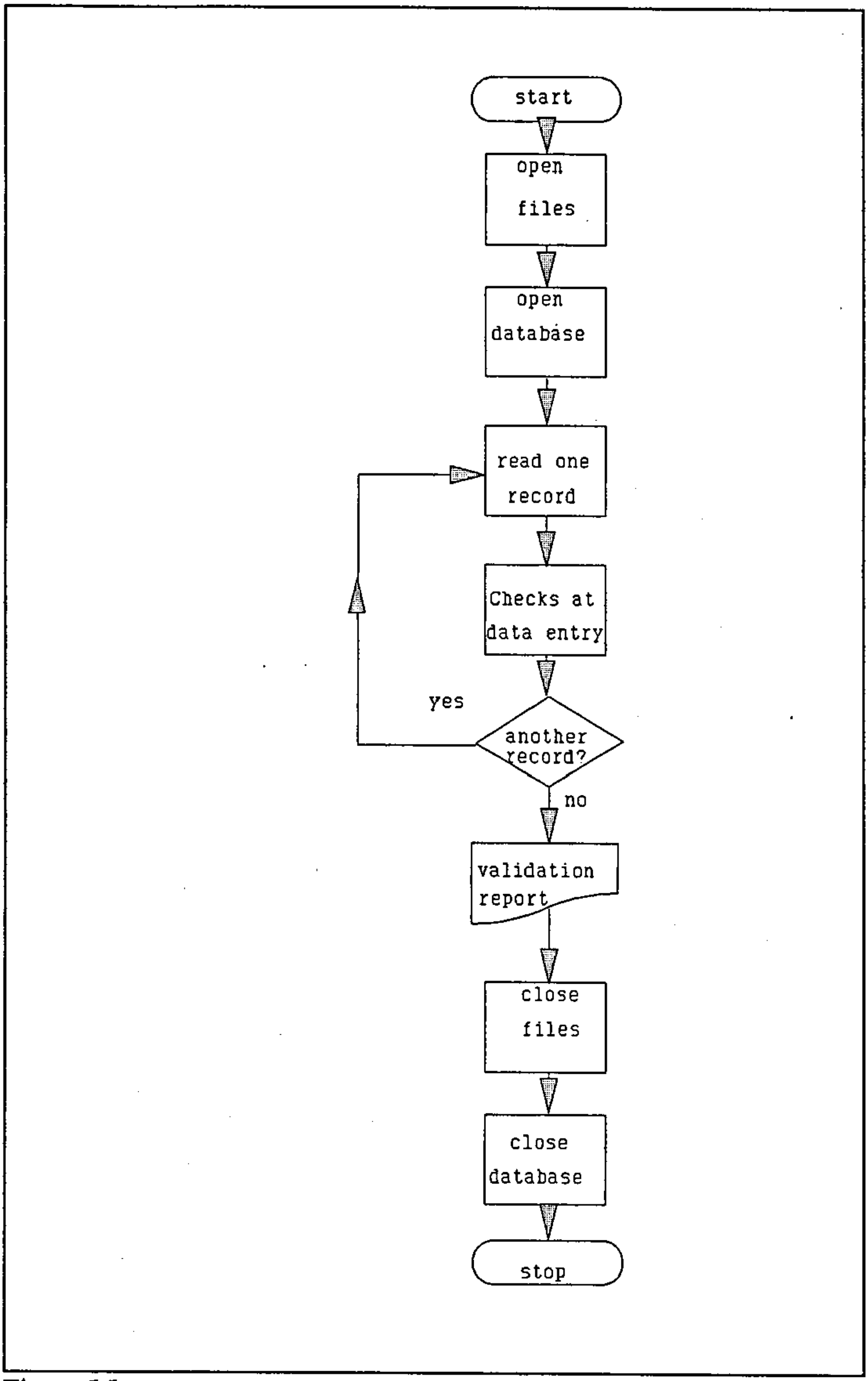

Figure 5.5
Flowchart of The First Stage of Validation using Modules

After constructing the specification, the modules can be written in pseudo-code together with the documentation for each module and from this the software can be written.

Before the declarations in a program, the following details are included:

1. The name of the programmer
2. The date the program is written
3. The issue number
4. The number of changes made
5. The description of the aims of the software

When the software has been written it should then be tested. Testing is extremely important in order to ensure the program provides meaningful results.

There are several stages in the testing of software. These include:-

1. Compiling the program and consequently identifying any compilation errors.
2. Executing the program. If execution is not successful then check for any obvious errors. For example, files incorrectly opened/closed, undeclared variables etc will prevent execution.

When all the execution and compilation errors have been corrected and the program appears to be working, the more arduous task of checking to make sure the program does what the programmer expects it to do, is tackled:

3. Constructing dummy data and manually working through the program noting the values of each variable.

4. At each calculation or validation check, print out the values of the variables and compare them with the manual calculations previously carried out.
5. Comparing final results from the program with manual solutions.
6. Carrying out sensitivity analysis. For example, use different inputs and check the consistency of the output, also check how the program deals with known erroneous data and compare the results with the expected solutions.

Documentation on how the software was constructed, what input is required, what the expected output is and how to execute this software ought to be written.

After the software has been tested and documented, it can be executed when required. However, protocols for control and maintenance for the software should be established.

On the Multics system all the software written can be archived on disk. This means that any file which is archived can only be edited or executed by extracting a copy from the archive. Thus after using the software, the copy can be deleted without losing the archived version. Archiving is a useful tool for controlling software for several reasons, and these include:-

1. Archived files take up less disk space, and therefore any programs which are executed periodically can be archived, thus saving immediate disk space.
2. The date the file is appended to an archive and whether it has been updated or not is retained thus providing a chronological history of that file.

3. Controlling changes made to programs is simple, since after editing, testing and documenting a program, the archive can be updated with the latest version of the software, thus ensuring the most recent issue of a program is subsequently always used.

The implementation of the structure for the development, testing and control of software discussed here, helps to achieve reliable and dependable results from a program.

Obviously, this is an important part of the administration of the database in order to maintain the integrity of any results obtained from the database.

5.5 Summary

This chapter has introduced the three major administrative aspects for ensuring a consistent and reliable database.

A flowchart showing the two stages of validation, ie, checks at data entry and consistency checks and the feedback loop to the companies, has been discussed. These two stages of validation have been dealt with in further detail together with illustrated examples.

The procedures devised and implemented by the Computer Centre for securing the database have been introduced both in terms of the corruption of data and the unauthorised access of the database. The methods for guarding against such threats to security have been shown in detail.

The final administrative procedure included in this chapter was software control and validation. The procedures used for developing, testing and maintaining software have been detailed and how they help to ensure the database integrity.

These administrative features of the database have been shown to be necessary in order to maintain the integrity of the database and any results achieved from statistical analysis.

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6. INITIAL EXPLORATION OF THE ELECTRONIC DATA

6.1 Introduction and Data Summary

The previous chapters have dealt with the collection of electronic component data and the setting up and administrating of the database. The current chapter introduces the initial exploration of the data in order to gain an overall picture of the dependability and reliability of those components stored in the database.

After the final database design had been achieved data started arriving at LUT. The first data set arrived at the end of 1986 and thus data has been transferred to LUT over a period of 2½ years. Table 6.1 illustrates a summary of the data stored in the database by August 1989.

Although these figures in themselves do not give much information, they highlight the large size of the population of components being followed. One point of interest from this table is the number of No Fault Found records (NFFs) contained in the database. No fault found means that when an equipment or board has failed and is sent for testing, the engineer tests the board but does not detect a fault and therefore the failure cannot be attributable to a particular component. There are many potential reasons for no fault found situations and they are very difficult to study. The causes of this no fault problem may include inadequate testing particularly for complex integrated circuits, software problems, inadequate training of the personnel operating the equipment, human error, spurious voltage pulses, bad connections etc. The database at LUT collects data on when and where a NFF occurred so that perhaps by exploring the database for say, trends in the number of NFFs in a particular PCB or looking at which component type failed immediately before or after the NFF or exploring the distribution of time to failure of a NFF etc. may help to identify some of the causes of NFFs in the database.

Table 6.1
Database Summary

Total no of Components	2.1×10^{7}
Total no of Component Hours	1.4×10^{11}
Total no of Failure Records	5331
Total no of NFFs	2544
Total no of Component Failures	2977
Total no of Component Categories	133
Total no of Component Categories with data	101
Total no of Component Categories with Failures	64

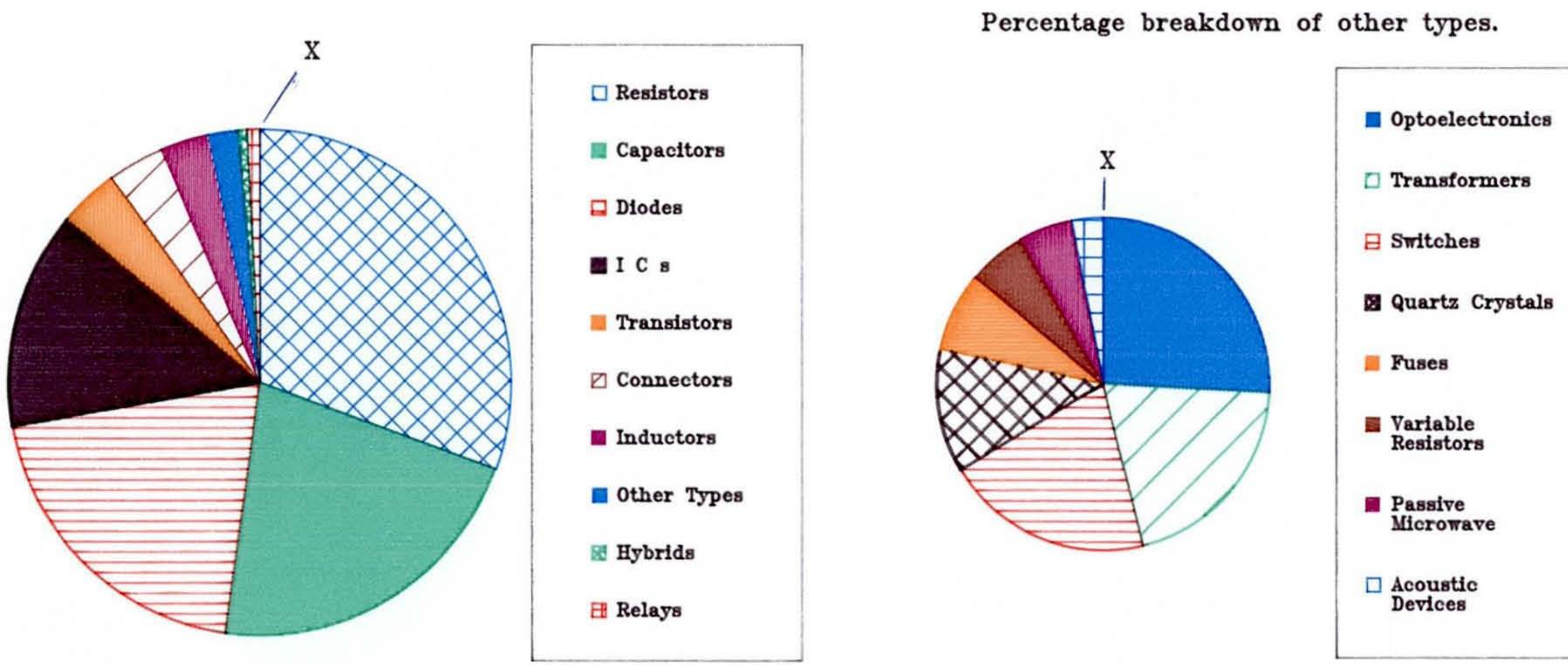
At present, NFFs account for about 50% of all the failure records in the database. This is therefore a fairly large problem. In fact, looking at summaries of the data over the past 2½years indicates that the rate of incidence of NFFs has not changed when compared to the total number of component failure records ie as more component failure records are observed, an equal number of NFFs are also observed.

This thesis does not show any exploratory analysis of the problem of NFFs, but it is hoped that future work will include this important study.

Figure 6.1 breaks down the population data given in Table 6.1 into a pie chart of the relative percentages of the number of components of a certain type in the

FIGURE 6.1

Percentage Number of Components in the Database



Total number of components is approx. 21 million

August 1989

database. Looking at the large pie in a clockwise direction starting at point X, it can be seen that resistors and capacitors account for more than 50% of the population of components. In fact about 80% of the components in the population are resistors, capacitors, diodes and ICs. The small pie illustrates the population of other types of components in the database.

The pie charts shown in Figure 6.1 give limited information. In particular they do not indicate the breakdown of the relative number of different component types operating in the field.

The remainder of this chapter is concerned with particular aspects of the data in the database, including the calculation of constant failure rates for components and their corresponding confidence limits and discussion of problems which have been identified through initial exploration of the database.

6.2 Failure Rate Hierarchy

As discussed in Chapter 2, most electronic component reliability prediction methods are based on the assumption that the distribution of times to failure is exponential ie the components exhibit a constant hazard rate. The initial exploration therefore takes the form of calculating failure rates for each component type in the database. Figure 6.2 shows a pareto analysis of failure rates for component types. The vertical axis is a log scale of failure rates in 10^9 component hours (FIT) and the horizontal axis shows coded component types [1]. (The descriptions of these components are shown in Table 6.2. which includes all the generic types of components used.) From Figure 6.2, the component types which appear to be in the top ten of troublesome components are mostly component types which, from the pie chart in Figure 6.1, have small numbers of components operating in the field, ie they consist of microwave devices, potentiometers, switches and acoustic devices. In fact from the first ten components in Figure 6.2, there is only one type of capacitor and one type of diode. Those components at the top of the hierarchy warrant further investigation as to why they appear to be the most troublesome components [2].

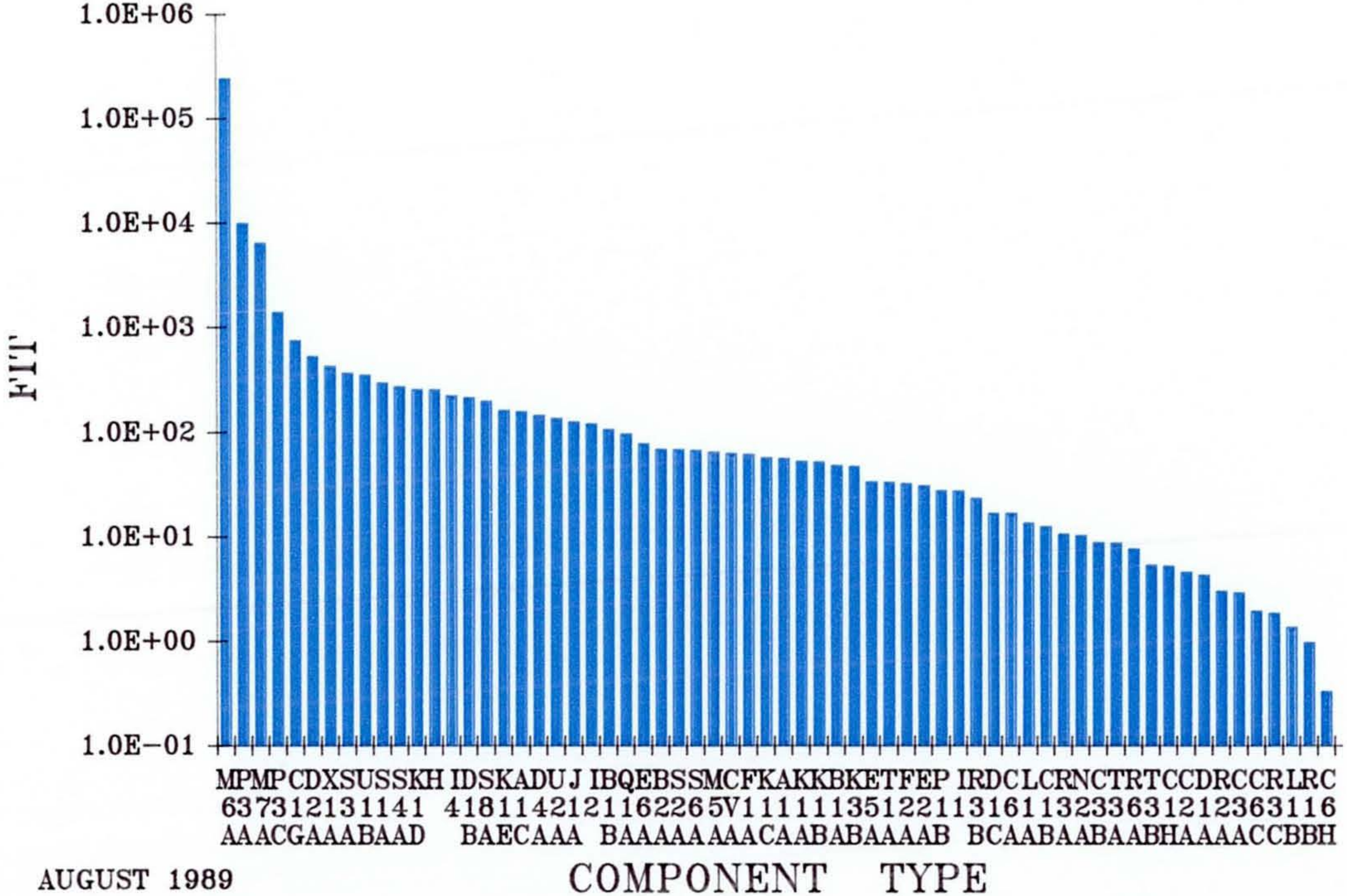


FIGURE 6.2
FAILURE RATE HIERARCHY

TABLE 6.2

Component Generic Descriptions

A1C	Pulse transformers
B1A	Coil activated relay
B1B	Coil activated/mercury wetted relay
B2A	Reed relay
CVA	Tuning/trimmer capacitor
D1A	pn Junction diode
D1B	Varactor diode
D1C	Avalanche/zener diode
D2A	Schottky barrier diode
D4A	PIN diode
E5A	Optoisolator (optocoupler)
E6A	Wire filament lamp
F1A	Wire filament fuse
F2A	Voltage surge protector
H	Hybrid circuit
I1xx	Bipolar IC (TTL.DTL.ECL.TIL)
I2xx	MOS IC (NMOS.PMOS.CMOS)
I4xx	JFET IC
JlA	Circuit breaker
K1A	Rectangular connector
K1B	Edge connector
K1C	Cylindrical connector
K1D	Spade connector
K1E	Coaxial connector
K3B	Feed through (filter) connector
M5A	Microwave filter
M6A	Microwave cavity

M7A	Microwave switch
P1B	Carbon film variable resistor
P3A	Wirewound variable resistor
P3C	Metal film variable resistor
Q1A	Crystal oscillator
R3C	Metal film resistor
R4A	Thick film resistor
R6A	Network of thick film resistors
S1A	Push button switch
S2A	Rocker switch
S3A	Keyboard switch
S4A	Rotary switch
S5A	Proximity switch
S6A	Microswitch
S7A	Lever switch
S8A	Thermostat
T1A	Bipolar transistor
U1B	Loudspeaker
U2A	Motor driven fan
U3A	Transducer (temperature)
U4A	ETI
X1A	Discrete (lumped) delay line
Z1A	Magnetic bubble memory.

It should be added that, looking at Figure 6.2, there are 40 component types out of the 64 shown in the figure which have FIT rates of 100 or less.

Failure rates, λ, have been calculated on the parts count basis, ie:

$$\lambda = \frac{\text{number of failures}}{\text{total number of component hours}} \qquad (6.1)$$

where component hours are calculated from the total number of components multiplied by the total number of operational hours in the field. They are calculated over the whole database and therefore include components used in different environments, screened to different levels and operational in different equipments.

6.3 χ^2 Confidence Limits

In order for the failure rates shown in Figure 6.2 to be of value, it is important to place confidence limits on the figures. Exact confidence limits were therefore calculated for each component type. The 95% χ^2 confidence limit for a failure rate is calculated from:

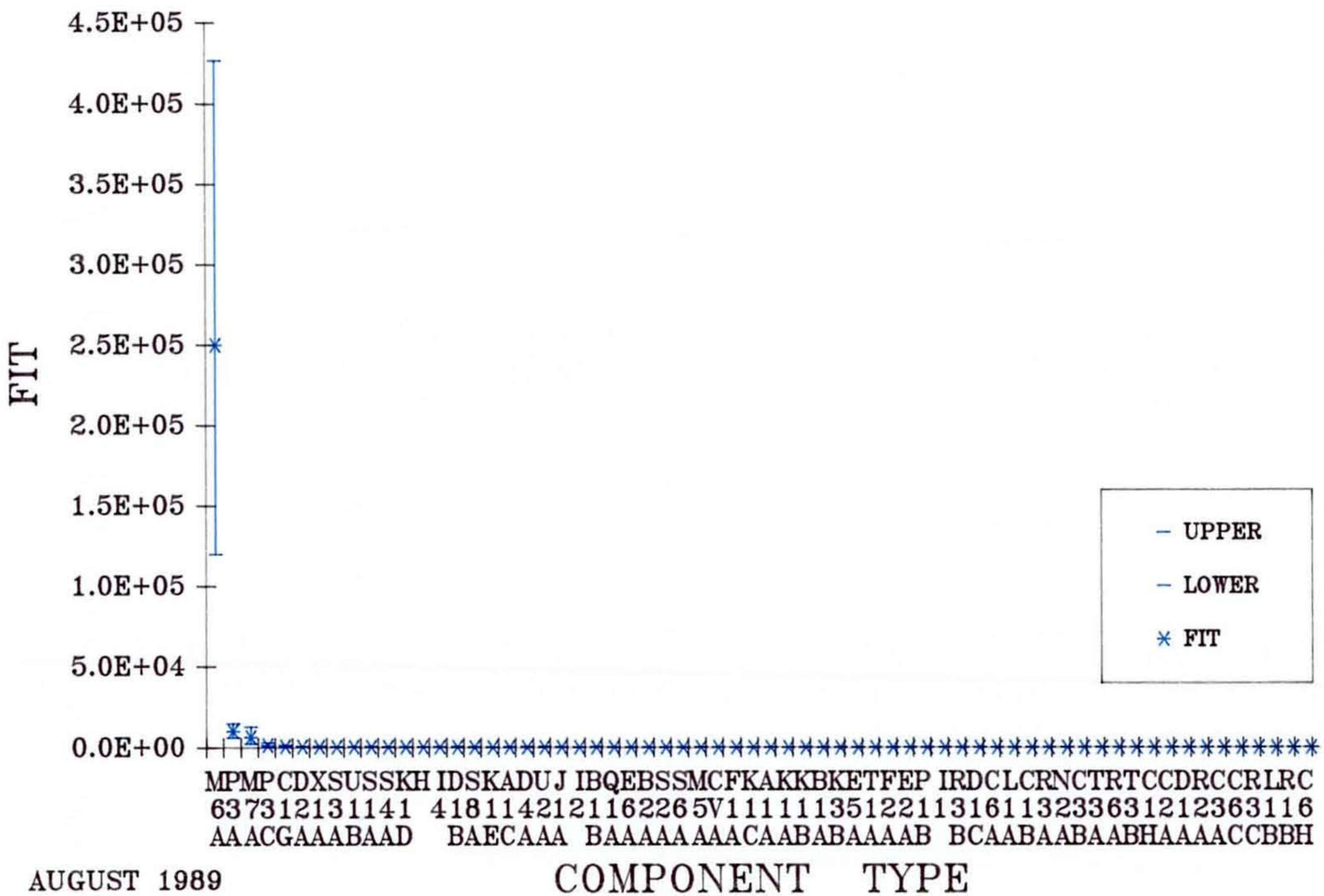
$$\lambda = \lambda\chi^2[(1\pm\gamma)/2;2r]/(2r) \qquad (6.2)$$

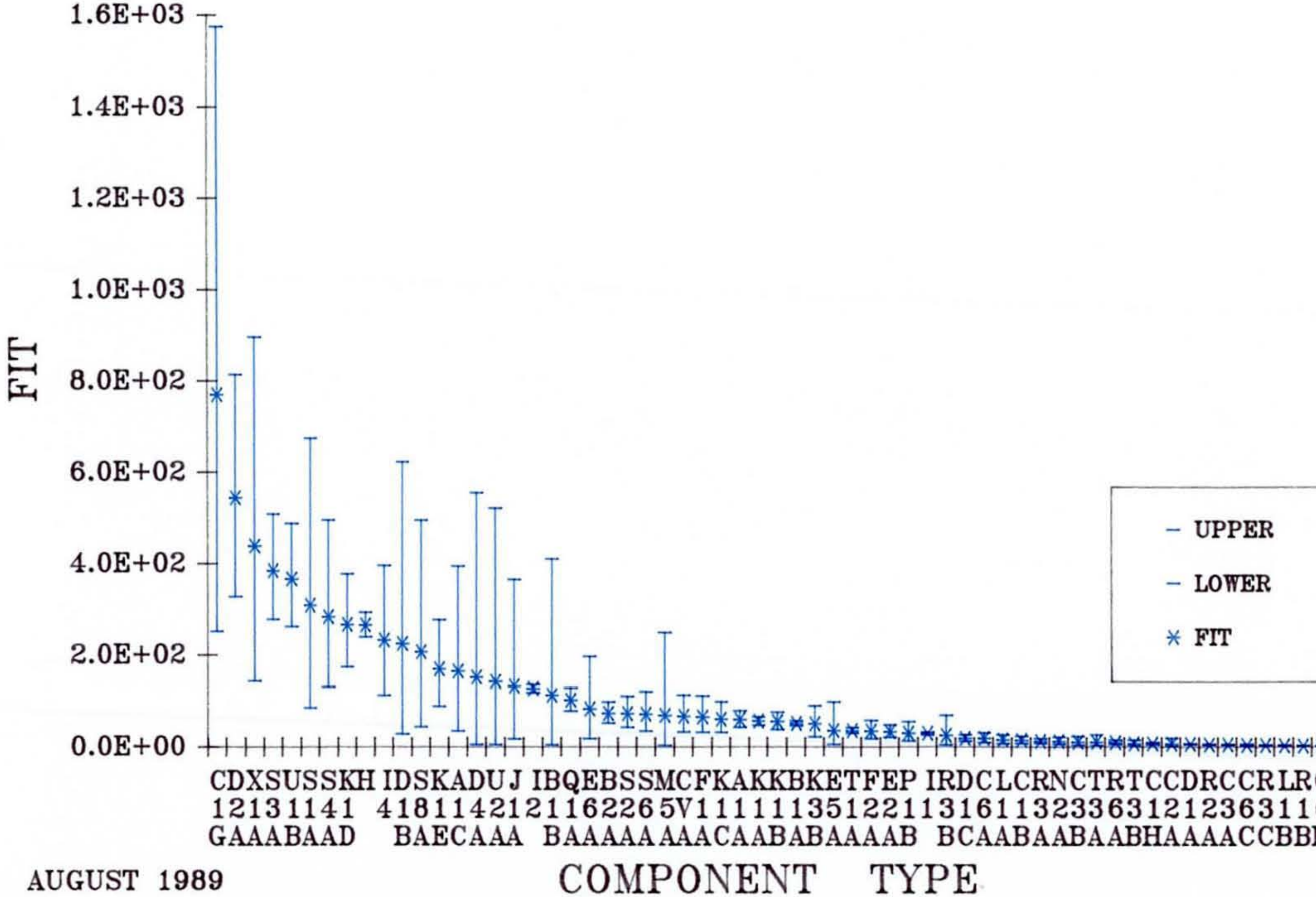
where λ is the failure rate and 2r is the degrees of freedom ie 2 times the number of failures [3].

The confidence limits are based on the assumption that the failures are exponentially distributed.

Figures 6.3 and 6.4 show the confidence limits for the failure rates and component types shown in Figure 6.2. The limits for M6A, the component showing the highest failure rate, mask the rest of the information because they are so wide. These limits show that the true failure rate for this component can be anywhere between about 120,000 and 420,000 FIT. Thus the confidence in the FIT rate of 249,785 for M6A is very low. Removing the first 4 problem components from the graph allows the data on the other component types to be seen more easily. Figure 6.4 shows the confidence limits and failure rates for the remaining components. From this, it can be seen that the confidence limits are fairly wide for those components nearer the top of the hierarchy. This implies not only that there are limitations in the confidence of the observed failure rates as they are known at present but also, due to the overlapping of confidence limits for different component types, how there may well be changes in the hierarchy of component failure rates as the data in the database becomes more complete. If, for example, the true failure rate for say, D1B (varactor diodes) is nearer the top of the limit (about 600 FIT) then its position in the hierarchy would move up.

FIGURE 6.3
95% Confidence Limits For Failure Rates





AUGUST 1989

FIGURE 6.4
95% Confidence Limits For Failure Rates

The present confidence limits indicate two courses of action ie:

1. Increase the data on those components with wide confidence limits in order to ensure that the present failure rate values are not due to spurious data from components failing due to unsatisfactory circuit design or other related operational reasons.
2. Investigate the reasons for components appearing at the top of the hierarchy.

In addition, Figure 6.4 shows that we can be 95% confident that about 40 component types out of 64 have failure rates less than 200. Moreover for component types H (hybrids) and I2 (MOS devices) the confidence limits are tight indicating that the true failure rate lies in a small range of values. Since the data is actual field data and not extrapolated test data as in Mil 217 the present figures for failure rates are likely to be more realistic than those failure rates obtained from other reliability prediction parts count methods for the same component types.

As the database grows the confidence intervals will become narrower.

6.4 Challenges in the Analysis of Integrated Circuits

6.4.1 IC Analysis

As can be seen in Table 6.2, the coding for Integrated circuits is fairly broad, ie

I1 Bipolar Devices
I2 MOS devices

In addition, to these broad codes, information concerning the part numbers of each integrated circuit is also contained in the database. However, looking at the confidence limits graph (Figure 6.4), MOS devices have a failure rate of 125 and have very tight confidence limits surrounding it. Due to this high level of confidence, it was possible to investigate further the reliability of MOS devices. However, both calculating failure rates or looking at the distribution of times to failure of an individual part number proved to be unsuccessful. The problem encountered was that there are many different part numbers in the database and therefore disaggregating down to part number level gave very little information with the exception of several custom ICs.

The custom devices exhibit high failure rates with many failures, but most of the rest of the part numbers have none or maybe 1 failure. From this, two courses of action were identified, namely:

1. The need to investigate the problem of custom devices.
2. The need for an intermediate level of coding of IC part numbers to allow more detailed analysis of the data.

The investigation of the custom chips involved contacting the appropriate company and requesting further information. It transpired that there was in fact a design fault in the devices. The problem arose from the original software, ie there was an undetected error in the software and this error was transferred into the IC when it was manufactured as hardware. This therefore is a design error and failures arising from such an error are not appropriate to the dependable nature of the database.

The further coding of the IC part numbers was conducted by the working group from a specification of what level of coding was necessary in order to do reasonable statistical analysis [4]. Table 6.3 illustrates the new coding to be adopted for all integrated circuits.

Table 6.3
Integrated Circuit Coding

FUNCTION	CODING
Digital	D
Microprocessor	U
Interface	I
Linear	L
Memory	M

The size of each functional type is to be coded in relation to:

Digital	No of gates
Microprocessor	No of bits
Interface	No of transistors
Linear	no of transistors
Memory	Total no of bits

From Table 6.3 the ICs will be coded as 4 digits. The first two digits indicate whether the IC is MOS or BIPOLAR etc. The second two digits will refer to the function and size of the device. (The function and size is to be coded as in Table 6.3.) In addition, the number of gates for digital devices will be coded by a single digit relating to a power of 10. For example, 100 gates would be coded by a 2 and 1000 gates would be coded as 3. The number of bits for microprocessors will be coded by a single digit relating to a power of 2. For example, a 16 bit microprocessor would have a code of 4. The number of transistors for interface and linear devices will be coded by a single digit relating to a power of 10. For example, a device with 1000 transistors will be coded with a digit 3. Finally, the total number of bits for memory devices will be coded by a single digit relating to the power of 2. If the maximum single digit of 9 is insufficient to give the total number of bits then letters starting with A should be used. For example, $2^A = 2^{10}$ or $2^C = 2^{12}$. At the time of writing this thesis the coding had not been fully implemented. However, it will allow the further analysis of particular families of ICs to be carried out.

6.4.2 Hybrid Circuit Analysis

The confidence limits for Hybrids shown in Figure 6.4 are also fairly tight. However, due to the individuality of particular Hybrids it is difficult to do any statistical analysis on them unless there is sufficient data on a particular part number. Unfortunately, this is not the case, and therefore no further analysis has been carried out on Hybrids.

6.5 Problems Encountered Concerning Usage

In order to calculate component hours the operational time of an equipment in the field needs to be known. The database contains information on the up and running date of an equipment, the end of the observation period date (end date) and the percentage of time the equipment is operational. When calculating failure rates for components, particularly with those at the top of the hierarchy, it became apparent how important the accuracy of usage is. Table 6.4 shows the breakdown of average usage figures given for each data source. The data sources in Table 6.4 cannot be identified for security reasons. There is no problem for those equipments which are operational 100% of the time, since these are not likely to change very much (for example, a telephone exchange is operational all the time). However, those equipments which are only operational for a short period of time require more accurate usage figures. For example, if the usage figure is given as 10% but there is an error of say 5% the total component hours would be 50% in error.

In general if usage is calculated from elapsed time indicator (ETI) readings then it will be reasonably accurate, unless the eti meter is faulty. However many of the usage figures are calculated from experience and knowledge of the systems in operation. For example, eti readings may only be available when equipments fail. Therefore the data source may use this information together with dates of when the equipment went into the field and when it failed to aid the calculation of percentage usage of the equipments in the field which have not failed.

Work is being carried out at Nottingham Polytechnic on the relationship between known usage and calculated usage for a particular equipment type [5]. Regression analysis is being used to find out whether the methods of calculating the usage figures are correct in relation to the observed usage for a particular equipment type.

Table 6.4
Summary of Usage for Data Sources

DATA SOURCE	MEAN USAGE
QX	98.5
QV	100
QW	7
QY	5.1
AA	7.34
AC	100
AD	25
HB	23
EA	5

It is important for the accuracy of results of any analysis using population data that the percentage usage value given in the data is reliable. However, in general, it is impossible to get all actual usage figures for each equipment in the field, and therefore we are reliant on accurate calculations.

6.6 Disaggregation of Data

6.6.1 Introduction

The failure rates shown in the previous Figures are calculated for each component type regardless of the operational environment of the equipment, the screened level of the component, the encapsulation method or the data source. These failure rates would be of greater value if they were calculated including the effect of some of these different variables.

This section therefore deals with failure rates broken down by environment, screening and encapsulation. It investigates the differences between ground mobile and ground benign, BS9000 screened components and other screening methods and hermetically sealed components and plastic encapsulated components.

6.6.2 Environment

There is information from 9 different data sources in the database as already noted in Table 6.4. From these 9 data sources there are equipments operating in 3 different environments. Table 6.5 shows the operational environment for equipments from each data source.

Table 6.5
Summary of Environments for each Data Source

DATA SOURCES		
GROUND MOBILE	GROUND BENIGN	NAVAL SHELTERED
AA	QX	AC
EA	QV	
QW	HB	
QY	AD	

The data from data source AC does not contain any failures and only has population data over a few months and is thus not very useful as yet. However, there is sufficient data in the other 2 environments to be able to make comparisons of failure rates for component types in these environments. Figure 6.5 shows a bar chart of failure rates for component types which are used in both ground benign and ground mobile environments. Again, the vertical axis is a log scale of FIT and the horizontal axis is component type. Before looking at this figure, we would expect failure rates for ground mobile to be higher than those for ground benign equipments due to the difference in the severity of the operating conditions.

FIGURE 6.5

Failure Rates in Ground Mobile and Ground Benign Environments

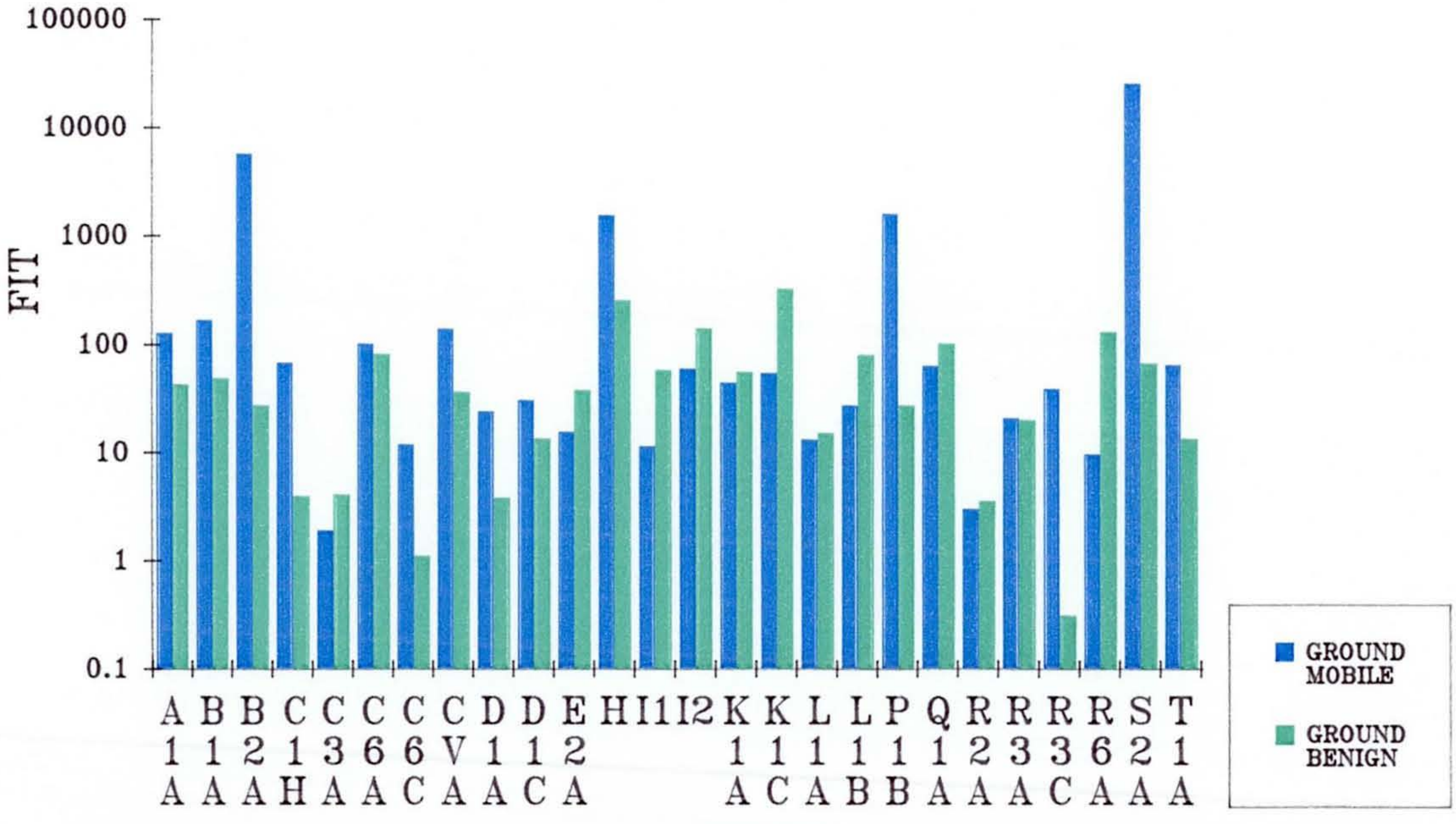


Figure 6.5, shows this indeed to be the case for many of the components. However, there are some component types for which the opposite is true. These components include I1 (bipolar ICs), I2 (MOS devices), K1C (Cylindrical Connectors), L1B (Inductors), Q1A (Quartz Crystals) and R6A (Thick Film Resistors).

Table 6.6
Summary of Data where FIT are higher in Ground Benign than in Ground Mobile

COMPONENT TYPE	NO OF FAILS		COMPONENT HOURS		FIT	
	GB	GM	GB	GM	GB	GM
I1	251	84	4.3E9	7.4E9	58	11
I2	690	67	4.9E9	1.1E9	141	58
K1C	2	10	6.2E6	1.9E8	320	53
L1B	2	4	2.5E7	1.5E8	80	27
Q1A	60	1	5.9E8	1.6E7	102	63
R6A	6	4	4.6E7	7.8E9	130	10

From Table 6.6, it can be seen that the component types that are exhibiting a much higher failure rate in ground benign systems compared to ground mobile systems, include, I1, I2, K1C, L1B, Q1A and R6A. The MOS devices (I2) as discussed in the previous section have exhibited design problems in some custom chips, which thus accounts for the observed high failure rate. The cylindrical connectors (K1C) may, in ground mobile environments, be more reliable. If the connector is tin plated then oxide which has built up between the contacts could be displaced by relative movement of the contacts caused by the shock and vibration occurring in a ground mobile environment. In benign environments these oxide films may grow unhindered eventually preventing a good connection.

However, investigation into reasons for the other components not exhibiting the expected relationship needs to be carried out. Perhaps the screened level of these components is higher in ground mobile equipments, or the encapsulation methods are different, or more likely there is insufficient data as yet to make accurate comparisons for some component types. In addition, the Quartz Crystal data (Q1A) seems suspicious because the number of failures from one particular data source in comparison to the number of failures of Q1A from other data sources is high (54). Moreover this data source contains data in a ground benign environment. Further investigation is therefore required to identify the reasons for this high failure rate.

The overall conclusion of this investigation is that failure rates do in fact vary with the operational environment of an equipment. The following statistics show the variation for components for which data on both environments is available:

50% of component types have higher failure rates in ground mobile than in ground benign.

27% of component types have about the same failure rates irrespective of environment.

23% of component types have higher failure rates in ground benign.

6.6.3 Screening Level

A similar analysis as that discussed in 6.6.2 can be carried out comparing BS9000 screened components with those components subjected to other screening methods. This comparison is of interest to the standardisation authorities. Table 6.7 shows the breakdown of data sources into those which have BS9000 screened components and those which use other unspecified screening methods.

Table 6.7
Summary of Screened Level for Data Sources

DATA SOURCES	
BS9000 SCREENING	OTHER SCREENING
AA	QX
EA	QY (K3B, M7A ONLY)
QW	HB
QY	AD
QV	

The breakdown shown in Table 6.7 is similar to that shown in Table 6.6. Almost all those BS900 screened components are operating in equipments in a ground mobile environment with the exception of data source QV. All those components which are screened to a different level are operating in ground benign conditions with the exception of 2 components in data source QY. The results of this comparison will therefore be similar to those obtained in the previous section. Figure 6.6 shows a bar chart of the comparison of failure rates for BS9000 components and other screening procedures. These results are almost identical to those obtained in the previous section. They show that about 50% of BS9000 screened components have higher failure rates than other screened components. At first glance these results appear to be surprising.

However, further investigation of the reasons for these results may help to explain the situation. Looking at each of the data sources, it was found that data source QX, which does not use BS9000 screened components, did in fact screen their components to a higher level than BS9000. By changing the analysis slightly, we can compare BS9000 plus higher screened components with other screening methods. Figure 6.7 shows a bar chart of this comparison. These results show that 58% of BS9000 or higher screened components have lower failure rates and 19% have the same. Only 23% of BS9000 or higher screened components now have higher failure rates, which may be due to environment, encapsulation methods, or the sparseness of data. However, the overall impression is that the higher the screening level the lower the failure rate for those component types under study.

FIGURE 6.6

Comparison of BS9000 Screened Components with other Screening Methods

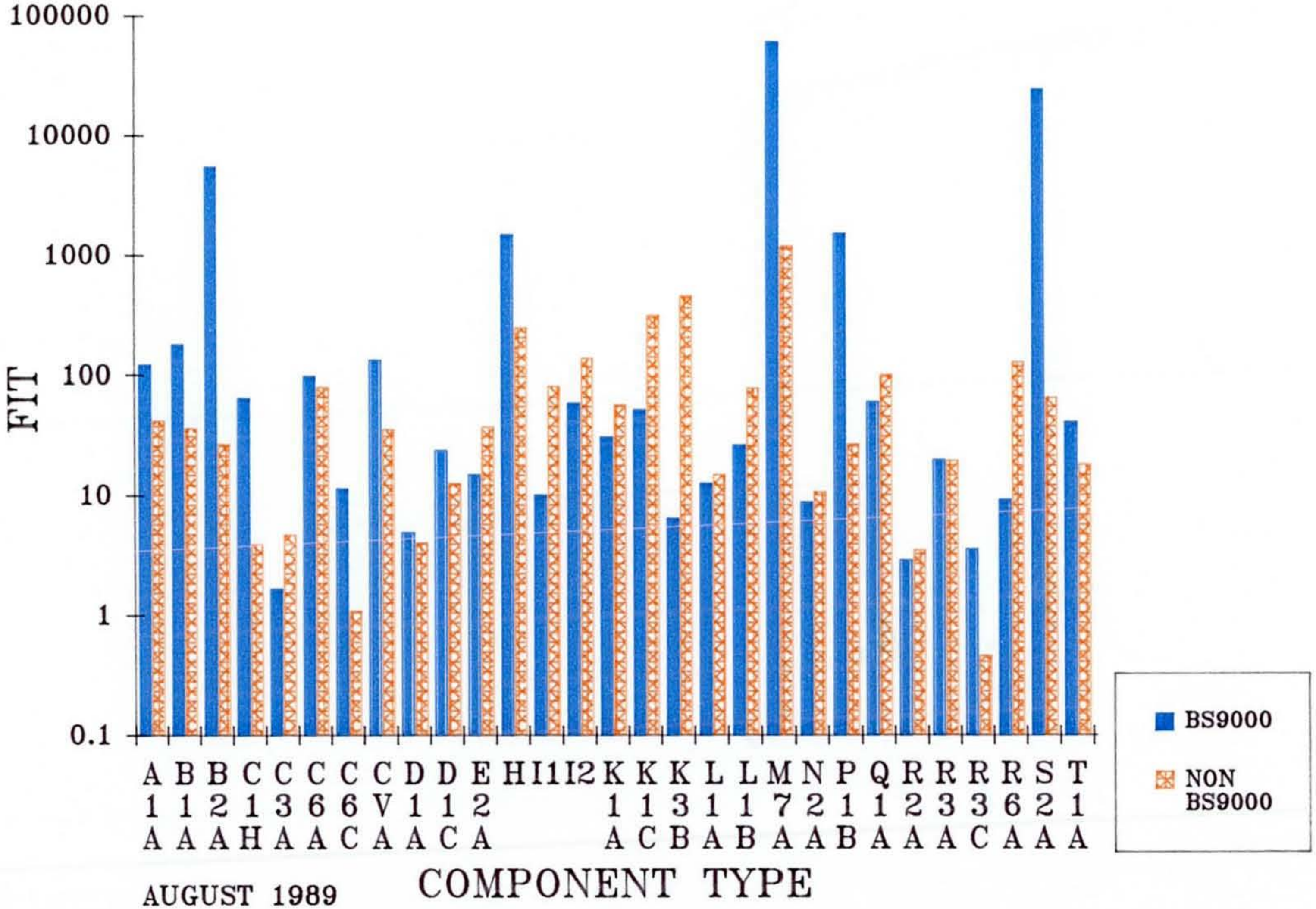
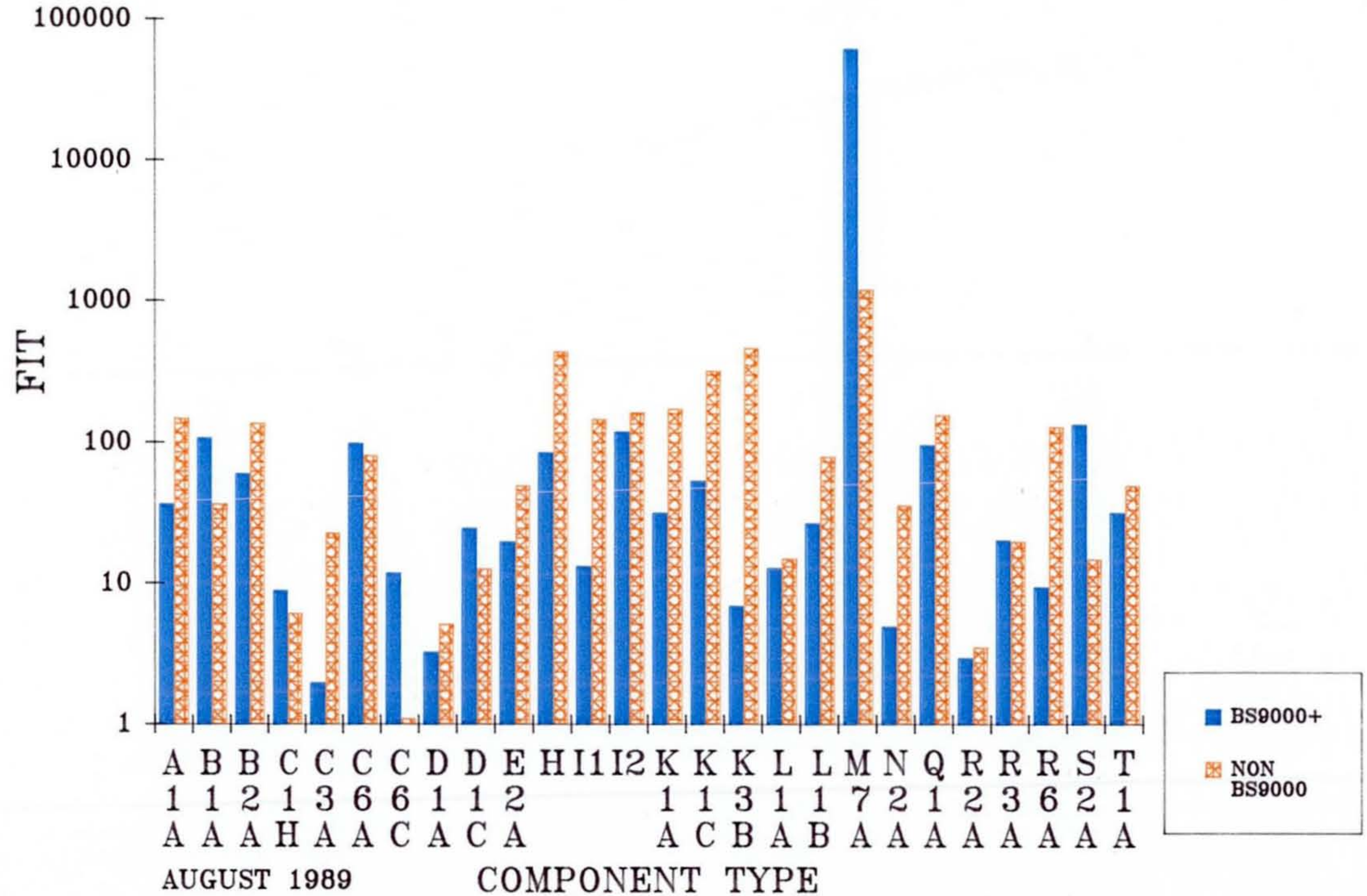


FIGURE 6.7

Comparison of BS9000 together with Higher Screened Components with other Screening Methods



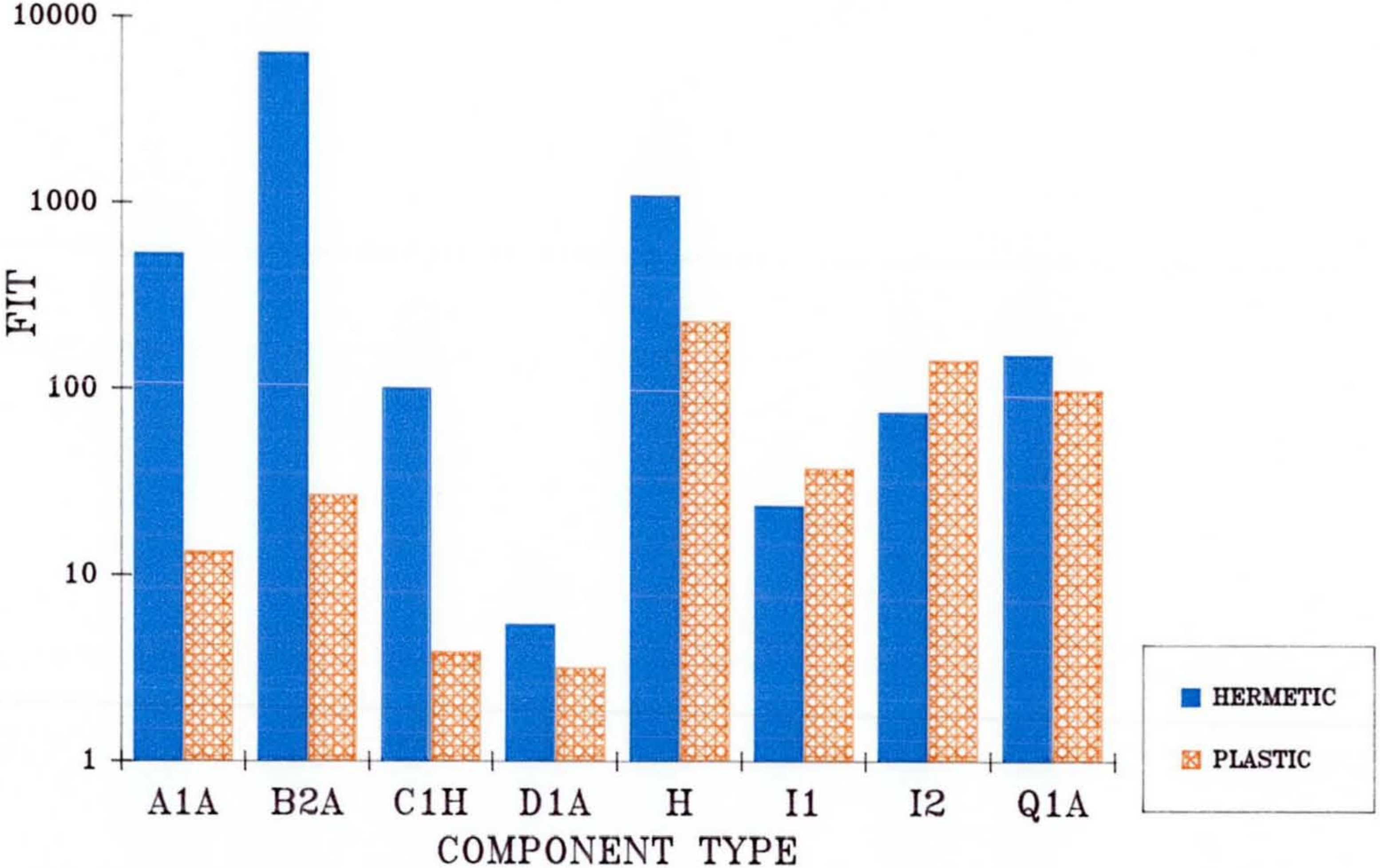


FIGURE 6.8

Comparison of Hermetic and Plastic Encapsulated Components

6.6.4 Encapsulation

The comparison between the failure rates of hermetically sealed encapsulated components and plastic encapsulated devices is another area of interest.

It is expected that hermetically sealed components are more reliable than plastic encapsulated components because they prevent the ingress of moisture thereby helping to prevent the activation of corrosion related failure mechanisms. Figure 6.8 shows a bar chart of the failure rates obtained for both plastic and hermetically encapsulated components and the converse of what is expected is revealed. Apart from the ICs, all the other hermetically sealed components appear to be less reliable than plastic encapsulated devices.

The reasons for this may be that we cannot investigate encapsulation alone, but need to explore the operational environment and the screening together with the differing encapsulation methods. With the exception of Q1A (quartz crystals) all those components with higher failure rates for hermetically sealed encapsulation have higher failure rates in the ground mobile environment. Perhaps the severity of the environment outweighs the benefit of using hermetically sealed components.

6.6.4 Overall Conclusions

In general, military equipments use BS9000 screened components and hermetically sealed components where relevant. It is therefore extremely important for national security that these should be reliable. The expected results of the previously discussed analysis would, therefore, be that components in ground benign environments are better than those in ground mobile environments because of the severity of the environment (perhaps with the exception of connectors). BS9000 screened components would be better than other screening methods. Hermetically sealed components would be more reliable than plastic encapsulated components. However, does the severity of ground mobile environment cancel out the advantage of using hermetically sealed components screened to BS9000 level? From the data the answer may be yes. For example Table 6.8 shows a summary of some of the results.

Table 6.8
Summary of Results

SUMMARY

COMPONENT TYPE	ENV	HIGHEST FIT SCREENING	ENCAPSULATION
A1A	GM	BS	HERMETIC
B2A	GM	BS	HERMETIC
H	GM	BS	HERMETIC
I1	GB	NON	PLASTIC
Q1A	GB	NON	HERMETIC

The first 3 components in Table 6.8 may indicate that the severity of the environment in which the equipment is operating outweighs the benefits of using hermetically sealed components. The bipolar ICs (I1) may be relatively worse because they are plastic encapsulated. The results of the quartz crystals (Q1A) are confusing and require further investigation. In fact, a request has been made to one of the companies to investigate possible reasons for these results.

These results, however, show that environment, screening and encapsulation contribute to the reliability of electronic components. In addition, it is important to investigate the effects of all three of these variables together where possible and not each one individually.

6.7 Difference in Data between Data Sources

All the results previously shown in this chapter have not only assumed a constant failure rate, but assumed that the data from each data source is homogeneous. This section looks at the differences between data sources with respect to several different component types.

Figures 6.9 to 6.11 are scatter plots of the number of failures against component hours for each data source. Each of these figures are concerned with different component types. If the data conformed to the constant hazard rate across all sources then these scatter plots would exhibit a straight line.

Figure 6.9 shows the scatter plot for B1A (coil activated relays). Each symbol denotes data from different data sources and the difference in colours indicates whether the equipment operates in ground mobile or ground benign environments. From this scattergram, we can see that all the data from ground mobile equipments are clustered around the origin indicating a small number of failures and a small number of component hours. In addition, they do not appear to form a straight line. The data points from ground benign equipments appear to be randomly scattered and therefore the assumption of constant hazard rate between different data sources in the same operational environment is not upheld.

FIGURE 6.9

COIL ACTIVATED RELAYS

Number of Failures agasinst Component Hours
for each Data Source

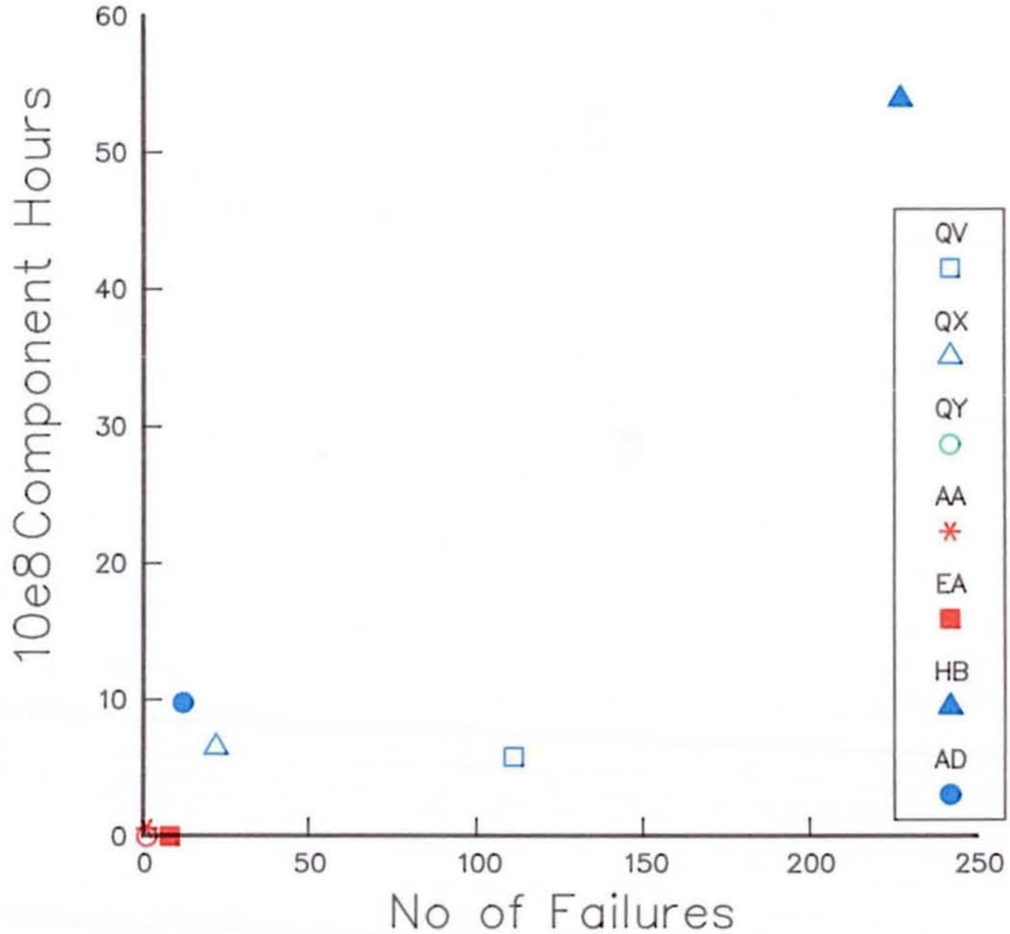


FIGURE 6.10

BIPOLAR TRANSISTORS

Number of Failures against Component Hours
for each Data Source

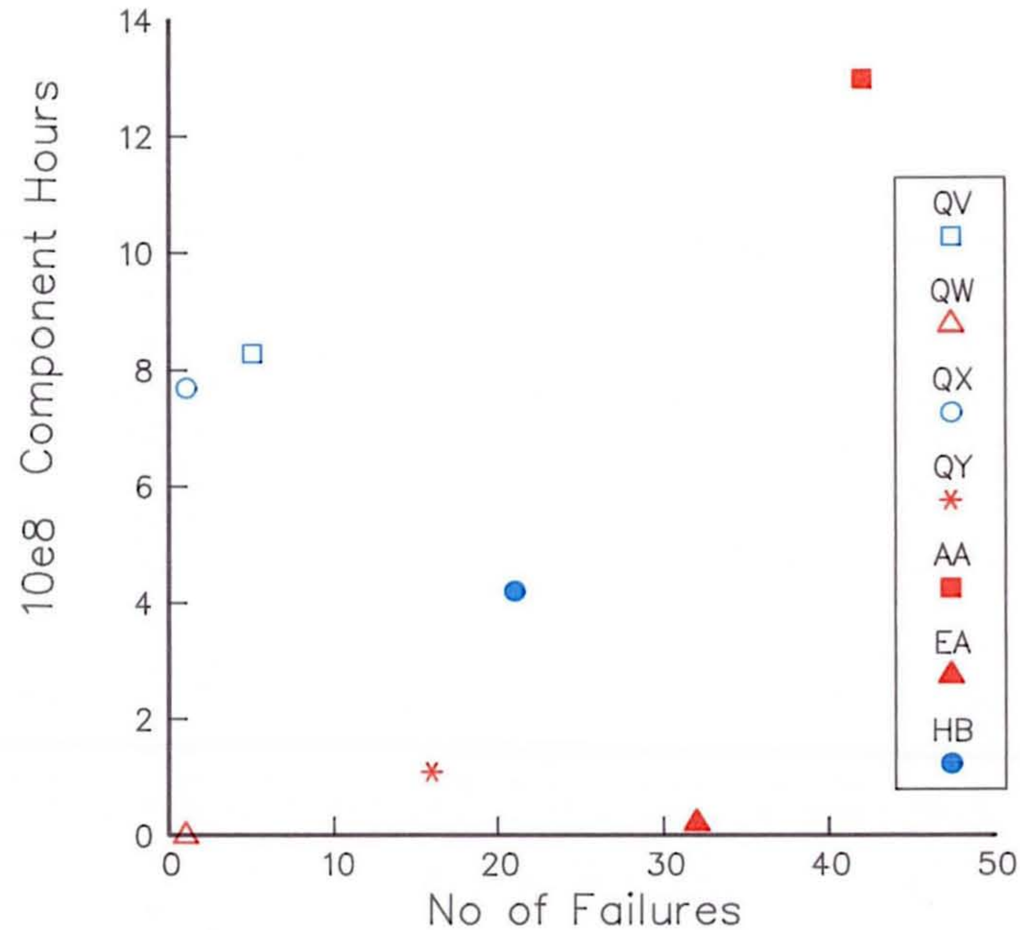


FIGURE 6.11

MOS DEVICES

Number of Failures against Component Hours
for each Data Source

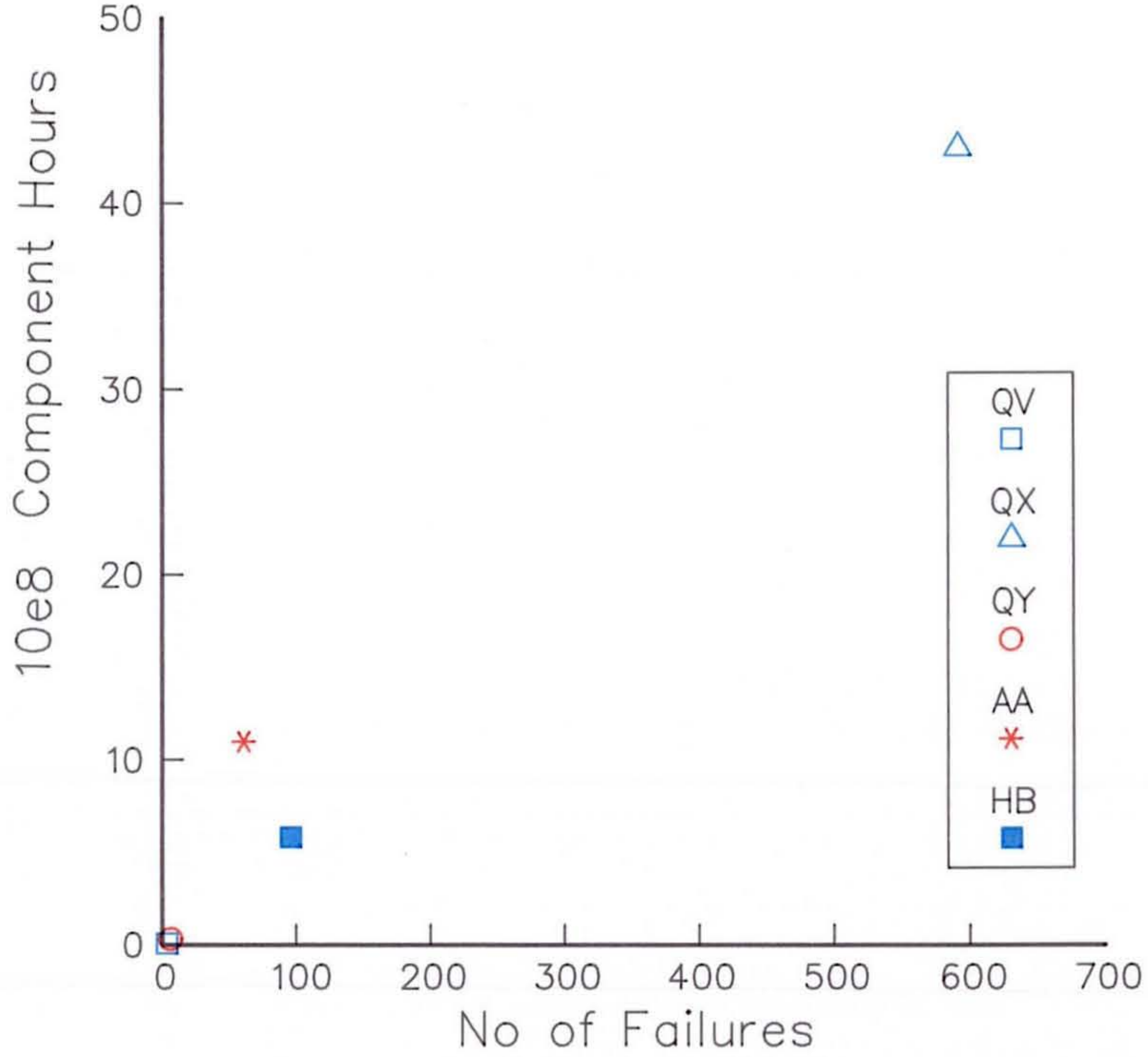


Figure 6.10 shows bipolar transistors (T1A). There appears to be no structure for data in both ground benign or ground mobile environments.

Figure 6.11 shows data for MOS devices. In contrast, to the other scattergrams, in this Figure there are two distinct lines through the origin. One is for data sources operating in ground benign environments and the other for equipments operating in ground mobile environments. This, however, is not conclusive since there are only two data points for ground mobile and only three for ground benign. A straight line can always be fitted to two points. However, the ground benign case may be valid.

The overall conclusion from these scattergrams is that it may not be appropriate to calculate constant failure rates for pooled data from different data sources. This may be due to other contributory factors such as screened level, encapsulation, the accuracy of usage figures or it may be that the assumption of constant failure rates for electronic components is incorrect. The next chapter will consider the investigation of the failure distribution of some components and whether the assumption of constant hazard rate is sensible.

6.8 Assumptions Required for Further Data Analysis

Due to the unavailability of certain data items there are a few data limitations. These data limitations are fairly minor but require certain assumptions to be made when analyzing the data. The data items which require assumption include:

1. Printed Circuit Board Serial Numbers
2. Screened Level of Non-Failed Components

Circuit board serial numbers and previous use are known only for failed boards. Therefore, unless a board fails, the serial number is unknown and only the design and parts list for a board of that type and the type of equipment the board is part of, is known. The assumption must therefore be made that any non failed board is always operational in a particular equipment type unless it fails.

The screened level of a component is only known for those components which fail, therefore assumptions must be made about the screened level of those non failed components. To make any assumptions an examination of the screened level for each component type in the failure file must be made. If there is only one screened level for all components of a particular type in all boards and equipments from a particular data source, then we assume that the screened level of the non failed components is the same as the failed components. However, if there is mixed screening for a particular component type in a particular data source then we must look at the equipment types and circuit board part numbers to investigate whether there is mixed screening at these levels for that component type. If at the board part number level, we find mixed screening for one particular component type then it is difficult to make assumptions concerning the screening of those non failed components of the same type. Looking at the encapsulation of a component may help. For example, if there are 6 p-n junction diode failures on a particular board and 3 are known to be screened to BS9000 level and the others are screened to some other level, then perhaps looking at the encapsulation method of these components will identify which are the BS9000 components. Thus, if the BS9000 components were hermetically sealed and the others were plastic encapsulated then we can assume that all the plastic encapsulated p-n junction diodes in that particular board type are screened to some other level and the hermetically sealed p-n junction diodes are all BS9000 screened components. Failing this scenario, then the company supplying the data must be contacted to provide further information for a solution to this problem to be found.

In practice, all the data sources in the database use one screening method for all their components, with the exception of data source QY. Three component types from this data source have different screening methods from all the other component types from this source. However, there is no mixture of screening for the same component type in a particular data source.

6.9 Conclusions and Summary

This chapter has considered the initial exploration of the database. Constant failure rates and their corresponding confidence limits have been shown for each component type for which there is failure data. The use of these failure rates is limited for several reasons:

1. The sparseness of some of the data which results in low confidence;

2. The pooling of the data from diverse data sources, different environments and screened levels;

3. The use of the unsubstantiated assumption of constant hazard rate.

However, this does not imply that these figures are not of value. On the contrary, due to the fact that the data comes from real field experience, they are at least as good as the predicted failure rates from other methods, notably MIL 217 (parts count).

It is important to analyze the data at the simplest level first and proceed to more complicated approaches. There is no point in applying complicated statistical models if we find that all the component failure rates are constant and there is no difference between different sources or environments etc.

This chapter also considered the comparison of constant failure rates between ground mobile and ground benign environments, BS9000 screened components and other screening methods and hermetically sealed components with plastic encapsulated components. The results of these comparisons showed that these factors do affect the failure rates for components. In particular for some components the use of hermetically sealed encapsulation methods does not appear to increase the reliability of those components when they are operating in the adverse environmental condition of ground mobile. In addition, the results showed that the higher the screening level of a component the lower the failure rate for that component type. These results are extremely interesting and give an initial impression of some of the factors influencing the reliability of electronic components. However, these results must be read with caution due to the sparseness of data causing wide confidence levels. It is likely that as the database grows the confidence bands will narrow and therefore we will have more confidence in the results obtained.

Further challenges faced during the analysis of the data have been discussed in this chapter including the coding of integrated circuits, the accuracy of the percentage usage figure for an equipment and the limitations of some of the data items. These are discussed together with proposed solutions.

Analysis of the data between different data sources was also shown. However, these results were not definitive. They indicated that pooling the data across diverse data sources within a particular environment may not be appropriate as the data may come from different distributions. This may be due to the inadequacy of the underlying assumption of constant hazard rate. This is not unexpected, but further caution must therefore be used when quoting any of the results previously shown.

Although, the assumption of constant hazard rate may not be valid, failure rates are useful in providing an engineer with a comparative figure which he is used to applying and which gives an idea of the reliability of an electronic component.

The next chapter considers what distributional form some electronic components follow and also describes the analysis methods employed for further analysis of electronic components.

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7. EXPLORATORY DATA ANALYSIS

7.1 Introduction

The previous chapter was concerned with the initial analysis of the data. The results of this analysis indicated that further exploratory analysis with regard to the failure distributions of electronic components was required.

This chapter is concerned with the development of an exploratory data analysis procedure to identify the way in which components fail and the factors which can influence their reliability. In addition, discussion on the identification of any design, replacement or source problems is highlighted.

Hazard plotting techniques are discussed and the results of these give an indication of the distributional form of certain component types.

7.2 Decision Table

As was seen in the previous chapter there are many different component types in the database with failure data. However, deciding which components to analyze first is quite difficult. If we choose those components at the top of the failure rate hierarchy, it is often found that there is very little data and therefore further statistical analysis is virtually impossible. A table of components has therefore been established to give a more explicit view of the data and to aid the decision of which component types to analyze further.

This decision table, shown in Table 7.1, shows a breakdown of the failure rates into total number of failures and total component hours [1]. This breakdown is more appropriate since if we consider a component at the top of the hierarchy then we would initially assume that this component type is the most unreliable. However, looking at how this failure rate is calculated may give a better impression. For example, a component with small component hours and a small number of failures may appear near the top of the hierarchy, but in reality the data is not sufficient to make any statement about the reliability of this component type. Similarly, a component with a large number of failures and small component hours may indicate a need to investigate the data further for design or replacement problems.

Table 7.1
Decision Table

	High FIT	Low FIT
HF, HCH	2	4
HF, LCH	1	3
LF, HCH	5	7
LF, LCH	6	8

HF - High Failures
LF - Low Failures
HCH - High Component Hours
LCH - Low Component Hours

The model in Table 7.1 indicates the order in which component types have been analyzed. Deciding what represents a high FIT, high number of failures etc. is subjective and based upon the actual data in the database. Each box contains those component types which fit the criteria.

Using the data in the database as of August 1989 a decision table can be constructed. Table 7.2 shows the current table of component types. (The component descriptions have already been identified in Chapter 6 Table 6.2) The components are split into groups. From Table 7.1, the worst situation is where there is a high failure rate, high number of failures and low component hours. It has been found in the investigation that components in this category are likely to be troublemakers only in one data source. Therefore investigation as to why these components are failing is necessary. Such a study does involve limited data exploratory analysis but is mainly concerned with failure mechanism studies. This aspect is not the subject of the present thesis. The exploratory data investigation takes the form of checking for potential design and replacement problems.

Table 7.2
Decision Table

Failures	Component Hours	FIT > 50	FIT < 50
>= 10	>= 10e6	A1A CVA I2 S3A Q1A B1A K1C F1A S6A S2A B2A H K1A K1B U1B	F2A C1B C3A E2A R3A T1A C6A D1A I1 R3C C1H D1C R2A R6A
>= 10	< 10e6	D2A P3A K1E M6A K1D I4	
< 10	>= 10e6	N2A	C2A C6H L1B T3A C3B K3B P1B T3B C6C L1A R1B
< 10	< 10e6	A1C B1B D4A P3C X1A E6A C1G M5A S1A U2A J1A D1B M7A S8A S4A	E5A R3B

The next group of components which can be analyzed are those with high FIT, high number of failures and high component hours. These component types may be genuine problem components across the whole population. This implies that the number of sources from which there is data on these components must be found. Those components in the group with data from many different data sources should then be further analyzed. This analysis takes the form of identifying the failure distribution and those factors which may affect the reliability of these component types. All data in this category must firstly be checked for any source related problems before carrying out any statistical analysis. After grouping the component types, what is done with this information?

Figure 7.1 shows a flowchart of the investigation procedures which are carried out for each component type.

In summary, the flowchart shows that:-

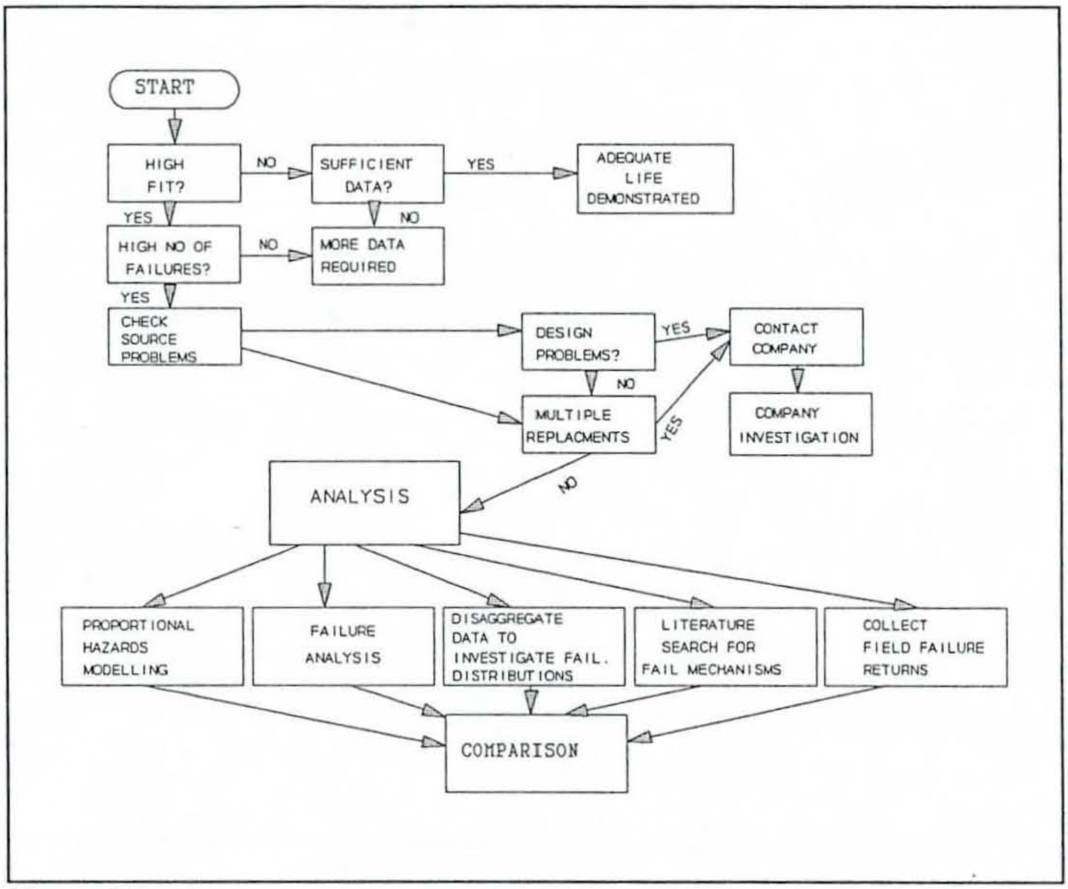


Figure 7.1
Flowchart of Order of Analysis

1. For those components with high failure rates and high number of failures, checks for source related problems are necessary.

2. For those components with high failure rate, high number of failures and data from many sources, that further analysis can proceed. This further analysis takes the form of statistical analysis, literature searches on the associated failure mechanisms, the collection of some of the field failed components for failure analysis and ultimately comparison between these forms of analysis to identify the reliability of

these component types.

3. For those component types with low failure rate then either more data is required to enable, further analysis or, if there is sufficient data then the analysis of these components can be carried out after all the problem components have been dealt with.

Tables 7.1 and 7.2 are used to separate the component types into groups to be analyzed and in addition they illustrate the investigation procedures before any analysis is carried out.

7.3 Design and Replacement Problems

7.3.1 Introduction

As mentioned in the previous section, checks are carried out on the data to identify any potential source related problems. These source related problems can be caused by a wrong design or as a result of the replacement policy of a particular company.

7.3.2 Design Problems

For example, if a component type appears to fail consistently in the same circuit reference position then the data source would be contacted to investigate the cause. In the previous chapter, the high failure rate of some custom ICs was discussed. These ICs were failing because of a design related problem. This problem was only identified when the company was contacted and asked to investigate the reason for the high number of failures of these devices. The company found that the equipment could power up in one of two states. The equipment sometimes failed to function in one of these states, but this could very often be remedied by switching off and on again. The failure to power up in the correct way every time was traced to a design fault in the IC. This fault was essentially the result of a software error which was not detected in the process of conversion to a hardware product. Consequently the device had been manufactured with an inherent design error. The design fault has been corrected by amendment and re-issued.

Similarly, many failures of a wirewound potentiometer (P3C) were found in a particular data set. The company investigated this problem and reported that the component was a multi-turn potentiometer and that failures were due to operators turning the control against the end-stop too many times thus forcing it through the end-stop. The problem was solved by replacing the part with a slipping clutch type of potentiometer which cannot be damaged in the above manner.

Another problem arose with bipolar transistors (T1A) from one data source. Many failures of the same type of device were identified. Investigation by the company showed that they were power switching transistors which were of poor quality due to contamination during manufacture. They were also being over-stressed and since the identification of these problems the source is no longer using these particular devices.

Further potential design problems have been identified concerning different bipolar transistors from another data source. Many transistors of the same part number were consistently failing. In addition, out of the 20 failed components of this type, 17 were on the same type of printed circuit board. By using the CODUS database, the part number of the component was identified as a low power npn switching transistor which is a fairly standard type of bipolar transistor. This high number of failures on one board type requires further investigation into the causes of this problem. The data source has therefore been contacted but is still investigating this problem.

Other component failures have been identified as possibly being design related problems, namely, quartz crystals (Q1A) and metal film resistors (R3C). However, these are still under investigation by the relevant companies.

7.3.2 Multiple Replacements

The replacement policy of a company can directly affect the number of reported failures of a component. For example, when investigating the failures of feed through filter connectors (K3B) from a particular source it was found that there were 35 failures reported. At each time a K3B failed, 4 other components of the same type also apparently failed. This occurred 7 times and appeared unlikely to be coincidental. After contacting the company to investigate this, it was found that the engineer repairing the equipment could not identify which of the 5 components failed and therefore replaced all 5 components. This obviously resulted in a high calculated failure rate for K3B and falsely indicated that these were problem components. To solve this problem, 7 failures were recorded instead of 35. Thus the calculated failure rate for feed through filter connectors dropped and they ceased to fall into the problem component category. From this illustration it is obvious that multiple replacements can cause artificially high failure rates.

In the previous section, two problems were discussed relating to bipolar transistors. The second of these was also affected by multiple replacements. Looking closely at the data for this type of component it was found that there were multiple replacements on some boards, especially early in their lifetimes. Figure 7.2 shows a bar chart for the number of failures in 5 hour intervals. All these failures are recorded for a specific board part number and split into board serial numbers. From this Figure it can be seen that the majority of the failures are occurring early in the operating time period and as time passes the number of failures is dropping. This information has been passed onto the data source and we are awaiting some explanation of the causes for this problem. Although there are multiple failures the realisation that these components are consistently failing in one board type implies that there may be a design problem, as discussed in the previous section.

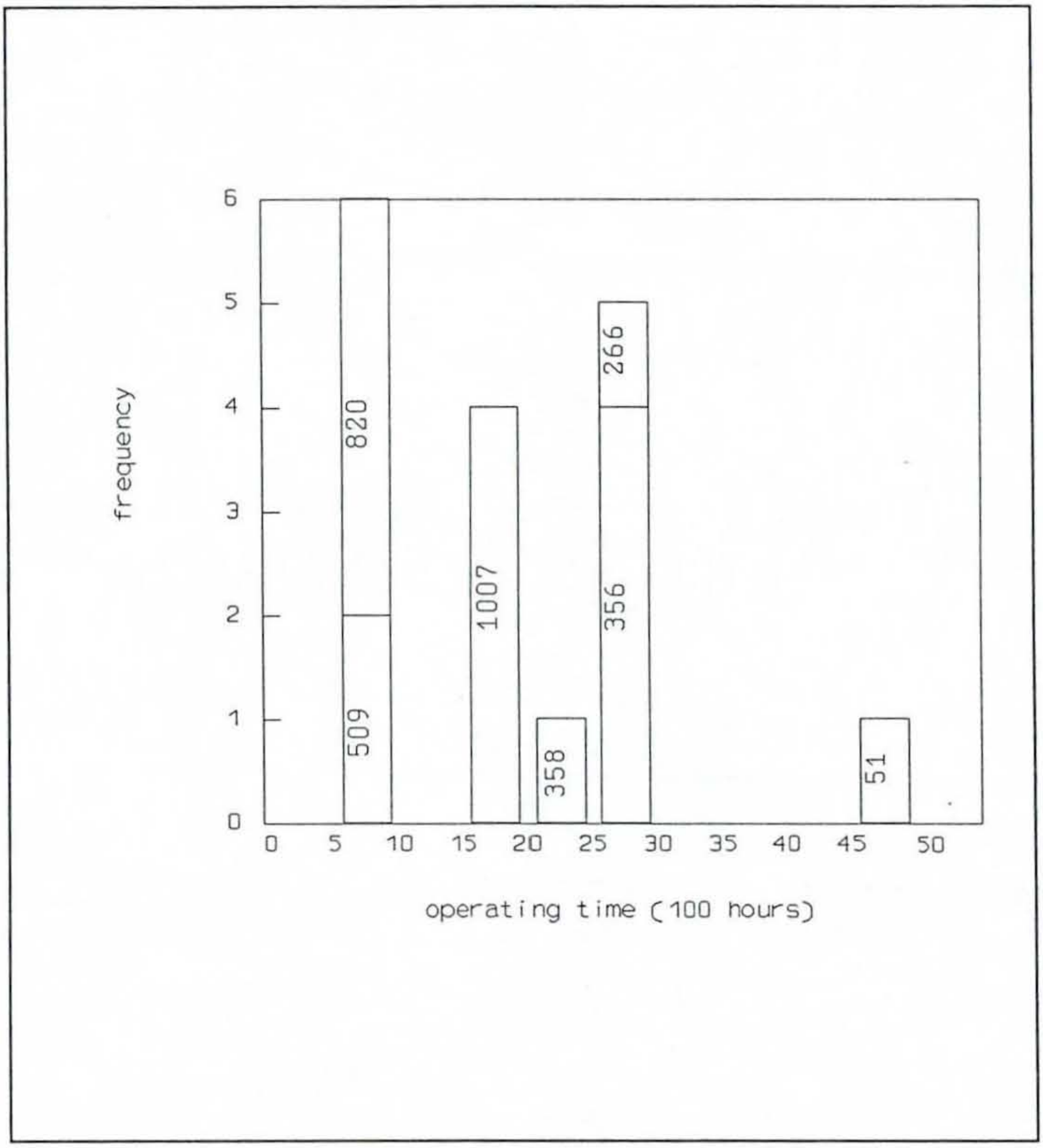


Figure 7.2
Frequency against Operating Time of Low Power NPN Switching Transistors for Circuit Board Serial Numbers of Board Type 22202

The illustrations above show that it is important to identify design and replacement problems before carrying out any further statistical analysis.

7.3.3 Data Independence

By identifying data with source related problems and removing it from the database data integrity is ensured. In addition, testing for design and replacement problems can be used as a tool for testing the independence of the data. To be able to carry out most statistical analysis, the data must be assumed to be independently identically distributed (i.i.d.). This means that there should be no trend in the time between failures and no serial correlation between events. Since the data is for non-repairable components entering the field at different times and is from different data sources it is unlikely that there will be any relationship between two failure of a certain component type and another. However, within data sources, there may be dependency in the data particularly if there are design problems where one failure may cause another. Alternatively, multiple replacements can occur as in the case of the K3B multiple replacements where 4 failures were apparently a direct result of 1 failure. Checking the data for such source related problems ensures that the assumption of i.i.d. is upheld. Further data analysis can then be carried out when any source related problems have been dealt with.

7.4 Modelling of the Time Metric

7.4.1 Introduction

In order to investigate the failure distribution of those component types with failures in box 2 of the decision table in Table 7.1 the data must firstly be in the correct form.

Data on non-failed components must be considered as well as data on failed components. The non-failed data is usually known as censored data. When systems are non-failed and their failure times are known only to be beyond their observed running time then this data is said to be censored on the right. Similarly, a failure time known only to be before a certain time is said to censored on the left. If all non-failed systems have a common running time then the data is said to be singly censored. Singly censored data arises when systems are started on test together and the data is analyzed before all systems fail. However, censored data may have differing running times intermixed with failure times. Such data is called multiply censored data. Figure 7.3 depicts such data. Multiply censored data usually comes from the field, because systems go into service at different times and have different running times. Figure 7.3a shows units entering the field at different times. The data is observed up until some known time T. To analyze such data, the operating times are brought back to a common starting point which is usually known as time $t=0$. Figure 7.3b therefore depicts the data shown in Figure 7.3a brought back to a common starting time. Thus Figure 7.3b shows the operating times for the failed and non-failed units during the period of observation.

The electronic component data is therefore multiply time censored ie running times are different from failure times because the systems containing the components went out into the field at different times.

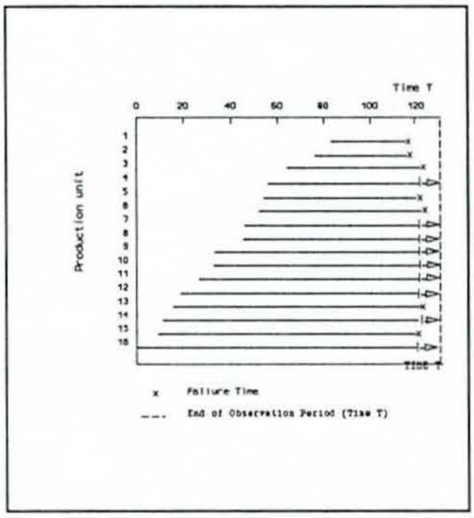


Figure 7.3a
Example of Multiply Censored Data

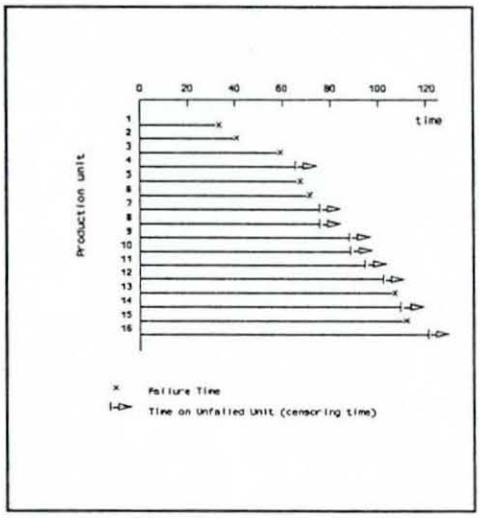


Figure 7.3b
Example of Multiply Censored Data Shifted back to a Common Origin

As was seen in chapters 3 and 4 the data collected on times to failure relates to the cumulative system operating time to failure and the circuit board operating time to failure. These times are in operational hours. In addition, data on previous use is collected, but is stored in days rather than hours. To calculate the observed running time of the system and consequently the censoring times of non failed components, the up and running date, the end date and the percentage usage of the system must be used. Thus if a component has never failed then it is operational for the whole observation period.

7.4.2 Renewal Theory

Because electronic components are non-repairable the modelling of the time metric for electronic components is less complex than for complete electronic systems. This means that when a component fails it is not repaired and does not appear in any other board or system after it fails. When analyzing non-repairable components we do not have the problem of reliability growth which can introduce complexities in the modelling of a repairable system.

Non-repairable electronic components therefore follow a renewal process [2]. Since we assume that a component remains on a PCB until it fails and is then immediately replaced with another component, we can extract certain features from this situation. These are:

1. The life of each component is a non-negative random variable.
2. The life of each component of a particular type has the same distribution.
3. The lives of different components of the same type are independent.

The underlying structure of this situation is that of a series of failures ordered in time. The time between failures is a random variable with a common distribution, not necessarily exponential, and is independent of previous events. Because electronic components are non-repairable and their times to failure are independent of each other then the time to failure of electronic components constitutes an ordinary renewal process. The renewal process is a mathematical model which explains the failure behaviour of real systems or in this case electronic components [3].

7.4.3 Description of the Software Developed

To extract the data in the correct form from the database two programs were written. These programs provide data on:

1. All the failure events.
2. All the non-failed events (censoring times).

The software on the failure events was written using the following model for non-repairable electronic components. Looking at Figure 7.4, suppose for simplicity there is only 1 circuit board in the field with 10 capacitors (C1A) and 10 connectors (K1A). If, for example, we want to look at the failure distribution of capacitors then we must use the information in Figure 7.4. At the last failure time, the data would consist of the following:

1. 1 failure occurring at 10 hours
2. 1 failure occurring at 30 hours
3. 1 censoring time at 30 - 20 hours ie a capacitor was operational for 10 hours before the end of observation
4. 8 censoring points at 30 hours for all those capacitors which did not fail

Thus a picture of the failure distribution of C1As is starting to build up. These failure times assume that the second failure did not occur in the same circuit reference position as the previous C1A failure. This must always be checked, since if two failures had occurred in the same circuit reference position then the censoring times would consist of 9 censoring points at 30 hours operational time. It should also be noted that 2 failures in the same circuit reference position may imply a design fault or replacement problem or something like this.

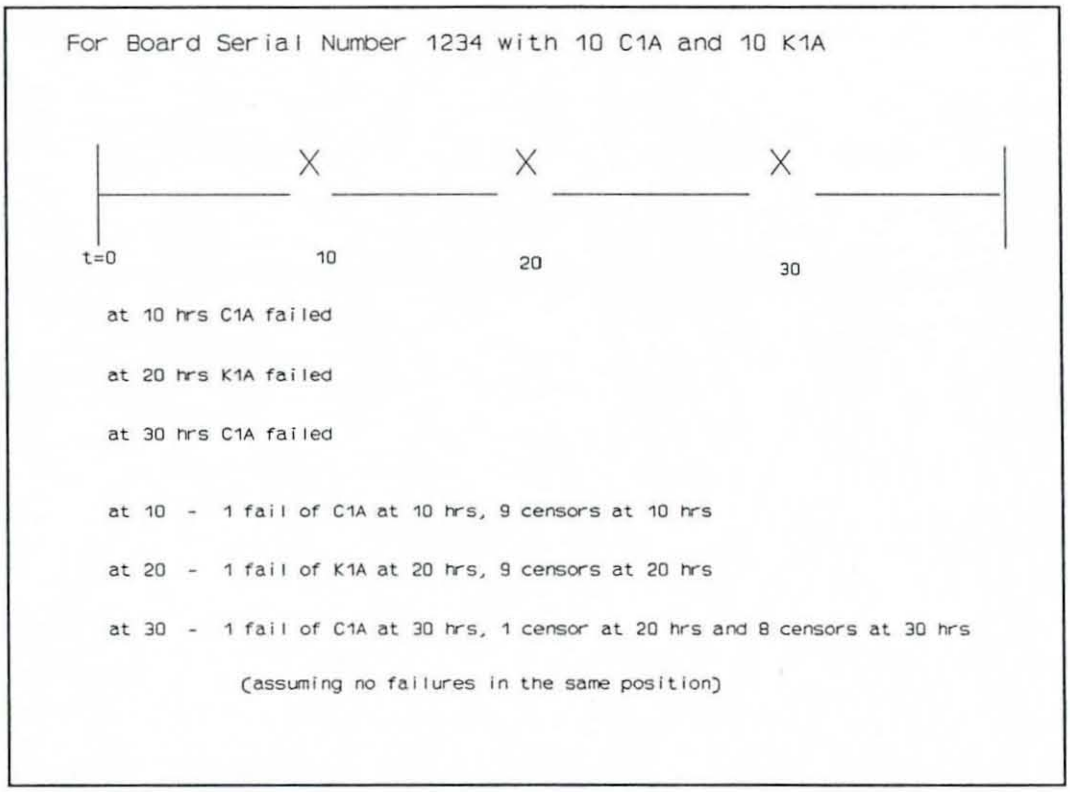


Figure 7.4
A Censoring Model for Non-Repairable Electronic Components

Using the database to build up a picture of the failure distribution, all the data from failed circuit boards with capacitors must be extracted in order to give information similar to that illustrated above. This is fairly complex since for each circuit board serial number data must be extracted on the previous use of the board and the operating time to failure of a board this time around. The failures and censoring points must then be calculated for each component of a certain type on the board.

Program 2 extracts all the censoring times for a particular component type within systems which have never failed. However, because there are millions of censoring points after the last failure time instead of extracting all these times, the number of censored points after the last failure is recorded. This is correct because hazard plotting is concerned with the ranks of the censored data and the actual times are not required. Therefore for those very large censoring times we require only the total number of censoring points. This obviously makes the extraction procedure quicker and simpler.

From the results of these two programs all the operational information for components of a particular type are known and can be used to explore the failure distribution of these component types.

7.5 Hazard Plotting of Pooled Data

7.5.1 Introduction

Data plots are used to display and interpret data because they are simple and effective. The graphical analysis of multiply censored data is called hazard plotting. In Chapter 2, the hazard distribution was shown for several empirical distributions. Thus interpreting hazard plots of field data can give an indication of the failure distribution of that data. A plot has several advantages over numerical methods and these include:

1. It is fast and simple to use.
2. It presents the data in simple form which thus aids the drawing of conclusions and subsequently helps to present data to others.
3. It provides simple estimates for a distribution.
4. It helps the assessment of how well a given theoretical distribution fits the data.
5. It helps to highlight and/or eliminate unusual

data points.

6. Non failed data can be used therefore giving a fuller representation of the data.

To illustrate how to make and interpret a hazard plot, an example taken from Nelson [4] is shown.

Table 7.3 shows data on both months in service of field windings before failure and windings still running from 16 diesel generators. Each running time is marked with a '+'. This means that up to the running time there had been no failures of a system. The data shown in Table 7.3 consists of failure times and censoring times. Firstly, the times are ordered from smallest to largest regardless of whether they are censoring or failure times. The times are then labelled with the reverse rank ie the earliest time is labelled with 16 as shown in Table 7.3. After labelling the reverse rank the hazard contribution is calculated for each failure as 100/k, where k is the reverse rank. For example, the winding failure at 70 months has a reverse rank of 11 and therefore the hazard is 9.1%. This hazard value is the observed instantaneous failure rate at the age of 70 months. The cumulative hazard values are then calculated from these values, as seen in Table 7.3.

Table 7.3
Example of Hazard Calculations

Time	Reverse Rank k	Hazard 100/k	Cum. Hazard
31.7	16	6.25	6.25
39.2	15	6.67	12.92
57.5	14	7.14	20.06
65.0+	13		
65.8	12	8.33	28.39
70.0	11	9.09	37.48
75.0+	10		
75.0+	9		
87.5+	8		
88.3+	7		
94.2+	6		
101.7+	5		
105.8	4	25.00	62.48
109.2+	3		
110.0	2	50.00	112.48
130.0+	1		

+ running time (censoring time)

Plotting cumulative hazard gives more meaningful results than looking at hazard values. The cumulative hazard values are then plotted on the horizontal axis against the time to failure on the vertical axis.

There is hazard paper available for different theoretical distributions. The choice of paper is determined by engineering knowledge. For example for electronic components, the first choice of hazard paper would be exponential. In Figure 7.5, the data for the above example is plotted on exponential paper. If the data fits a rough straight line then the conclusion would be that the distribution adequately fits the data. If the data does not follow a straight line then the data should be plotted on some other hazard paper.

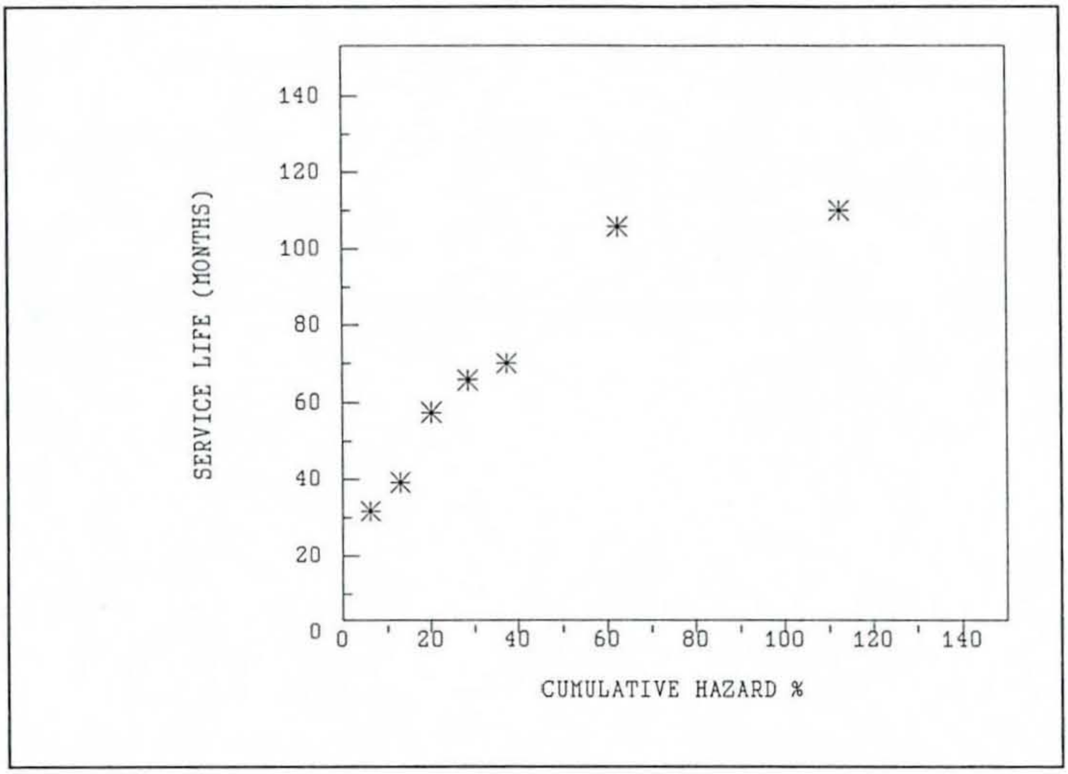


Figure 7.5
Exponential Hazard Plot for Example Data of Table 7.3

In order to use these hazard plotting techniques one basic assumption which must be satisfied is that the time between events are i.i.d. [5].

The curvature of the plot on exponential paper indicates the nature of the hazard rate. Figure 7.6 shows curves for increasing, decreasing and constant failure rate as plotted on exponential paper. Exponential hazard paper is rectangular graph paper. Figure 7.5 therefore shows an increasing hazard rate indicating that this data should be best plotted on Weibull paper. It is not thought necessary to show this on Weibull paper at this stage.

However, if for example, a best-fit line was fitted to the data shown in Figure 7.5 then the estimate of the parameter λ , the failure rate, from exponential paper,

is found by entering the hazard plot at 100% on the cumulative hazard scale.

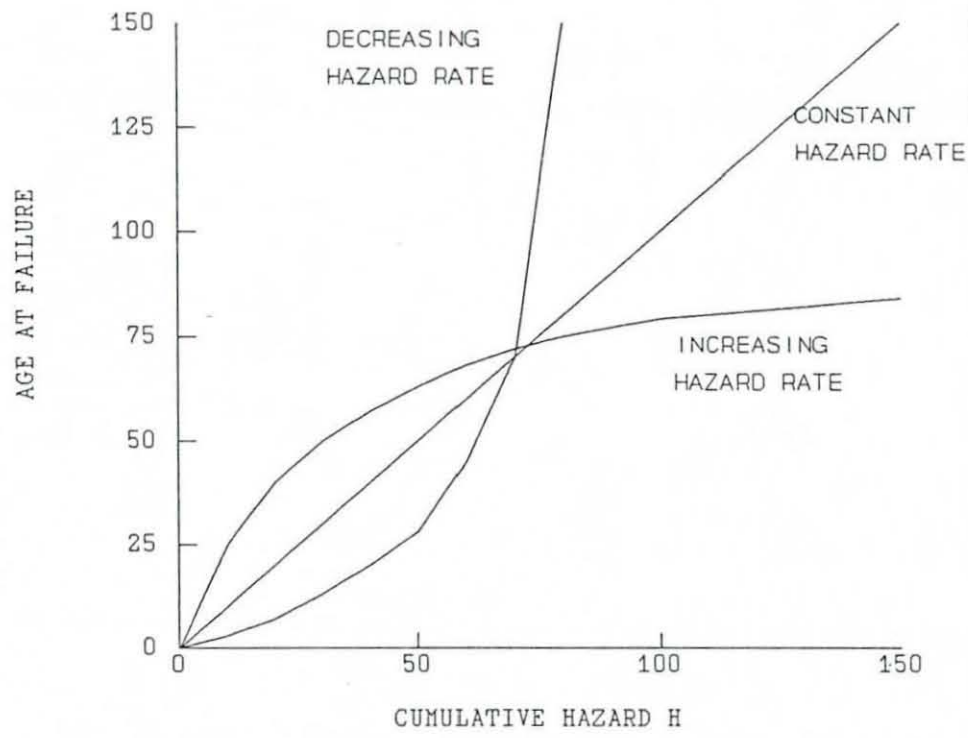


Figure 7.6
Cumulative Hazard Functions

Then moving to the fitted line, the corresponding point on the vertical axis gives the mean time to failure. The failure rate of the exponential distribution is the reciprocal of the mean time to failure. Thus from this example $\lambda = 1/120 = 0.008330$ or 833 winding failures per 1000 months.

Hazard papers have been developed for the basic theoretical distributions: the exponential, normal, lognormal, Weibull and extreme value distributions. These hazard plotting papers are obtained from the general theory on hazard and cumulative hazard functions [4], [5].

Hazard plotting paper for the Weibull distribution is log-log graph paper. The slope of the best fit straight line on Weibull hazard paper can be shown to be equal to $1/\beta$. Thus the slope is used to estimate the shape parameter β. In addition, for $H=1$ (100%), the corresponding time t equals α, and therefore α can be estimated graphically.

As mentioned in Chapter 2 a Weibull distribution has a hazard rate that increase(decreases) if the shape parameter β is greater(less) than 1, and a shape parameter of 1 corresponds to a constant failure rate.

From the above discussion we can now start to look at some hazard plots which have been drawn for some of the electronic components in the database.

7.5.2 Bipolar Transistors (T1A)

The decision to explore the failure pattern of Bipolar transistors was made for historical reasons. As can be seen from Table 7.2, they do not appear to be problem components, as they are in box 4 from Tables 7.1 and 7.2. However, when they were chosen for analysis there was insufficient data in the database to be able to analyze any other component types in sufficient depth. There are 118 T1A failures and there is failure data from 4 different data sources.

In addition data from Data Source QV is not included in any of the following analysis because this data is not trackable. The actual operating time to failure of a particular board this time around is not known for any of the boards in this system.

Figure 7.7 shows on exponential paper the hazard plot for T1As for pooled data. Comparing this shape with those in Figure 7.6 we can deduce that the bipolar transistors have a decreasing hazard rate. To verify this the data is then plotted on Weibull hazard paper. Figure 7.8 shows that the data fits a reasonable straight line. The β value is estimated from the fitted line as 0.3, indicating a decreasing hazard rate.

It is received wisdom in the profession, without any published data to support it, that some semiconductors exhibit a decreasing hazard rate. This analysis actually confirms this concept at least for a particular semiconductor device category.

Figure 7.7
Cumulative Hazard Plot For T1A

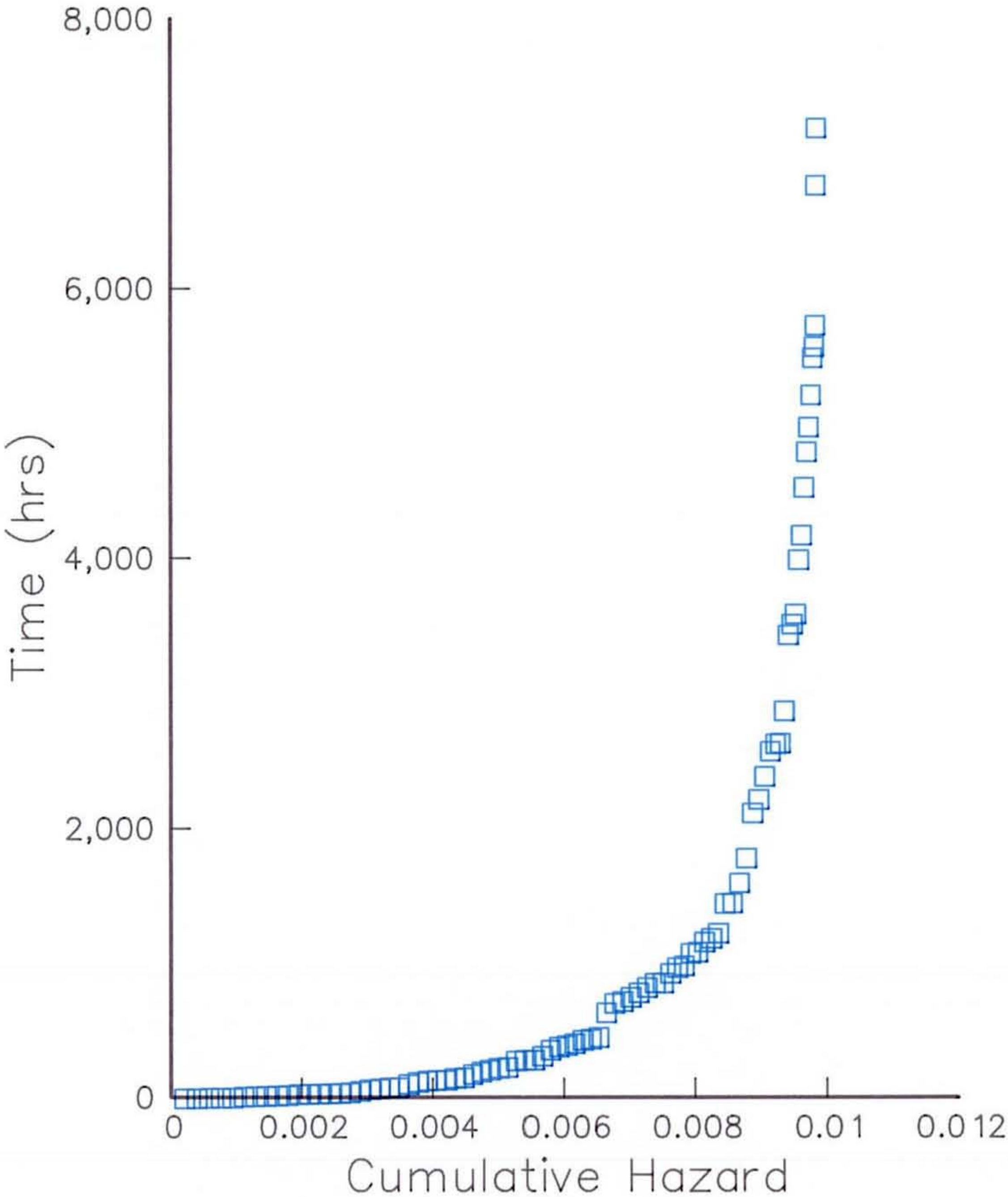
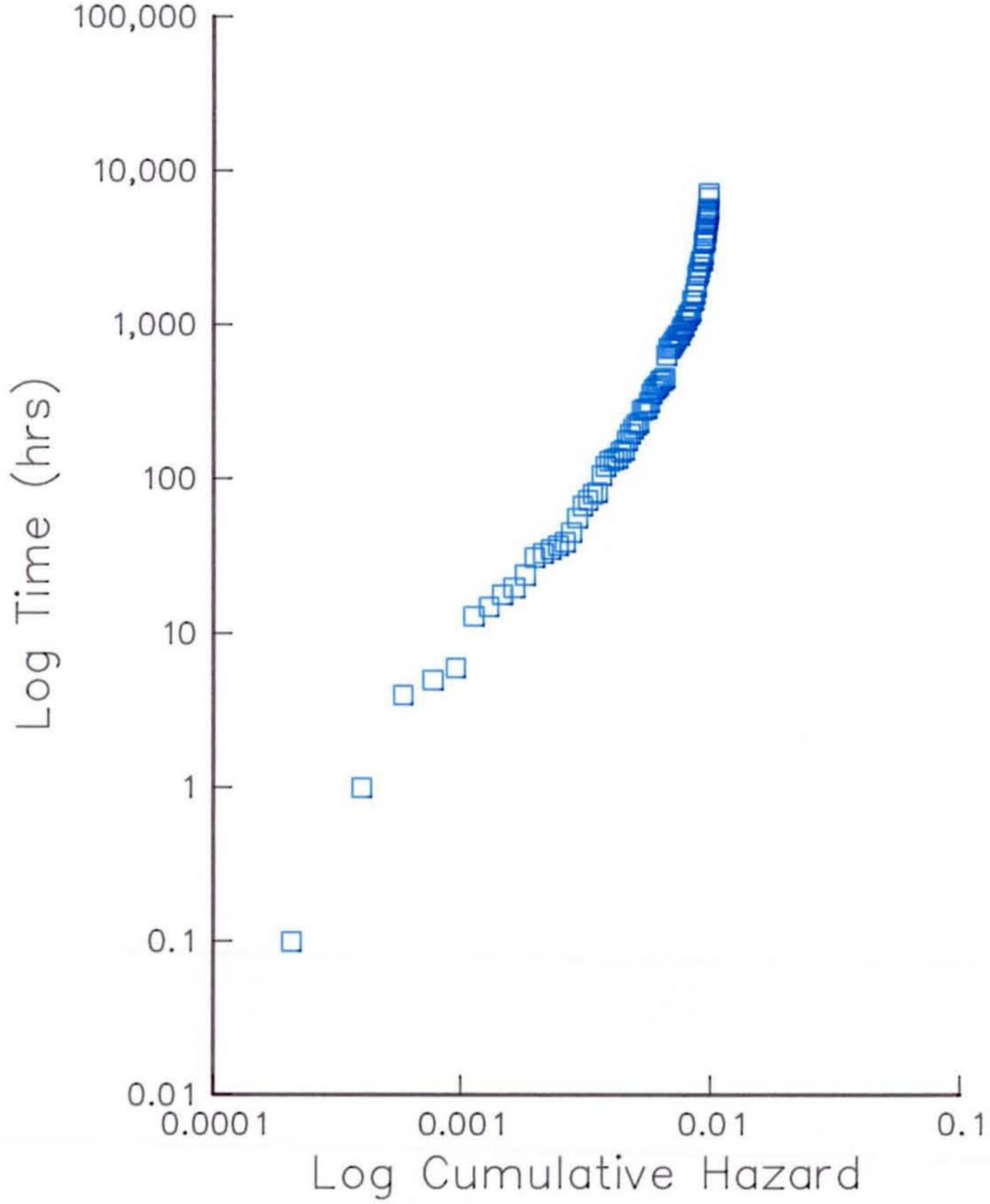


Figure 7.8
Log Cumulative Hazard Plot For T1A



The linear fit of this line is not conclusive. Looking at Figure 7.8 two separate lines can be fitted. The change in gradient is around 1000 hours. The β value of the first line is approximately 0.4 and the β value of the second is approximately 0.1. This means that up to 1000 hours, although the data shows a decreasing hazard rate, the failures were occurring more often than in the second fitted line. This change in gradient could be due to the fact that the data is pooled over different data sources. To investigate this further the data should be split into data sources and re-plotted.

In addition, the results of this graphical analysis show that there are outliers at 0 hours. Discussions with the company providing these very early life failures concluded that these failures occurred in the first 24 hours of operation. The cause of these early life failures is not known and therefore they must be treated as outliers and not design faults.

From these hazard plots we can see that bipolar transistors do not have a constant hazard rate. Caution must, however, be used when quoting these results because this data is pooled over different data sources with different environments, different screened levels etc. Notice also that the last failure point is around 10,000 hours, about 14 months. This is not a very long period of time and therefore we may only be looking at early life failures ie the first part of the bath-tub curve. The next year or so of data is therefore crucial to be able to observe whether the hazard rate continues to fall or whether the distribution changes its slope as in the bath-tub curve. Moreover, the results of this analysis may indicate that the screening or burn-in procedures applied are insufficient to eliminate early life failures.

7.5.3 Rectangular Connectors (K1A)

Rectangular connectors were chosen to be analyzed because they are, as can be seen from Tables 7.1 and 7.2, in group 2. The data was first checked for design and replacement problems but no evidence of such problems was found. The sample cumulative hazard plot for K1As was then constructed (Figure 7.9). This hazard plot shows a decreasing hazard rate similar to that shown for the T1As in Figure 7.7. Figure 7.10 shows the data plotted on Weibull hazard paper. Similar to the plot for T1A, there are outliers at very early times ie between 1 and 10 hours. The remainder of the data appears to fit a reasonable straight line with a β value of approximately 0.342. Since the β value is less than 1, the hazard rate is therefore decreasing. To obtain the characteristic lifetime ie α, the scale parameter, we must look at the cumulative hazard of 100%. However, since there is a very small proportion of all the data failing in the observed population it is not advisable to extend the fitted line so far beyond the last failure time. All that can be reasonably stated is that after 100,000 hours of operation, 0.08% of rectangular connectors have failed out of the sample population.

As with the T1A results, we must be cautious about the K1A results. Firstly, they are pooled from different sources and different environments etc. Secondly, the last failure point occurs at around 14,000 hours (19 months) which is not a very long period of time.

Figure 7.9
Cumulative Hazard Plot for K1A

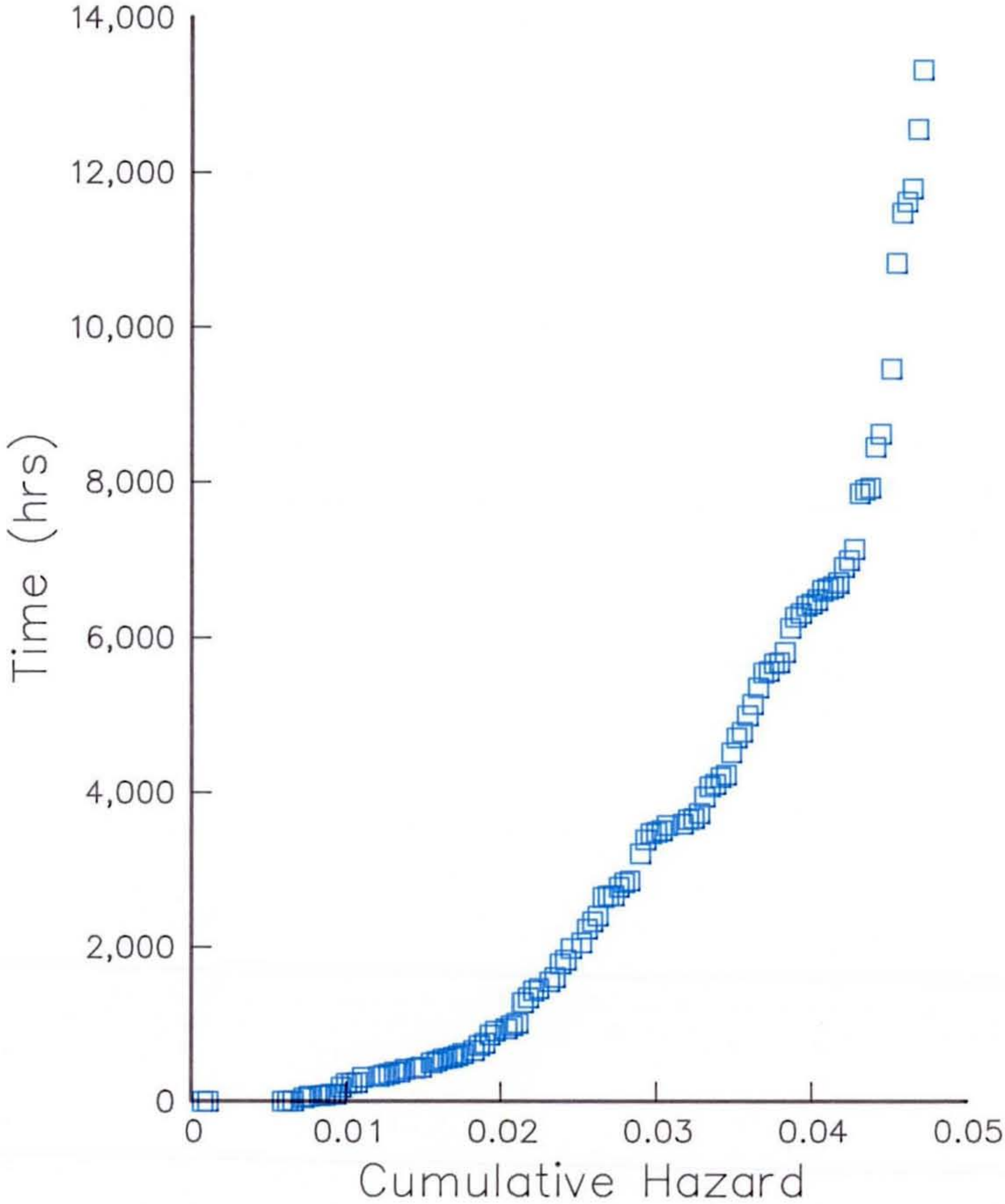
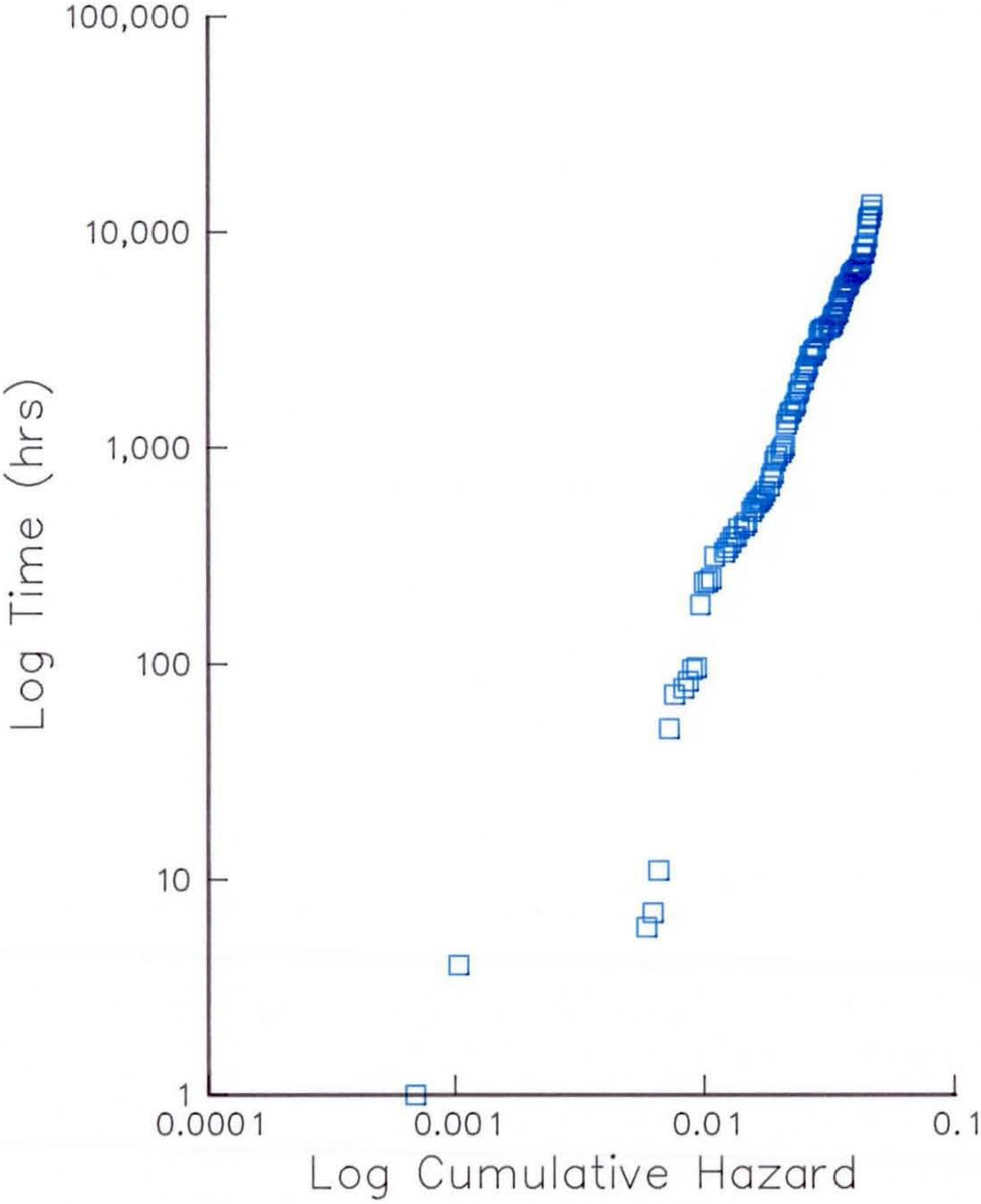


Figure 7.10
Log Cumulative Hazard Plot for K1A



7.5.4 Coil Activated Relays (B1A)

Coil activated relays were chosen for further analysis because, like the rectangular connectors, they appeared in group 2 of Figures 7.1 and 7.2. Similarly, after checking for design problems and multiple replacements, hazard plots were prepared using the pooled data, using both exponential and Weibull hazard paper.

Figure 7.11 shows the data on exponential hazard paper. Again the curve shows a decreasing hazard rate similar to those shown for T1A and K1A. Figure 7.12 illustrates the data on Weibull hazard paper. Apart from a couple of outliers occurring before 10 hours operational time, the data appears to fit a Weibull distribution with β value equal to 0.204, which again indicates a decreasing hazard rate. Like the previous hazard plots, the last failure point is around 14,000 hours operational time and the data may be showing only early life failures.

Figure 7.11
Cumulative Hazard Plot for B1A

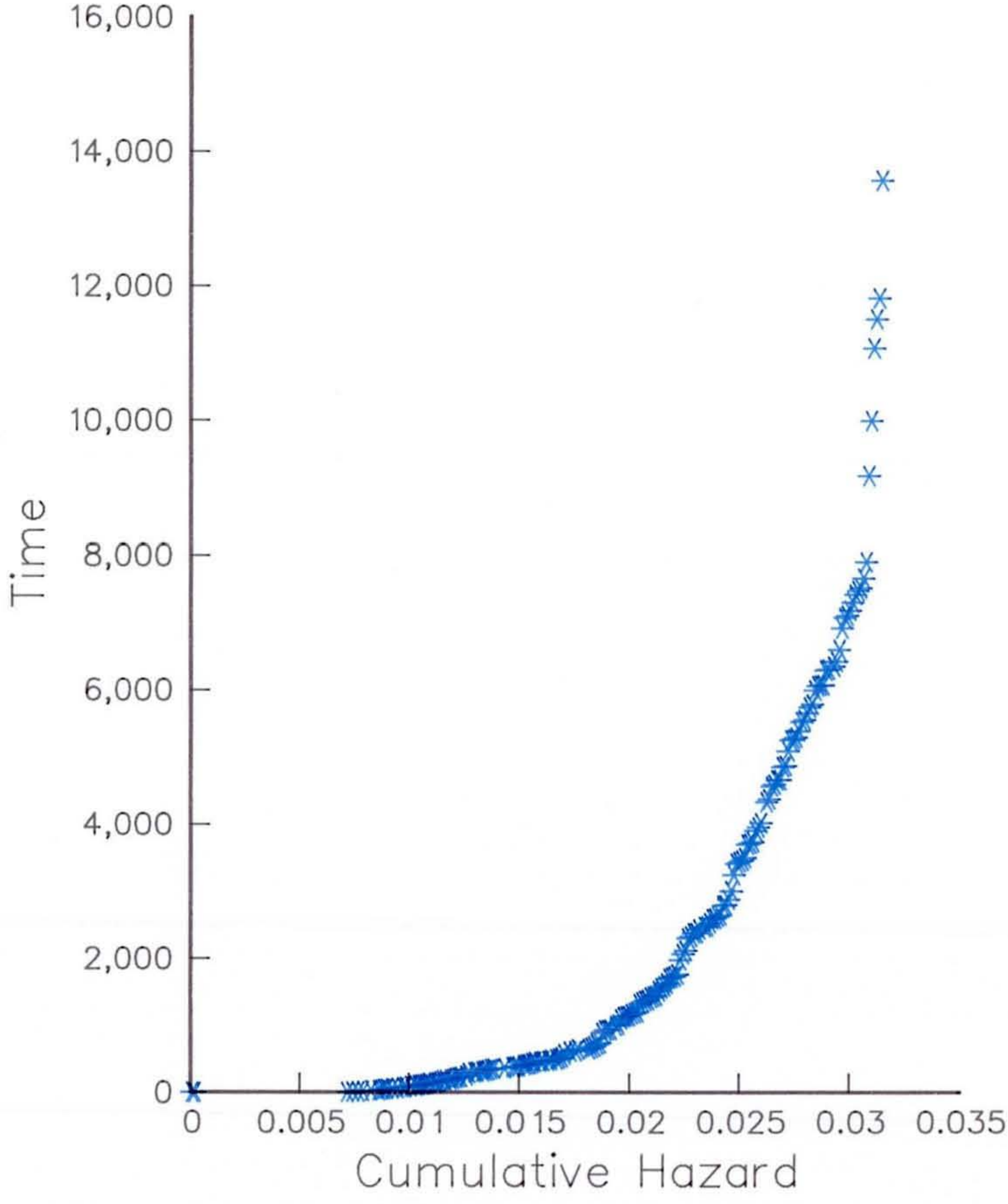
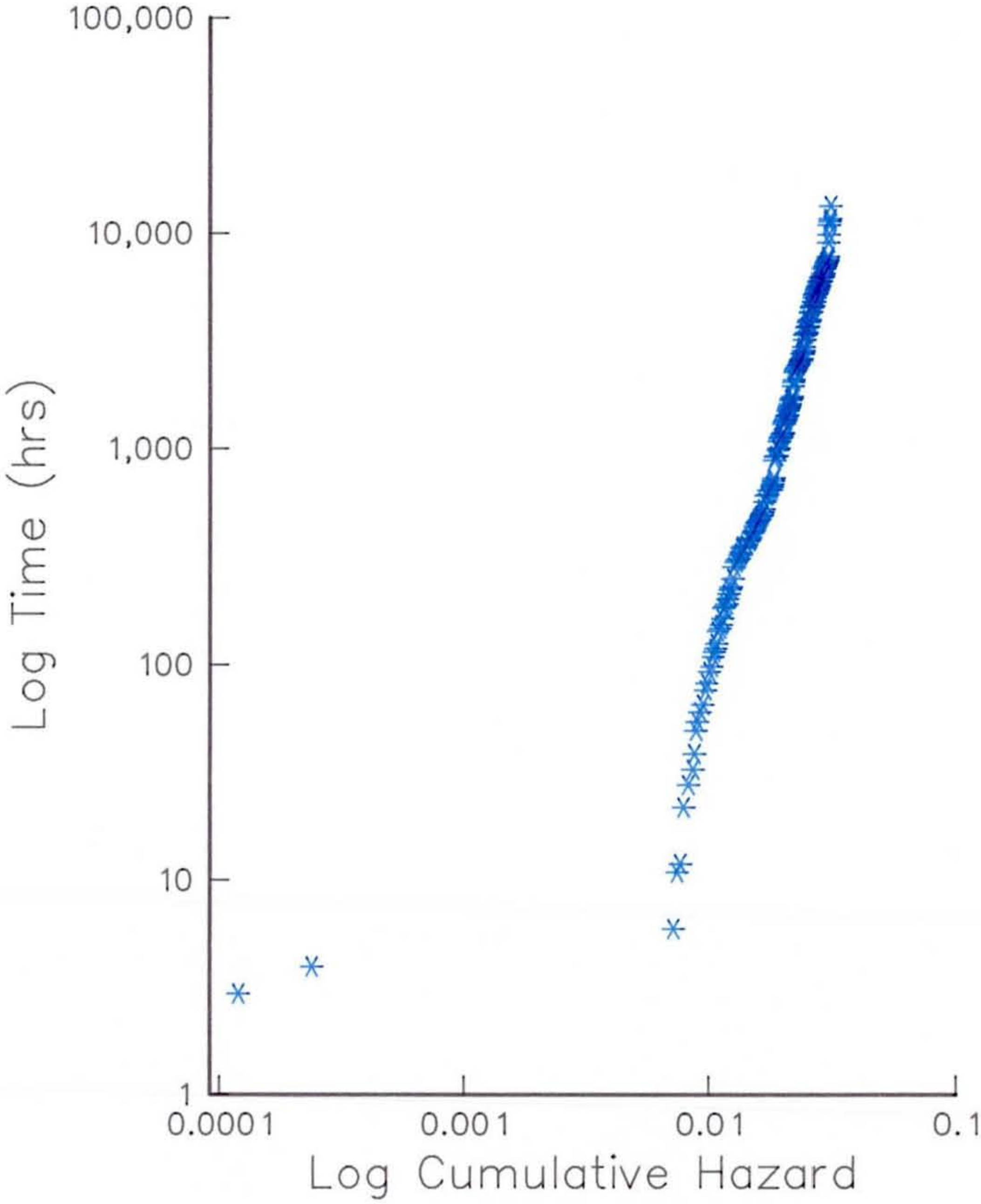


Figure 7.12

Log Cumulative Hazard Plot for B1A



7.5.5 Conclusions

From the three Weibull hazard plots illustrated, it appears that all three components analyzed fit a Weibull distribution and exhibit a decreasing hazard rate. This is a very interesting discovery since most reliability prediction methods assume a constant hazard rate. This conclusion implies that the screening or burn-in procedures for these components may not be adequate and therefore are not detecting inherent defects which cause early life failures.

In all three analyses the last failure point is around 10,000 to 14,000 hours which is about 1 to 1.5 years of operation and the time span for non-failed components ranges up to approximately 3 years of operation. We may therefore be observing only early life failures and may be looking at the first part of a bath-tub type curve. Further data will provide more conclusive evidence on the long term behaviour of these components.

In addition, the data analyzed is pooled data, and this analysis takes no account of differences in possible external factors.

7.6 Hazard Plotting of Disaggregated Data

7.6.1 Introduction

As discussed and illustrated in Chapter 6 certain external factors can affect the reliability of most electronic components. This section looks at the use of hazard plotting for comparing the distributional form of components between different data sources and system operational environments. In addition, by looking at the differences between data sources, we will be able to determine whether it has been sensible to pool data over different sources.

7.6.2 Bipolar Transistors (T1A)

In the previous chapter we compared the failure rates of components operating in ground benign and ground mobile environments. Since there is data on bipolar transistors in both of these environments we will now illustrate hazard plots of these two environments.

Figure 7.13 shows a hazard plot for both ground benign (GB) and ground mobile (GM) environments. The curvature of the GM plot implies a decreasing hazard rate. However, the curvature of the GB plot is not so obvious. Plotting the data on Weibull hazard paper shows the difference in the failure distributions of bipolar transistors in GM and GB environmental conditions. From Figure 7.14, the β value for GM is approximately 0.3, ignoring the outliers which are very early failures. The β value for bipolar transistors in Ground Benign environments has been found to be approximately 0.4. Notice that the distributions for GM and GB are almost parallel with only a slight change in gradient.

Figure 7.13
Cumulative Hazard Plot for T1A

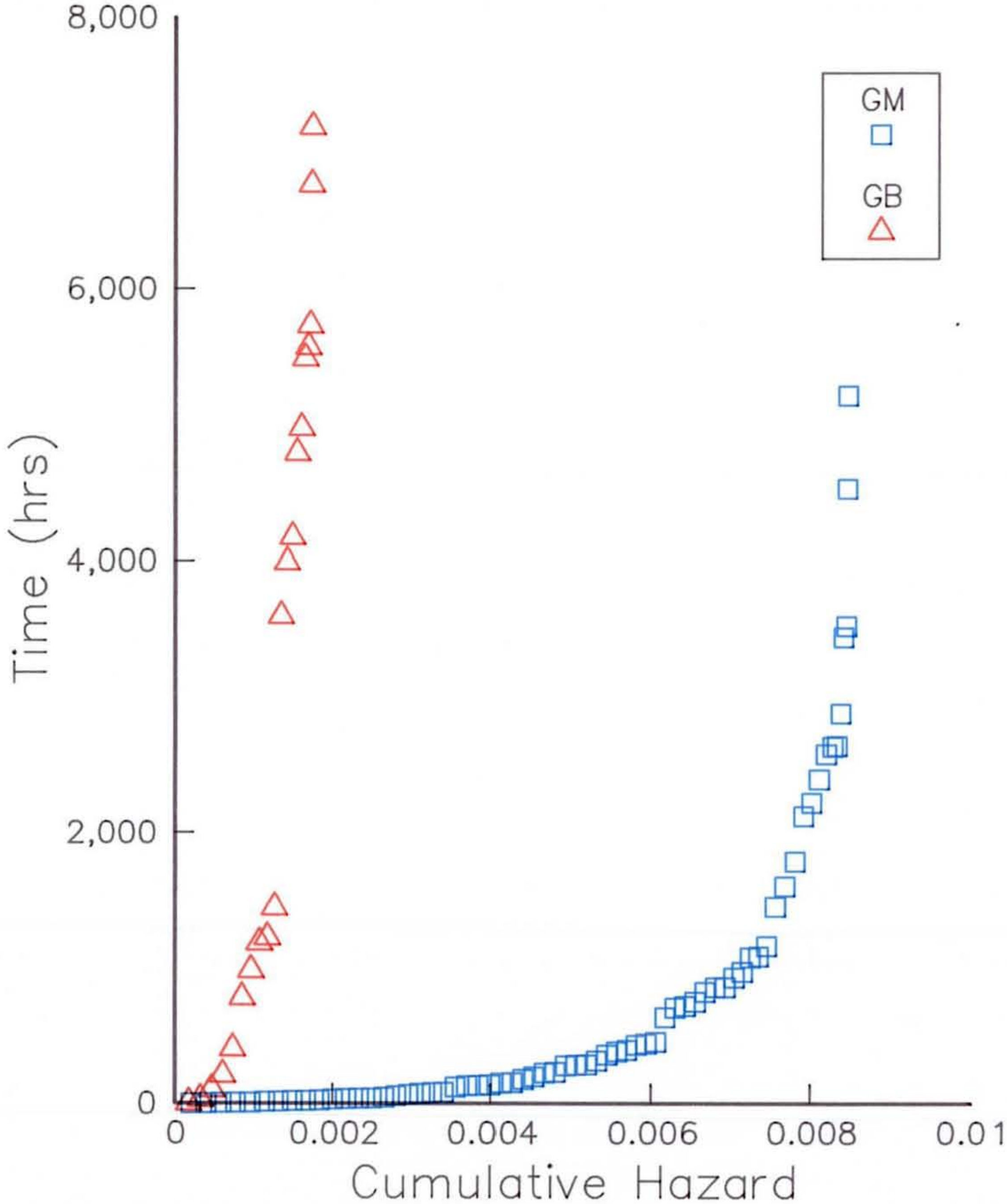
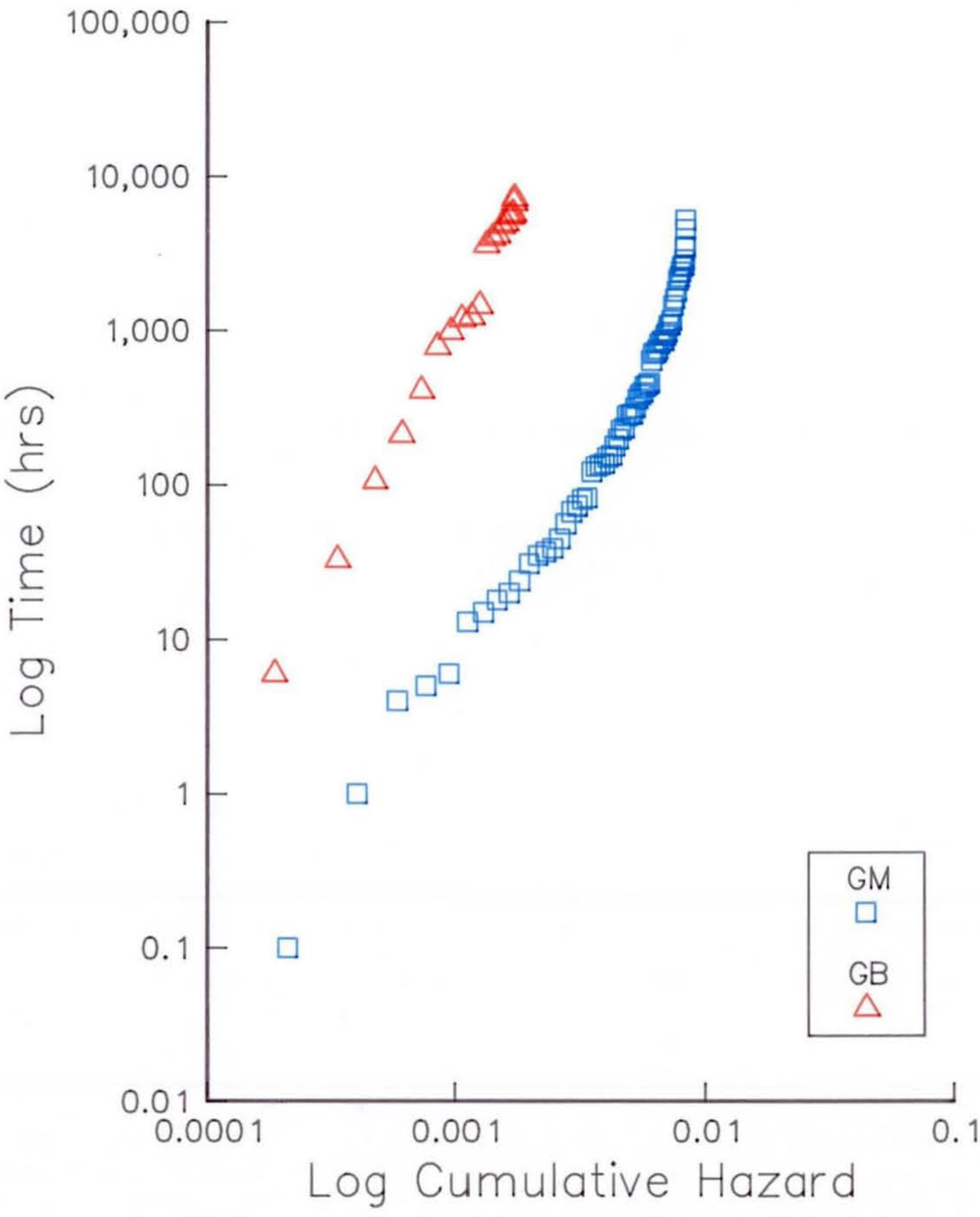


Figure 7.14
Log Cumulative Hazard Plot for T1A



The failure distributions of T1A in GB and GM environments therefore appear to be Weibull distributions but with slightly different shape parameters. In addition the plot for GM data is almost identical to the hazard plot for the pooled data this is due to the uneven split of data between the two environments.

In order to carry out the above analysis the data had to be aggregated over different data sources. It is therefore important to look at whether there are any differences in the failure behaviour of different data sources.

In the previous chapter (6), it was shown that there may be differences in the failure pattern of different data sources for the same component type. However, the result of this analysis is limited because it was based on the constant hazard rate assumption. Figure 7.15 shows an exponential hazard plot for bipolar transistors for different data sources. It is very difficult to see any pattern from this plot because one data set masks the others. Data set EA masks the others because there are less T1As operating in the field and therefore the instantaneous hazard rates at each failure point are significantly larger than those in the other data sets. The data can be seen much clearer on the log-log plot. Figure 7.16 shows the Weibull hazard plot for each data source. These plots are more complex and therefore more difficult to explain than the previous plots.

Firstly looking at data set HB, ignoring the very early life outliers, a straight line may be fitted giving a β value of 0.63. However, this data set is quite sparse and caution must be used when interpreting such information.

Figure 7.15
Cumulative Hazard Plot For T1A

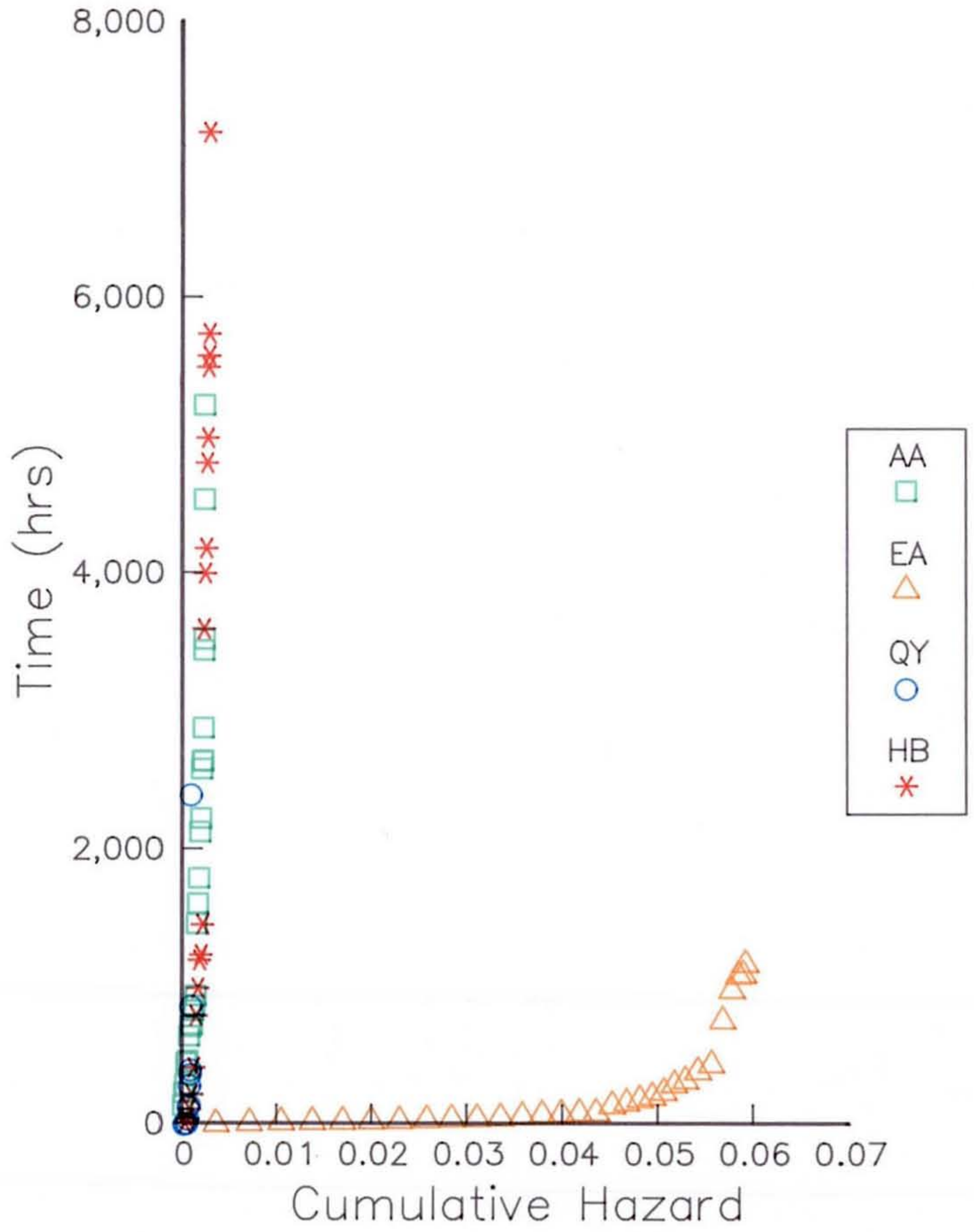
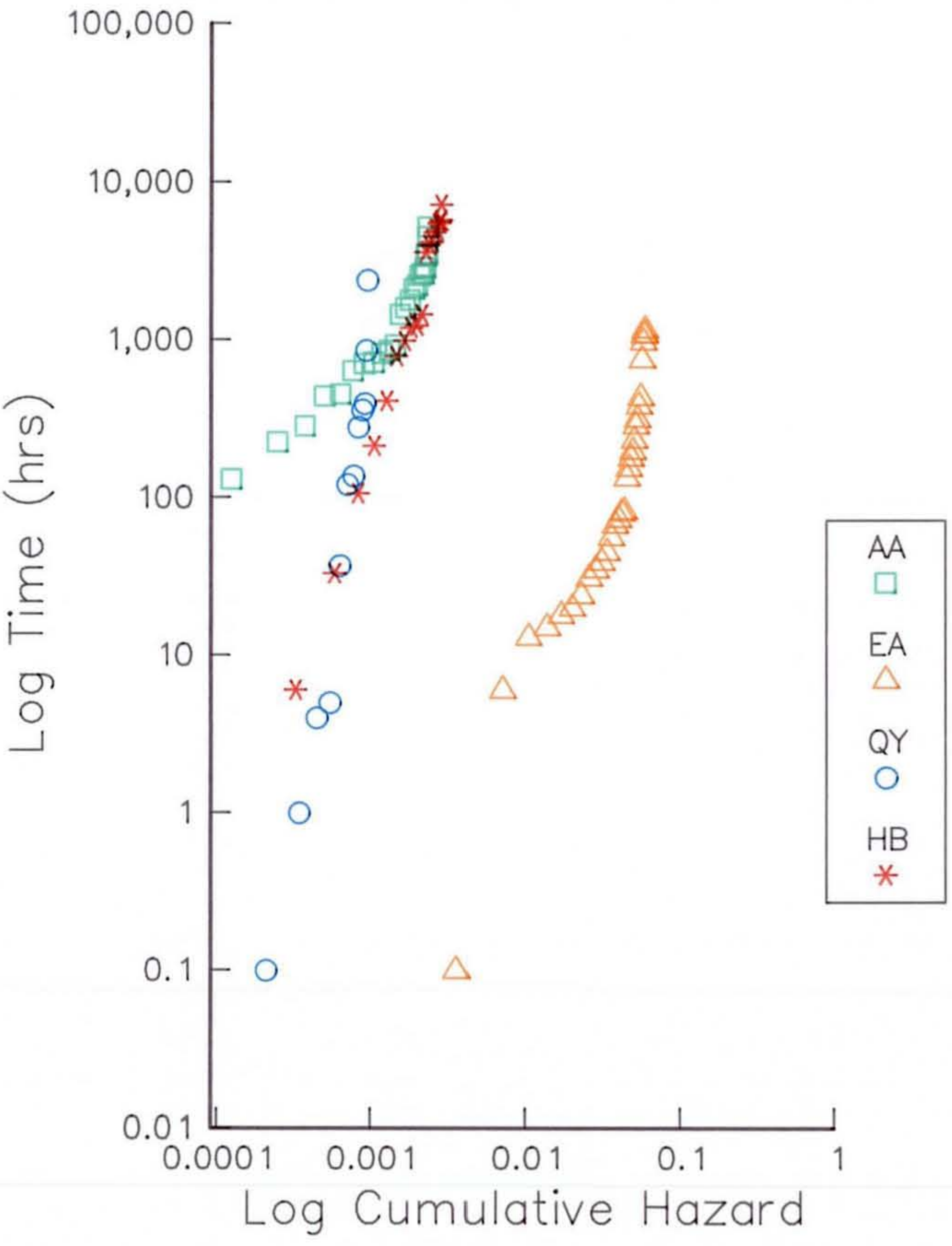


Figure 7.16
Log Cumulative Hazard Plot For T1A



Secondly looking at data set AA, there are more data points in this data set than in HB. Also, it appears more complex. One line cannot be adequately fitted to this data. It would be more appropriate to fit 2 lines to the data. The change in the gradient of these two lines could be due to two different dominant failure mechanisms in the components. Investigation by the company of what physically happened to these components must be carried out to find out what has caused this change in gradient.

The previous section on design and replacement problems highlighted that there may be design problems associated with this particular data set and the observed hazard plot substantiates this. The β values for each dominant failure mechanism are 1.92 and 0.65 respectively. The first set of failures exhibit an increasing hazard rate implying that there is some sort of wear-out mechanism involved due to perhaps a contamination problem or a poor quality component. The bar chart shown in Figure 7.4 indicated that most of the failures were occurring early in the observed life time and would thus account for this observed increasing hazard rate. Investigation into the likely causes of this observed wear-out will be carried out by the data source. The second distribution shows a decreasing hazard rate which is consistent with all the previous results on bipolar transistors.

Similarly, data set EA illustrates that there may be two dominant failure mechanisms shown by a change in gradient of the fitted lines on Weibull hazard paper. This implies that the data fits a Weibull distribution but with 2 different β values. The β value for the first failure mechanism is equal to 0.92 and 0.243 for the second failure mechanism. As with data set AA the shape parameter for the first distribution is higher than that for the second failure distribution. As discussed in section 7.3, there were some problems associated with certain bipolar transistors used in this data set. The change in gradients of the distributions may therefore have been caused by the switch from a contaminated component to a better quality component. In fact it was recommended that all components of this type be changed because of the poor quality level. However, only those equipments that were returned due to failure had these components changed. The change in the β value was probably due to the reduction of those problem components at risk in the total population of bipolar transistors in data set EA and therefore a different failure mechanism may have become more dominant.

Data set QY is different. Apart from the early failures at 1 hours, the data adequately fits a Weibull distribution with a β value equal to 0.093. This data set, however, is quite sparse which could account for the very small shape parameter.

The conclusion from the hazard analysis of bipolar transistors for different sources indicates that they all appear to fit a Weibull distribution with a decreasing hazard rate. However, they all have different β values and in some cases there appears to be a mixture of Weibull distributions resulting from differing dominant failure mechanisms.

7.6.3 Rectangular Connectors (K1A)

The data on rectangular connectors comes from 4 different data sources. However, there are only a few failure points in both data sets AA and QY. These have been ignored since most of the data comes from sources HB and QX and the equipments from these sources operate in a ground benign environment only, it is not feasible to make any comparison of the failure distributions of K1As between GB and GM. This analysis therefore only looks at the difference between data sources.

Figure 7.17 shows the exponential hazard plot for the different data sources. Notice that there is not enough data in data sets QY and AA to draw any conclusions and so they have not been plotted. However, both data sets HB and QX exhibit decreasing hazard rates although with different shape parameters. Figure 7.18 shows the same data on Weibull hazard paper. Firstly looking at data from source QX, the data appears to fit a Weibull distribution with a β

value of 0.54. Similarly, data set HB, with the exception of a few outliers, fits a Weibull distribution with a β value of 0.271.

This data therefore is less complex than the bipolar transistor data and both data sets from the rectangular connector information fit a Weibull distribution with a decreasing hazard rate.

Figure 7.17
Cumulative Hazard Plot for K1A

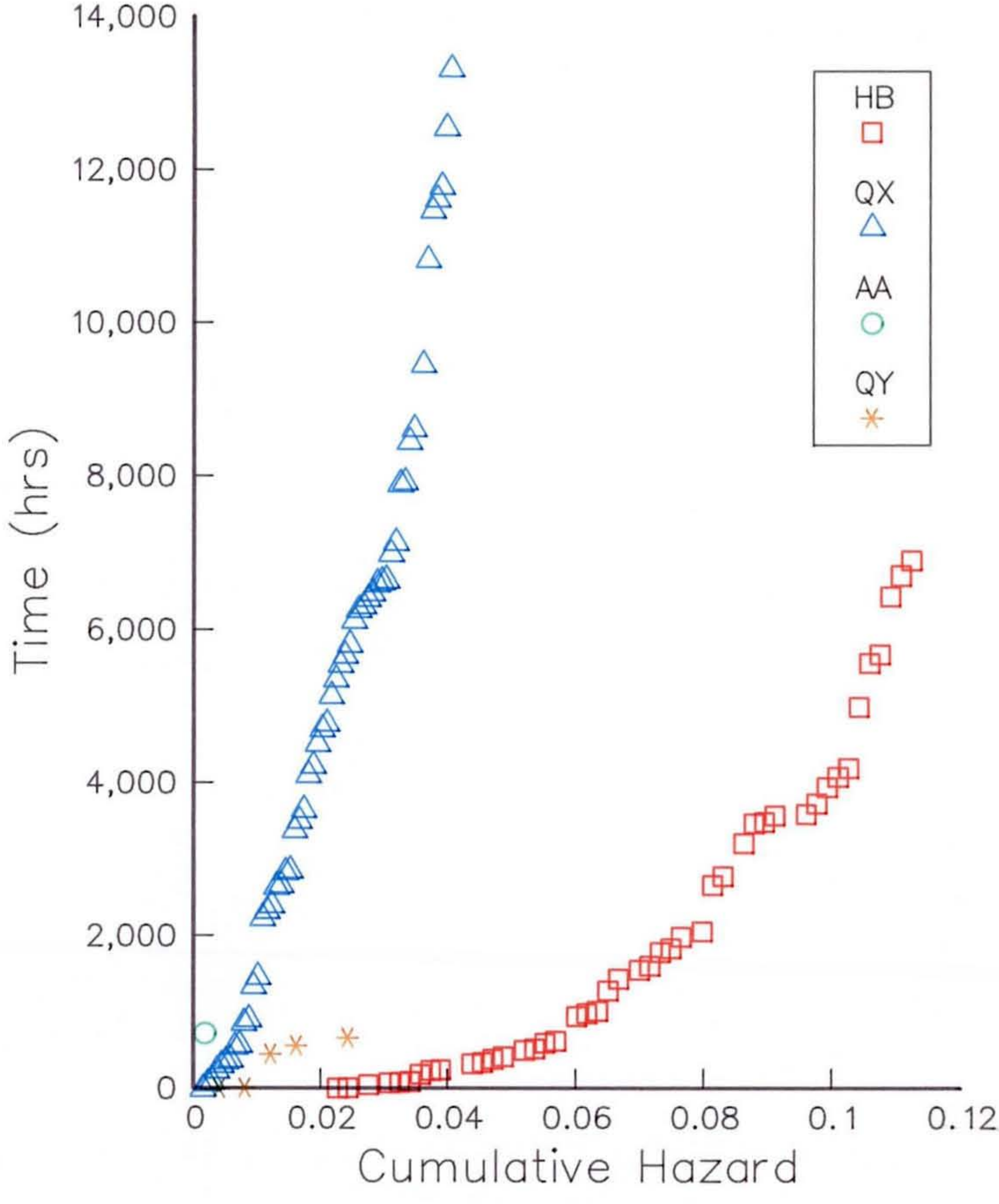
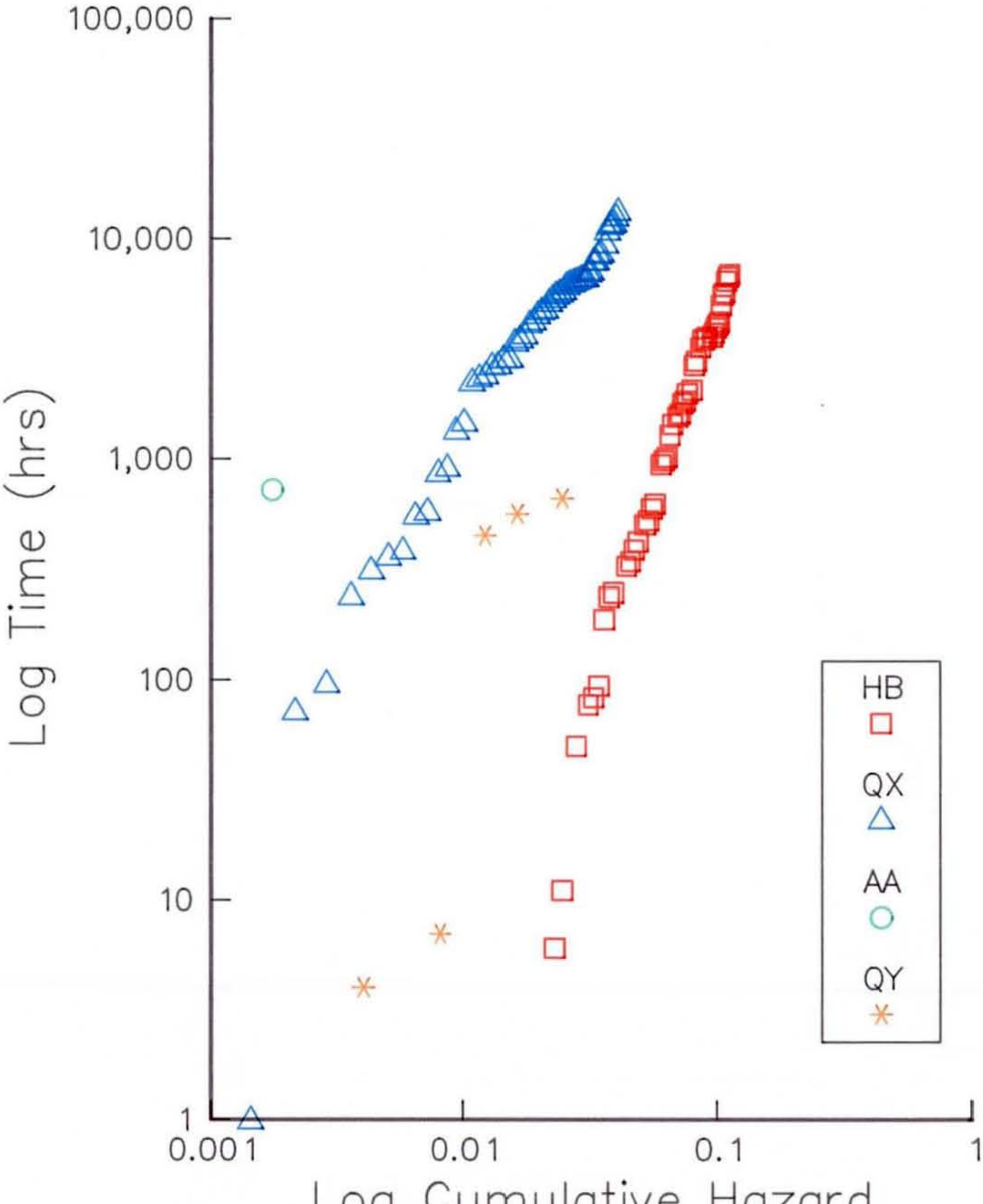


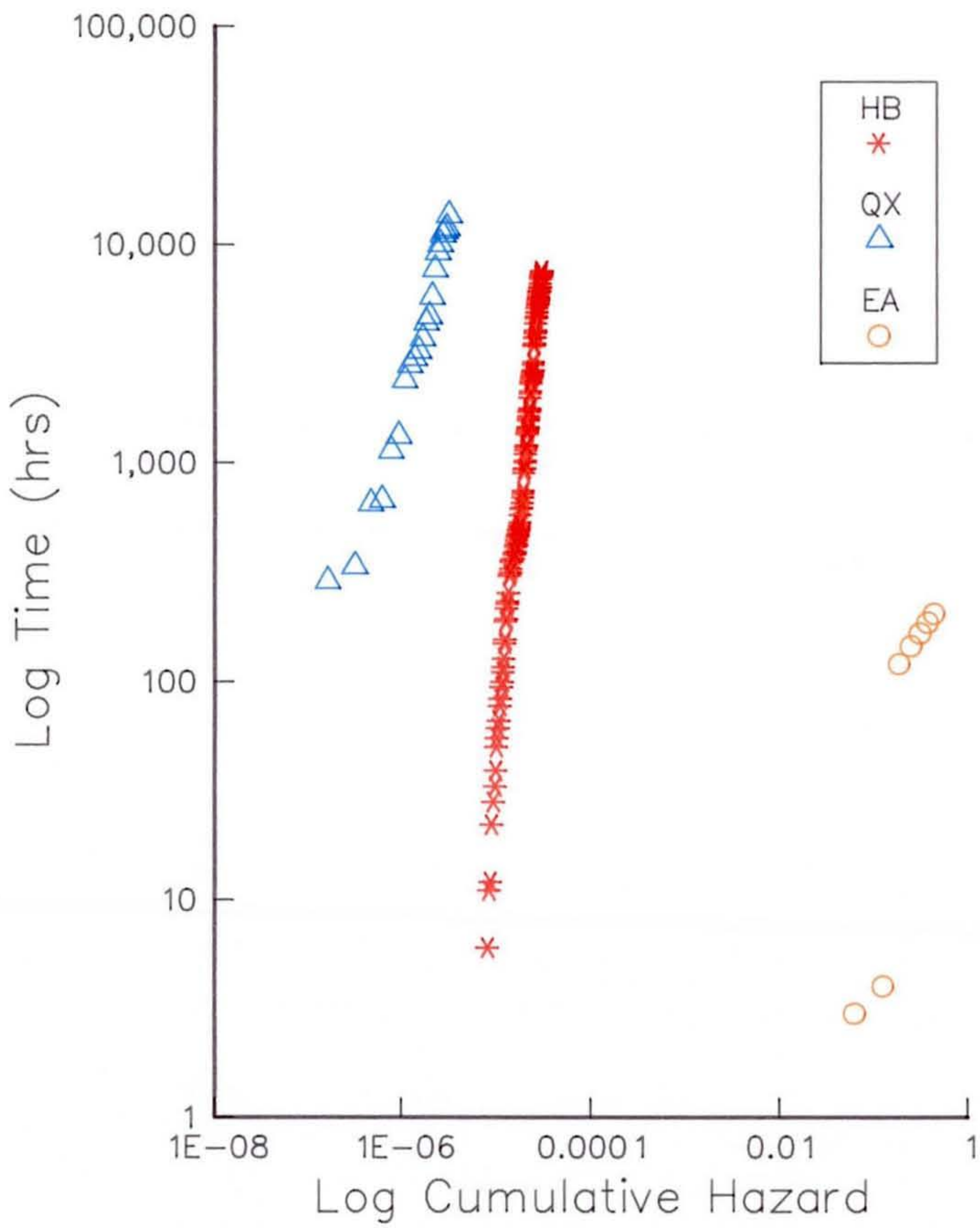
Figure 7.18
Log Cumulative Hazard Plot for K1A



7.6.4 Coil Activated Relays (B1A)

As in the rectangular connector data there is only sufficient data on two data sources and consequently a comparison of the effect of environments on the failure distribution is not feasible. Plotting the data on exponential paper did not give much information because data set EA masked the rest of the information. Figure 7.19 shows the data on log-log paper. Both data sets appear to fit a Weibull distribution each with different shape parameter. The β value for HB is approximately 0.154 and the β value for QX is 0.66. These results are consistent with those obtained for K1As and illustrate that although each data set has different β values both data sets follow a Weibull distribution with a decreasing hazard rate.

Figure 7.19
Log Cumulative Hazard Plot for B1A



7.6.5 Conclusions

Disaggregating the data too much can make the data seem sparse. However, it is important to know whether the data from different data sources follow the same empirical distribution before pooling the data. All the data analyzed in this section appeared to follow some form of Weibull distribution. However, there are some peculiarities between different data sources for bipolar transistors.

Both the results from K1A and B1A were consistent ie they showed that for the two different data sources with failure data, the failure distributions for K1A and B1A followed a Weibull distribution with β values less than 1. This may imply that the burn-in procedures for these components are not adequate and are resulting in the observed early life failures.

The data on bipolar transistors (T1A) produced more complicated results. For data sources HB and QY the data fitted a Weibull distribution with different β values both less than 1. However, data sources AA and EA both showed a mixture of Weibull distributions. These mixtures may be due to two different dominant failure mechanisms resulting in the change of the shape parameter. The cause of the change in β value for data set EA is likely to be due to the replacement of poor quality components for higher quality components. However, the likely cause of the change in the β value for data set AA is not yet known.

Table 7.4 shows a summary of the results of the hazard plotting of the three component types for different data sources. The overall conclusions from this are that all the data analyzed follows a Weibull distribution with a decreasing hazard rate and therefore it seems reasonable to pool the data from different data sources.

Table 7.4
Summary of Results

DATA SOURCES	COMPONENT TYPE	VALIDITY OF WEIBULL DISTRIBUTION	β VALUE	COMMENT
HB	T1A	YES	0.63	
AA	T1A	YES	1.92, 0.65	2 failure mechanisms possible
EA	T1A	YES	0.92, 0.24	
QY	T1A	YES	0.09	
HB	B1A	YES	0.15	
QX	B1A	YES	0.66	
HB	K1A	YES	0.27	
QX	K1A	YES	0.54	

T1A - Bipolar Transistors
K1A - Rectangular Connectors
B1A - Coil Activated Relays

The analysis of the bipolar transistor data between different environments showed that there is a difference in the shape parameters of components in ground mobile environments and those in ground benign environments. The results show that the β value for ground mobile data is less than that for ground benign data. However the difference is not large and may be spurious. These results are interesting because we would expect that components in GM would be screened to BS9000 level and therefore would be adequately burnt-in. However, the results of this analysis show that although the components are BS9000 screened they still exhibit a decreasing hazard rate. This implies that there are early life failures due to perhaps inherent defects which could have been found during burn-in. These results, however, should be used with caution since more data is necessary to substantiate these conclusions.

7.7 Summary

This chapter has illustrated the establishment of an analysis procedure for the reliability of electronic components. It has shown how components are chosen for further analysis and emphasised the importance of testing the data for design and replacement problems.

The technique of hazard plotting has been introduced and discussed with a sample data set.

Hazard plotting has subsequently been applied to pooled data for three different electronic components namely, bipolar transistors, rectangular connectors and coil activated relays. The results of these hazard plots showed that all three components follow a Weibull distribution with a decreasing hazard rate.

Hazard plotting techniques have also been used to investigate the differences between different data sources. The results of this analysis showed that all the data from the different data sources for each component type exhibited a Weibull distribution with a decreasing hazard rate. Particular peculiarities have been shown for the bipolar transistors from two data sources and possible causes for these peculiarities have been highlighted.

Finally, comparison of the distributional form of bipolar transistors in ground benign and ground mobile environments has been illustrated. As expected this showed that there is a difference in the shape parameters of their respective Weibull distributions.

Most importantly this chapter has shown that the electronic components analyzed do not fit the constant hazard rate assumption.

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8. THE PROPORTIONAL HAZARDS MODEL

8.1 Introduction

In this chapter we investigate the use of a distribution free regression approach to analyzing electronic component reliability data. The particular model which is employed is the Proportional Hazards Model (PHM).

As discussed in Chapter 2 it is usual to apply the model in a distribution free form, whereby it is utilised to investigate the significance of particular explanatory variables.

The PHM has been shown to be a very powerful method in a number of diverse reliability applications [1], [2]. In this chapter we illustrate the use and potential of the technique for analyzing electronic component reliability data. It is therefore not appropriate to provide, in this chapter, the detailed mathematical background to the model, the interested reader however is referred to [3], [4].

The data that has been analyzed by the PHM technique is the bipolar transistor data (T1A). From Chapter 7 it was seen that this data set had potentially more explanatory information than other component data sets contained in the database to date.

This chapter then, outlines the potential explanatory variables which can be incorporated and consequently discusses the appropriate models that may be formulated.

Results will be shown and conclusions given as to the appropriateness of applying such a model formulation to electronic component reliability data. In addition, tentative estimates of the minimum amount of information required to apply this technique will be highlighted.

8.2 Extraction of the Data for Analysis

To extract the bipolar transistor data from the database, firstly the variables of most interest to electronic engineers had to be selected, for example, environment, screening, mounting and encapsulation. Then, using the software discussed in the previous chapter (7), the variables corresponding to each failure and censoring time were extracted.

A problem arose in that the data matrix of the auxiliary information and all the censoring times was very large (in excess of ½million observations). The analysis programs available at Nottingham Polytechnic [1] therefore had to be modified to allow for the analysis of extremely large data sets. The data was ranked from largest to smallest time, with a column to indicate the rank of the observation. The files were then reduced by grouping the observations with the same rank and covariate information. In addition all the censored items after the last failure time were grouped together for each unique set of covariates and the frequency was held in the file. This reduced the file considerably ie from 12226 to 446 records. These modifications and their implications are discussed in an Appendix to the paper by Marshall et al. in [5]. These changes were implemented and the data was regarded as being in a form that allowed transformation to the data form required for PHM.

8.3 Potential Explanatory Variables

As mentioned in the previous section (8.2) the following variables were thought to be of primary interest, ie:

System Operational Environment
Screened Level
Data Source
Usage
Mounting Technology
Encapsulation Method

For the T1A data there was some information on all of these variables. To use the model each individual variable must be coded. For example, for a variable on two different levels, say environment on ground benign and ground mobile, a binary explanatory variable must be coded. In this analysis ground benign was coded as 0 and ground mobile as 1. The full coding for the T1A data is shown in Table 8.1.

Table 8.1
Covariate Coding

ENVIRONMENT	ENCAPSULATION	MOUNTING	CODE
Ground Benign	Hermetically sealed, glass ceramic	Radial wired	0
Ground Mobile	Hermetically sealed, sealant not known	Axial wired	1
	Hermetically sealed welded	Dual in line	2
	Plastic transfer molded	Surface Mount	3
	Hermetically sealed, solder	Flat pack	4

As shown in Table 8.1, there are two different environments ie ground mobile and ground benign, 5 different encapsulation methods and 5 different mounting technologies. Table 8.1 shows only the coding for each individual variable and does not imply any relationships between any of the variables.

In addition to Table 8.1, there is also data from 6 different data sources. Table 8.2 shows the coding for this information.

Table 8.2
Data Source Coding

DATA SOURCE	CODE
AA	1
QX	2
QW	3
QY	4
EA	5
HB	6

With regard to the screening level of bipolar transistors there is a problem. There is a lack of variability of screening methods within each data source. In fact, there is only one screening level for each data source.

Table 8.3 illustrates the relationship between screening, data source and environment.

Table 8.3
Relationship between Data Source, Screening and Environment

DATA SOURCE	SCREENING	ENVIRONMENT
1	BS9000	Ground Mobile
2	OTHER	Ground Benign
3	BS9000	Ground Mobile
4	BS9000	Ground Mobile
5	BS9000	Ground Mobile
6	OTHER	Ground Benign

From this table it can be seen that data sources 1,3,4 and 5 use BS9000 screened bipolar transistors and data source 2 and 6 use other screening levels. In addition, the system operational environment is also linked to data source and screened level ie data sources 1,3,4 and 5 operate in ground mobile environments with BS9000 screened components and data sources 2 and 6 operate in ground benign environments using other screened components.

Due to this information, covariates for screening level and environment could not be analyzed in the same model because of their direct relationship. Thus environment was included as a covariate but not screening level.

The information of most interest concerning encapsulation is the comparison between the reliability of components which are hermetically sealed and those that are plastic encapsulated. This is because in general hermetically sealed components are more expensive than plastic. Plastic encapsulated components are however not considered suitable for use in high humidity environments or for high temperature operation.

The inclusion of usage ie the percentage of time the equipment is operational is useful as an indication as to whether low use equipments which are most probably switched frequently on and off are less reliable than those equipments which operate continuously. This however may not be conclusive since there may be errors in the calculation of usage (as discussed in the previous chapter ie 7). However, it may give an indication as to whether the difference in figure for usage contribute to the failure of bipolar transistors.

All the information discussed was thought to be of great interest and would therefore be incorporated in a proportional hazards model. These variables include: environment, data source, usage, encapsulation and mounting.

8.4 Sparseness of the Failure Data

At the time of analysis, the population of bipolar transistors in the field was in excess of 586,000 with 121 failures. We therefore were looking at a very small data set with respect to the number of failures. The failure data broken down by environment, usage, data source, encapsulation and mounting for this data set is shown in Table 8.4

Table 8.4
Number of Failures broken down by the Covariates

DATA SOURCE	USAGE (%)	ENVIRONMENT	ENCAPS.	MOUNTING	NO OF FAILED COMPONENTS
1	27	1	0	0	2
1	27	1	0	4	1
1	27	1	2	0	39
2	90	0	1	0	1
3	7	1	2	0	1
4	5	1	2	0	20
4	7	1	2	0	1
4	8	1	2	0	1
5	5	1	0	0	30
5	5	1	3	0	1
6	23	0	0	0	1
6	23	0	0	1	2
6	23	0	2	0	17
6	23	0	2	1	1
6	23	0	4	0	3
					121

Table 8.4 shows the failure data matrix and the number of failures for each row. From this it is clear that the data matrix is very sparse. Table 8.5 lists some of the features of this data matrix.

These data problems noted in Table 8.5 restrict the number of covariates used in the model because of the lack of variability across each cell. As a result of this lack of variability in the data it has been found necessary to look at two separate models, these two models are:

Model 1 The Data Source Model
Model 2 The Environment Model

Table 8.5
Conclusions from Table 8.4

1.	Companies 2 and 3 have only 1 failure respectively.
2.	With 117 out of 121 failures occurring with mounting type 0 (radial wired) there is insufficient information to make comparisons of different mounting.
3.	Usage is highly associated with data source so that the inclusion of covariates for both company and usage would result in the problem of multicollinearity ie linear relationship between data source and usage [1].
4.	There is only one failure for plastic encapsulated devices, therefore comparisons between plastic and hermetic are impossible.
5.	As previously discussed, environment is related to data source.
6.	There are only 25 failures in ground benign compared to 96 failures in ground mobile. However, it is important to note that there are more censoring points in ground benign than in ground mobile. In addition, failures in ground benign are almost totally associated with company 6 (only 1 failure from company 2). Due to the lack of variability in the data for ground benign, it was not possible to include both data source and environment in the same PHM model. Two models were therefore implemented.

The conclusions from the application of these models can be found in the following section.

8.5 The Proportional Hazards Analysis of Bipolar Transistors

8.5.1 Introduction to Proportional Hazards Modelling

The Proportional Hazards Model is structured upon the hazard. It is assumed for each bipolar transistor that the associated hazard function can be decomposed into the product of a base-line hazard function, common to all bipolar transistors, and an exponential term, incorporating the effect of the values of the explanatory factors specific to each individual component, ie:

$$h(t,z_1,z_2,.....z_k) = h_0(t)\exp(\beta_1 z_1 + \beta_2 z_2 +..+\beta_k z_k) \qquad (8.1)$$

where z_i's are the values of the explanatory factors, $h_0(t)$ is the base-line hazard function and t is the operating hours to failure. The z_k values can either be measured values or indicator values representing, for example, different data sources. The β_k values are unknown parameters of the model and represent the effect on the hazard of the explanatory factors. The β_k values are required to be estimated and tested to see whether each explanatory variable has an effect on the variation on observed times to failure. These explanatory variables are assumed to have a multiplicative effect on the base-line hazard function so that for different values of the explanatory factors, the hazard functions are proportional to each other over all time t.

The base-line hazard function $h_0(t)$ represents the hazard a component would experience if the explanatory factors all take the value of zero.

As discussed earlier because the covariates for data source almost solely define the other information available and the lack of variability within the other variables, the initial analysis of Model 1 concentrates on using covariates for company only. In addition, because environment is of interest and is related to data source, the second model concentrates solely on the effect of environment.

8.5.2 The Data Source Model (Model 1)

Before applying this technique it is important to look at the pattern of failures through time for each data source. Figure 8.1 illustrates operating time to failure for each data source. From this it can be observed that there is only one failure for companies 2 and 3 and that company 4 has 8 failures at 0 hours. Notice also that company 6 has a gap in data between about 1600 hours and 3500 hours. The reason for this would need to be investigated by contacting the appropriate company. In addition companies 4 and 5 have earlier and fewer failures compared to companies 1 and 6.

Since data source 6 is the data set associated with ground benign, initially the model took that as the base. In addition, due to the small number of failures for data sources 2 and 3, these were also included in the base. From this there were therefore covariates for data source 1, 4 and 5 to compare against the base, ie:

$$h(t,z_1,z_4,z_5) = h_0(t)\exp(\beta_1 z_1 + \beta_4 z_4 + \beta_5 z_5) \tag{8.2}$$

Using the distribution free approach the β values can be estimated. The detail of the methodology of this approach is not developed here. However, reference can be made to [6], [7], [1].

The distribution-free approach first iteratively estimates the effects of the covariates using the partial likelihood. This technique, essentially, employs a method of scoring based upon a Taylor series expansion for each step in the iteration, for maximising the partial likelihood, starting with initial values of zero. After convergence, tests on whether each explanatory variable has any significant effect are based upon the asymptotic normality of the estimates. A stepwise

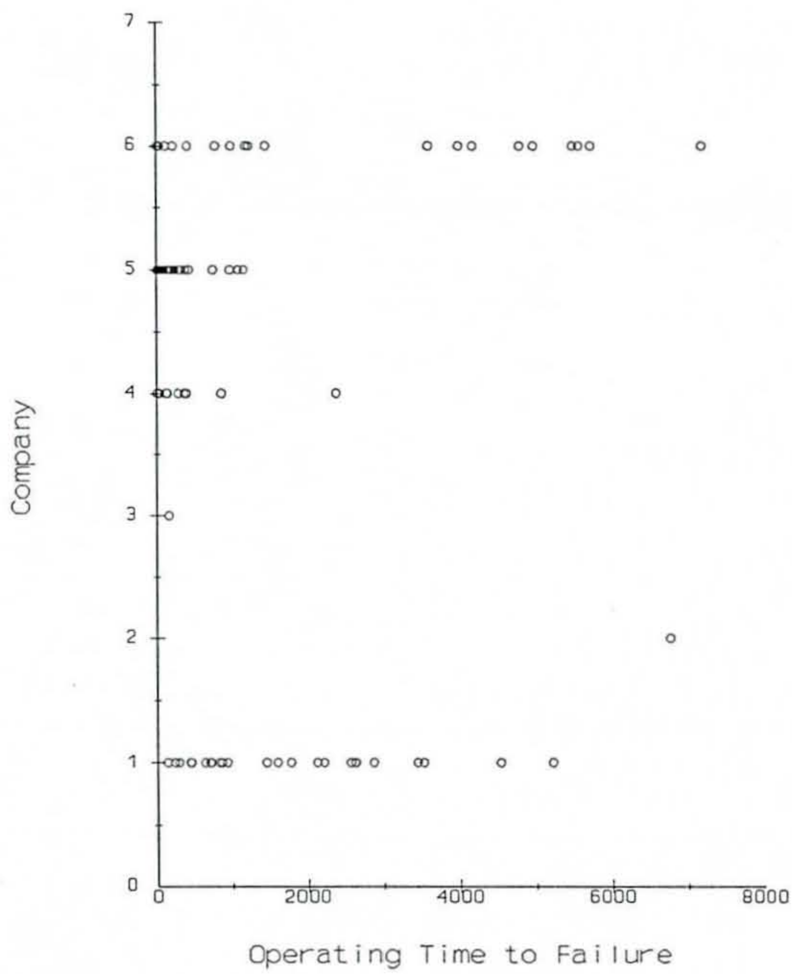


Figure 8.1
Plot of Data Source against Operating Time to Failure

regression procedure is then incorporated into the model. In the backwards procedure, non-significant explanatory factors are excluded one at a time and the model rerun until all factors are significant.

Chi-squared tests can also be conducted for the explanatory ability of the whole set of covariates included. This test is based on the Likelihood Ratio Statistic and compares the likelihood under the fitted parameter values and under the assumption that they are all zero [3].

After the estimation of the covariates $\beta_1,...\beta_k$, a distribution-free estimate of the base-line hazard function is obtained. This is based upon discrete hazard contributions at each of the times at which failures were actually observed to occur. By plotting the estimated base-line hazard function on appropriate hazard paper, comparisons to particular standard distribution forms can then be made.

8.5.3 Results and Diagnostics of The Data Source Model

The software developed at Nottingham Polytechnic uses a backward stepwise regression procedure. A problem was encountered in the analysis of the model in equation 8.2. This was a problem of near monotonicity [8] for the covariate for data source 4. The problem of monotonicity occurs when there is little overlap of failure times between the covariates. Looking at covariate 4 then in Figure 8.1, it can be seen that the majority of failures for data source 4 occur before the first failure of data source 1. In fact over half the failures for this data source occur in the first hour of observation and therefore there is no overlap between these failure times and the other data source failure times. Apart from data source 5 with one zero hour failure, data source 4 is the only one to encounter switch on problems. This indicates therefore that covariate 4 would be infinitely worse than the other covariates which is obviously not the case. The most immediate solution to this problem is to omit the covariate from the analysis. However, as an alternative to dropping data source 4 from the analysis, the base can be changed. The base was therefore changed to data source 2, 3 and 5, and the model was then:

$$h(t,z_1,z_4,z_6) = h_0(t)\exp(\beta_1 z_1 + \beta_4 z_4 + \beta_6 z_6) \qquad (8.3)$$

Using the backwards stepwise regression model, covariate 4 was firstly eliminated. The elimination criteria is based on the p-values. The p-values give the probability of extreme values occurring by chance. Thus a small p-value indicates a highly significant covariate. When a covariate is eliminated it is then contained in the base and the model is then rerun. Thus the new base contained 2, 3, 4 and 5. After the second iteration of the stepwise regression, covariate 6 was eliminated and finally convergence was reached with one significant covariate remaining. Table 8.6 shows the β values, the z-scores (normal deviates) and p-values for this analysis. The z-scores test the null hypothesis that the significant variables are equal to zero against the two sided alternative that they do not equal zero.

Table 8.6
Results of Data Source PHM Model

DATA SOURCE	β VALUES	Z - SCORE	p - VALUE (ONE SIDED)
1	-0.74	-0.387	0.001
4*	-0.11	-0.348	0.348
6*	-0.37	-1.508	0.066

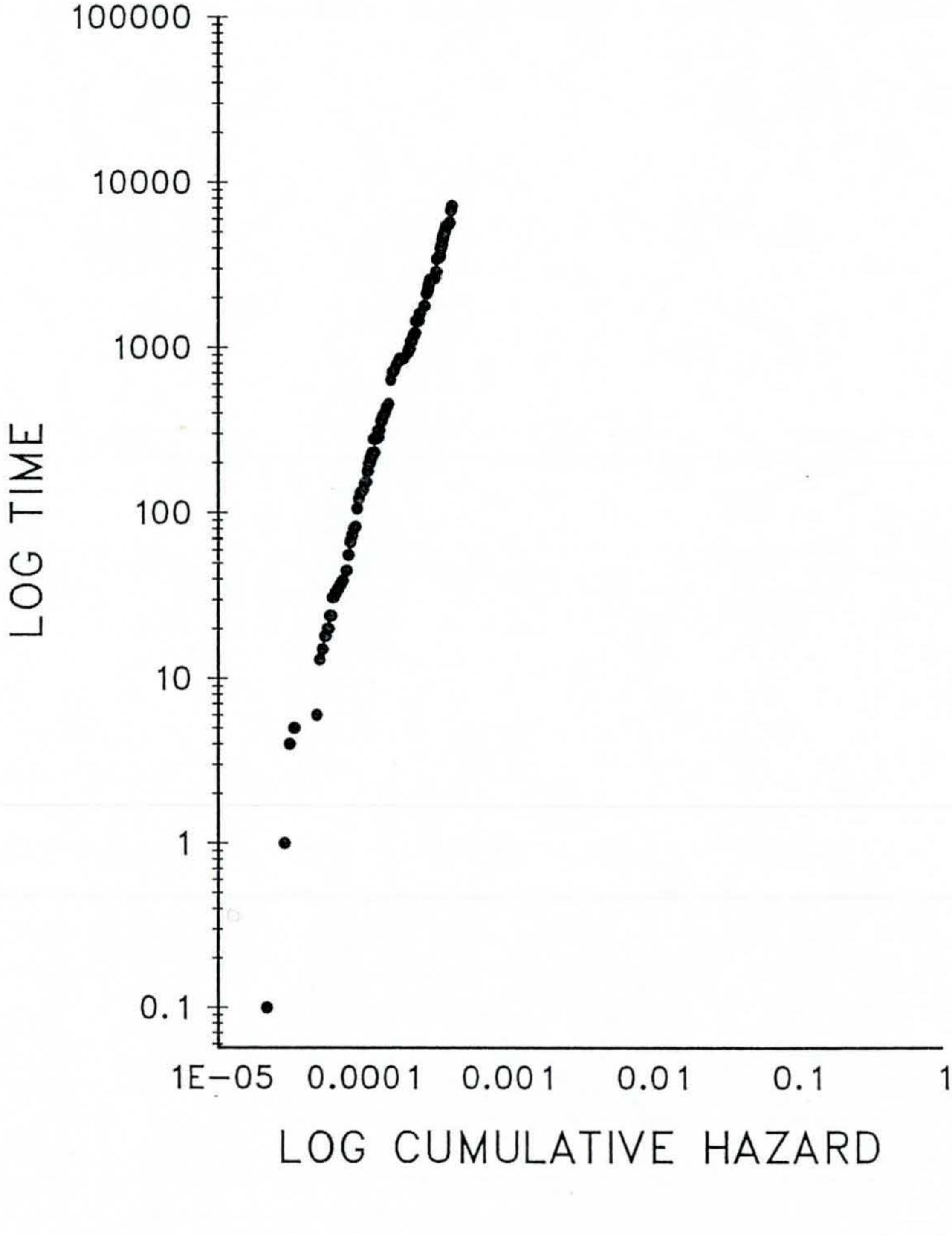
* Values when covariate omitted from model

From Table 8.6, covariate 1 is seen to be the only significant variable. Also the β coefficient, seen in the table, for data source 1 (-0.74) indicates that the hazard for this company is smaller than for the rest and thus on average the operating times to failure for bipolar transistors from company 1 are longer than for those from other companies. The significance of the β value means that data source 1 is statistically different from the rest of the data sources.

A Weibull hazard plot for the base-line hazard for this analysis is shown in Figure 8.2. The straight line on the plot indicates the appropriateness of the Weibull distribution for the base-line. The value of the shape parameter taken from the plot (0.32) indicates a decreasing hazard which is consistent with the analysis in the previous chapter (7). Note also that if we considered the first four points as coming from a different Weibull distribution, the resultant shape parameter would be even lower than the overall hazard. In addition this result contradicts the assumption of constant failure rate for bipolar transistors.

FIGURE 8.2

Base-Line Hazard Plot for Data Source Model



In order to evaluate the appropriateness of the PHM to this data two diagnostic tools can be employed, ie Proportionality plots and Cox and Snell residual Plots [9], [3], [10], [11], [12], [13].

The most commonly applied method for testing the proportionality assumption is a proportionality plot. This plot is obtained by splitting the data on the significant covariate and running the analysis procedure on the 2 levels of the covariate. In this case the two groups correspond to data source AA (coded as 1) and all the other data sources. The diagnostic is obtained by plotting for each stratum, the log cumulative base-line hazard against time [3], [11]. If the proportionality assumption is valid then the plot should show constant vertical separation between the groups. This constant vertical separation should correspond to the significant value of β obtained from the analysis. This is only the case for models with one significant covariate.

Figure 8.3 shows a proportionality plot for the significant covariate (data source AA). This plot shows approximately a constant vertical separation and from experience this implies that the proportionality assumption is valid.

The second diagnostic tool which assesses the goodness of fit of the PHM is provided by the Cox and Snell variance stabilised residual plot [12], [13]. If the model is appropriate then the residuals which are defined to be

$$\hat{e}_i = \hat{H}(t, z_1, z_2, \ldots z_k) \qquad (8.4)$$

should be similar to a sample drawn from the unit negative exponential distribution. The observed residuals are calculated from equation 8.4 and the expected residuals can be shown to be defined as:

$$\hat{e}_i = -\ln\widehat{R}(e_i) \qquad (8.5)$$

where $\widehat{R}(e_i)$ is the product limit survivor function [2].

FIGURE 8.3

Proportionality Plot for Data Source Model

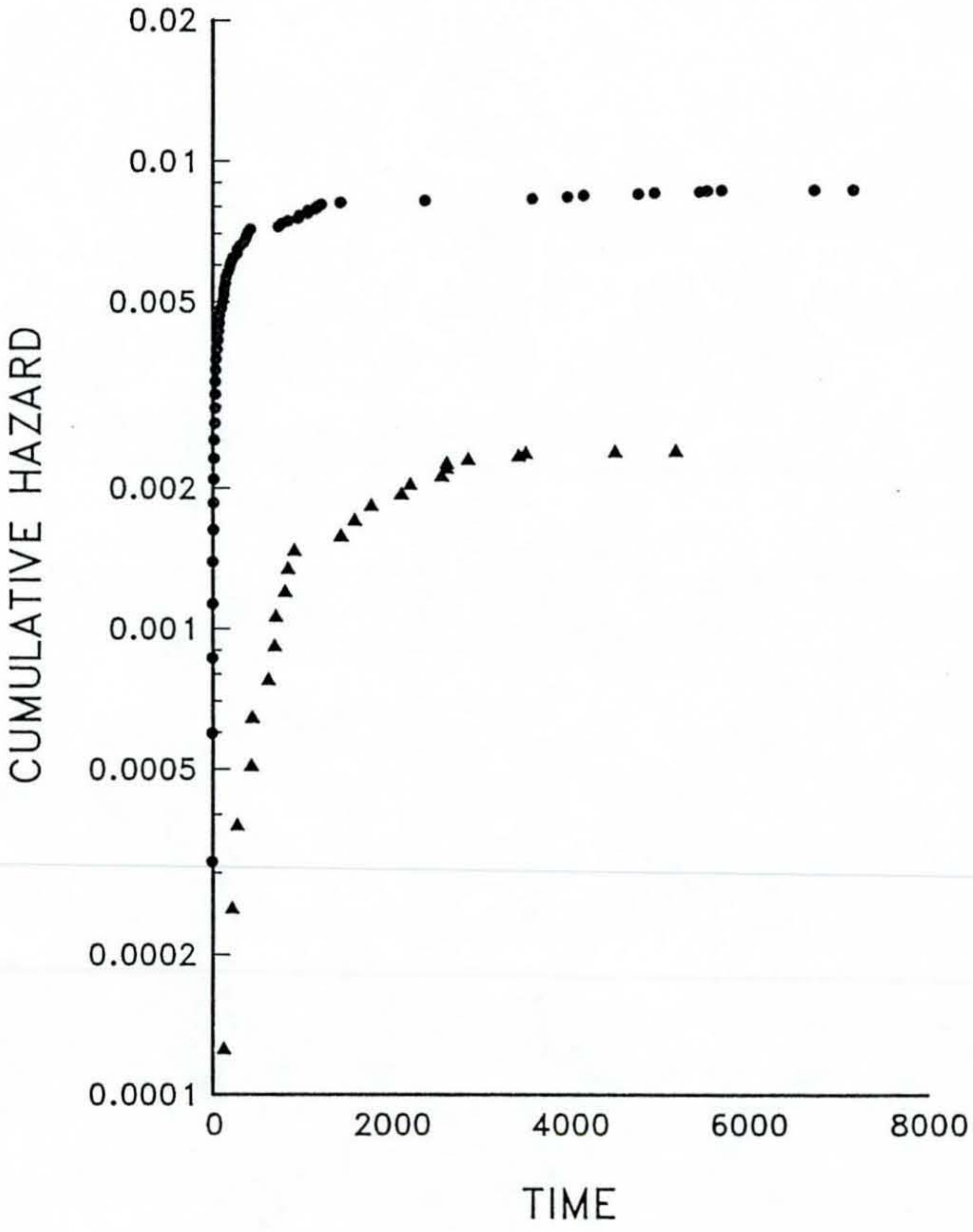
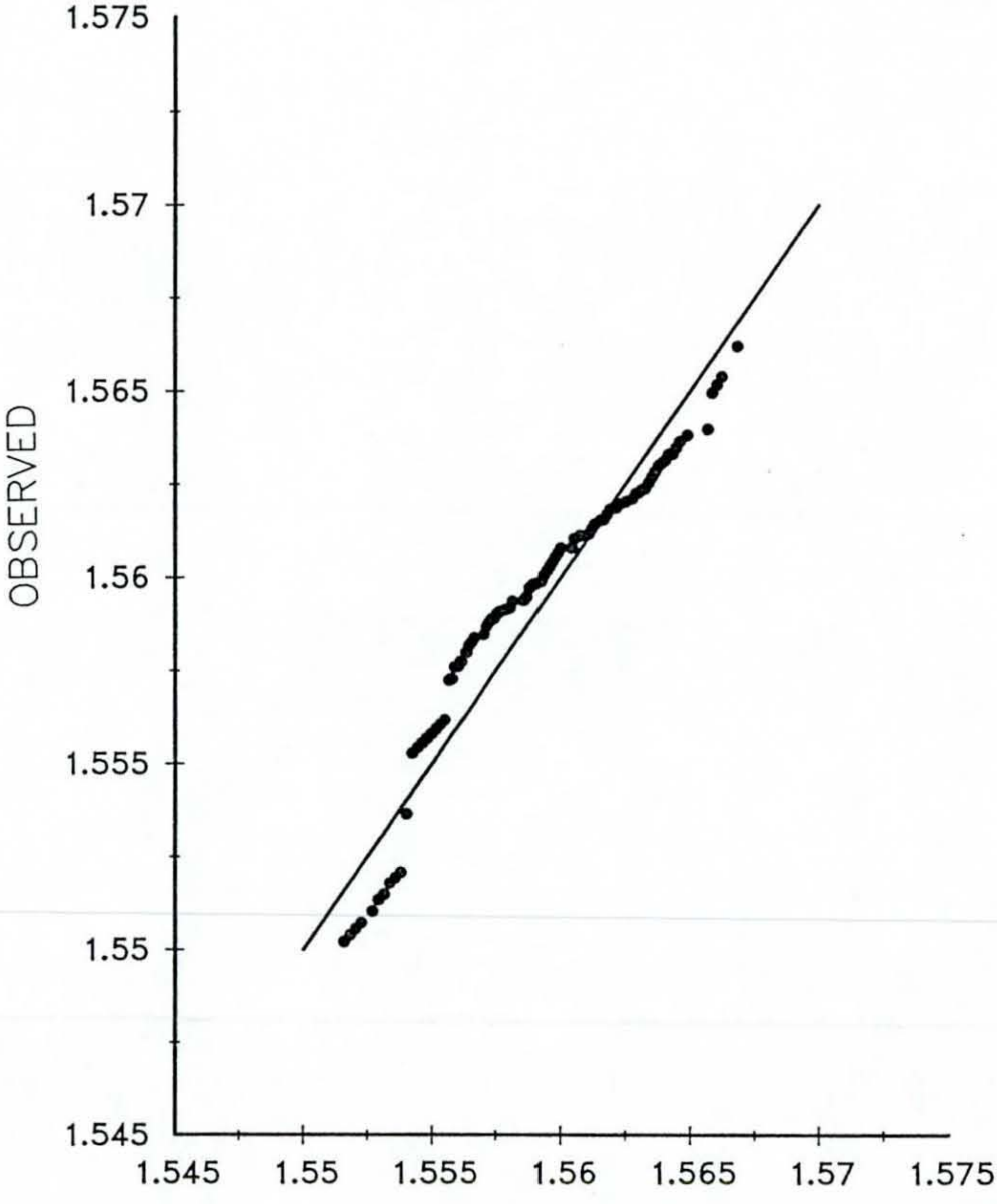


FIGURE 8.4

Variance Stabilised Cox and Snell Residuals

for Data Source Model



Hence plotting the observed residuals against expected residuals should give a 45 degree line through the origin. Figure 8.4 shows such a plot. From this the residuals, transformed to stabilise the variance, appear to follow approximately a 45 degree line, showing the model is a good fit to the data.

The two diagnostic tools discussed above show that the results obtained from the data source model are valid.

8.5.4 The Environment Model (Model 2)

Due to the problem of multicollinearity it was not possible to include both data source and environment in the same model. However, because the effect of environment is of primary interest to engineers, a separate model for environment was constructed. This model investigated the difference between bipolar transistors operating in ground benign and ground mobile environments.

There are 25 failures in ground benign of which 24 are from data source 6 (HB) and 96 failures in ground mobile. Using ground mobile as the base the proportional hazards model is:

$$h(t,z_1) = h_o(t)\exp(\beta_1 z_1) \tag{8.6}$$

Using the full data set the effect of ground benign on the base-line hazard can be estimated using the proportional hazards approach.

8.5.5 Results and Diagnostics of The Environment Model

The significant coefficient for ground benign was found to be -0.741. The z-score was found to be -3.190 and the one sided p-value was 0.0007, indicating the significance of the result. This shows that ground benign has a lower hazard than ground mobile. This result is as expected since ground mobile is a far harsher environment than ground benign. We would therefore expect that the hazard for components operating in ground mobile environments would be higher than those operating in ground benign environments.

To evaluate whether the results from this model are valid, a proportionality plot and a Cox and Snell residual plot are shown.

Figure 8.5 shows the proportionality plot for the environment model. From this it can be seen that there is constant vertical separation between the two groups and therefore the proportionality assumption is not violated.

In addition looking at Figure 8.6 the Cox and Snell variance stabilised residual plot it can be seen that the model is a good fit and consequently the result that bipolar transistors in ground benign environment exhibit a lower hazard than those in ground mobile is valid.

The base-line hazard plot estimated from this model is almost identical to that in Figure 8.2. This is because of the lack of variability in the data analyzed. It therefore shows a good fit to the Weibull distribution with a decreasing hazard. Due to the proportionality assumption the bipolar transistors in ground benign environments will follow a Weibull distribution but with a different shape parameter from that of the base-line distribution.

FIGURE 8.5

Proportionality Plot for The Environment Model

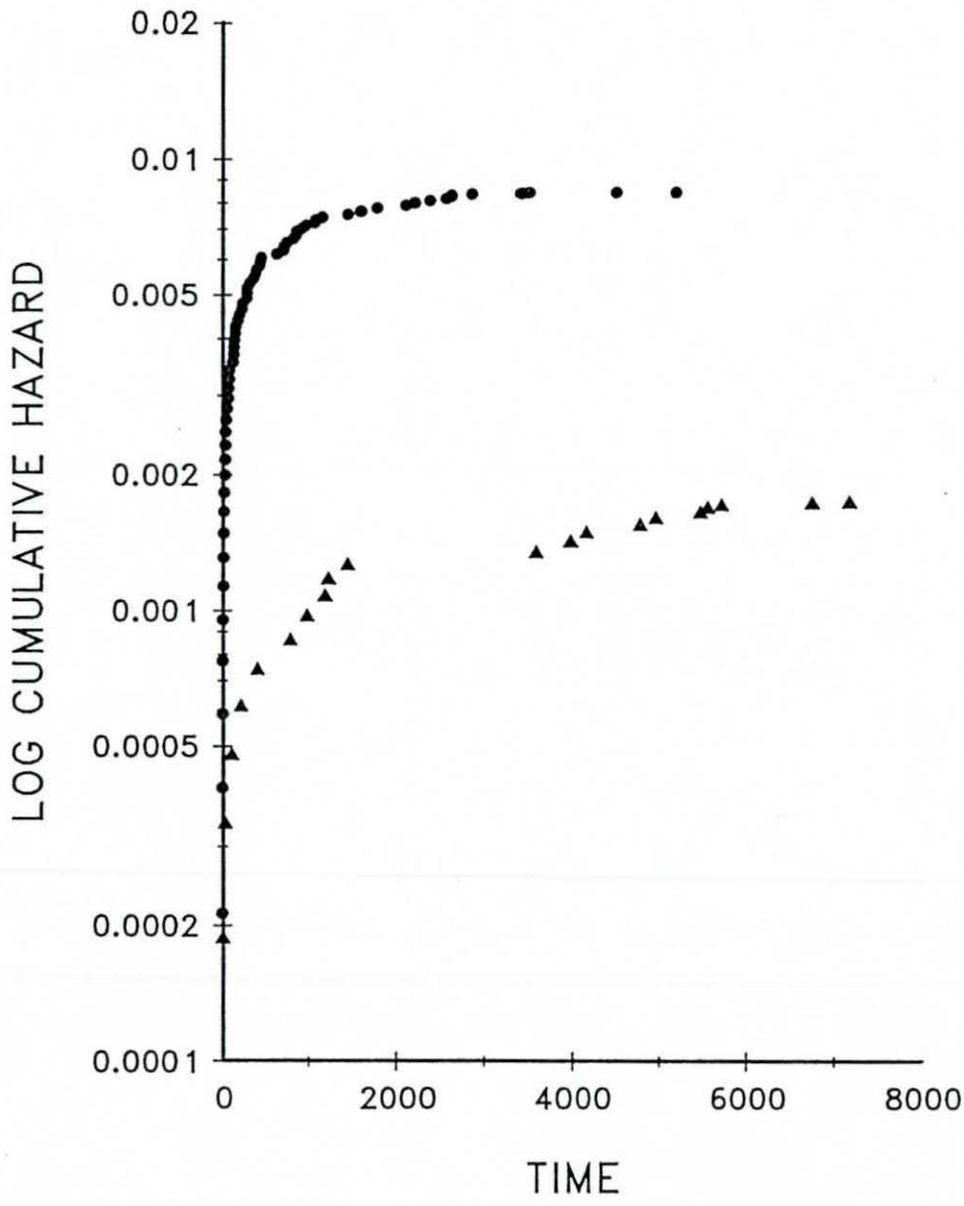
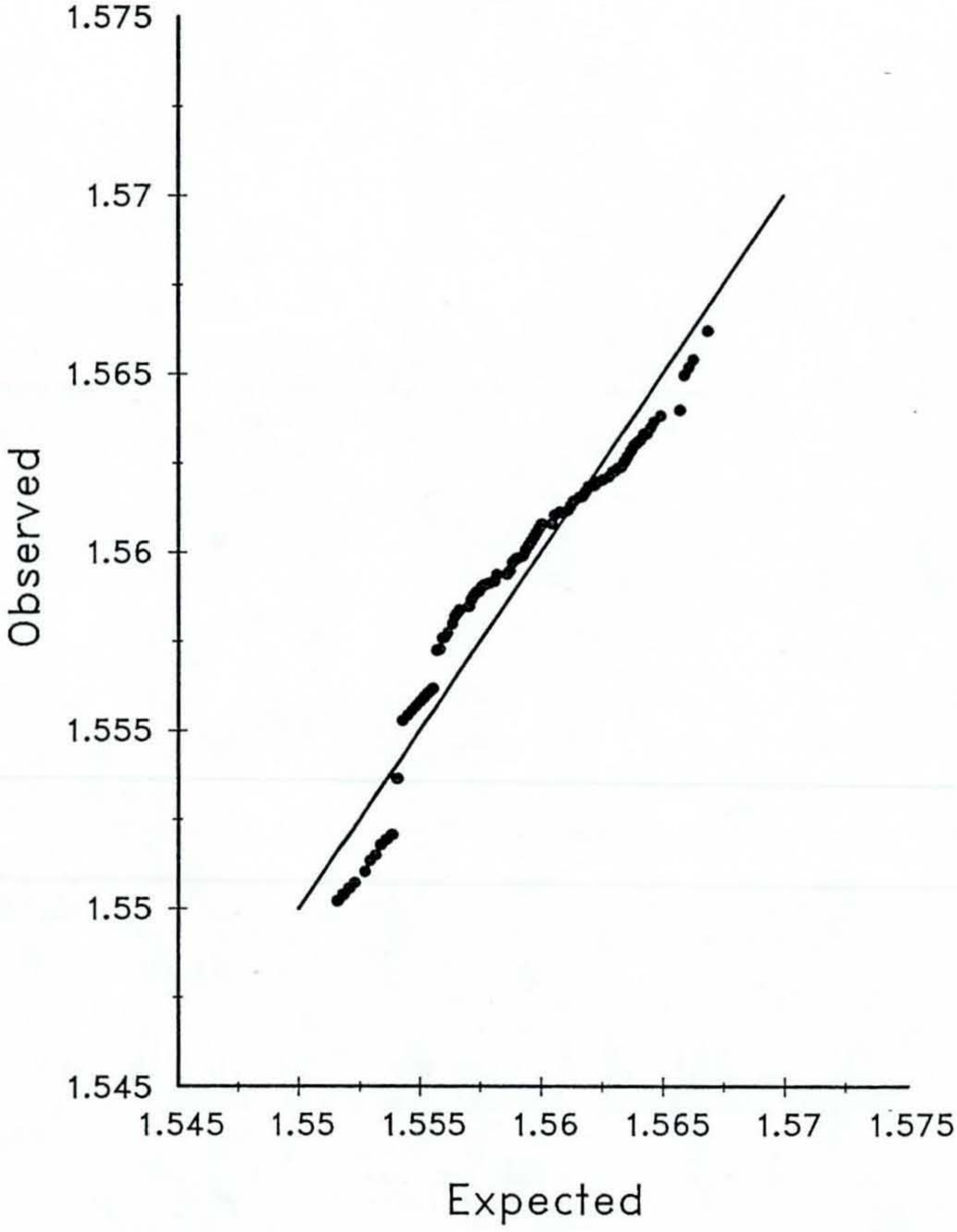


FIGURE 8.6

Variance Stabilised Cox and Snell Residual Plot for The Environment Model



8.5.6 Conclusions of the Proportional Hazards Analysis

This analysis has shown that PHM can be applied to electronic component reliability data and in particular bipolar transistor reliability data.

However, there have been challenges in this application with respect to the large amount of censoring information and the sparseness of the failure data when broken down by the potential explanatory factors.

This sparseness in the failure data resulted in only two limiting models being employed. The first model looked at the difference in the behaviour of bipolar transistors from different data sources. The results of this analysis showed that one data source (AA) had a lower hazard than the rest and that the base-line hazard function showed a Weibull distribution. The diagnostics validated the appropriateness of the model.

The second model compared the behaviour of bipolar transistors in ground mobile environments to the behaviour of those in ground benign environments. This analysis concluded that bipolar transistors in ground benign environments exhibit a lower hazard than those in ground mobile environments. Again the diagnostics validated the appropriateness of the fitted model.

The results of the total analysis using both models are not surprising and correspond to those obtained by hazard plotting in the previous chapter (7). Since the application of PHM to highly censored data is not straightforward, is it worthwhile applying this technique if similar results can be obtained using simpler techniques? Although the results of this analysis have been limited, this was due to the sparseness of the data. Therefore in the future, when there is more data available across different covariates perhaps this method may be even more enlightening.

The problem of the direct relationships between data source, environment, screening level and usage will probably not disappear in the near future because of the way in which the data is collected. However, we may be able to look at the interaction between environment, data source and usage in future analyses. Due to data limitations this analyses cannot be carried out at present.

In addition, the covariate data source is vague in that there is likely to be great variations within each company which may be unmeasurable. In particular, the covariate for data source will include the data collection methods. Thus comparison between data sources may only highlight the difference between data collection methods within the companies. Perhaps one of the conclusions of this analysis is that more information is required about the data collection methods used by different companies. For example, why are there so many 0 hour failures for data source QY (coded as 4) and why is there a gap in failure times for data source HB (coded as 6). This type of information is crucial in determining the true failure distribution of electronic components in the field.

To conclude, this present analysis of bipolar transistors using PHM has been invaluable in providing experience in the steps required to transform the data into the required format for PHM and in identifying gaps in the data. It has also shown the potential benefit of using this technique provided there is sufficient data.

In addition, it has reinforced the conclusion that, as well as the other component categories analyzed in Chapter 7, the bipolar transistors under study do not in fact follow a constant hazard rate but exhibit a Weibull distribution with a decreasing hazard.

8.6 The Future Application of PHM

As mentioned in the previous section, the PHM analysis of bipolar transistors (T1A) was reduced considerably because of the lack of failure data in each cell, as shown in Table 8.4. However, when more failure data is input to the database, how much more would be required for a more definitive analysis of the factors shown at the beginning of section 8.3 and in Table 8.1 and what models could subsequently be applied?

Firstly, it should be noted that a covariate for usage may never be used because of the relationship between usage and data source. This relationship may never change even if more data becomes available. Secondly, screening level is synonymous with environment at present. However, this may well change in the future. Thus it is not likely that a covariate for usage will ever be used in future PHM models of T1As. However, this is not the case for screened level.

This analysis is not true for environment, data source, encapsulation and mounting. The reason for not including covariates for encapsulation and mounting in the previous analyses was due to the sparseness of the failure data, ie most of the failure information was on hermetically sealed components and only 1 from plastic and most of the mounting information was on radial wired mounted components. Thus no comparisons could be made. Environment and data source could not be included in the same model because the failure data in ground benign environments came from one data source. This lack of variability in the GB data introduced a problem of multicollinearity.

What data therefore is required to be able to construct a model which will include environment, data source, different encapsulation methods and different mounting technologies? It is not possible mathematically, in this discussion, to predict the number of failures required in each cell which will allow such a model to be constructed and analyzed. Such a discussion has not previously been mentioned in the literature available on PHM. However, tentative suggestions can be made and the formation of such models constructed to give some idea as to the potential use of PHM.

Figure 8.7 shows a flowchart of the groups of information available at the present time. The flowchart shows a hierarchy of the relationships between the data items. The data items shown in this figure are those for which there is at least some information ie failed or non-failed. Thus from this flowchart comparisons between different encapsulation methods, different mounting techniques etc. could be made providing the number of failures for each covariate was reasonably large and balanced between the covariates.

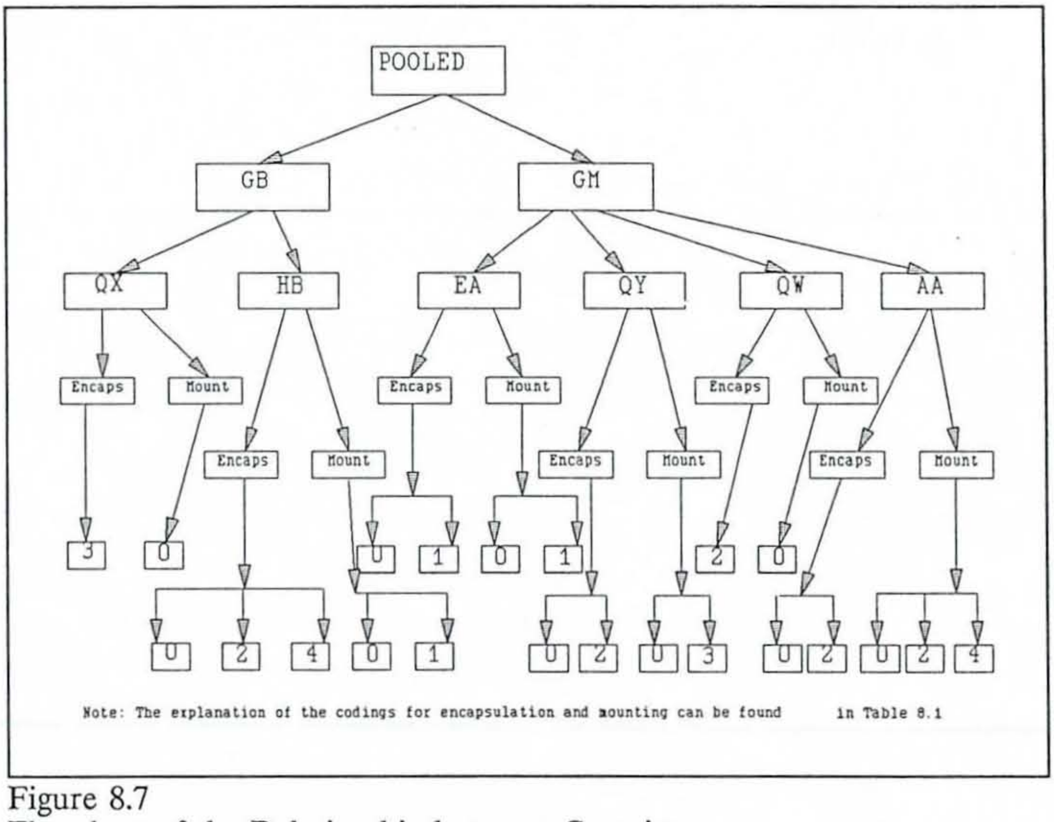


Figure 8.7
Flowchart of the Relationship between Covariates

We now concentrate more closely on mounting. Figure 8.7 illustrates a flowchart for mounting. If a model incorporating the effect of different mounting technologies was constructed and if there were at least 50 failures of each type of mounting then such a model could be analyzed. This does not imply that there would be any significant results as this depends on the amount of censoring information, the actual operating times to failure and the number of failures within each cell. However, assuming there is not a problem with monotonicity in the failure times of particular covariates then this model could be implemented.

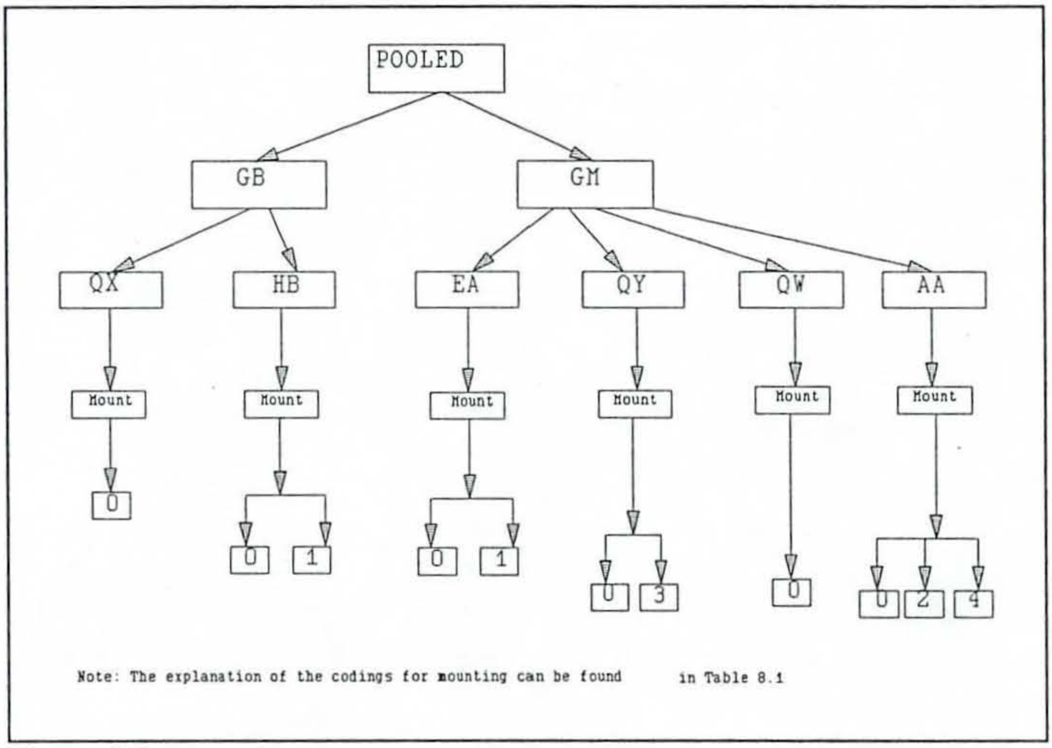


Figure 8.8
Flowchart of Covariate Mounting

If then we wanted to construct a model which not only investigated the significant differences between different mounting technologies but wanted to include data source and environment, would this be possible?

There would be a slight problem with some of the mounting covariates if data source was included as a covariate. In particular, at present mounting types flat pack, dual in line and surface mount are each associated with only one data source. This lack of variability within data source would cause a problem in the implementation of such a model. It would therefore be possible to include radial wired and axial wired as covariates for mounting. This model then could have covariates for environments GB and GM, for data sources QX, HB, EA, QY, QW and AA and for mounting technologies radial and axial wired. Again, providing there were, say, at least 50 failures in each of these cells then this model could be implemented.

If we now consider encapsulation methods, then a similar approach could be made. Figure 8.9 shows a flowchart for the different encapsulation techniques with data available. If we consider a model for encapsulation only then we could compare all of these encapsulation methods providing each cell had more than about 50 failures each. In addition, a comparison between plastic and hermetic could be included in such a model.

However, if we included data source and environment in such a model problems may occur similar to those discussed in the mounting example. Because at present data for plastic transfer moulded and hermetic sealed (sealing method unknown) are associated with only one company then there would be a problem incorporating both data source and these encapsulation methods as covariates in one model. Thus at the moment, we may construct a model which compared 3 different hermetic encapsulation methods, data source and environment. However, again providing there were at least 50 failures in each cell, such a model could be implemented.

These hypothetical models which have been described also have limitations. However, such limitations may be overcome by using covariates of interactions between certain variables. For example, looking at the encapsulation model, if we constructed covariates for environment then for the interaction between data source and encapsulation we could in fact use both the data on plastic devices and hermetically sealed devices. The results of such an interactive model would point us to those significantly different interactions from the base. The data

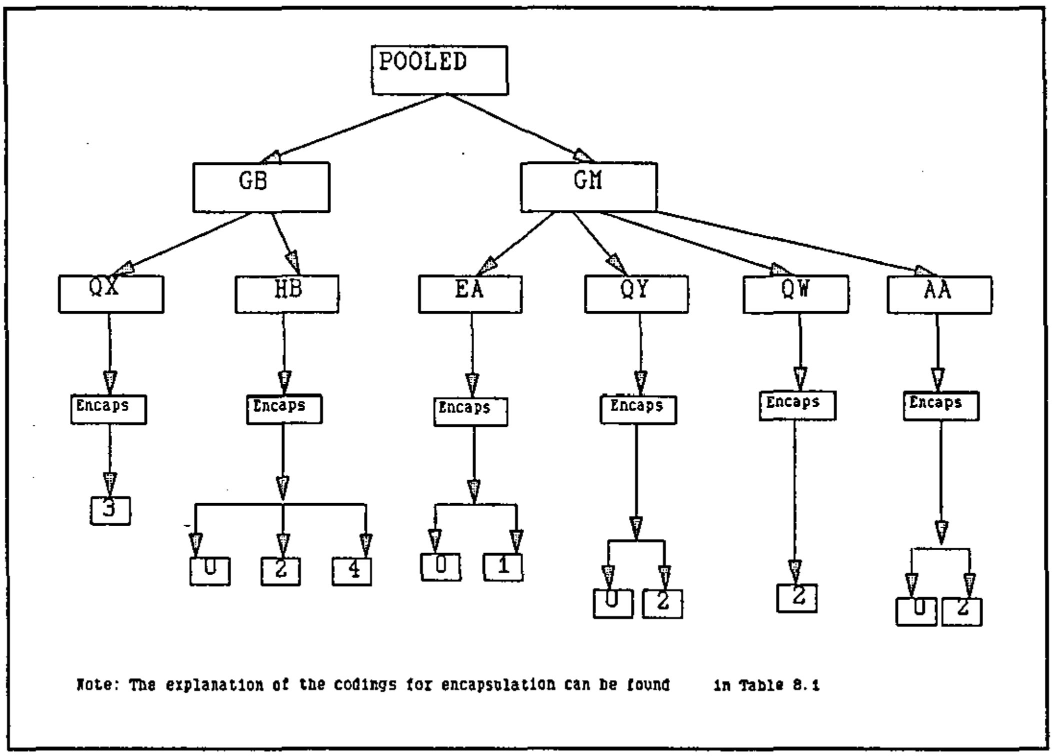


Figure 8.9
Flowchart of Encapsulation Coding

required for the implementation of such a model would include sufficient failures

in each cell.

In these examples of constructing models for bipolar transistors, the total number of censored events required within each cell has deliberately been ignored. This is because it is impossible to state any specific number. However, the amount of censored events on bipolar transistors that is presently available in the database is vast (in excess of 500,000). It is therefore likely that there will be enough censored information to implement such models. However, in the case of the interaction models, there may well be too much censoring information for the PHM programs to be able to deal with successfully. This may well be a further problem in the future which will have to be considered.

This section has investigated potential proportional hazards models using the data groups which we already have on bipolar transistors. The models discussed were initial ideas on where to start if there was sufficient data. PHM should be done in such an exploratory manner. Thus after implementing the suggested models further models could be implemented by perhaps using the results of each analysis to point to the most interesting covariates.

In addition some tentative numbers of failures have been mentioned which would be required to implement any of the models. Thus looking at Figure 8.6 again, if we had, for example, 150 failures for each data source, this would probably allow the above mentioned models to be implemented provided the data was balanced between the different covariates ie not weighted towards any one in particular.

From this the total number of pooled failures for bipolar transistors would have to be around 1,000. To achieve this number of failures may take a long period of time. In addition, if the number of failures and censored events increase with the same proportion as at present then the database will be totally swamped with censoring information which may introduce further complications into the implementation of PHM.

The discussion in this section was based on experience of the data and speculation as to a sufficient number of failures required to implement a particular model. It was not possible to mathematically give such a number as this has not been mentioned in any of the PHM literature to data.

To conclude this section we return to some of the discussion which was contained in Chapters 6 and 7 referring to the decision of which component types on which to carry out further analysis. Before proceeding to the PHM stage of analysis of any component type it is important to look at the χ^2 confidence limits around the failure rate as this gives some indication of the quality of the data. Chapter 6 dealt with this in detail. However, we could perhaps use the χ^2 confidence intervals as an indication of whether to carry out PHM on any particular component type.

Rearranging the 95% χ^2 confidence interval and using the normal approximation for the number of failures greater than 30, we can estimate the number of failures and the corresponding range of failure rates. Table 8.7 shows for 95% confidence the true failure rate will be between +11% and -10% if the number of failures in each cell is approximately equal to 300. The implication of Table 8.7 is that using these figures, it would be unadvisable to proceed with further analysis of a particular component type if there were less than 50 failures in a given cell for a particular component type.

Table 8.7
95% Chi Square Confidence Intervals the Failure Rate

Number of Failures	Percentage around the Failure Rate	
	+	-
300	11	10
150	16	15
100	20	19
50	30	25

These Confidence Intervals are only valid for exponential failure rates. However, they give some guidance on the number of failures required to provide reasonable results from any analysis.

8.7 Summary

This chapter has introduced the Proportional Hazards Model as a technique for identifying those variables which have a significant effect on the hazard of electronic components.

It has discussed the extraction of the data from the database which is necessary for the implementation of PHM.

A particular application of PHM has been illustrated with respect to data on bipolar transistors. The formation of the models have been discussed and the potential covariates highlighted.

It has been shown that because of the sparseness of the data only a limited analysis could be implemented. It was shown that covariates for encapsulation and mounting could not be incorporated in a model because of this sparseness in the data. This analysis therefore consisted of two models. These two models have been analyzed using this technique and results together with diagnostics have been discussed.

The results of the first model ie The Data Source Model, indicated that the data on bipolar transistors for one data source in particular (AA) was significantly different from the other data sources. In addition, the base-line hazard function was shown to follow a Weibull distribution with a decreasing hazard. Diagnostics for the model have been shown and indicated the appropriateness of the fitted model.

The conclusions obtained from the implementation of the second model ie The Environment model, indicated that data on bipolar transistors in ground benign environments was significantly different from data in ground mobile environments. Moreover, the significant β value was shown to be negative thus indicating a lower hazard for bipolar transistors in ground benign than in ground mobile environments. The resultant base-line hazard function also exhibited a Weibull distribution with a decreasing hazard.

The results from these two models are not too surprising and correspond to those results obtained in Chapter 7.

In addition to the implementation of two PHM models, the amount of data required to carry out a more definitive analysis was discussed. Tentative estimates of the number of failures in each cell were given (50) with further discussion on the models which could therefore be implemented.
This chapter has not only shown the results of particular applications of PHM to bipolar transistors but has also investigated the future applications.

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9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Introduction

The last chapter of this thesis highlights the conclusions which have been made based on the work of the author as discussed in Chapters 4, 5, 6, 7 and 8.

This chapter brings together the main points of this thesis and provides recommendations for the future development of both the database and of the analysis of stored data.

9.2 The Electronic Component Reliability Database

The database was originally set up in order to investigate which component types consistently cause failure in electronic systems. In order to achieve this aim a suitable database had to be set up.

The final database design was based on a relational model. It was designed in order to be able to explore the data and retrieve as many pieces of information as possible. For example, widely different tasks such as the investigation of recurring circuit board failures, investigation of component failure behaviour with respect to different variables, exploring system behaviour in the field etc. can be carried out using the data in the database. In retrospect, the relational model has proved to be the most appropriate data model mainly because of its flexibility.

The main advantages of this database include:

(i) Robustness
(ii) Accessibility
(iii) Ease of updating

These three major advantages help to ensure that the aims of the project can be fulfilled. From some of the preliminary statistical analysis already carried out in chapters 6, 7 and 8 it can be concluded that this database design is fulfilling its main objective.

9.3 Data Integrity

An appropriate database design is crucial in order to make progress towards achieving any results from such a project. However, data integrity is also crucial.

Data integrity means that any data that enters the database can be validated for correctness and meaningfullness. Therefore any results from statistical analysis are also valid.

Three important areas of data integrity have been discussed in Chapter 5. These are:

(i) Data Validation
(ii) Database Security
(iii) Software Control

Ensuring that the data is valid and secure implies that any results achieved from statistical analysis can be used. It has been found that in many cases if there were no data validation checks carried out on the data then there would be many data errors contained in the database. These errors would cause many problems when attempting to analyze the data. It is therefore concluded that such validation checks are necessary in order to ensure data integrity.

In addition, any software written to extract data must itself be validated and controlled since it has been found in practice that there is a significant danger of extracting information which superficially looks correct but is not quite what the programmer initially set out to extract. This problem is particularly frequent when using a query language such as SQL or LINUS. It is therefore important to validate and control software in order to ensure that any data extracted for analysis purposes is as expected.

The aims of the project can only start to be realised after an appropriate database has been designed and set up and after controls on such a database are initiated in order to ensure data integrity.

9.4 Data Analysis

9.4.1 Introduction

The data analysis which has been undertaken has been concerned with analyzing data at several levels. These levels include:

(i) Failure rates for both pooled and disaggregated data have been calculated. In addition investigations concerning design and replacement problems have been carried out as part of this first level of analysis.

(ii) Hazard plotting analysis of both pooled and

(iii) disaggregated data for 3 particular component types has been carried out.

(iii) The use of the proportional hazards model for electronic component data, in particular, bipolar transistor data has been investigated.

9.4.2 First Level of Analysis

9.4.2.1 Failure Rates

A failure rate hierarchy of components was constructed to quantify those components types which have failure rates. χ^2 Confidence Intervals were placed around these failure rates. From this it was concluded that there was, at this time, insufficient data contained in the database on most component types in order to quote these failure rates with confidence. However, this of course was not true for all component types. In particular the confidence bands surrounding MOS devices and Hybrids were fairly tight indicating that the true failure rates lie close to the calculated value.

In addition, from this failure rate hierarchy it can be concluded that 40 out of 64 component types have FIT (Failure UnITs in 10^9 component hours) less than 200.

The failure rates discussed above used pooled data. However failure rates were also calculated for data in different environments, from different data sources, using different encapsulation and screening methods.

It was found for those components where comparison was possible that, in general, most component types operating in ground mobile environments exhibited a higher failure rate than those of the same type operating in ground benign conditions.

Investigating the difference in failure rates using different screening levels showed that most of those component types which were screened to BS9000 or higher levels exhibit lower failure rates than those which are screened to a lower level.

The comparison of component failure rates using different encapsulation techniques was limited due to the sparseness of data. However the results available showed that hermetically sealed components have a higher failure rate than plastic encapsulated devices. This is contrary to what is expected. It should be noted however that those component types which were hermetically sealed were used in systems operating in ground mobile environments. Therefore the reason for this unexpected result could perhaps be that the severity of the environment outweighs the benefit of using hermetically sealed components.

The differences between the data from different data sources was also examined. This analysis concluded that there was in fact a difference between data sources. In addition it was found that it may not be appropriate to assume constant failure rates for pooled data from different data sources.

9.4.2.2 Design and Replacement Problems

Exploring the database highlighted problems specific to particular components from particular data sources.

These problems were related to the design of the particular components or to misuse. The repair methodology used in which, in order to play safe, more components than the specific one at fault were removed from the printed circuit board.

It was concluded that there were design faults inherent in several component types. These included a particular MOS custom chip, a particular type of bipolar transistor and some wirewound potentiometers. Further potential design faults were flagged but these are still under investigation by the data source.

A problem associated with multiple replacements was also identified. For a particular feed through filter connector 35 failures were reported. In fact there were only 7 real failures. This was due to the engineer replacing all 5 connectors each time a failure occurred. Under these circumstances it is important that only 1 failure be recorded in the database.

These problems which were identified by exploring the database provide further information about the particular component types and such information was found to be crucial when further analyzing the data.

9.4.3 Second Level - Hazard Plotting Analysis

Hazard plotting was carried out on data for 3 component types in order to investigate the distributional form of the data. It was concluded that data from all three of the component types examined, ie bipolar transistors (T1A), rectangular connectors (K1A) and coil activated relays (B1A) exhibited a Weibull distribution with a β value less than one (a distribution which is decreasing with time).

The data analyzed was pooled and therefore hazard plots were carried out, where possible, for the three component types broken down by environment and data source.

It was also concluded that for both K1A and B1A, for the 2 different data sources with failure data available, a Weibull distribution could again be fitted with β values less than 1. Each data source showed a different β value.

The results for the T1A analysis which included data from 4 sources were however more complicated. The data from 2 sources exhibited Weibull distributions with β values less than 1. However, the data from the other two data sources showed a mixture of Weibull distributions, with β changing as a function of time. These mixtures may have been caused by 2 different failure mechanisms which are dominant at different times resulting in a change in the value of the shape parameter.

Hazard plots of the combined T1A data in different environments showed that bipolar transistors in both ground benign (GB) and ground mobile (GM) environments follow a Weibull distribution with $\beta < 1$. However the β value for GM is less than that for GB.

The conclusions of the hazard plotting analysis have been consistent in that all the plots showed some form of Weibull distribution with a decreasing hazard rate. This decreasing hazard rate points to a burn-in process occurring. The reasons for observing this decreasing hazard rate could be due to inadequate burn in procedures and could indicate that the screening procedures are not sufficient to eliminate all early life failures. Alternatively this decreasing hazard rate could be due to the short period of time over which the data has been collected (about 4 years). Perhaps there will be a change in the value of the shape parameter in time.

The decreasing hazard conclusion is extremely interesting in view of the fact that most reliability prediction techniques use models based on a constant failure rate assumption. These results for 3 component types indicate the importance of this analysis.

9.4.4 Third Level - Proportional Hazards Modelling (PHM)

The analysis carried out on the data using PHM was limited due to the sparseness of the data. The number of covariates which were incorporated in the models were reduced due to this sparseness. However for the bipolar transistor data two models were successfully applied.

The first model incorporated covariates for different data sources. The results of this model showed that there was one data source which was significantly different from the other data sources. The results showed that the data from this data source had a lower hazard rate than the rest and that the baseline hazard function exhibited a Weibull distribution. Diagnostics for PHM validated the appropriateness of this model.

The second model incorporated covariates for 2 different environmental conditions ie ground benign (GB) and ground mobile (GM). The conclusions from this analysis were that bipolar transistors operating in GB exhibit a lower hazard than those in GM environments. The base-line hazard also exhibited a Weibull distribution. The diagnostics of PHM confirmed the validity of applying such a model.

These results correspond to those obtained from hazard plotting as discussed in the previous section.

The application of PHM to electronic component data was unfortunately limited. However the results achieved were extremely interesting. Although limited, this analysis has provided experience in applying this type of data to PHM. It has highlighted the types of problems which are likely to be encountered and given some suggestions on how to overcome them.

This technique will be more useful when more failure data becomes available at the covariate level. This will allow comparisons of the effect of different variables in the overall hazard distribution of a particular component type. Tentative estimates have been given as to the required expansion in the database size necessary to gain more useful results from PHM. It has been estimated that around 1000 failures would be required for each component type. In addition these failures would have to be balanced between the covariates of interest.

9.5 Overall Conclusions

The overall conclusions of this thesis are that a secure dependable database has been successfully designed and implemented in order to explore the causes of failure in electronic components.

In addition, detailed mathematical preliminary analyses have been employed and the conclusions from these have shown that for bipolar transistors, rectangular connectors and coil activated relays the assumption of constant failure rate may not be applicable. The results of the analyses of these 3 component types indicated that their failure times all follow a Weibull distribution with a decreasing hazard rate.

The analysis also concluded that there is a difference in the failure behaviour of those components in different environments and from different data sources. Although distributed in a Weibull manner they exhibit different β values, all less than 1.

It should also be noted that although the data analyzed exhibited a Weibull distribution with decreasing hazard this does not imply that the calculation of constant failure rates gives no information. Constant failure rates give an initial impression of the performance of a component and the importance of this first impression is unquestionable. The simplicity of the calculation of constant failures rates allows reliability engineers to acquire a first impression quickly. However these present results show that caution must be used when making reliability predictions based on constant failure rates since some components, in certain conditions, are now known to show a decreasing hazard rate as a function of time.

9.6 Recommendations

The conclusions of this thesis have initiated new ideas on the development of future work on reliability databases. This section outlines some recommendations for the future development of the database and the analysis of the stored data.

(i) Validation

Due to the importance of the data validation routines, fine tuning of such routines are recommended. Obviously, over the 3 year period the validation software was improved. However, as more data is collected more potential validation problems can occur. Validation is therefore an ongoing process and all validation software should be assessed for completeness at frequent time intervals. This fine tuning will help to ensure data integrity.

(ii) Database Classification

In order to gain the optimum use of this detailed database, the ideas discussed in Chapter 4 concerning the 3 databases (raw, commercial and research) should be developed. The commercial database would be the most useful and would contain failure rate information and confidence intervals both for pooled data and disaggregated data. Summaries of the results of exploratory data analysis and PHM could also be included in such a view of the database. This commercial database would be required to be 'user friendly' and it is therefore recommended that a 'front end' interface should be implemented specifically for the commercial database. Such a database would be attractive to most companies involved in any area of electronics.

(iii) Confidence Interval Improvement

The future analysis of the data in the database should continue the analysis already carried out. As more data arrives the confidence intervals surrounding the failure rates should narrow thus providing more dependable estimates of the failure rates of electronic components. Thus failure rates and confidence intervals should be calculated at frequent intervals so that this narrowing can be observed.

(iv) Hazard Plotting Analysis

As the database expands it is recommended that hazard plotting techniques continue to be employed. Other component types than those already analyzed should be examined in order to investigate their failure behaviour both for pooled and disaggregated data. Moreover, after data expansion the hazard analysis which has been discussed in this thesis should be repeated in order to observe whether the results are consistent as more data is input.

(v) The Use of PHM

The problems associated with the application of PHM to electronic components was discussed in chapter 8. As the database expands PHM will be a powerful tool in identifying those variables which affect the hazard rate of electronic components. It is therefore recommended that PHM be applied to other component type data and using many of the potential variables contained in the database, for example, circuit reference position, component failure mode, encapsulation, mounting, substrate etc.

(vi) Increase in Size of the Database

From the PHM analysis carried out so far it is tentatively estimated that there should be about 50 failures for each covariate and that there should be a balance between the numbers of failures for those covariates which are to be included in the analysis. This implies that the database must expand dramatically (at least 10 times the number of failures at present observed for each component type from each data source). These estimates are tentative, however the main point is that in order to be able to carry out realistic comparative analysis of the failure behaviour of electronic components a lot more data is required.

(vii) Extension to System and Subsystem Analysis

Due to the robustness of the database, it is recommended that statistical analysis at board and system level should be carried out. This will give some insight into why components are failing in specific boards and systems. This work has just started at Nottingham Polytechnic (January 1990) and is already underway at the DIA. These projects should provide interesting results. In addition analysis of No Fault Data would also be of great interest to the data sources who provide the data.

From these future analyses perhaps new models for the reliability of particular electronic components could be developed, ie models which do not assume distribution forms which are unsubstantiated by the data.

9.7 Summary

This chapter has discussed the main conclusions which have arisen from the work carried out by the author and discussed in chapters 4, 5, 6, 7 and 8.

Recommendations for future work have also been identified.

APPENDICES

APPENDIX A

Further Developments of the Electronic Component Database

APPENDIX A

As discussed in Chapter 4 the database is stored on a Honeywell Multics at the Computer Centre using Multics Relational Data Store (MRDS). However the Honeywell Multics was due for replacement in July 1989. It was therefore recognised that a new relational database package had to be purchased.

After going to exhibitions on INGRES and ORACLe and reading literature on databases it was decided to purchase ORACLE. This decision was made primarily by the Computer Centre. However the author had some input as she was involved in attending both INGRES and ORACLE exhibitions together with the Computer Centre staff.

ORACLE is a relational database with many additional features. The main ORACLE package is called SQLPLUS which is based on the database language SQL (SEQUEL). SQL is fairly similar to LINUS which was used by MRDS. However SQLPLUS allows more complicated queries than LINUS and it was recognised that most of the software which had to written in PL/1 using DSL routines could be written using SQLPLUS. In addition to SQLPLUS there are also 3rd generation language interfaces to ORACLE which allow SQL queries to be embedded in say 'C ' programs.

Other features of ORACLE include SQLREPORT, SQLMENU, SQLCALC, SQLFORMS, SQLLOAD, etc. These are optional extras within ORACLE which allow specific tasks to be carried out.

Some of the reasons for choosing ORACLE include:

1. Relational.
2. Robustness. Many specialist products which will allow any type of extraction from the database.

3. Support. The company is an expanding company and appeared to have good support staff.
4. Implementation. To get the basic database up and running would be fairly straightforward.
5. Speed.
6. Compatibility. SQL is similar to LINUS and the design would remain the same as in MRDS. The data could be transferred from Multics as text and loaded using SQLLOAD.
7. Front End. Because of the number of specialist products a front end should not be too difficult to write and implement using say SQLFORMS.
8. SQL is becoming an industry standard for 4th generation languages and therefore is the most appropriate to use.

Before purchasing ORACLE the author went on a course with Computer Centre staff to learn how to use ORACLE and to think about the implementation of the database using ORACLE.

In the short term after the package was bought it was stored on a Sun which was networked. When the new mainframe arrived the database was then transferred from the Sun.

The author changed jobs before the database moved onto the new mainframe and is no longer involved in the administration of the database.

APPENDIX B

An Electronic Component Reliability Database.
Proc. 10th ARTS, Bradford, 1988.

AN ELECTRONIC COMPONENT RELIABILITY DATA BASE

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ABSTRACT

The Paper discusses the problems arising in the establishment of a omputerised database for the field failures of electronic components. he purpose and aims of the program are described, together with the ifficulty in establishing a satisfactory data format of sufficient enerality and the identification of a suitable database structure. The ractical need for data validation is discussed, together with the nature f validation applied.

Analysis of the data in the base is in the early stages but an verview is provided of early results together with implications for the uture.

INTRODUCTION

The majority of reliability studies on electronic components have een concerned with the determination of failure rates under 'artificial' onditions such as simulation or accelerated life tests. Failure rates etermined from such tests are then extrapolated to what might be expected nder field conditions. Unfortunately, these extrapolations are often ubject to doubt if only because multiple failure mechanisms may well be nvolved. Even in the most simple devices bimodal failure distributions an be found, and the level of modality may rise as the complexity of the evice increases [1].

The availability to equipment manufacturers of failure rate data or electronic components is essential for system reliability prediction. or this purpose the failure rate models published in MIL-HDBK.217(E) [2] re those predominantly used by the industry. These models have been erived in the main from test bed and accelerated life studies. Manufact-rers have commented that the models can be wildly pessimistic when compared ith observed field performance, particularly in the case of modern micro-lectronic devices. The complexity of some of the models and the difficulty n obtaining satisfactory values for all of the terms illustrates the roblem in predicting failure rates under field conditions. This is articularly demonstrated by the failure rate model for microelectronic levices:-

$$\lambda_p = \pi_Q[C_1\pi_T\pi_V + (C_2 + C_3)\pi_E]\pi_L$$

here λ_p is the failure rate expressed as the number of failures per 10^6 ours, π_Q is the quality factor relating to the quality level of the roduction, π_T is the temperature acceleration factor based on technology, π_V is the voltage derating stress factor, π_E is the application environment actor, C_1 and C_2 are the circuit complexity failure rates based on gate ount, C_3 is the package complexity failure rate and π_L is the device earning factor.

A study centred at Loughborough University of Technology (LUT) and ponsored by the MOD (DCVD) commenced in September 1984 to investigate he failure behaviour of electronic components when used in equipments in he field. The aim of the study is to identify component types which are major cause of field failure in equipment, the conditions under which ailure occurs and the nature of the failure mechanisms. The intention s to build up a structured component failure database over a period of ime.

By its very nature such a study involves the co-operation of several lectronic equipment manufacturers. LUT held discussions with many systems anufacturers, and although a number of companies expressed a willingness o become involved, LUT finally entered into detailed discussions with he research centres of three major British companies, viz:

Plessey Research (Caswell) Ltd.
Marconi Research Centre, GEC Research, Great Baddow
STC Components, Harlow

It was recognised that the research centres were in the best position o identify suitable data sources within their groups. Given the importance f the project, separate contracts were let by the MOD to the companies. ubsequently a contract was also let to Trent Polytechnic to provide a tatistical input to the project.

Earlier, a pilot study involving two Danish companies, co-ordinated y the Danish Engineering Academy (DIA) under sub-contract to LUT had een initiated. Figure 1 shows the organisational structure of the project eam. The number of data sources varies between companies and is growing ith time.

The project is unique in that three major companies in competition n the market place are jointly involved in a field study of this type. he success of the project, under such circumstances, is partly due to he confidentiality guaranteed by LUT to each of the individual companies. ndividual data sets are desensitised by coding and lose their identity hen the data is pooled.

DATA SOURCES

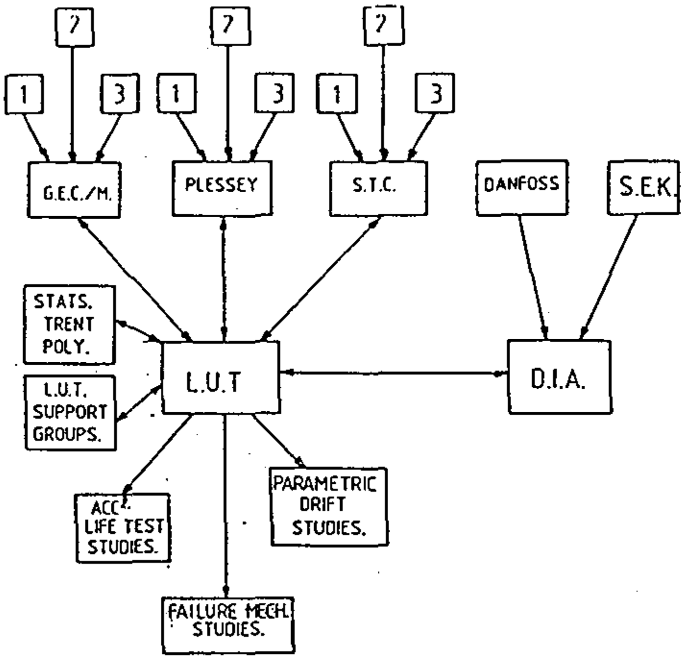


Figure 1 Organisation of Information Flow

Within the framework of the organisation two levels of group meetings ake place. Co-ordination meetings are held twice yearly. These meetings re a forum which enables senior members of the consortium to meet and iscuss progress and future policy. However, it was realised in the arly stages that a Working Party, including those involved in the cquisition, transfer and processing of data was needed to undertake the etailed work of the project.

THE FORMULATION OF A DATABASE

The main task initially confronting the working group was to stablish a data input format. This format requires information at the ystem level (equipment) and subsystem level (printed circuit board (pcb)) n order to obtain the necessary data at the component level. Due to the ierarchical structure of the data, trackability at the system and subsystem evel is essential in order to obtain dependable data at the component evel. Such trackability, for example, would require a detailed knowledge f the repair loops of pcb's, including knowledge of their previous use nd storage.

To achieve meaningful statistical analysis, information is required, ot only on component failures, but on those components which have not ailed and are at risk in the field during the period of observation.

The final data format was arrived at after considerations of the nimum information necessary for analysis. Typically, this basic inform- ion would be of the form:

) equipment identification (type, serial-no)
i) operational environment (ground benign etc.)

iii) installation, failure, first and subsequent repair dates etc.
iv) failure mode of equipment
v) equipment condition when failure occurred
- mode of operation immediately after repair
vi) identification of failed component
- component type
failure mode/position or circuit reference [3]

Discussions of the practicalities of obtaining this data resulted n a final data format containing additional information and was more etailed in relation to the reporting of the minimum information required.

After the establishment of the data input format, discussions egarding the selection of types of equipments to be followed in the ield needed to be made. The criterion for equipment selection was based n the dependability of the data only.

In order that the companies could establish suitable sources within heir organisations, a check list based on the requirements of the data ormat was devised. The final equipment selections were based on these heck lists which were discussed in detail by the Working Party. Not all pproached sources could meet the data minimum requirements. In some ases it was possible to make minor modifications to the existing reporting ystems to satisfy the minimum requirements. However, major modifications f reporting systems were impractical. This in practice meant that the ompany co-ordinators had to assess several sources within their organisation before final selection.

After the initial equipment selection had been finalised, the orking group addressed the practical problems associated with the detailed oding of the data input.

The type and manner of data recording, not surprisingly, differs etween data sources. Since the data to be transferred to LUT was equired in a fixed detailed format, varying degrees of translation from ither existing databases or paper records had to be performed by the ompanies. This information, however, is not always recorded in a manner hat allows it to be directly extracted from the data records. Of articular importance, requiring special attention, are the generic coding escriptions of the components, and the differences in the recording of he time metric between the different sources.

Descriptions of the same component type can vary between data sources; some descriptions are based on use and others, for example, by ower rating. No suitable existing listings of component descriptions, .g. CODUS, MIL-217, were compatible across all data sources. Indeed, hese descriptions were inconsistent with the wider aim of the project, hich in addition to the statistical output requires failure mechanism nalysis on the problem components to be carried out at LUT. With this n mind, a component generic type listing was devised at LUT, based on material and construction to be used by all companies.

The detailed generic coding requirement means, in practice, that the company co-ordinators are involved in extensive translation from parts lists to the LUT Format. Although slowing the rate of data transfer somewhat, the final result is a database which will allow component field ailure behaviour to be linked to specific failure mechanisms. This is n important relationship to determine, in any component reliability study.

The need for component times to failure requires, because of the ierarchical nature of the data, knowledge of the operating time of equip-ent, downtime, circuit board replacements etc. In some instances equip-ents are fitted with modern electronic elapsed time indicators giving se to accurate time metrics. This is not, however, always the case and ie required times can only be arrived at from knowledge of delivery ates, commissioning dates and up and running dates etc. The method of omputation of the various times required in the data format is indicated y a suffix letter. This letter is used to highlight the relative ccuracy of the data. The use of such letter indicators ensures the ntegrity of the data used in any statistical analysis.

Although it is not possible in this paper to discuss in detail very coding consideration of all the elements in the data format, the ollowing examples illustrate some of the topics which warranted detailed orking Party discussions regarding methods of reporting and/or obtaining ie information:-

i) Environment codings

ii) Component encapsulation and mounting technology
- this detailed information is not normally given in parts lists

iii) Screened level of components

iv) Coping with either simultaneous failures or replacements

v) Circuit reference position of components etc.

t is seen that the construction of the finalised data format has been rrived at only by a team effort requiring both engineering and statistical xpertise. The identification of the required data, associated codings nd the protocols of data transfer have been addressed, and resulting in practical working document. This working document is in ring binder orm facilitating updates and replacements.

Although the data input format has been finalised and a final orking document compiled, supplementary information on the data is equired by LUT. A soft information document has been compiled in order o highlight the details on, for example, the repair loop of an equipment, ie computation methods, the reasons for using particular indicators etc. his soft information provides additional knowledge about the data.

Initially it was thought, based on pilot studies in Denmark, that ie database could be held on an IBM PC AT. It soon became evident, owever, that this would be limiting with regard to the storage facilities equired for the data and the necessary statistical software packages. t was, therefore, decided to use the Honeywell Multics mainframe based n the Computer Centre at LUT, for data storage and analysis. The nitial concept of storing the data comprised of 4 data files, namely:-

(i) Failure information
(ii) Population information

(iii) Component parts lists
(iv) Failure analysis

However, since this required extensive programming in order to :plore and retrieve the data, a structured database package was considered. ready in existence on the mainframe was a relational database (Multics :lational Data Store), which with an efficient database design, would lfill the needs for storage, retrieval, updating and exploration of the ta. Designing a relational database [4] for this hierarchical data ructure posed a few problems. Some of the problems considered include:-

) The need for updating the database. This is a basic consideration since the collection of data on equipments in the field is an ongoing situation.

i) The hierarchical nature of the data does not naturally conform to the relational database structure.

ii) Minimising duplication in the data not only to improve the efficiency of storage and retrieval, but to reduce some of the workload of companies.

v) The realisation of a database, which is not an accounting system performing the same routines periodically, but a database in which retrieval of data is flexible and exploration possible.

Together with advice from the Computer Centre at LUT, a final sign was achieved.

As illustrated in Figure 2, the database consists of 4 relations. lations 1 and 2 contain the parts list of a piece of equipment, i.e. e types and totals of subassemblies in a piece of equipment, with the rresponding component types and totals in each subassembly.

1. BOARD STRUCTURE

Co	Board Design	Component Type	No of Components

2. EQUIPMENT STRUCTURE

Co	Equip Type	Board Design	No of Boards

3. EQUIPMENT IDENTIFICATION

Co	Equip Type	Equip Serial No	Up and Running Date	End Date

4. FAILURE

Co	Equip Type	Equip Serial No	Board Design	Board Serial No	Up and Running Date of Board	Component Type	Time to Failure

Figure 2 Database Design

The third relation gives the details on the information concerning ıich equipments are in the field and over which periods they are operating. elation 4 includes all the data on a component failure. For example:-

(i) which equipment it was in
(ii) which board it was part of
(iii) when it failed
(iv) which position it failed in
(v) why it failed etc.

This design is now up and running and has proved to be working ficienctly. The advantages of this database design include:-

:) Updating - population updating need only occur in relation 3, the period of observation would change unless there has been a redesign of a piece of equipment or printed circuit board.

.i) Obviously, defining the structure of a piece of equipment (from relations 1 & 2) indicates that the company need only code and transfer this data once, thus reducing some of the work load of the companies.

.ii) Exploration of the data can take place by writing the necessary software. This exploration could take the form of, for example, differences in the reliability of different screened components, different encapsulation methods, different mounting technology etc.

ıese examples highlight the advantages of a database which has been :signed for research purposes.

Apart from the relations discussed above, a fifth data file exists. ıis file contains the results of any failure analysis carried out on a .rticular failed component, and therefore provides additional information :garding this failed component. Included in one of the fields in the :ilure Relation (relation 4) is a reference number which directly points a failure analysis record in the fifth file, thus linking some of the mponent failures with their corresponding failure mechanisms and helps highlight some of the differences between sources.

Since the collection and storage of data have been finalised, gether with the compilation of a full working document, the protocols data transfer and data validation were considered.

TRANSFER AND VALIDATION OF DATA

The data transfer procedure to LUT is displayed in Figure 3. The mmunication medium for three of the companies is magnetic tape, while e fourth, the DIA, communicates via IBM compatible floppy disks. Reading e magnetic tapes has not posed many problems. The data on floppy disks transferred from the IBM PC AT using Kermit Protocols, and in general, fairly successful. However, one recurring problem happens when non-ASCII aracters are contained in one of the files. The file cannot be transrred to the mainframe until they are detected and deleted.

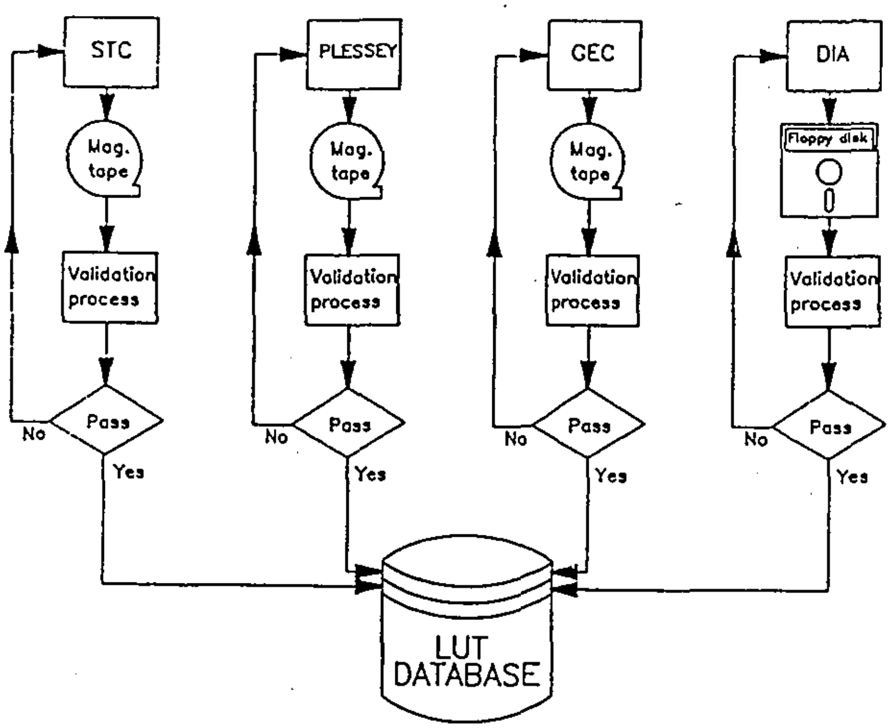


Figure 3 Data Transfer Procedure

After successfully reading the data into the system it is rigorously amined. This is known as data validation [5].

The data processing system must obviously guard against the possi- lity of erroneous data being admitted to the database. The probability such errors occurring is very high, and the effect of not discovering rors is detrimental to the quality and integrity of the data within the tabase. Therefore, all input files are subjected to examination by a ta validation program which exhaustively inspects all file records for ssible errors. The detection of most errors is at rapid computer eed, but correction tends to be a human process which involves collecting ckground information, correcting the data and finally proceeding through e data preparation and transcription stages again.

The data validation procedure used in this study has three levels checking.

npany Validation

Each of the companies has its own database system which stores and ansforms the information into the format required by LUT. They each ploy their own data processing systems, including data validation pro- dures, before writing the data onto a magnetic tape.

ecks at Data Entry

After successfully reading and storing the data, the validation ftware is run. If the data passes, it is automatically entered into a database package before being pooled in the main component database. However, if the data fails the checks, the program flags up the erroneous fields and corresponding locations. Having detected the errors, amendments then have to be carried out (Fig. 4). The procedure for correcting erroneous data involves discussions with the relevant company contact. If the problems are minor, then amendments are made almost immediately. However, with more complex problems the complete data set would be investigated and amended by the company before being resubmitted to LUT.

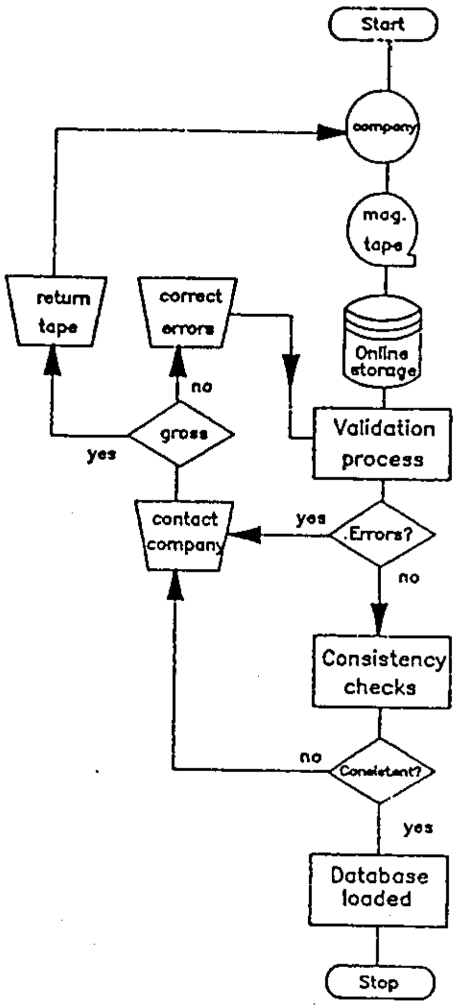


Figure 4 LUT Data Validation Procedure

The validation programs detect the following types of errors:-

i) Fields containing illegal characters. For example, numeric fields containing I instead of 1.

ii) Duplicate records.

iii) Wrong Codings - the component generic description code contains, in general, three characters. Errors have occurred when, at most, only two of these characters have been present in the field. A list of all valid component types exists. Therefore, if anything other than these occur, an error is flagged. An example of this would be TIA instead of TlA. Obviously, this is a keying error.

iv) Out of Range Values - an error will occur if the equipment operating time is less than the circuit board operating time. Similarly, if circuit board up and running date is less than manufacturing date.

v) Missing Information - contained in the working document is a list of essential fields. This means that these fields must be fully completed in the data format. If any of this essential data is missing, then an error will occur. For example, missing screened level of a component, missing mounting, substrate or encapsulation of a component type.

vi) Numeric Fields - previous use is recorded in days, thus if either a letter or a space occurs in this field an error message is flagged.

') Valid Dates - for example, if the month number is zero or greater than 12, then an error has occurred.

'i) Length of Fields or Records

These are practical examples of the types of checks employed. The rors mentioned above are actual problems encountered during validation.

nsistency Checks Using Database Manipulation

These routines use the database manipulation procedures which check e consistency across the four relations. Similarly, if the files being lidated are updates, the routines check the consistency between those cords previously stored and validated for this data set. For example, e type of questions asked include:-

) Are the failed component types in the population?

i) Are all the failed equipments and pcb's described in the population?

ii) Is the operating time of a piece of equipment less than its total observation period.

If any errors are flagged while running these procedures, then scussions are held with the relevant company to obtain the best possible lution to the problem.

On average, this validation loop including company interchange has cycle of two days. However, this cycle is dependent on the complexity the errors identified.

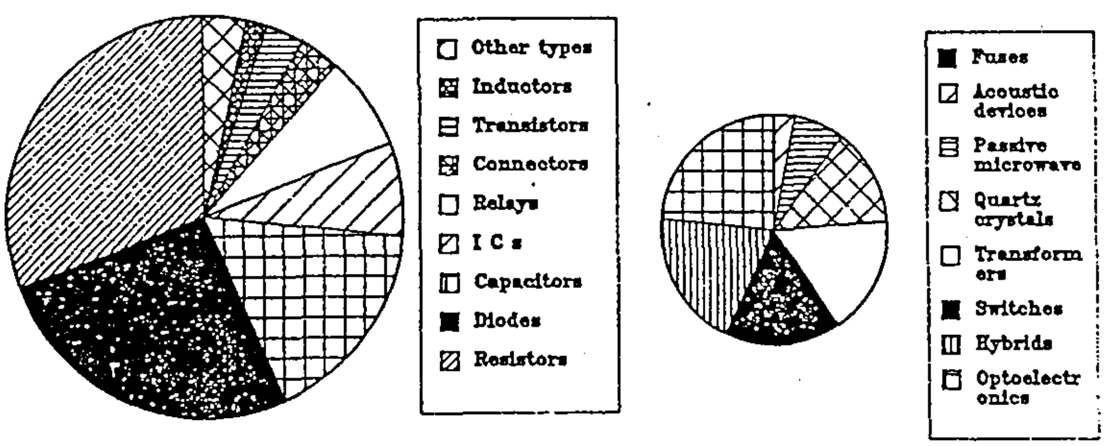
Apart from computer validation procedures, manual exploration of e data is carried out. This involves scanning across each field and wn each record, searching for any data which may appear odd. For ample, in one data set, it was found that the serial number of a rcuit board was the same as the serial number of the equipment, high-ghting the need for further investigation of the data. Identifying is occurrence aided in the comprehension of the repair loop for the rticular equipment under discussion.

During discussions concerning the data collection, a debate con-rning the need for validation checks occurred within the Working Party. was felt, by some members, that the validation procedures carried out the companies would be sufficient to detect the majority of errors. wever, this has been shown to be untrue. Indeed, the validation process scribed above has proved to be successful in identifying erroneous data d thus ensuring the quality and integrity of the data in the pooled mponent database.

OVERVIEW OF EARLY RESULTS

Much of the work to date at LUT has been concerned with the tting up of the database, the coding format and the establishment of pendable sources of data. Therefore analysis of the data is in the eliminary stages.

The database currently contains information on 70 out of 125 differ-to component generic descriptions with an approximate total of 3.9 x 10 component hours. Figure 5 illustrates the percentage number of mponents in the data base per component grouping.



Percentage breakdown of other types.

Figure 5 Percentage Number of Components in the Database broken down by Component Type

Failure rate calculations have been carried out together with their sociated 95% confidence limits, as shown in Figure 6. The overlapping confidence limits around the failure rates of different component pes, indicates that the confidence surrounding this hierarchy of problem nponents is low. One slight change in any of the failure rates would st certainly result in an alteration of the hierarchy. Similarly, the nfidence surrounding each individual failure rate is low, in particular ose components showing the highest failure rates. Figure 6 highlights ose component types for which more data is needed. However, as more ta arrives, the confidence limits will become narrower and eventually e hierarchy of problem components will reach a steady state. The gend describing the component types in Figure 6 is shown in Table 1.

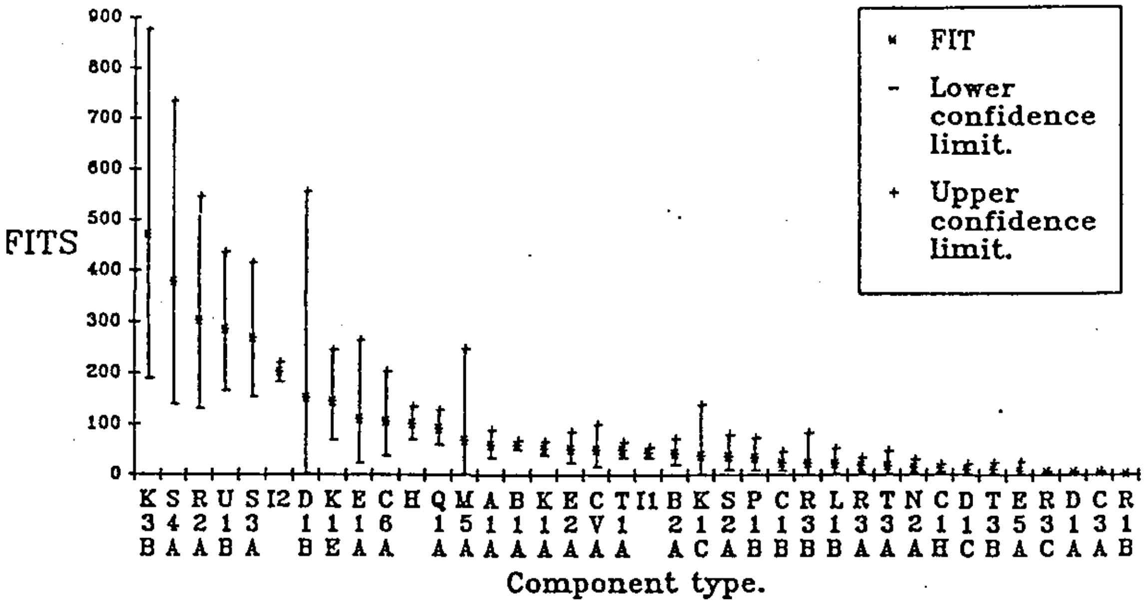


Figure 6 95% Confidence Limits for Failure Rates per Component Type

TABLE I

LEGEND FOR FAILURE RATE GRAPH (Figure 6)

COMPONENT TYPE	COMPONENT CODINGS	DESCRIPTION
Integrated Circuits and Hybrids	I1	Bipolar
	I2	MOS
	H	Hybrid
Optical Devices	E1A	Photosensors
	E2A	LEDs
	E5A	Optocouplers
Transistors	T1A	Bipolar
	T3A, T3B	MOS
Diodes	D1A	PN-Junction
	D1B	Varactor
	D1C	Avalanche
Switches	S2A	Rocker
	S3A	Keyboard
	S4A	Rotary
Relays	B1A	Coil Activated
	B2A	Reed
Connectors	K1A	Rectangular
	K1C	Cylindrical
	K1E	Coaxial
	K3B	Feed Through Filter
Transformers	A1A	General Types
Fixed Resistors	R1B	Carbon Film
	R2A	Metal Oxide
	R3A	Wirewound
	R3B	Metal Foil
	R3C	Metal Film
Variable Resistors	P1B	Carbon Film
Non Linear Resistors	N2A	Varistor
Capacitors	C1B	Aluminium, foil, solid electrolyte
	C1H	Tantalum, sintered, solid electrolyte
	C3A	Ceramic Multilayer
	C6A	Polystyrene Foil
	CVA	Tuning/Trimmer Variable
Acoustic Devices	U1B	Loudspeaker
Quartz Crystal	Q1A	Crystal Oscillator
Inductor	L1B	Loaded Inductor
Passive Microwave Devices	M5A	Filter

IMPLICATION FOR THE FUTURE

Despite major progress, it is of course early days in the development nd use of the database. Initial results are promising, but it is only s the data content builds up that meaningful comparisons and assessment, nd the physical investigation of major failure mechanisms, will become ossible.

As expressed above, in carrying out such comparisons and analysis f electronic component reliability, an exploratory approach will be taken. xploratory Data Analysis (EDA) is now an established methodology in tatistical analysis [6], and is beginning to be widely used in Reliability ork [7]. The emphasis is on searching the data for unexpected structure hat is then employed in its analysis, rather than on the confirmation of priori assumptions.

One particular statistical tool to be used in conjuntion with this xploratory approach is Proportional Hazards Modelling (PHM) [8 & 9]. HM can in a sense be regarded as a generalisation of the MIL-HDBK-217 pproach [10]. In contrast to MIL-217, however, PHM does not assume onstant failure rates, nor a priori determined π-factor. Indeed, the pproach makes no distributional assumption nor assumptions as to what actors effect the failure rates of components, nor how or by how much. nstead, these are determined by the data.

The fundamental equation on which PHM is based is the assumed ecomposition of the hazard function for a component into the product of generic or base-line hazard-rate (ho(t)) and a term incorporating the ffects of possible explanatory factors, ($Z_1, \ldots, Z_k$) corresponding to omponent characteristics, use and environment:

$$h(t;z_1,\ldots,z_k) = h_o(t)e \exp (\beta_1 z_1 + \ldots + \beta_k z_k)$$

The β_i's are the parameters, like π-factor, that can be estimated rom the data by the method of Partial Likelihood and tested for statis- ical significance. The base line hazard can then be studied using azard plots, graphical and other methods.

In the current context, like most engineering applications, it is ikely to be necessary to try several versions of the model exploratorily or a particular component type, with varying time metrics, and methods f defining factors. Any attempt to predict the nature of the results ikely to be obtained is accordingly premature.

The work of the project has, however, already established many mportant precedents with implications for the future. Not least of hese is the establishment of an active and co-operating working group ith participation from competing companies, academic institutions and OD. This achievement, together with the construction of an efficient ata acquisition system and a feedback loop on field problems, bodes well or the future of the project and is very much in line with the principles f R & M 2,000 and the move from prediction to achievement (IEEE 1987). t is to be hoped that in the fullness of time, by co-operation throughout urope, the base will take on, or become part of, a wider European rspective.

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APPENDIX C

The Analysis of Electronic Component Reliability Data.
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THE ANALYSIS OF ELECTRONIC COMPONENT RELIABILITY DATA

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Abstract

The paper describes the development of analysis procedures for data within the Electronic Component Reliability Database at Loughborough University of Technology. The database includes data acquisition from Plessey, GEC, STC and two Danish Companies.

Earlier papers have described the content and administration of the database and the path to establishing the database. The current paper concentrates instead on the analysis of the data within the base. The structure of the base has facilitated an exploratory approach to analysis and enabled the identification and calibration of relevant environmental, mounting, screening and other influences upon failure behaviour to be made from the data itself rather than from prior assumptions.

1. INTRODUCTION

The establishment of an electronic component field failure database centred at Loughborough University in the United Kingdom has been described in two papers [1,2]. At present several data sources both in the U.K. and Denmark are actively involved in this field failure study. A detailed reporting format has been developed using statistical and engineering expertise, and is used to assess the dependability of the data collected and processed by the companies. Because of the number of individual companies involved it is possible to follow a wide range of equipments, both military and commercial, in several operational environments. Historical data, at present up to seven years old, is also processed if shown to be dependable by meeting the requirements of the reporting format.

The database has been designed around the detailed reporting format and, in practice, this means that component behaviour can be evaluated not only with respect to time but with regard to other important parameters such as environment, screening level, encapsulation, mounting etc. Data has been coming into the database from the sources for approximately two years and the database is expanding both in terms of the volume of data and the number of sources actively involved.

2. CONVENTIONAL METHODS OF ANALYSIS

Electronic component field failure and population data is essential for systems reliability prediction. The accuracy of such predictions depends on the failure data that is used. Blanks [3] has stated that no matter how excellent the mathematical modelling, how precise the analysis and how detailed the resulting formulae, ultimately the prediction can be no more accurate than the numerical data substituted in them. The majority of reliability studies on electronic components unfortunately, but understandably, have been carried out under accelerated conditions since data collection is expensive and time consuming. Failure rates are than extrapolated from such tests to what might be expected under field conditions. These extrapolations are often subject to doubt if only because multiple failure mechanisms are usually involved.

The most widely used failure rate models which incorporate π factors to take account of effects such as environment, screening etc. are those published in MIL-HDBK-217, [4]. It is not uncommon for reliability predictions basea on the Parts Stress Analysis method to be a contractual obligation for system suppliers. Much criticism has been voiced with regard to predictions based on MIL-HDBK-217, particularly with regard to the wildly pessimistic predictions for some semiconductor devices when compared with observed field performance data. This is not entirely unexpected as, in general, the models are derived from test bed, accelerated life and limited fragmented field failure data. In addition the concept of a constant failure rate has not been substantiated, in practice, for all electronic components and indeed is not accepted by many [5,6]. However, reliability models based on a constant failure rate assumption are attractive from a systems engineers stand point as they are in principle simple and easily interpreted.

Electronic component field failure data is available, notably that presented in the British Telecom 'Handbook of Reliability Data for Components Used in Telecommunication Systems' [7]. The failure data presented is limited, however, in that it is derived from inland telephone exchanges only, operating in benign environments. In order to give failure rate data on a wide range of components it has been necessary to obtain data in some cases from 'one or more alternative sources with minimal supporting evidence'. Although the data is of use to the suppliers of telecommunication equipment, it is of limited use to manufacturers of equipments operating in environments other than benign as again the models presented are of an empirical nature.

The need to establish an electronic component field failure database to allow more detailed analysis and to study the behaviour of components under different environments to determine the factors affecting their field failure behaviour is the basis of the Loughborough database.

3. DATA IMPLICATION OF IMPROVEMENTS TO CONVENTIONAL ANALYSIS METHODS

Historically, most reliability databases have reflected the type of data structure and implicit assumptions underlying the conventional methods of analysis [8]. This is a "chicken-and-egg" situation, since it can be claimed that the analysis methods in conventional use have evolved to make use of data available. On the other hand, it has frequently also been claimed that there is not much point in collecting extensive detailed failure data since conventional analysis methodologies are unable to make use of its richness of structure.

To break this closed loop of conservatism, it was necessary at the start of the project to identify the data requirements that would be necessary to extend beyond conventional analysis. The intention was to realistically identify the nature and extent of data that would be necessary to allow analysis without the restrictive assumptions of constant hazard and pre-determined π-factors, and to allow empirical comparison to be made between sets of data that were previously inaccessible.

The process of defining the data requirement was a long and arduous one, and is discussed in some detail elsewhere [2]. The important points are that it was undertaken by a Working Group including both data-providers and would-be users, and that it was fundamentally iterative in nature with proposals being challenged for their adequacy and consistency in data provision, as well as the realistic achievement of data capture. To this end, whilst some data requirements were soon identified as essential to the intentions of the project, other data features were regarded as desirable only, and relegated to "non-essential" status.

The essential features of the data was that instead of capturing data on a failure-count or failure-rate basis (i.e. number of failures/total of exposure times), data was required in a format that provided individual component time to failure information. This needed to be directly cross-referenced to detailed component and environmental specification for both failures and non-failures. For the various forms of exploratory analysis foreseen, the data structure needed to contain information on component encapsulation, mounting technology, screened level and circuit reference position as well as a detailed categorisation of component type. At the equipment level, environment was essential as well as detailed up and running date, observation end date and failure time information on equipments and boards.

The definitions of all such terms evolved out of the divisions of the Working Group and were (and are) well documented. Such definitions needed to change over time as new data sources became available and conflicts appeared.

The problem with all reliability data collection is that unlike other forms of statistical data, reliability field data is the product of at least three distinct processes. These both contribute to and mask its information content.

1. Firstly, there is the f a i l u r e p r o c e s s itself that we wish to find out about. Unfortunately we must remember that in practice the failure information available to be obtained is a direct product of the deployment employed and monitored.

2. Secondly, there is the l o g i s t i c s u p p o r t s y s t e m, since failure information is typically only obtained as a by-product of repair and replacement activities. In a similar way, population at risk information is frequently only available, if at all, from deployment data.

3. Finally, there is the d a t a c o l l e c t i o n s y s t e m to provide the data for analysis. Typically, this must make use of partial collection already in existence for diverse or unclear purposes.

In the current context, the data requirements were realistically identified given the restrictions imposed by equipment structures and deployments, logistic support systems, and already existing partial data collection systems that varied considerably. In a sense, the essential data requirements represented the minimum that would satisfy the requirements of analysis desired. It was a minimal set of what was regarded as standard features of field reliability data.

Nevertheless, problems have still arisen in the operation of the data system, due to the complexities of reliability field data. In places these could be resolved by further investigation of the data in the database, in other cases they had to be resolved by sometimes likely and sometimes arbitrary assumptions. For example, can one be sure that screened level of replacement components is the same as that of the components they replace or whether a component in exactly the same position in nominally identical items of equipment have the same screened level? The latter question could be partially resolved by searching for mixed screening levels at equipment and then board level. Similarly, mounting technology of replacement components had to be assumed identical to the components they replace. The most major assumption, of course, is to work with component 'failure' data that effectively arises from multiple component replacements upon board repair, often when the components are still in working condition. Investigative approaches are needed when this is suspected to minimize the error.

4. ANALYSIS METHODS

The database design facilitates an exploratory approach to the analysis of the data.

When a component fails in a system, the information stored in the database details how and when it failed, together with descriptive details of the device itself. An abbreviated version of the database design can be found in [2]. The database contains information, not only on the failure characteristics of a component, but also on systems out in the field. This data consists of information about the environment the system is working in, the percentage of time the system is operational and the full component listing broken down by circuit board part number. One of the aims of the study is to detect some of the possible factors which may affect the reliability of electronic components, for example, screening, environment, encapsulation etc.

As discussed in earlier sections, in general, the industry standard for the reliability of electronic components is indicated by the failure rate or inversely as the mean time to failures (MTTF), and is given by:

$$\lambda = \text{total number of failures/total component hours}$$

or

$$MTTF = 1/\lambda$$

These reliability indicators assume that a constant failure rate exists, excluding the phenomena of "infant mortality" and "wear out".

Figure 1 shows a flowchart of the two stages of analysis to be discussed below.

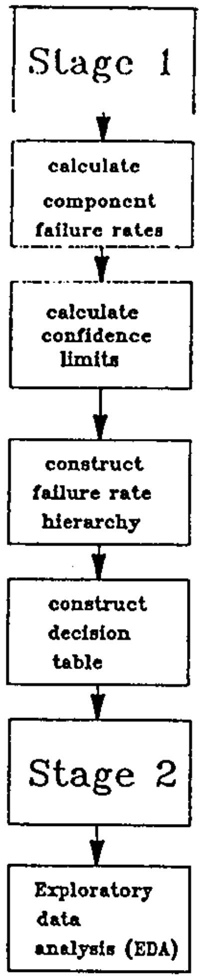

Fig. 1. Flowchart of the stages of analysis

4.1 The First Stage of Analysis - Failure Rates

Preliminary calculations carried out on the data are the failure rates per component type. This gives the first impressions of the reliability of each component type in the field, and from these an hierarchy of problem components can be obtained as shown in Figure 2. The component categories shown in Figure 2 have previously been identified [1]. X^2 confidence limits for these failure rates have been calculated in an attempt to qualify this hierarchy and to indicate those components which may require additional date [2,9].

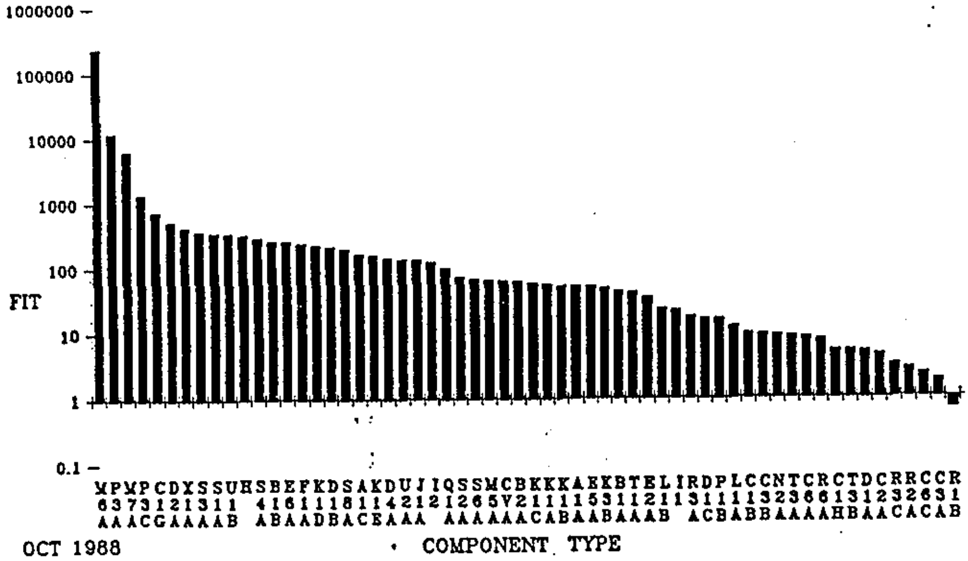

Fig. 2. Bar chart of failure rates for each component type

A table has been established to give a more explicit view of the data (Table 1). This table shows a breakdown of the failure rates into total number of failures and total component hours. For example, a component type which is at the top of the hierarchy implies that this component type is the most unreliable. However, looking at how this failure rate is calculated may give a better impression. Thus a component with small component hours and small number of failures may appear at the top of the hierarchy but, in reality the data is not sufficient to make any statement about the reliability of this component type. This hierarchy can, therefore, be misleading in some instances. Similarly, a component with a large number of failures and small component hours may indicate a need to investigate for design problems or replacement policy.

Table 1. Table for identifying the component type order for analysis
(Failure rate in FITS)

	High Fits	Low Fits
HF, HCH	2	4
HF, LCH	1	3
LF, HCH	5	7
LF, LCH	6	8

HF - High Failures **HCH - High Component Hours**
LF - Low Failures **LCH - Low Component Hours**

The model in Table 1 indicates the order in which component types can be analysed. Deciding what represents a high 'Fit' (i.e. the number of failures in 10^9 component hours), high number of failures etc. is purely subjective and based upon the actual data in the database. Each box contains those component types which have, for example, high number of failures, high component hours and high Fits etc. When this table is complete the first stage of investigation can begin.

This first stage of investigation is concerned with checking for design problems, establishing the repair policy of multiple failures, together with any source related problems, before any further exploratory data analysis (EDA) takes place. For example:

1. Check the number of sources providing the information on the component type under investigation;

2. Breakdown number of failures and total component hours by source;

3. Check for design problems and multiple failures.

Highlighting possible design problems is important not only to the company manufacturing the equipment, but in order to understand the failure pattern of the data. Similarly, if there are multiple 'failures' of the same component type it is important to know whether these are in fact real failures or are a consequence of the replacement policy carried out by the company. The flowchart in Figure 3 shows the order of this stage of investigation. Basically, if any problems relating to a particular source are found then the company involved is contacted and asked for further information relating to the component type under investigation.

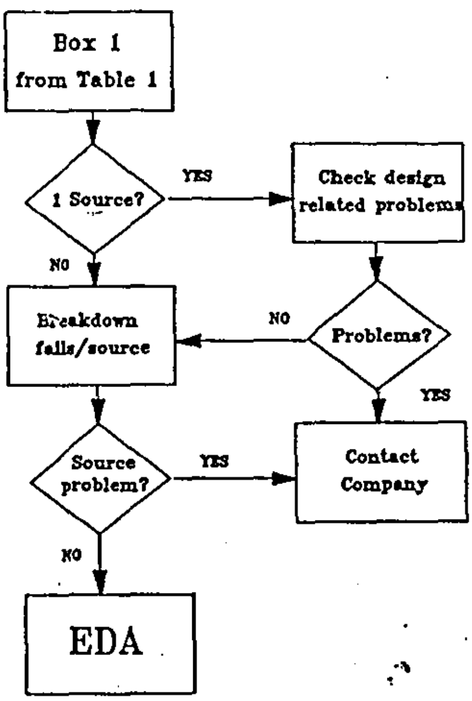

Fig. 3. Flowchart of order of analysis

4.2 Stage 2 - Exploratory Data Analysis (EDA)

EDA involves using simple graphical and tabular methods to highlight any patterns or irregularities in the data. It increases not only the understanding of the nature of the data and failure phenomena, but also indicates the type of analysis which is appropriate. When patterns or trends are identified they can be built into models for analysis, so that results will be more meaningful.

Standard techniques for analysing reliability data assume that the time between events are independently and identically distributed (iid). Exploratory techniques such as checking for trend and serial correlation in the data will reveal where these assumptions are upheld.

Past papers have discussed [10] the need for EDA and the techniques employed. However, they are mostly concerned with repairable systems. This data is based on non-repairable electronic components coming from numerous different repairable systems. This introduces a more complex approach to EDA. In order to pool this component data from different sources, it is important to explore the data for different time patterns between sources, environments, screening etc. Checking for design and multiple replacements have to be previously carried out, thus eliminating some of the dependencies within the database.

The time metric in the database is operating time to failure, not calendar time. This is the time a piece of equipment has been switched on. The time between events is only relevant for a given item of equipment and is meaningless for pooled data. Thus a different approach to exploring this data is required.

There are 4 stages of exploratory analysis currently employed i.e.:-

1. Failure rates broken down by source, environment etc.;

2. Operating time to failure against failure number plots for pooled data, for different equipment types (sources) and different environments;

3. Hazard plotting;

4. Proportional Hazards Modelling (PHM);

Item 1 above is basically calculating component failure rates for each source etc. and comparing them. If, for example, out of 4 sources, 1 source is consistently different from the other 3 over all component types, then investigation of that source is required. As explained earlier, failure rate calculations have their limitations; they do not give any indication of when the failures occurred and only give an average value. However, they do give a reasonable first impression of the data.

After exploring any of the inconsistencies of source data, item 2 is carried out. This involves simply plotting the operating time to failure of a given component type against failure number. Again, breaking down by source or environment, gives an indication of the failure pattern associated with this component type.

By only considering failures, as in the previous items, information on the population at risk is lost. However, hazard plotting of the component types takes into consideration the censoring times and gives a more optimistic representation of the data. Similarly, plotting time against cumulative hazard for different sources or environments gives an indication of any differing failure distributions between these factors. Hazard plotting also highlights whether the assumption of constant failure rate is in fact valid or not [11]. Examples of these figures are discussed in section 5.

The fourth item is a further development of this exploratory approach. Proportional Hazards Modelling (PHM), as discussed in many texts [12,13,14], incorporates explanatory variables such as source, environments, screening etc. into the model and consequently highlights whether they are in fact significant contributory factors of the failure distribution of the component. Hazard plotting alone merely takes account of the censorings when calculating the hazard contribution, but PHM actually uses the censorings in the calculation of the likelihood, thus improving our understanding of the failure pattern. Furthermore, it assumes no distributional form and empirically estimates the hazard distribution, taking into account the significant covariates established by the model. By including PHM as an exploratory tool, different explanatory variables can be incorporated into the model, consequently giving more information. Thus for example, having found environment and source are significant factors contributing to the hazard of a component type, then the model can be extended to include further variables such as screening level of the component, batch number, circuit reference position etc. Many different explanatory variables can be incorporated into the models thus approaching a more accurate representation of the failure of an electronic component.

4.3 Problems Encountered in the Analysis

The database to date contains information on 18 million components and 98 billion component hours, representing a vast amount of data. However, there are in fact only 4,500 failures of which about 50% are due to "no fault found". Thus the amount of censorings is vast compared to the number of failures. This causes several problems when analysing the data, two of which are:

1. Disaggregation - sparseness of the failure data does not allow the analysis of component types to be broken down by source, environment, screening etc. It appears that, apart from a few component types, information across sources is sparse.

2. Vast number of censorings causes numeric problems in PHM software [15].

These problem can be overcome by:-

1. Encouraging the companies to provide data from other sources thus building up the amount of data in the database. However, this problem will only be overcome in time.

2. Developing the software to cope with the large censorings and make use of the natural groupings of population data which appear in the database. It is believed that this problem has now partly been solved.

5. PRELIMINARY RESULTS

As described in section 4, the first stage of analysis is to calculate the failure rates for each component type and produce a barchart displaying the failure rate hierarchy. Figure 2 has shown such a failure rate hierarchy. The failure rate scale is log, since the difference in failure rates from the highest to the lowest is large. From this figure it is apparent that the first 4 worst component types are M6A (microwave cavity), P3A (wirewound variable resistor), M7A (microwave switch) and P3C (metal film variable resistor).

However, further information categorised as in Table 1 is shown in Table 2. This table shows that although there are very high failure rates for P3C and M7A, they have a small number of failures. Thus further analysis can be concentrated on the other two components at the top of the hierarchy. The other component types, namely P3A and M6A, have a high number of failure~ but a small number of component hours. This highlights a need for investigation into the number of sources providing the data and consequently checking for design errors. In this case there is only one source providing the data and they have been contacted and asked to investigate this problem.

Table 2. Illustrative example of table for identifying the component type order for analysis

Failures	Component Hours	Fit > 500	Fit < 500
>= 10	>= 10e7		I1 D1A T1A R2A B2A 12 A1A H
>= 10	< 10e7	D2A M6A P3A	K1D K1E
< 10	>= 10e7		C3B C6A C3B C2A L1A C6C CVA K3B R6A L1B
< 10	< 10e7	P3C M7A C1G	A1C D1B B1B S4A C1B D4A S1A S6A

Further design problems have been identified by using this iterative approach. However, they will not be discussed in this paper.

The next stage of analysis involves exploratory data analysis. The component under investigation in the following examples are bipolar transistors (T1A). The reason for choosing this component is historical. However, there is information from 4 sources on this component.

Figure 4 shows aggregated operating time to failure against failure number for T1A. This plot indicates that as time progresses the time between events increases. By breaking down the data by environment, i.e. GB - ground benign and GM - ground mobile, we can see more clearly which environmental condition is contributing to this increasing trend.

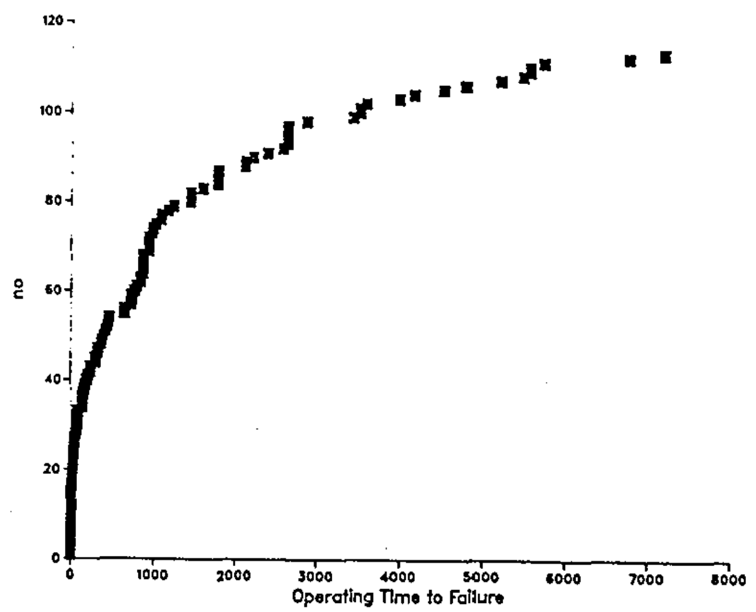

Fig. 4. Failure number against operating time to failure for T1A

Figure 5 shows that bipolar transistors under GM conditions fail with a different pattern from those under GB conditions. In the GB environment the time between failures increases earlier than under GM conditions. In this case, the more severe environment of ground mobile is showing an increasing trend in times between failures which may not be surprising.

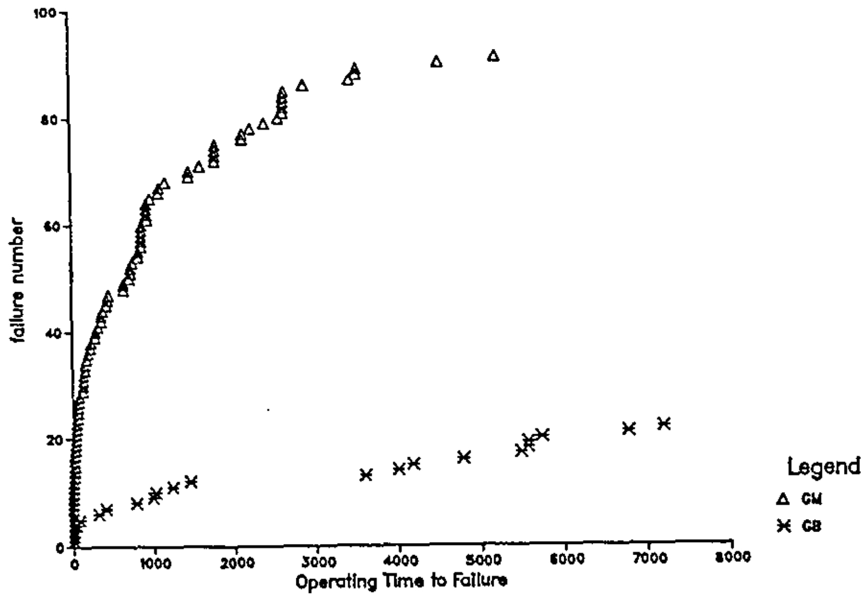

Fig. 5. Failure number against operating time to failure for T1A for two different environments

Although we have highlighted the presence of a trend in this particular data set, cumulative hazard plots may give us some further indication of the nature of this trend. Figure 6 shows time against cumulative hazard for T1A from the aggregate data. This plot exhibits a decreasing hazard rate corresponding to infant mortality.

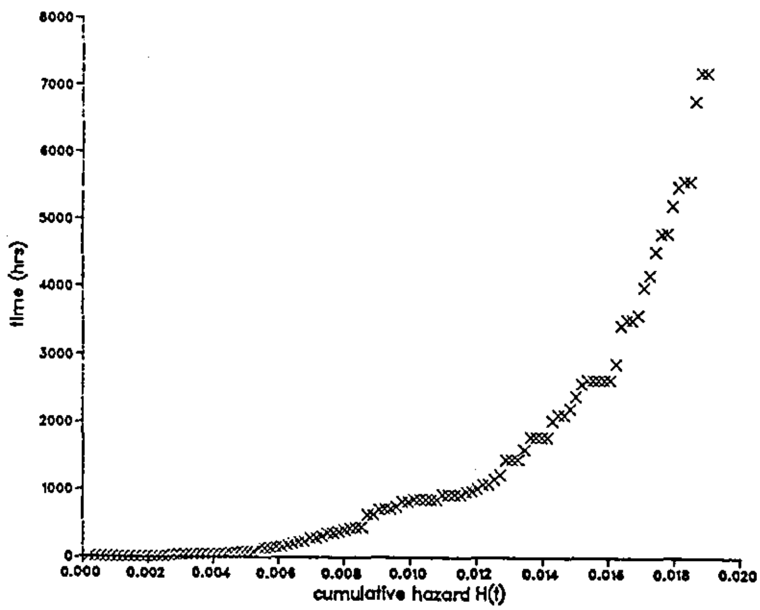

Fig. 6. Cumulative hazard plot on linear scale for T1A

This data is then plotted on Weibull hazard paper (log/log scale) in Figure 7 to estimate some of the parameters. On Weibull hazard paper the shape parameter β is equal to the reciprocal of the gradient of the fitted line [9]. However, it is important to note that, at this stage of the analysis, we are not particularly interested in the exact values of the parameters but in the shape and trend of the distribution.

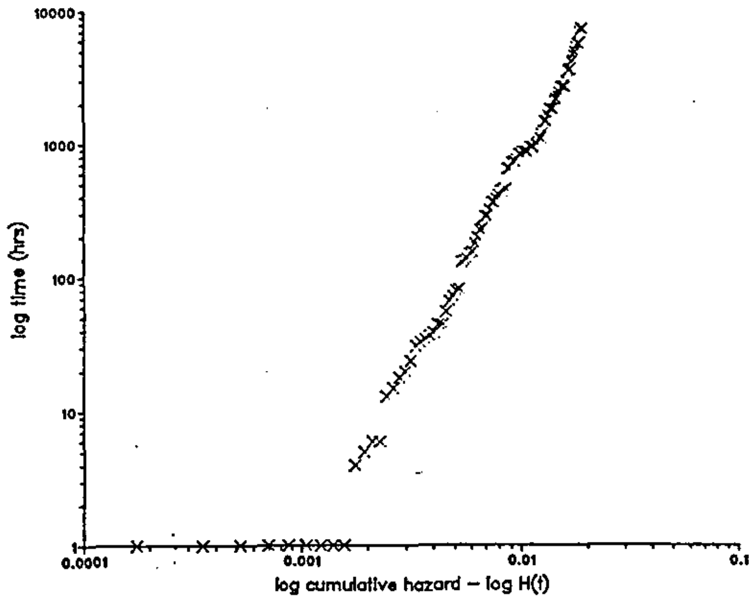

Fig. 7. Cumulative hazard plot on Weibull hazard paper for T1A

In Figure 7, apart from those points at 0 hours, the data appears to fit a Weibull distribution with a β value of approximately 0.336, indicating a decreasing hazard rate. Comparing the hazard plots of the two differing environments may give further information about the contributory factors of the failure distribution of bipolar transistors.

Figure 8 shows time against cumulative hazard for GB and GM environmental conditions for T1A.

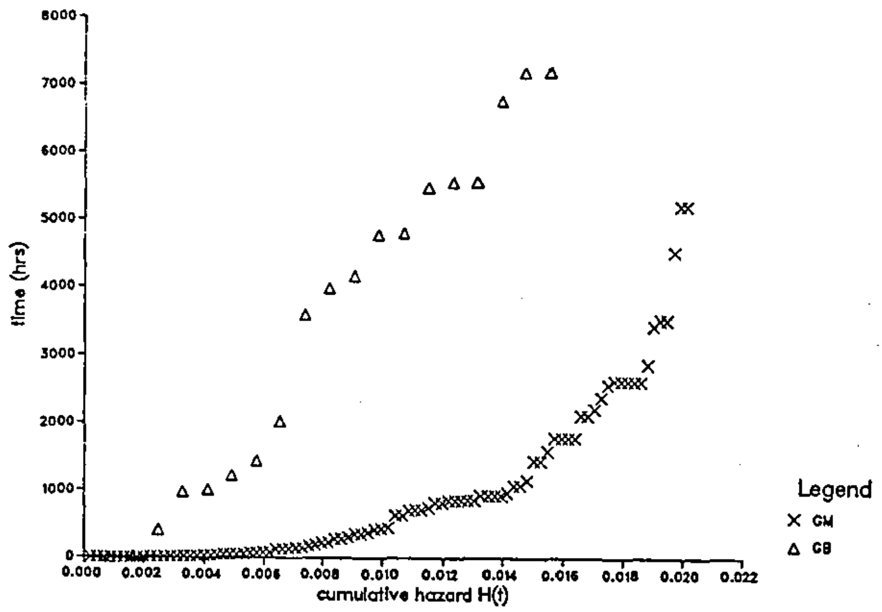

Fig. 8. Cumulative hazard plot on linear scale for T1A for two different environments

The curvature of the GM plot implies a decreasing failure rate which is similar to that in Figure 6. However, the curvature of GB is not so obvious. Plotting the data on Weibull hazard paper shows the difference in the failure distributions of bipolar transistors in GM and GB conditions.

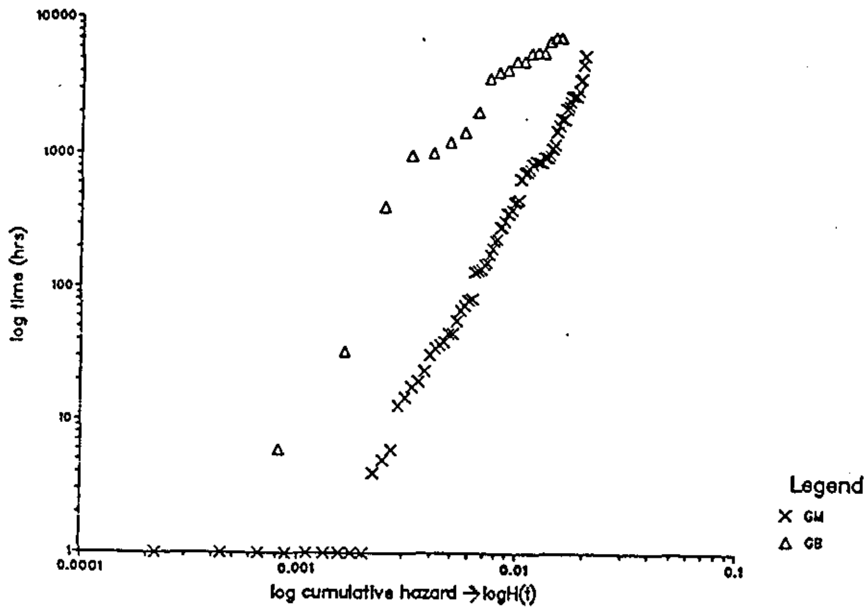

Fig. 9. Cumulative hazard plot on Weibull hazard paper for T1A for two different environments

The β value for GM is approximately 0.325, ignoring the 0 hour failures, thus indicating a decreasing hazard rate. However, it may be dubious to fit one line to the GB plot.

However, one must be careful in coming to firm conclusions on the basis of this limited analysis because:-

1. There is less data on GB than on GM in the database for this component type;

2. There may be significant external factors which affect the failure distribution of this component type for both GM and GB environments;

3. There may be different failure modes mixed in the data.

4. There are different component screening levels in the data.

5. Since GB is a less severe environmental condition than GB, we would expect differing failure distributions;

6. The GB plot in Figure 8 may in fact approximate a straight line which would imply a constant hazard rate;

7. This analysis takes no account of different technologies; thus further breakdown of the part numbers may explain the different trends.

From the exploratory analysis above it is obvious that further exploration is required, in order to model the failure distribution of this component type. PHM may help to highlight further explanatory variables and thus bring us closer to a fuller representation of the failure distribution of bipolar transistors.

6. CONCLUSION

This paper has developed a methodology for the analysis of field failure data of electronic components. It has shown that a field failure hierarchy can be established, and the data used to obtain an analysis of the effect of various aspects such as environment etc. on component failure. A detailed example has been given with regard to discrete bipolar transistors. This analysis shows that bipolar transistors have a complex failure pattern and do not, in general, fulfil the constant hazard rate assumption. These graphs also show that environment affects the failure distribution of these devices.

ACKNOWLEDGEMENTS

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APPENDIX D

Proportional Hazards Analysis of Electronic Component Reliability Data.
Proc 11th ARTS, Liverpool, 1990.

PROPORTIONAL HAZARDS ANALYSIS OF ELECTRONIC COMPONENT RELIABILITY DATA

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ABSTRACT

This paper addresses the challenge of analysing electronic component reliability data arising in diverse environments and applications. Most reliability data has such potential associated explanatory variables, the electronic component reliability data analysed in this paper is no exception. MIL HDBK 217E accounts for these explanatory variables by incorporating π factors. These factors are determined a-priori and give the magnitude and effect of the explanatory variables.

The data analysed in this paper originates from the field failure of electronic components database held at Loughborough University of Technology (LUT). This database is part of a joint project funded by the British MOD, with participants from both electronics companies and academic institutions, namely, STC, GEC, Plessey, LUT, Nottingham Polytechnic and the Danish Engineering Academy (DIA).

The proportional Hazards Model (PHM) has been employed in an exploratory approach and includes such covariates as system operational environment and data source. This paper presents the results on the application of PHM to field data on Bipolar Transistors (T1A) and provides an insight into those factors which significantly influence the failure of these types of devices.

INTRODUCTION

The reliability of electronic components has been a source of study for about 40 years. The majority of such studies have been concerned with the determination of failure rates under 'artificial' conditions such as simulation or accelerated life tests. Failure rates determined from such tests are extrapolated to what might be expected under field conditions. However, these extrapolations are often subject to doubt if only because multiple failure mechanisms may be involved.

Due to some of the problems associated with accelerated life test data and the lack of field data, a study centred at LUT sponsored by the British MOD was initiated to investigate the failure behaviour of electronic components used in equipments in the field [1].

After discussion with many systems manufacturers, three major British Electronic companies became the main data providers ie STC, GEC, Plessey, together with two Danish Electronic companies subcontracted through the DIA. In addition a contract was placed with Nottingham Polytechnic to provide statistical input to the project.

The project has progressed and now has an established database on the field failure of electronic components [2]. This database was designed specifically for the purpose of exploring the data in order to identify those characteristics which may contribute to the failure of electronic components, for example, screening level, environment, encapsulation, mounting. In addition, both non-failed information and failure data is collected in order to establish the lifetimes of those electronic components contained in the database. Data has been coming into the database from sources for approximately 3 years and thus the database is expanding both in terms of volume of data and the number of sources involved.

THE PROPORTIONAL HAZARDS MODEL (PHM)

Previous analyses of the data contained in the database have been concerned with the calculation of constant failure rates for different component types and the comparison of such failure rates for components in different environments and using different screening methods. These analyses have proved both interesting and useful for electronic reliability engineers. However, they may not provide a true reflection of the failure behaviour of electronic components.

Further analysis using hazard plotting techniques for bipolar transistors have shown that these components do not in fact fail exponentially but fit a Weibull distribution with a decreasing hazard [3]. In addition this analysis highlighted the differences in the failure pattern for T1As in ground mobile and ground benign environments. Investigation of other component types such as Rectangular Connectors and Coil Activated Relays have also exhibited a similar decreasing hazard. Further details on these analyses can be found in [4].

Due to the many possible factors which may affect the reliability of electronic components and the uncertainty over the distributional form of failure times (exponential or not), the Proportional Hazards Model which allows for an unspecified distributional form and explanatory factors was employed.

The proportional hazards model is a particularly flexible model, which can be used to isolate the effects of many factors on the hazard function of an electronic component [5]. As previously mentioned there are many factors which have potential impact on electronic component reliability, PHM can incorporate and quantify some of these factors aa explanatory variables.

The proportional hazards model is structured upon the hazard It is assumed for each component type that the associated hazard function can be decomposed into the product of a base-line hazard function, common to all components of a certain type, and an exponential term incorporating the effect of the values of the explanatory factors specific to each individual component, ie

$$h(t, z_1, \ldots, z_k) = h_o(t) \exp(\beta_1 z_1 + \beta_2 z_2 + \ldots \beta_k z_k) \qquad (1)$$

where z_i's are the values of the explanatory factors, $h_o(t)$ is the base-line hazard function and t is the time metric of performance for components, ie operating hours.

The z values can be either measured values, for example percentage time an equipment is switched on, or indicator variables representing, for example, encapsulation methods, environments, etc. The β's are unknown parameters of the model and represent the effect on the hazard of the explanatory factors. These β's are required to be estimated and tested to see whether each explanatory variable has an effect on the variation in observed times to failure. These explanatory variables are assumed to have a multiplicative effect on the base-line hazard function, thus the hazard functions for components, say, with different encapsulations are proportional to each other.

The base-line hazard function h_o represents the hazard a component would experience if the explanatory factors all take the value of zero.

It is fairly obvious then that the application of PHM to the reliability of electronic components would be of great value.

PHM owes its origins to a seminal paper given by Professor D R Cox [6]. At first PHM was mainly applied in the biomedical field, but in recent years the number of applications to reliability data has been increasing [7].

However, in the field of electronic component reliability, there have been very few applications.

The models in MIL HDBK 217E for electronic components are of a similar form to PHM. However the distribution is assumed exponential and the covariates are estimated from accelerated life tests data [8]. Landers and Kolarik, in 1986, published a paper comparing PHM and MIL HDBK 217E [9]. However, this approach is limited because of the assumption of a constant hazard rate and the validity of the accelerated life test data used.

Similarly, Ascher published a paper on the application of PHM to transistors [10]. However, this application was based on a hypothetical transistor and was intended to illustrate the potential use of PHM in the reliability of transistors but real data would obviously have been of greatest interest.

To date, the two papers discussed, [9] and [10] are the only published applications of PHM to non-repairable electronic components.

THE ELECTRONIC COMPONENT RELIABILITY DATA

The database contains information on 1.8 million components and 98 billion component hours. However, there are in fact only about 4,500 failures and about 50% of those are due to 'no fault found'. Thus the amount of censorings is vast compared to the number of failures. Due to the volume of information available for analysis the proportional hazards modelling computer routines employed at Nottingham Polytechnic had to be substantially changed to cope. See Appendix 1. There is information on about 90 out of 125 different component generic descriptions. Obviously, a decision as to which component types should be analysed first must be made [3].

Due to the sparseness of the data, many component types with data cannot be disaggregated by source, environment, screening etc. Apart from a few component types information across data sources is sparse. The data set chosen for the application of PHM contained data on bipolar transistors. This was chosen since exploratory data analysis had already been carried out because there was information across different data sources and environments.

The time metric of the data is operating time (in hours), t in equation (1). The censoring times are calculated from the difference between the up and running date and the end of the observation period. This figure is then multiplied by an estimate of the percentage of time the system was operational (usage), thus giving an operating time for a censored equipment. The operating time to failure of component is collected by the companies. The accuracy of the estimation of usage is currently under investigation and is obviously dependent on the data source and their methods of data collection [11].

In order to extract the censored information for a component, we find for each different equipment type the total number of bipolar transistors. Subsequently, for each equipment serial number of a particular type which did not fail, we can extract the operating time and therefore finally arrive at the censoring times for all those components in equipments which did not fail. Extracting the operating time to failure of a bipolar transistor is straightforward since the database contains such data. The uniqueness of this database is in the fact that all circuit boards are tracked and therefore the previous use and operating time to failure this time around is known.

POTENTIAL EXPLANATORY VARIABLES FOR ELECTRONIC COMPONENTS

The variables which are of most interest and therefore should be investigated for each component include:

System Operational Environment
Encapsulation Method
Data Source
Mounting Technology
Screened Level
Usage

Most of these variables are of the type which can be found in MIL 217E models. Table 1 shows the variables for TIAs.

TABLE 1
Bipolar Transistor Variables

Encapsulation	Mounting	Environment
Hermetically sealed, glass ceramic	Radial wired	Ground Benign
Hermetically sealed, not known	Axial wired	Ground Mobile
Hermetically sealed, welded	Dual in line	
Plastic Transfer Moulded	Surface Mount	
Hermetically sealed, solder	Flat pack	

From Table 1 there are two different environments, 5 different encapsulation methods and 5 different mounting technologies. In addition to the information in Table 1, there is data from 6 different data sources (company).

With regard to the screening level of a bipolar transistor, because there is only one screening level for each data source it is not possible to include screening level separately. For example all data from companies 1, 3 4, 5 are screened to BS9000 level and data from companies 2 and 6 are company screened. In addition, the system operational environment is also linked to screening level and the data source i e companies 1, 3, 4 and 5 operate in ground mobile environments with BS9000 screened components and companies 2 and 6 are operating in ground benign environments. Table 2 summarises this information.

TABLE 2
Screening level/Environment for Company

Company	Screening Level	Environment
1	BS9000	Ground Mobile
2	Other	Ground Benign
3	BS9000	Ground Mobile
4	BS9000	Ground Mobile
5	BS9000	Ground Mobile
6	Other	Ground Benign

Due to the information contained in Table 2 it was decided that we could not use covariates for the company and the environment in the same model because they are linearly dependent.

The information of interest concerning encapsulation is the comparison between the reliability of components which are hermetic or plastic encapsulated. This is because, in general, hermetically sealed components are more expensive than plastic. Also plastic encapsulated components are not suitable in high humidity environments or for high temperature operation.

The inclusion of usage ie the percentage of the time the equipment is operational, is useful as an indication as to whether low use equipments which are most probably switched frequently off and on are less reliable than those systems which are continuously operational. This may not be conclusive since there may be errors in the calculation of usage. However, it may give an indication as to whether the differences in figures for usage contribute to the failure of bipolar transistors.

All the information mentioned above was thought to be of great interest and would therefore be incorporated in a proportional hazards model.

ANALYSIS OF BIPOLAR TRANSISTOR DATA

The analysis reported in this paper concentrates on bipolar transistors (T1A), with data provided by each of the data suppliers involved in the project. The investigation of this particular bipolar transistor data was not only to see if proportional hazards modelling could be utilised in the analysis procedure for the database, but if successfully applied, to establish a structural approach for the analysis of other component types.

The population of bipolar transistors in the field is in excess of 586,000. The failure data available broken down by company, encapsulation, mounting, usage and environment for this data set is given in Table 3.

TABLE 3
Failure Information for Bipolar Transistors

Company	Encapsulation	Mounting	Usage	Environment	No. of failed components
1	0	0	27	1	2
1	0	4	27	1	1
1	2	0	27	1	39
2	1	0	90	0	1
3	2	0	7	1	1
4	2	0	5	1	20
4	2	0	7	1	1
4	2	0	8	1	1
5	0	0	5	1	30
5	3	0	5	1	1
6	0	0	23	0	1
6	0	1	23	0	2
6	2	0	23	0	17
6	2	1	23	0	1
6	4	0	23	0	3
				Total =	121

Note that the failure data matrix is sparse and the relationship between different cells, for example, failures on ground benign are almost totally associated with company six (code 0 in environment column).

With 117 of 121 failures occurring with mounting type coded 0 there is insufficient information to make comparisons of different mounting types. As stated in Table 3 the usage is highly associated with company so that the inclusion of covariates for company and usage would result in the problem of multicolinearity in the covariates. For this reason covariates for usage were omitted from the analysis of this component type. Since encapsulation is almost entirely hermetic comparisons with plastic cannot be made. For other component types and future analyses the problem of relationships between the covariates should occur to a lesser extent.

Since company almost solely defines the other information available the initial analysis concentrated on using only covariates for company. In Figure 1 a breakdown is shown of the times to failure for the component for each company.

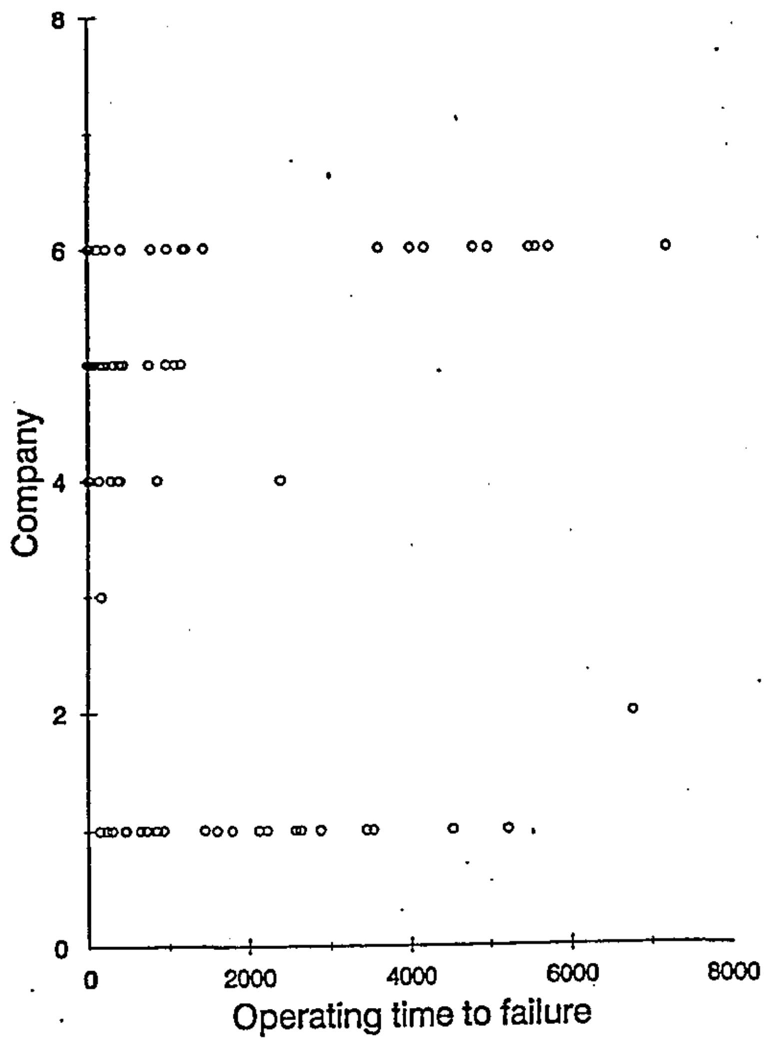

Figure 1. Operating Time to Failure/Company.

Figure 1 shows the pattern of failures through time for each company. From this it can be observed that there is only one failure for companies 2 and 3. Note also that for company 4 there are 8 failures at 0 hours. The pattern revealed in Figure 1 proved to be extremely useful in interpreting the results from the proportional hazards analysis.

For the initial proportional hazards modelling analysis, company 6 was taken as the base since it was associated with ground benign. Due to the small numbers of failures for companies 2 and 3, these were also included as the base. We therefore had covariates for company 1, 4, 5 to compare against the base. This analysis highlighted the problem of near monotonicity [12] for the covariate for company 4. The problem of near monotonicity occurs when there is little overlap of failure times between the covariates causing the problem. The most immediate solution is to omit the covariate from the analysis.

Looking again at Figure 1 it can be seen that the vast majority of failures for company 4 occur before the first failure for company 1. In fact, over half the failures for this company occurred during the first hour of observation resulting in the problem with analyses. Apart from one failure for company 5 at time 0, it is seen that company 4 is the only one to encounter switch on problems.

Omitting the covariate for company 4 and running the proportional hazards model with a backward stepwise regression procedure, whereby in each run the most non-significant covariate is removed from the model and the model rerun with the remaining covariates, we found only company 1 to be statistically significant and different from the rest. As an alternative to dropping company 4 from the analysis we changed the base to companies 2, 3 and 5. The results were consistent and are shown in Table 4.

TABLE 4
Comparisons between different companies

Company	β Coefficient	Z-score	p value one-sided
1	-0.74349	-0.38724	0.0001
4 *	-0.11368	-0.3475	0.3475
6 *	-0.37286	-1.5035	0.0664

* Values when covariate omitted from model.

From Table 4 the β coefficient for company 1 (-0.74) indicates that the hazard for this company is smaller than for the rest and thus on average the time to failure for bipolar transistors is longer. A Weibull hazard plot for the base-line hazard for this analysis is shown in Figure 2. The straight line on the plot indicates the appropriateness of the Weibull distribution for the base-line. The value of the shape parameter (0.32) taken from the plot is in agreement with previous analysis on the individual cells in the data matrix [3].

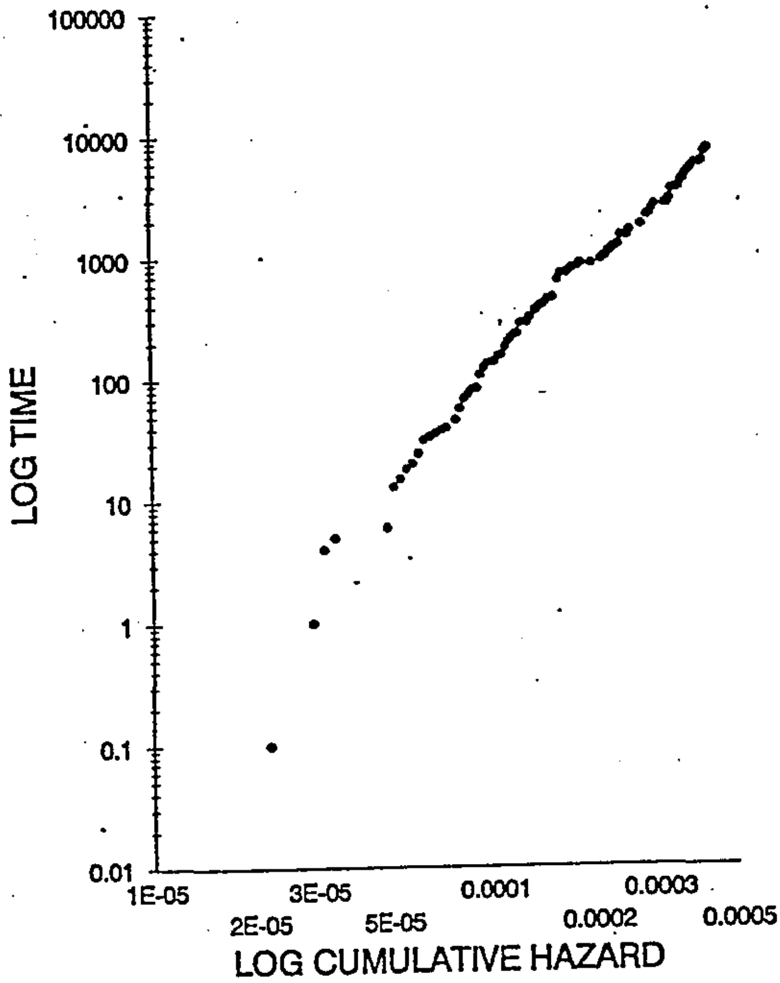

Figure 2. Base-line hazard plot.

In Figure 3 a proportionality plot is shown for company 1. This plot investigates whether the covariate does indeed, as assumed, have a proportional effect on the hazard. The plot is obtained by splitting the data on the covariate (in the case of a binary covariate into two groups) and running the analysis procedure on each group. If the assumption is valid, then the plot on appropriate axes should show constant vertical separation between the groups [7]. Figure 3 clearly shows the assumption to be valid.

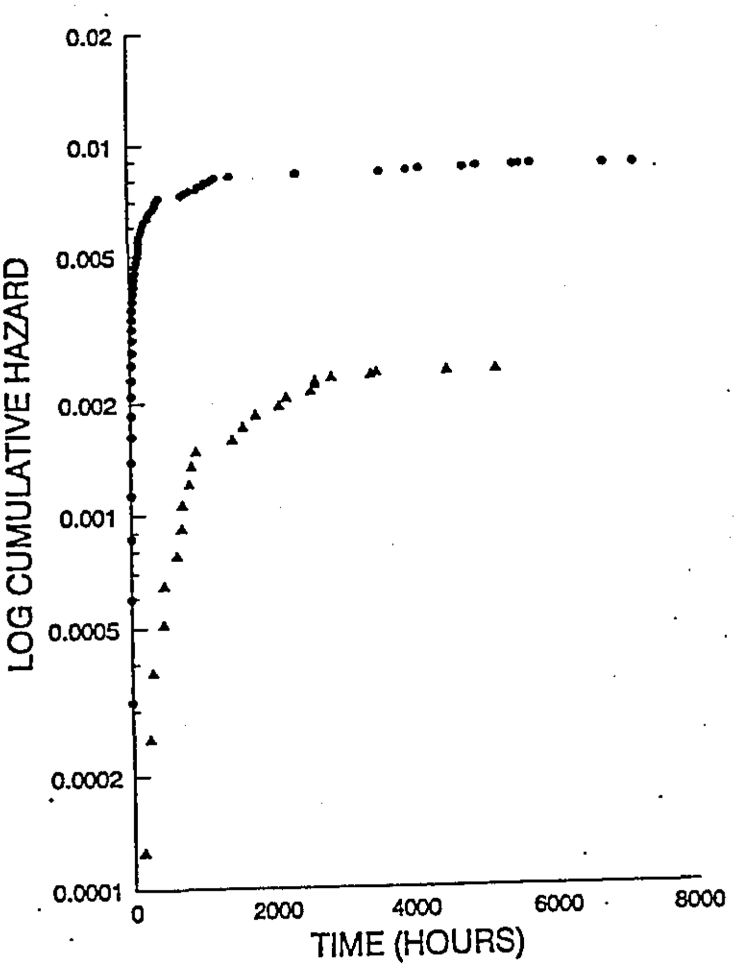

Figure 3. Proportionality Plot.

The Cox and Snell (1968) variance stabilised residual plot [13], [14], [15] is shown in Figure 4. If the model is appropriate then the residuals from the model should be similar to a sample of observations drawn from the unit exponential distribution. Plotting on appropriate scales, the observed residuals against expected residuals should give a 45 degree line (through the origin), this is the case for Figure 4.

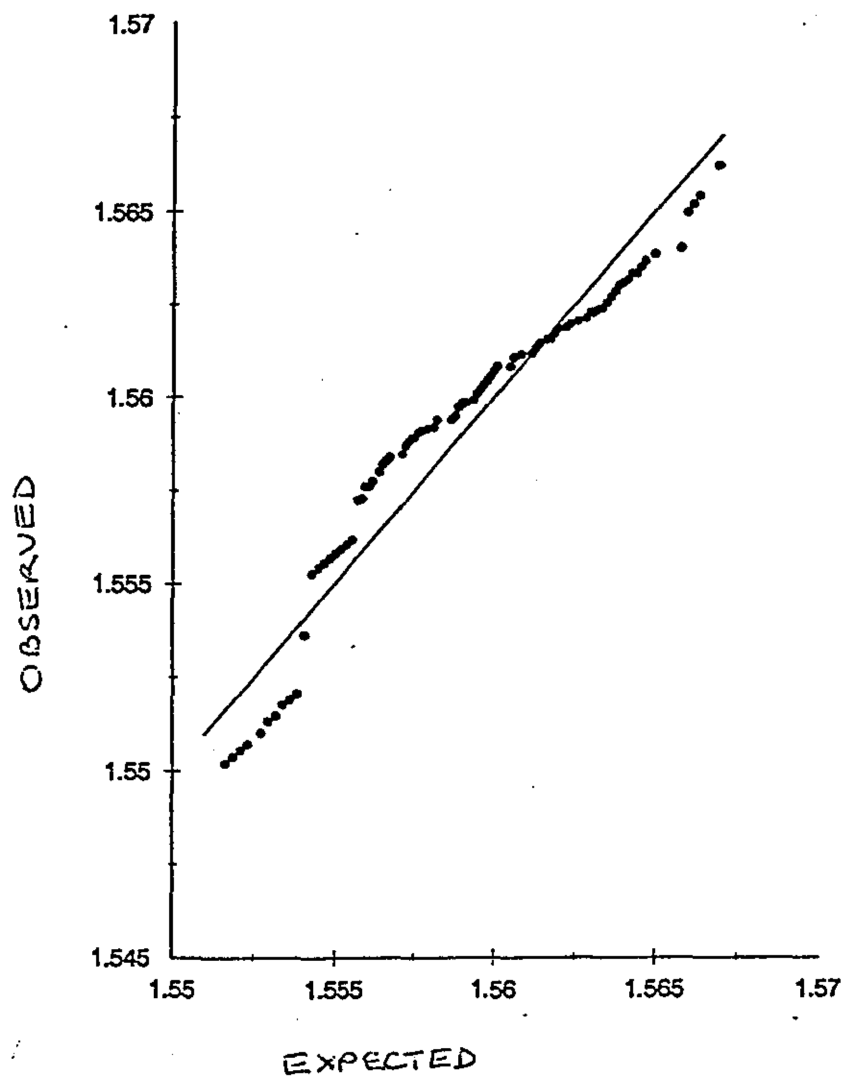

Figure 4. Variance Stabilised Cox and Snell Residuals.

Notwithstanding the diagnostics suggesting the good fit of the model in the initial analysis, consideration was given to the appropriateness of including information from companies 2, 3 and 4. With the majority of company 5's failures occurring before the first failure on company 1, the information for company 5 was therefore omitted from the next analysis discussed here.

We were thus left with 66 failures and just over 410,000 censorings for the comparison of companies 1 and 6. With company 6 as the base and running the model we obtained the results as shown in Table 5.

TABLE 5
Comparisons of companies 1 and 6

β	z	p value (one sided)
-0.27964	-1.0707	0.1421

Although the β coefficient indicates that company 1 has a lower hazard than company 6, the β is non-significant on a two-tailed 5% test. Figure 5 shows a Weibull hazard plot for the data (since there are no significant covariates the plot is the result of combining the data from companies 1 and 6). The straightness of the plot shows the appropriatenesss of the Weibull, the scale parameter again reinforcing previous convictions. Due to the relationship between environment and company this meant that they could not be contained in the same proportional hazards model.

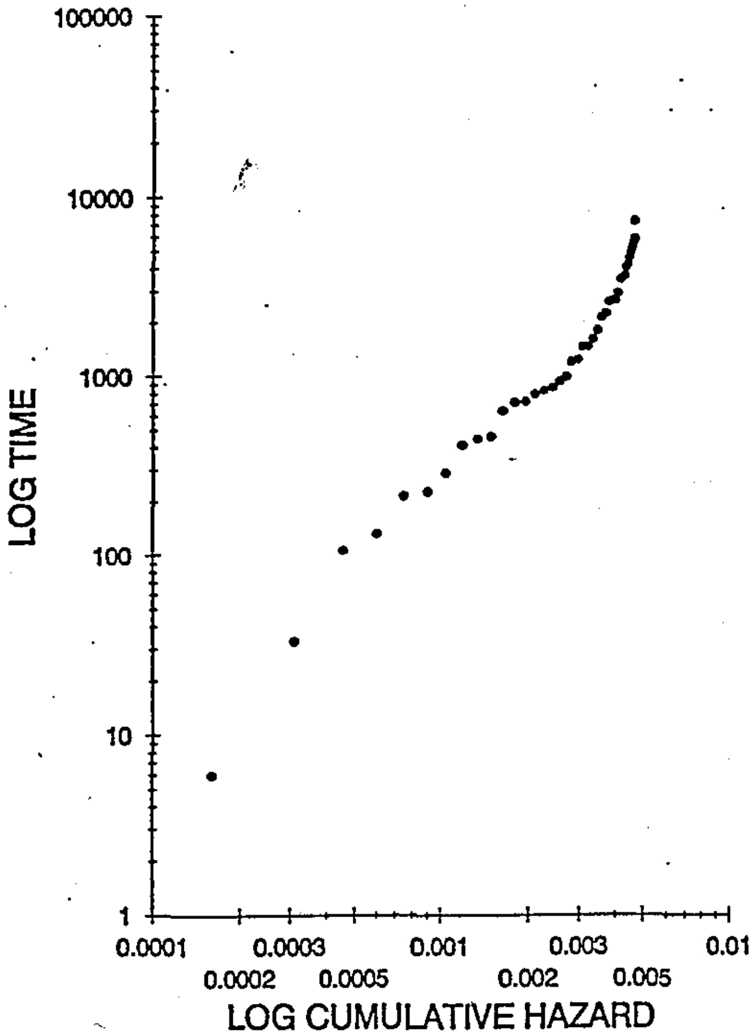

Figure 5. Weibull hazard plot.

Utilising the full data set analysis was focussed on the environmental information, with ground mobile as the base comparison for ground benign. The results obtained from this analysis showed the β coefficient for ground benign (-0.74141 with a p-value of 0.0007) was significant and that ground benign had a lower hazard compared to ground mobile.

We present in Figure 6 the Schoenfeld [22] partial residuals for this covariate. The partial residuals are essentially the observed value of the covariate minus the expected value for each failure point. From these plots we are looking for outlying values or gaps where no residuals are shown. The two lines in Figure 6 are typical for a binary covariate. However, in the upper band, corresponding to failures on ground benign, there is a period from 1600 to 3500 where no failures occurred, thus separating the failures into two distinct groups. The reason for the apparent grouping is not obvious.

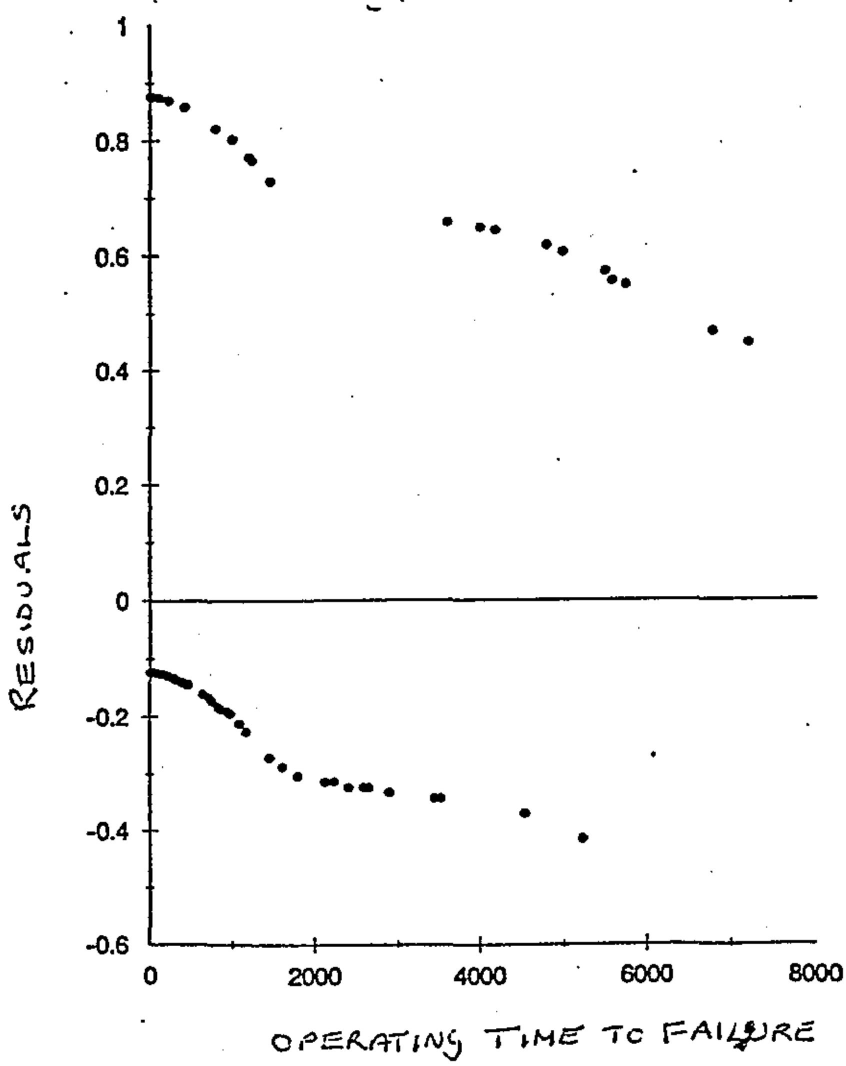

Figure 6. Schoenfeld Partial Residuals.

From Table 3 the ground benign information can be seen to have been supplied by companies 2 and 6. For company 2 over 98% of the censoring information occurred after the last failure observed on all of the data. This unusual data set together with company 3's information which contained only 1 failure, was omitted and subsequent analysis then showed the comparison of ground mobile and ground benign to be statistically non-significant.

SUMMARY AND CONCLUSIONS

Due to the sparseness of the data on bipolar transistors it was not feasible to include all the variables of interest. In addition, because of the relationship between data source and environment it was not possible to include both data source and environment as covariates in the same model. Thus they were considered separately.

The results from this analysis indicated that bipolar transistors from company 1 were more reliable than those in the other companies. However, caution must be used when interpreting these results due to the particular peculiarities of each of the different company data sets. Such peculiarities include the large number of 0 hour failures in company 4, the few numbers of failures for companies 2 and 3 and the vast number of censoring for companies 2 and 6.

Several positive aspects have arisen from this analysis. These include the consistency of the shape of the base line hazard. In both analyses the failures for bipolar transistors have exhibited a Weibull distribution with a decreasing hazard. This is consistent with previous analysis carried out on this data. Thus the assumption of a constant hazard rate is not valid for this data.

The possible reasons for this decreasing hazard could be that the burn-in procedures are not sufficient to eradicate weak components. Similarly, perhaps the methods employed for designing printed circuit boards are done in an iterative manner whereby unless a design problem is encountered with a particular component type then the design is assumed to be correct.

In addition, the analyses of this data provided useful experience in the steps required to transform the data from the database into the required format for PHM. This gained experience can be built upon as more appropriate data becomes available on other component types.

Although this application has been limited it has shown that when more data becomes available PHM will be a useful tool in the analysis of electronic component field reliability data.

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We would also like to thank Mr J A Jones at Loughborough University for his help in extracting the data from the database.

APPENDIX 1
ADAPTATION OF PROPORTIONAL HAZARDS MODELLING PROGRAMS

The application of proportional hazards modelling to electronic components (non-repairable items) with the auxiliary information held in the database causes no problem in itself. The problems arise in the analyses when the number of each component, especially censored observations, in the field is considered along with the auxiliary information that forms the covariates. It is of course possible to consider subsets of the data or to concentrate only on the failure information. However, this may well produce unsatisfactory analysis.

The adaptation of the proportional hazards modelling programs employed at Nottingham Polytechnic to allow for the analysis of extremely large data sets has two main themes:

1. Instead of holding failure, censoring, covariate values and other required information within the programs this information is continually read from a data file. To allow for this change extra preparation is required in the creation of the data file for proportional hazards modelling analysis. In particular the data in the file must be ranked from largest to smallest time, with a column to indicate the rank of the observation.
2. The grouping of observations with the same rank and covariate information. Again to allow for this change extra preparation must be investigated in the creation of the data file for analysis. Also to accommodate this change the proportional hazards modelling equations such as partial log-likelihood, first partial differntial of the log-likelihood and information matrix had to be changed.

The changes discussed in 1 and 2 have a major impact on how the diagnostics for the model are obtained. For the base-line hazard it is now more convenient to use Breslow's [16], [17] formulation rather than in the original Kalbfleisch and Prentice [18] routines the Kalbfleish and Prentice [19] estimate. Breslow's estimate is a first order approximation to that of Kalbfleisch and Prentice. The base-line hazard is used to check appropriate distributional forms such as Weibull or Lognormal for the model. The base line hazard is also used in the proportionality plots, [20], [21].

It was found that the Schoenfeld [22] residuals require little adaption, mainly because they are defined only at failure points. We have placed a limit of 100 different possible combinations of covariates for the failures at each failure point. This of course is easily extended. The Schoenfeld residuals are used to compare observed covariate values against the expected covariate value.

Since empirical influence functions (see [24], [25] and [7]) are defined at both failure and censoring points and for each observation the value of the empirical function for each of the significant covariates depends on the number of risk sets the observation is a member of and whether a failure or not then the introduction of 1 and 2 require substantial programming changes. For each covariate in the model the set of empirical influence values are used in an informal manner to investigate the effect of each observation on determining the β coefficient.

The Cox and Snell [13] residuals for the model (see [20]) also requires a substantial amount of reprogramming. If the model is appropriate for the data then the Cox and Snell residuals should be somewhat similar to a sample from the unit exponential distribution.

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APPENDIX E

An Exploratory Approach to the Reliability Analysis of Electronic Component Field Data.
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AN EXPLORATORY APPROACH TO THE RELIABILITY ANALYSIS OF ELECTRONIC COMPONENT FIELD DATA

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ABSTRACT

This paper discusses some results from data analysis carried out on particular component types contained in the Electronic Component Reliability Database at Loughborough University of Technology.

Earlier papers have described the content, administration and development of analysis procedures for data in the database.

The main assumption made in previous analyses concerning the distribution of field failures of electronic components is one of a constant failure rate. The current paper concentrates on identifying whether this assumption is in fact valid for the data on those particular component types which have been analyzed.

In addition, the structure of the database facilitates an exploratory approach to the data analysis. This involves the identification of the effects of such variables as environment, data source and screening, and other variables which may have an influence on the failure behaviour of electronic components.

1. INTRODUCTION

The establishment of an electronic component field failure database centred at Loughborough University of Technology (LUT) in the United Kingdom has been described in two papers [1,2]. At present several data sources both in the U.K. and Denmark are actively involved in this field failure study. A detailed reporting format has been developed using statistical and engineering expertise, and is used to assess the dependability of the data collected and processed by the companies. Because of the number of individual companies involved it is possible to follow a wide range of equipments, both military and commercial, in several operational environments. Historical data, at present up to seven years old, is also processed if shown to be dependable by meeting the requirements of the reporting format.

The database has been designed around the detailed reporting format and, in practice, this means that component behaviour can be evaluated not only with respect to time but with regard to other important parameters such as environment, screening level, encapsulation, mounting etc. Data has been coming into the database from the sources for approximately three years and the database is expanding both in terms of the volume of data and the number of sources actively involved.

2. CONVENTIONAL METHODS OF ANALYSIS

Electronic component field failure and population data is essential for systems reliability prediction. The accuracy of such predictions depends on the failure data that is used. Blanks [3] has stated that no matter how excellent the mathematical modelling, how precise the analysis and how detailed the resulting formulae, ultimately the prediction can be no more accurate than the numerical data substituted in them. The majority of reliability studies on electronic components unfortunately, but understandably, have been carried out under accelerated conditions since data collection is expensive and time consuming. Failure rates are then extrapolated from such tests to what might be expected under field conditions. These extrapolations are often subject to doubt, if only because multiple failure mechanisms are usually involved.

The most widely used failure rate models which incorporate factors to take account of effects such as environment, screening etc. are those published in MIL-HDBK-217, [4]. It is not uncommon for reliability predictions based on the Parts Stress Analysis method to be a contractual obligation for system suppliers. Much criticism has been voiced with regard to predictions based on MIL-HDBK-217, particularly with regard to the wildly pessimistic predictions for some semiconductor devices when compared with observed field performance data. This is not entirely unexpected as, in general, the models are derived from test bed, accelerated life and limited fragmented field failure data. In addition, the concept of a constant failure rate has not been substantiated, in practice, for all electronic components and indeed is not accepted by many [5,6]. However, reliability models based on a constant failure rate assumption are attractive from a systems engineer's stand point as they are in principle simple and easily interpreted.

Electronic component field failure data is available, notably that presented in the British Telecom 'Handbook of Reliability Data for Components Used in Telecommunication Systems' [7]. The failure data presented is limited, however, in that it is derived from inland telephone exchanges only, operating in benign environments. In order to give failure rate data on a wide range of components it has been necessary to obtain data in some cases from 'one or more alternative sources with minimal supporting evidence'. Although the data is of use to the suppliers of telecommunication equipment, it is of limited use to manufacturers of equipments operating in environments other than benign, as again the models presented are of an empirical nature.

The need to establish an electronic component field failure database to allow more detailed analysis and to study the behaviour of components under different environments to determine the factors affecting their field failure behaviour is the basis of the Loughborough database.

3. ANALYSIS METHODS

3.1 Introduction

The database design facilitates an exploratory approach to the analysis of the data.

When a component fails in a system, the information stored in the database details how and when it failed, together with descriptive details of the device itself. An abbreviated version of the database design can be found in [2]. The database contains information, not only on the failure characteristics of a component, but also on systems out in the field. This data consists of information about the environment the system is working in, the percentage of time the system is operational and a full component listing. One aim of the study is to analyze the factors which affect the reliability of electronic components, namely environment, encapsulation, screening, etc.

Figure 1 shows a flowchart of the two stages of analysis carried out.

3.2 Stage 1 - Initial Analysis

Stage 1 initially involves the calculation of component failure rates from available data. Such calculations have the underlying assumption of a constant failure rate. From these an hierarchy of problem components can be obtained as shown in Figure 2. The component categories shown in Figure 2 have previously been identified [1]. χ^2 confidence limits for these failure rates have been calculated in an attempt to qualify this hierarchy and to indicate those components which may require additional data [2,9].

In order to determine a priority for analysis a decision table was constructed as shown in Table 1. The model in Table 1 indicates the order in which component types are analyzed and is related

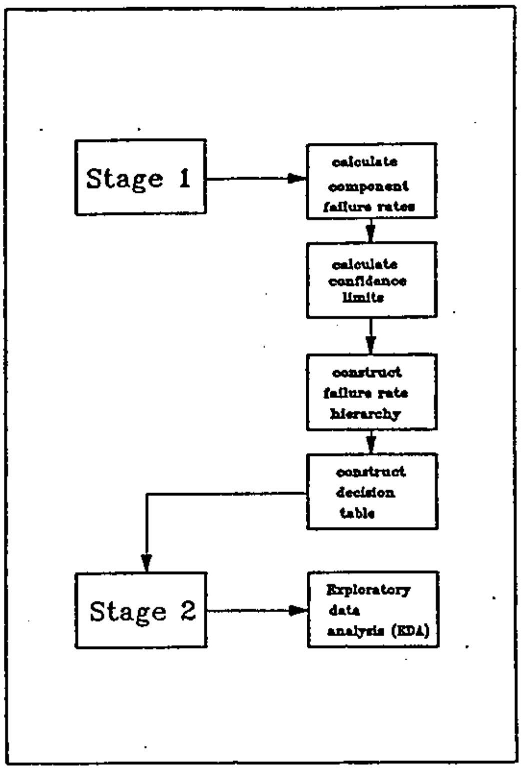

Fig. 1. Flowchart of the Two Stages of Analysis

to the volume of data. Each box in the table represents various combinations of component failure rates, component hours and number of failures for each component type.

The first stage is concerned with exploring the data in order to investigate design problems and source related problems. This is essential, especially when data is pooled from multiple sources. This will take the form of:

1. Checking the number of sources providing the information on the component type under investigation;

2. A breakdown of the number of failures and total component hours by source;

3. Checking for design problems which usually involves repetitive failures in the same circuit reference position.

Highlighting possible design problems is important not only to the company manufacturing the equipment, but in order to understand the failure pattern of the data. Similarly, if there are multiple 'failures' of the same component type it is important to know whether these are in fact real failures or are a consequence of the replacement policy carried out by the company. The flowchart in Figure 3 shows the stages of data analysis. When problems relating to a particular source are identified, the company is requested for supplementary information.

Table 1. Decision Table for Component Analysis (Failure Rate in Fits)

	High Fits	Low Fits
HF, HCH	2	4
HF, LCH	1	3
LF, HCH	5	7
LF, LCH	6	8

HF - High No. of Failures
LF - Low No. of Failures
HCH - High No. of Component Hours
LCH - Low No. of Component Hours

3.3 Stage 2 - Exploratory Data Analysis (EDA)

EDA involves using simple graphical and tabular methods to highlight any patterns or irregularities in the data. It increases not only the understanding of the nature of the data and failure phenomena, but also indicates the type of analysis which is appropriate. When patterns or trends are identified they can be built into models for analysis, so that results will be more meaningful.

Standard techniques for analyzing reliability data assume that the time between events are independently and identically distributed (iid). Exploratory techniques such as checking for trend and serial correlation in the data will reveal where these assumptions are upheld.

Past papers have discussed [10] the need for EDA and the techniques employed. However, they are mostly concerned with repairable systems. The LUT database contains reliability data on non-repairable electronic components which themselves come from numerous different repairable systems. This introduces a more complex approach to EDA. In order to pool this component data from

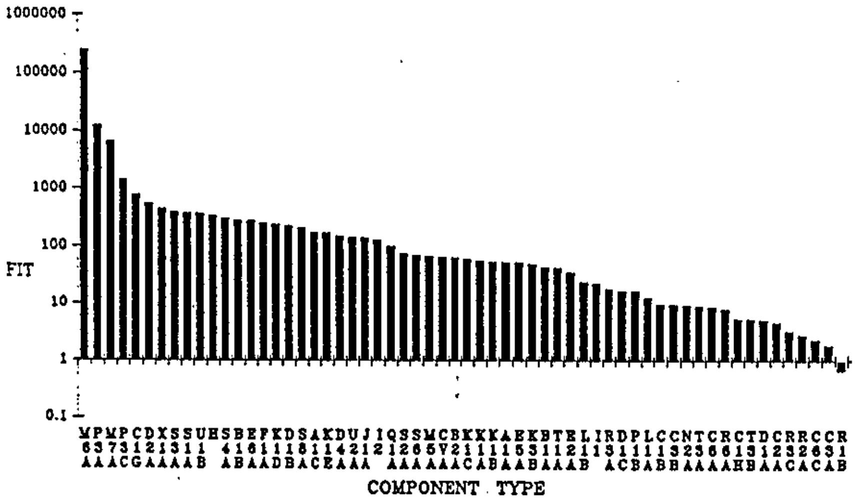

Fig. 2. Bar Chart of Failure Rates for Each Component Type

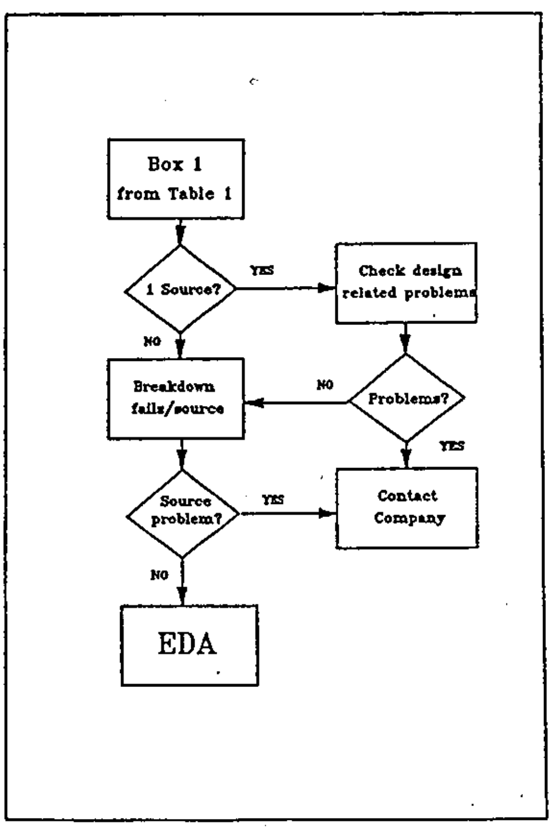

Fig. 3. Flowchart of Order of Analysis

different sources, it is important to explore the data for different time patterns between sources, environments, screening etc. Checks for design and multiple replacements have to be previously carried out, thus eliminating some of the dependencies within the database.

The time metric in the database is operating time to failure, not calendar time. The time between events is only relevant for a given item of equipment and is meaningless for pooled data. Thus a different approach to exploring this data is required.

Exploratory analysis currently employed involves:

1. Failure rates broken down by source, environment etc.;

2. Operating time to failure against failure number plots for pooled data, for different equipment types (sources) and different environments;

3. Hazard plotting;

4. Proportional Hazards Modelling (PHM).

During the analysis carried out in (1) above, if the failure data from one source is consistently different from the others over all component types, then this needs to be investigated at source. Failure rate calculations have their limitations. They are an average value and do not give any indication of when the failures occurred. However, they do give a reasonable first impression of the data.

After exploring any inconsistencies in the source data, Stage 2 above is carried out. This involves plotting the operating time to failure of a given component type against failure number. Again, breaking down by source or environment, gives an indication of the failure pattern associated with this component type. The population at risk has not been considered at this stage.

Stage 3 involves hazard plots for different component types and takes into account censoring times and gives a more realistic view of the data. This involves knowledge of the operating time of the non failed components as well as the failed components. Similarly, plots of time against cumulative hazard for components from different sources, environments, encapsulation, screening etc. give an indication of differing failure distributions between these factors. Hazard plotting also highlights whether the assumption of constant failure rate is in fact valid [11]. Examples are discussed in Section 4.

The fourth stage of EDA is a further development of this exploratory approach. Proportional Hazards Modelling (PHM), as discussed in many texts [12,13,14], incorporates explanatory variables such as source, environments, screening etc. into the model and consequently highlights whether they are in fact significant contributory factors to the failure distribution of the component. Hazard plotting alone merely takes account of the censorings when calculating the hazard contribution, but PHM actually uses the censorings in the calculation of the likelihood, thus improving our understanding of the failure pattern. Furthermore, it assumes no distributional form and empirically estimates the hazard distribution, taking into account the significant covariates established by the model.

The model can also be extended to include further variables such as screening level of the component, batch number, circuit reference position etc. Many different explanatory variables can be incorporated into the models thus approaching a more accurate representation of the failure of an electronic component.

3.4 Problems Encountered in the Analysis

The LUT database to date contains information on 18 million components and 98 billion component hours, and approximately 6,500 failure records representing a vast amount of data. The amount of censorings is vast compared to the number of failures. This causes numeric problems in PHM software [15].

4. PRELIMINARY RESULTS

As described in Section 3, the first stage of analysis is to calculate the failure rates for each component type and produce a barchart displaying the failure rate hierarchy. Figure 2 has shown such a failure rate hierarchy. The failure rate scale is log, since the difference in failure rates from the highest to the lowest is large. To date the component types at the top of the hierarchy are microwave cavities (M6A) wirewound variable resistors (P3A), microwave switches (M7A) and metal film variable resistors (P3C).

The decision model shown in Table 1 is expanded to contain actual component data in Table 2. The table shows that although there are very high failure rates for P3C and M7A, they have

Table 2. Identification of Components for Analysis

Failures	Component Hours	Fit > 50	Fit < 50
≥ 10	≥ 10^6	A1A CVA I2 S3A K1C Q1A B1A D2A F1A S6A K1D S2A B2A H K1A K1B K1E U1B	C1B C3A E2A R3A T1A C6A D1A I1 R3C C1H D1C R2A R6A
≥ 10	< 10^6	M6A P3A	
< 10	≥ 10^6	A1C E6A J1A S4A	C2A E5A C1B R3B C3B K3B N2A T3A P1B C6C L1A R1B T3B
< 10	< 10^6	B1B D4A P3C X1A C1G M5A S1A U2A D1B M7A S8A	

a small number of failures. Thus, further analysis cans be concentrated on the other two components, namely P3A and M6A, which have a high number of failures but a small number of component hours. This highlights a need for investigation into the number of sources providing the data and consequently checking for design errors. The reasons for these high failure rates have been investigated by the data source.

The next stage of analysis involves exploratory data analysis. The component type under investigation in the following examples are bipolar transistors (T1A). Data on these components have been provided from 4 sources.

Figure 4 shows aggregated operating time to failure against failure number. This plot indicates that as time progresses the time between events increases. By breaking down the data by environment, i.e. GB - ground benign and GM - ground mobile, we can see more clearly which environmental condition is contributing to this increasing trend.

Figure 5 shows that bipolar transistors under GM conditions fail with a different pattern from those under GB conditions. In the GB environment the time between failures increases earlier than under GM conditions. In this case, the more severe environment of ground mobile is showing an increasing trend in times between failures which may not be surprising.

Although the presence of a trend in this particular data set has been highlighted, cumulative hazard plots may give further indication of the nature of this trend. Figure 6 shows time against cumulative hazard for bipolar transistors from the aggregate data. This plot exhibits a decreasing hazard rate corresponding to infant mortality.

This data is then plotted on Weibull hazard paper (log/log scale) in Figure 7 to estimate some of the parameters. On Weibull hazard paper the shape parameter β is equal to the reciprocal of the gradient of the fitted line [9]. However, it is important to note that, at this stage of the analysis, we are not particularly interested in the exact values of the parameters but in the shape and trend of the distribution.

In Figure 7, apart from those points at zero hours, the data appears to fit a Weibull distribution with a β value of approximately 0.336, indicating a decreasing hazard rate. Comparing the hazard plots of the two differing environments may give further information about the contributory factors of the failure distribution of bipolar transistors.

Figure 8 shows time against cumulative hazard for GB and GM environmental conditions.

The curvature of the GM plot implies a decreasing failure rate which is similar to that in Figure 6. However, the curvature of GB is not so obvious. Plotting the data on Weibull hazard paper shows the difference in the failure distributions of bipolar transistors in GM and GB conditions.

The β value for GM is approximately 0.325, ignoring the zero hour failures, thus indicating a decreasing hazard rate. However, it may be dubious to fit one line to the GB plot.

However, one must be careful in coming to firm conclusions on the basis of this limited analysis because:

1. There is less data on GB than on GM in the database for this component type;

2. There may be significant external factors which affect the failure distribution of this component type for both GM and GB environments;

3. There may be different failure modes mixed in the data;

4. There are different component screening levels in the data;

5. Since GB is a less severe environmental condition than GB, we would expect differing failure distributions;

6. The GB plot in Figure 8 may in fact approximate a straight line which would imply a constant hazard rate;

7. This analysis takes no account of different technologies; thus further breakdown of the part numbers may explain the different trends.

From the exploratory analysis above it is evident that further exploration is required, in order to model the failure distribution of this component type. PHM may help to highlight further explanatory variables and thus bring us closer to a fuller representation of the failure distribution of bipolar transistors.

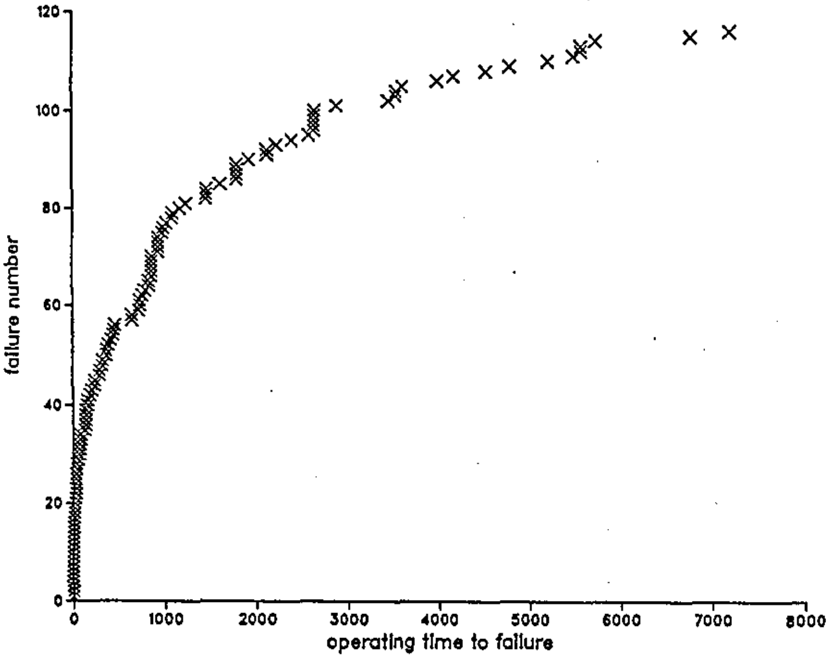

Fig. 4. Failure Number Against Operating Time to Failure for Bipolar Transistors (T1A)

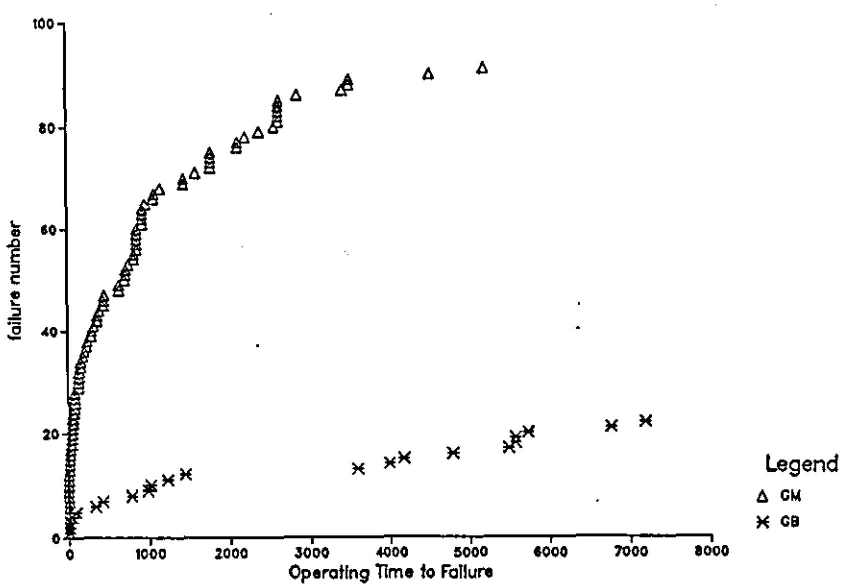

Fig. 5. Failure Number Against Operating Time to Failure for Bipolar Transistors for Two Different Environments

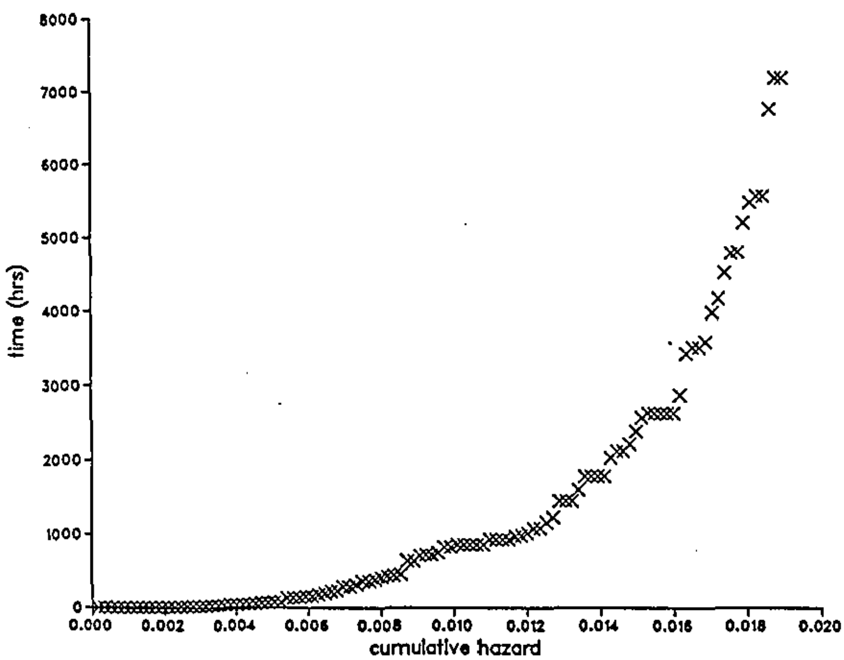

Fig. 6. Cumulative Hazard Plot on Linear Scale for Bipolar Transistors

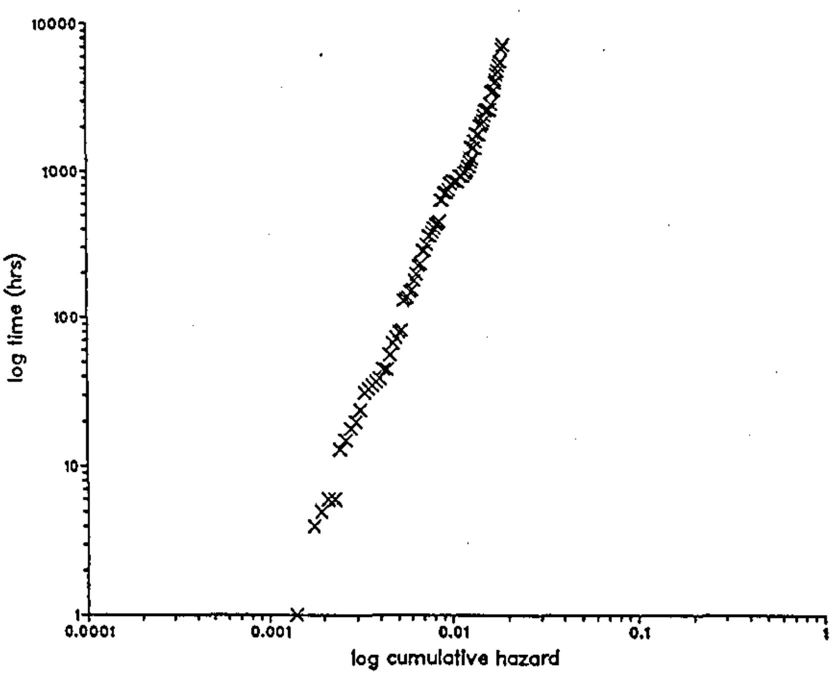

Fig. 7. Cumulative Hazard Plot on Weibull Hazard Paper for Bipolar Transistors

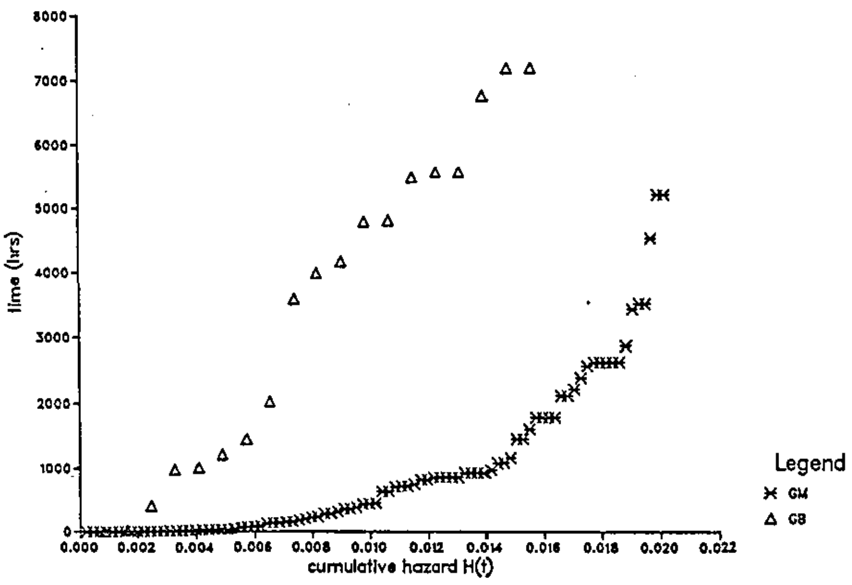

Fig. 8. Cumulative Hazard Plot on Linear Scale for Bipolar Transistors for Two Different Environments

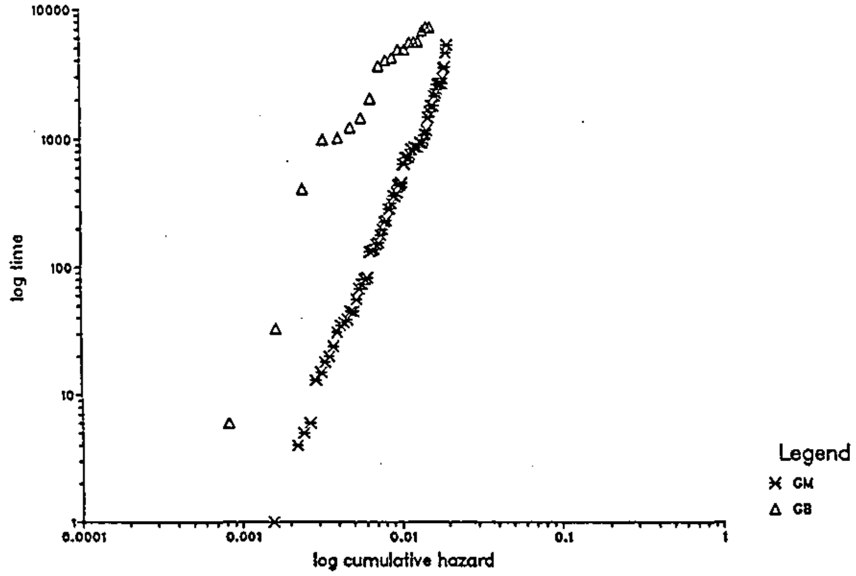

Fig. 9. Cumulative Hazard Plot on Weibull Hazard Paper for Bipolar Transistors for Two Different Environments

5. CONCLUSION

This paper has developed a methodology for the analysis of field failure data of electronic components. It has shown that a field failure hierarchy can be established, and the data used to obtain an analysis of the effect of various aspects such as environment etc. on component failure. A detailed example has been given with regard to discrete bipolar transistors. This analysis shows that bipolar transistors have a complex failure pattern and do not, in general, fulfil the constant hazard rate assumption. These graphs also show that environment affects the failure distribution of these devices.

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