THE DESIGN AND APPLICATION OF A DATA LOGGING SYSTEM TO MONITOR DISCRETE ELECTRONIC COMPONENTS

by

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".... when you have reached the mountain top, then you shall begin to climb.

And when the earth shall claim your limbs, then you truly dance."

Kahlil Gibran

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Finally, there are many people too numerous to mention who have been helpful on various occasions. Their assistance has also played its part.

ABSTRACT

A Data Logger has been designed and developed by the author. The Data Logger is used to take measurements on electronic components.

The Data Logger is outlined. It is described in terms of the hardware from which it was built. It is also described in terms of the software through which it is controlled using an Apple microcomputer.

An experiment on multilayer ceramic capacitors is detailed. A further experiment on optocouplers is outlined. Both experiments make full use of the Data Logger.

In concluding, the Data Logger is found to work best with two and three terminal components. Some changes are discussed, enabling the Data Logger to be compatible with the IBM PC format.

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ABBREVIATIONS

A	amps
ADC	analogue to digital converter
CTR	current transfer ratio
Ea	activation energy
eV	electron volt (≅ 1.602 x 10^{-19} coulomb)
F	farads
F(t)	cumulative distribution function (c.d.f.)
GPIB	general purpose interface bus
Hz	hertz
Ic	collector current
IEEE	Institute of Electronic and Electrical Engineers
I/O	input/output
k	Boltzman's constant (8.623 x 10^{-5} eV/K)
K	kelvin
L	inductance
m	meter
mA	milliamp
MLC	multilayer ceramic capacitor
MTBF	mean time between failure
MTTF	mean time to failure
t	time
T	temperature
V	volts
V_{CE}	collector emitter voltage

V_F	forward voltage
V_{SAT}	saturation voltage
η	characteristic lifetime
Ω	ohms

1. I N T R O D U C T I O N

1.1 OUTLINE OF THESIS

This thesis aims to give the reader a detailed account of the design and application of a Data Logging System to Monitor Discrete Electronic Components.

It first introduces the reader to the background behind this Data Logger. The background of reliability and reliability analysis. It then provides a brief look at data logging to give an idea of the scope of data logging, then finally a summary of different generic component types and an idea of what kinds of failures may be associated with them.

Next the Data Logger built at Loughborough University of Technology is introduced and its design features, the hardware that it uses and the software that runs it are described in detail. The construction of the Data Logger is described.

Chapter three is about the Data Logger applications. It discusses the general applicability of the system, defining what it can and can not be used for. Following this an account is given of the specific work that it has been used for, mainly on optocouplers and on ceramic capacitors. Then a brief account of some of the smaller applications that it has been used for is given.

Finally, in the conclusions the design, software and component application are assessed. This is followed by suggestions for improvements, some of which have already been put into use. A summary concludes the thesis.

1.2 RELIABILITY ANALYSIS

1.2.1 Introduction

Reliability can be described as the probability that a system will operate to an agreed level of performance for a specified period, subject to specified environmental conditions.

Reliability engineering has two sides to it, in practical terms. They are:

(i) Designing for Reliability

This means that when an equipment or component is manufactured, it is built in such a way that it will be intrinsically reliable. For instance, the materials used will operate over a specific temperature range so this equipment or component is designed to run at temperatures within the temperature ranges of all materials used. Alternatively, a piece of equipment is designed so that if one component fails, then the equipment still works because another component, or set of components, will also cover that need e.g. in a power supply a diode may be needed to rectify the input. If two diodes are used in parallel then if one fails, rectification will still take place.

(ii) Reliability Analysis

This means studying systems to assess their reliability. It involves both experimental and mathematical techniques. The experimental techniques usually take the form of stressing or overstressing the system using temperature, electrical, humidity and mechanical stresses (particularly the first three in dealing with electrical systems). Information is taken from these experiments and used to assess reliabilities and how they may be improved. Studying systems in the field is also an established method of obtaining reliability information.

1.2.2 Reliability Theory

In order to understand Reliability Analysis it is necessary to know something of the Reliability Theories that are commonly used.

Going back to our original definition we see that reliability is a probability and that a failure distribution can be plotted against time which will look typically like Figure 1.1.

This gives the probability of a failure after a time t of F(t), and will clearly start at or near 0 and increase to 1 with time (when all components will have failed).

There are many different reliability distributions used to assess and model reliability, but some of the more commonly used

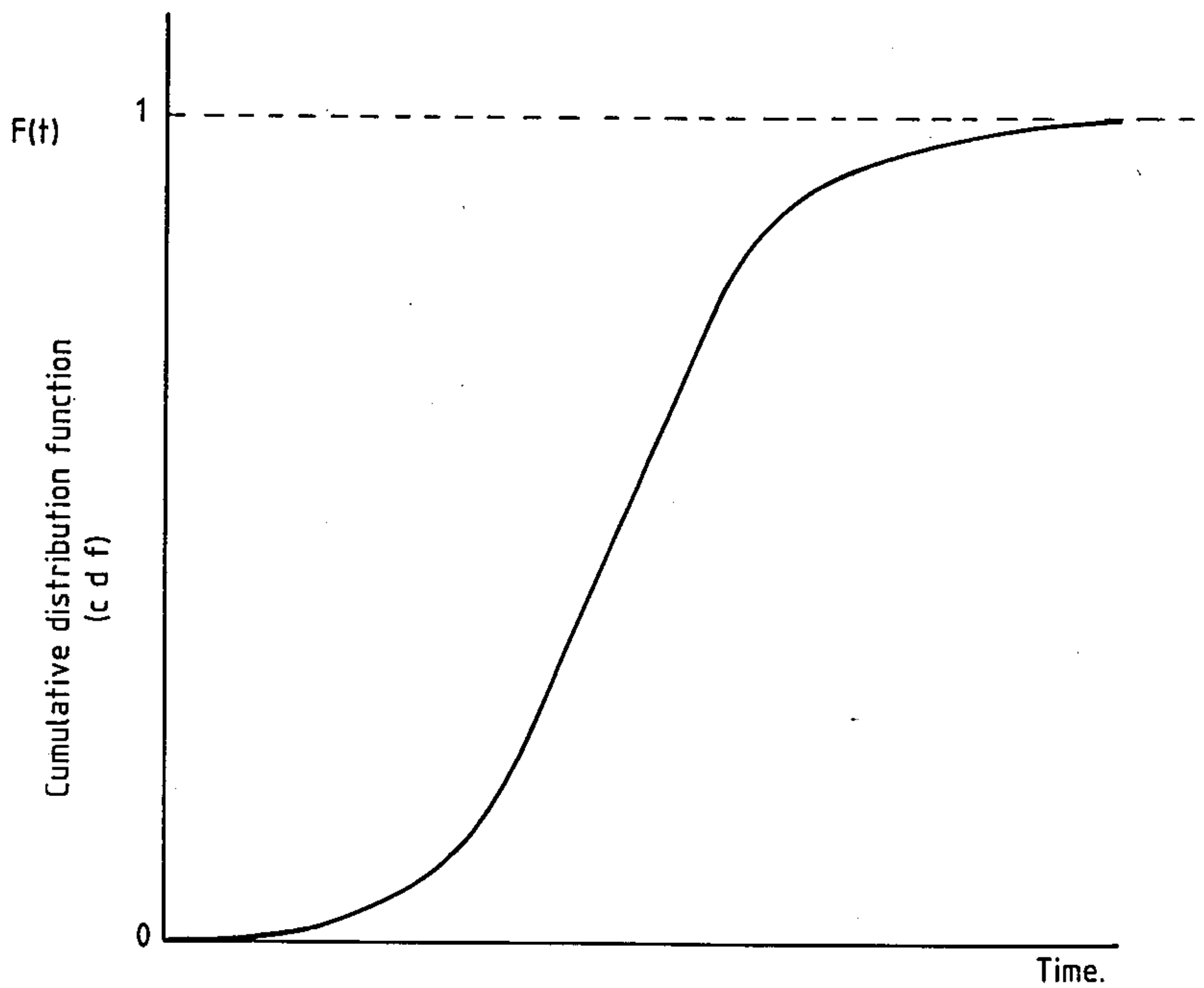


Figure 1.1. A typical cumulative distribution function.

ones are the Normal, the Log Normal, the Exponential and the Weibull which may be found described in any text on reliability engineering [1]. Other commonly used distributions include Poisson and Binomial.

There are two influences on the reliability of a system:

(i) Manufacture

(ii) Use

The way a system is manufactured will put limits on its lifetime. For instance, if there are contaminants in chemical processes, this can affect performance and reliability. Physical defects incurred during manufacture can also have the same effect.

There are two different ways in which a system may fail.

(i) Catastrophic failure - the system becomes totally unusable.

(ii) Parametric failure - the system no longer performs within its original tolerances but still works.

The usual way to put a time on failures is to use Mean Time To Failure (MTTF), or for repairable systems, where repair is being considered Mean Time Between Failure (MTBF). These are detailed in Appendix 3. These ideas are based on samples of systems as opposed to the behaviour of an individual system. The inverse of MTTF gives the failure rate λ or f(t). This is usually very small and so is defined as number of failures per 10^6 component hours.

The accepted model of failure rates for any system against time is the "bathtub curve", see Figure 1.2.

Any sample of components will have three defined periods of its lifetime:

(i) Infant mortality - this represents failures from badly manufactured components which will rapidly fail.

(ii) The 'useful life' - during this time there are few failures and the failure rate is constant. Those failures that do occur are random and attributed to longer failure mechanisms than in the infant mortality region, and the operating environment of the system.

(iii) Wear out - the systems are coming to the end of their natural life and consequently failure rate once again increases.

In accelerated life testing temperature is often used in order to speed up natural processes. The rate of a chemical reaction is governed by the Arrhenius Equation [2] which states:

$$r = A \exp\left(-\frac{E_a}{k}.\frac{1}{T}\right) \qquad \text{Equation (1)}$$

r = reaction rate

A = constant

E_a = activation energy (specific to process)

k = Boltzman's constant (8.623×10^{-5} eV/k)

T = absolute temperature

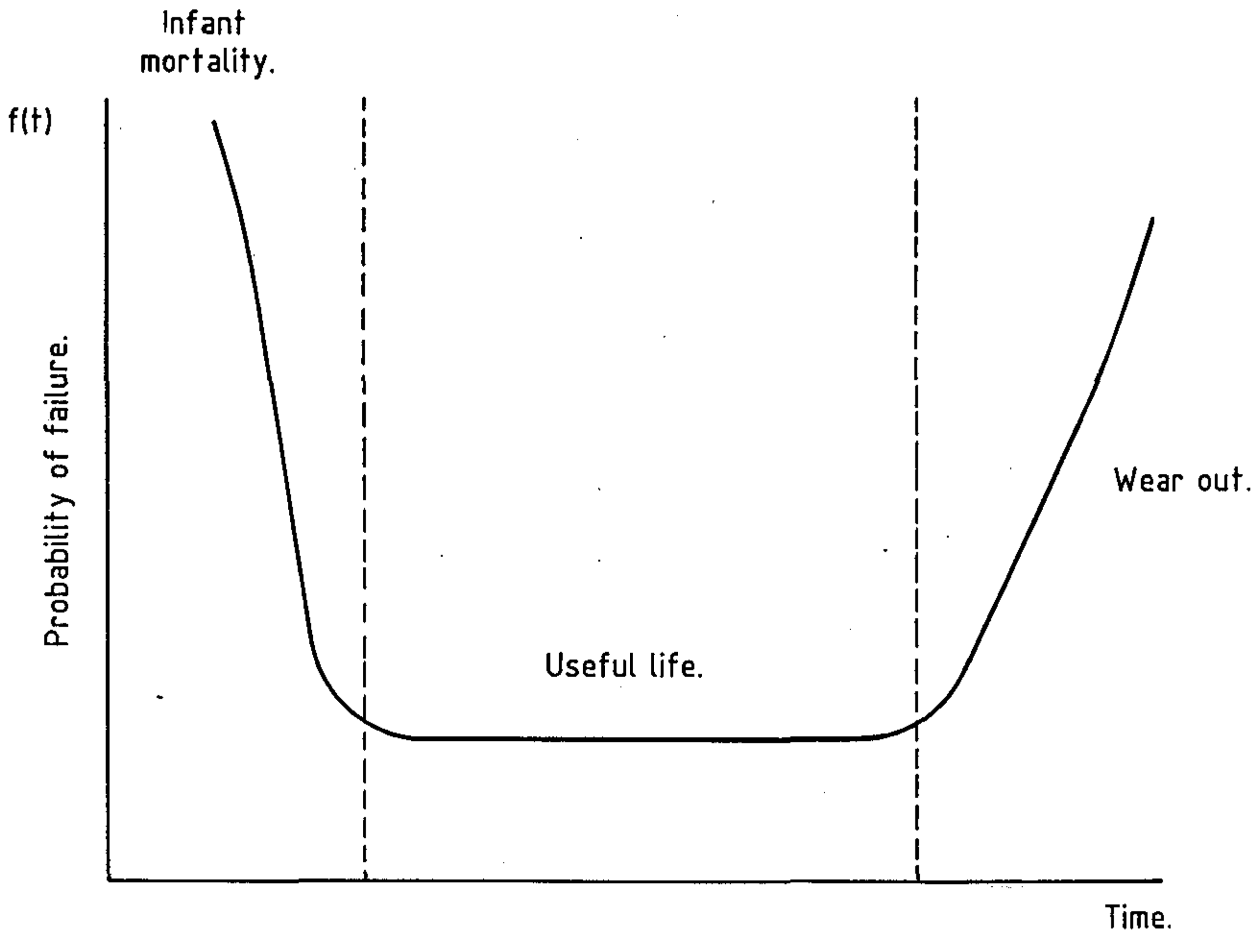


Figure 1.2. The bath tub curve.

This equation needs to be used with discrimination because the assumption must be made that the same conditions and reactions occur at T_1 as at T_2 in order to compare r_1 and r_2. It is, however, often very useful and in common use.

Rearranging Equation (1) we can get

$$\ln(r) = \ln(A) - \frac{E_a}{k}.\frac{1}{T} \qquad \text{Equation (2)}$$

which we can then plot as a "y = mx + c" line for two or more higher temperatures, see Figure 1.3. This allows us to extrapolate failure rate down from accelerated conditions to normal usage conditions. It is also possible to calculate A, E_a and the rate of reaction for a given temperature.

It is possible to use an Arrhenius Plot to determine whether different failure mechanisms are dominant under different conditions. This can be illustrated using the following theoretical situation.

Any failure mechanism has an activation energy E_a associated with it. Different failure mechanisms will have different activation energies. The gradient of an Arrhenius Plot equals E_a/k. Hence if a plot shows a change of gradient, see Figure 1.4, or if a plot has a different gradient compared to a plot from similar conditions but with a different stress factor changed (e.g. voltage), see Figure 1.5, then the activation energies are different. This implies different dominant failure mechanisms.

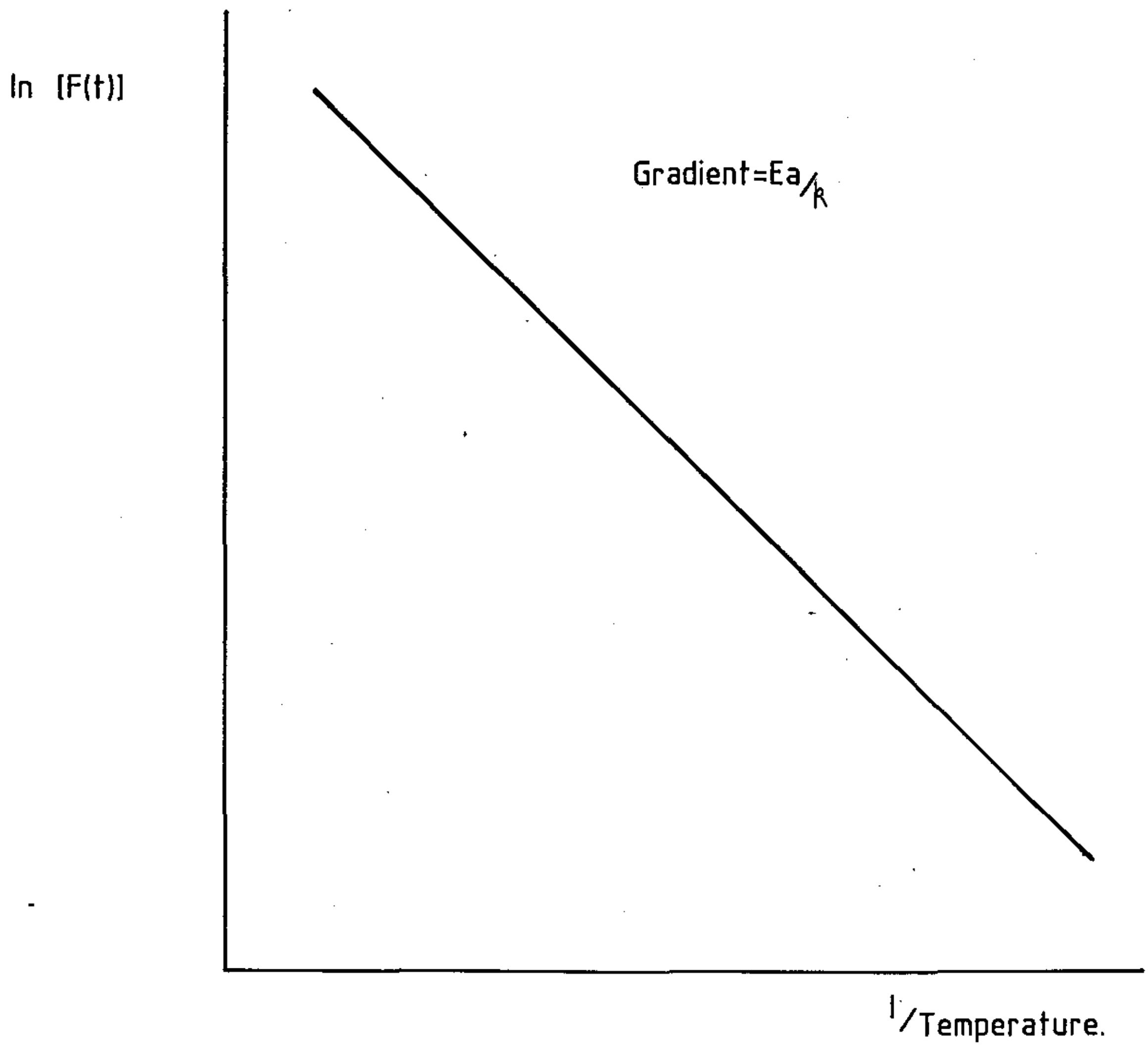


Figure 1.3 An Arrhenius Plot.

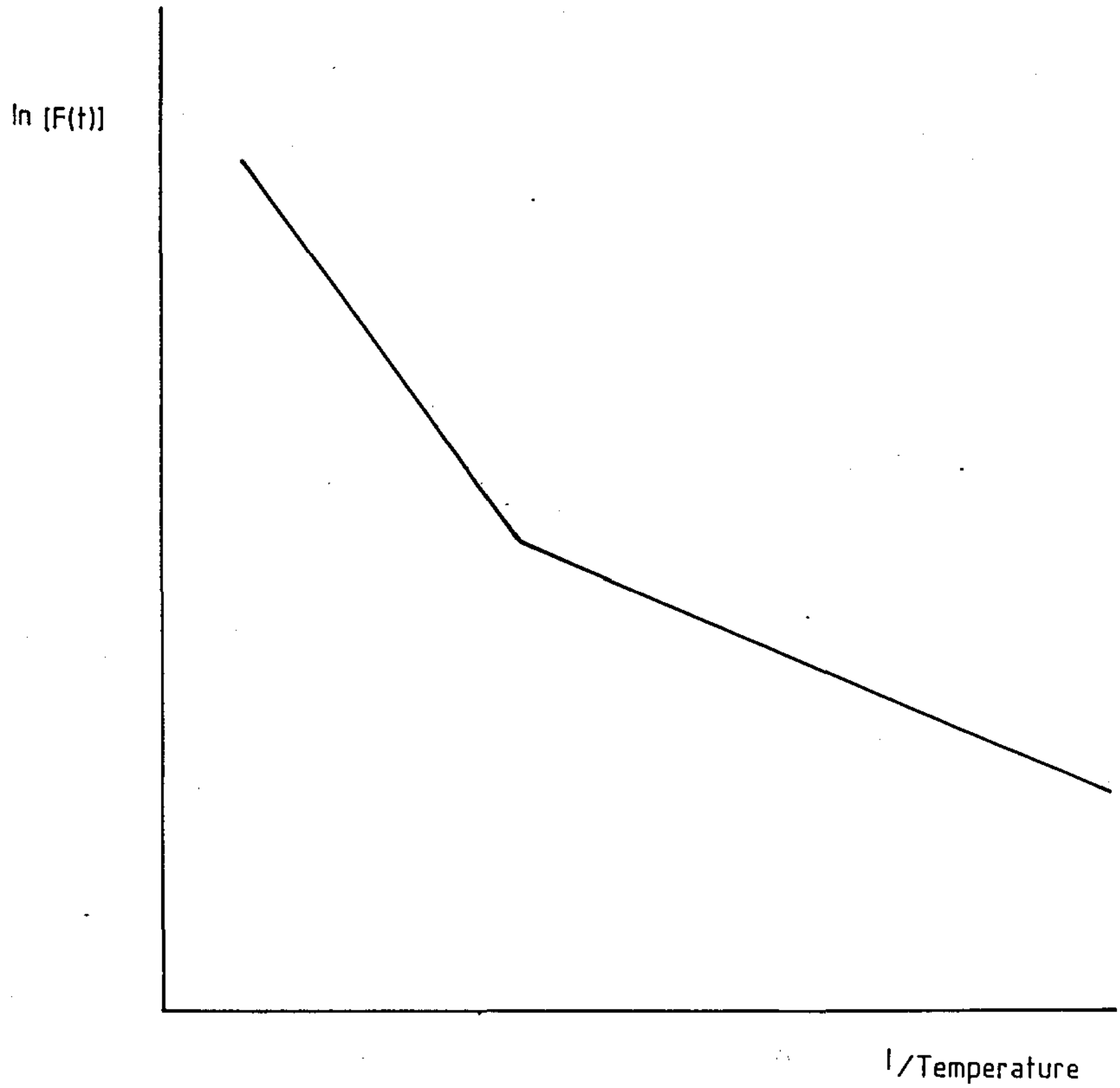
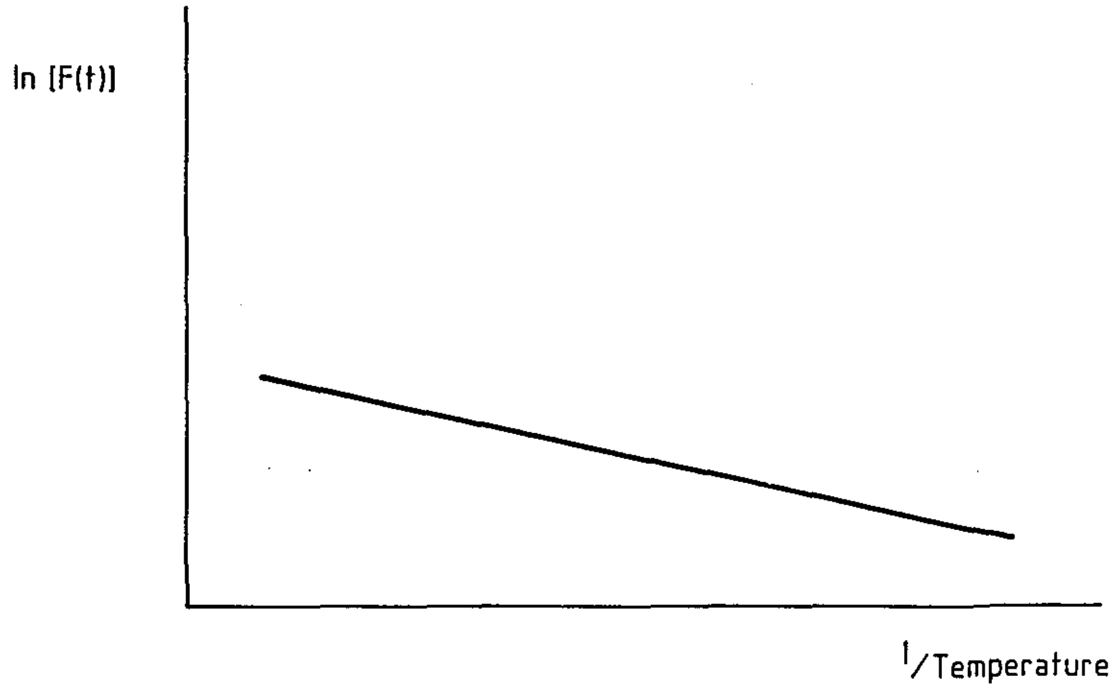


Fig. 1.4 An Arrhenius Plot indicating different dominant failure mechanisms at different temperatures.



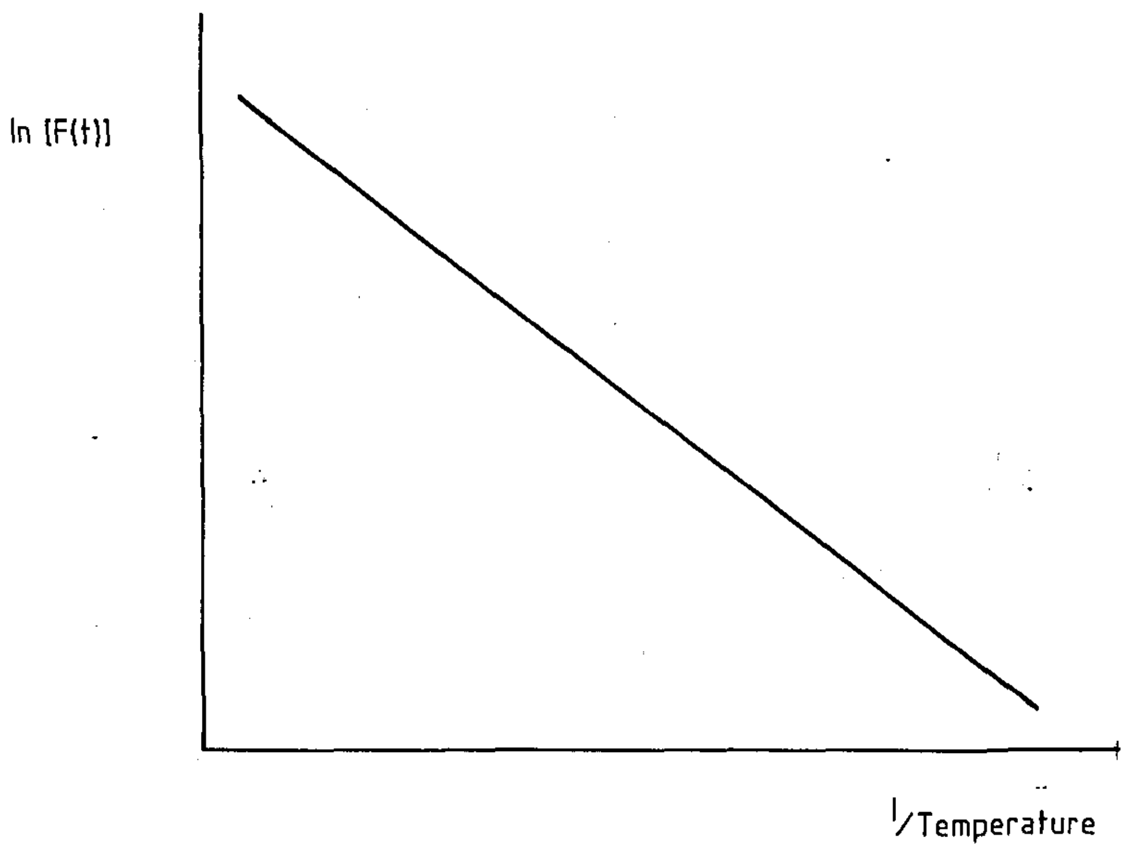


Fig. 1.5 Two Arrhenius Plots showing different dominant failure mechanisms at different stresses (other than temperature).

This is a very useful technique in accelerated life testing [3].

The Weibull function [4] is used extensively in accelerated life testing. This is a statistical distribution which is popular because it can be fitted to a wide variety of circumstances. A detailed description of its use is given in Appendix 4.

1.2.3 The Historical and Industrial Importance of Reliability

It is within the last forty years that Reliability has become a field within its own right. Before 1940 most related work concentrated on quality control or maintenance problems, and reliability in itself was not considered. With the advent of the Second World War and increasing complexity of electronic equipment, reliability came into its own. By the 1950's several formal studies had begun on reliability which set specification standards for the reliability of electronic equipment. One of the best known of these is AGREE [5] (Advisory Group on the Reliability of Electronic Equipment) formed by the U.S. Department of Defence in 1952. Today there are similar standards widely used like MIL-217 [6], BS9000 [7] and by British Telecom.

In industry today reliability engineering is used to increase the reliability of products and to improve production. For any product there is an optimum expenditure on reliability in relation to subsequent benefit, see Figure 1.6 [8].

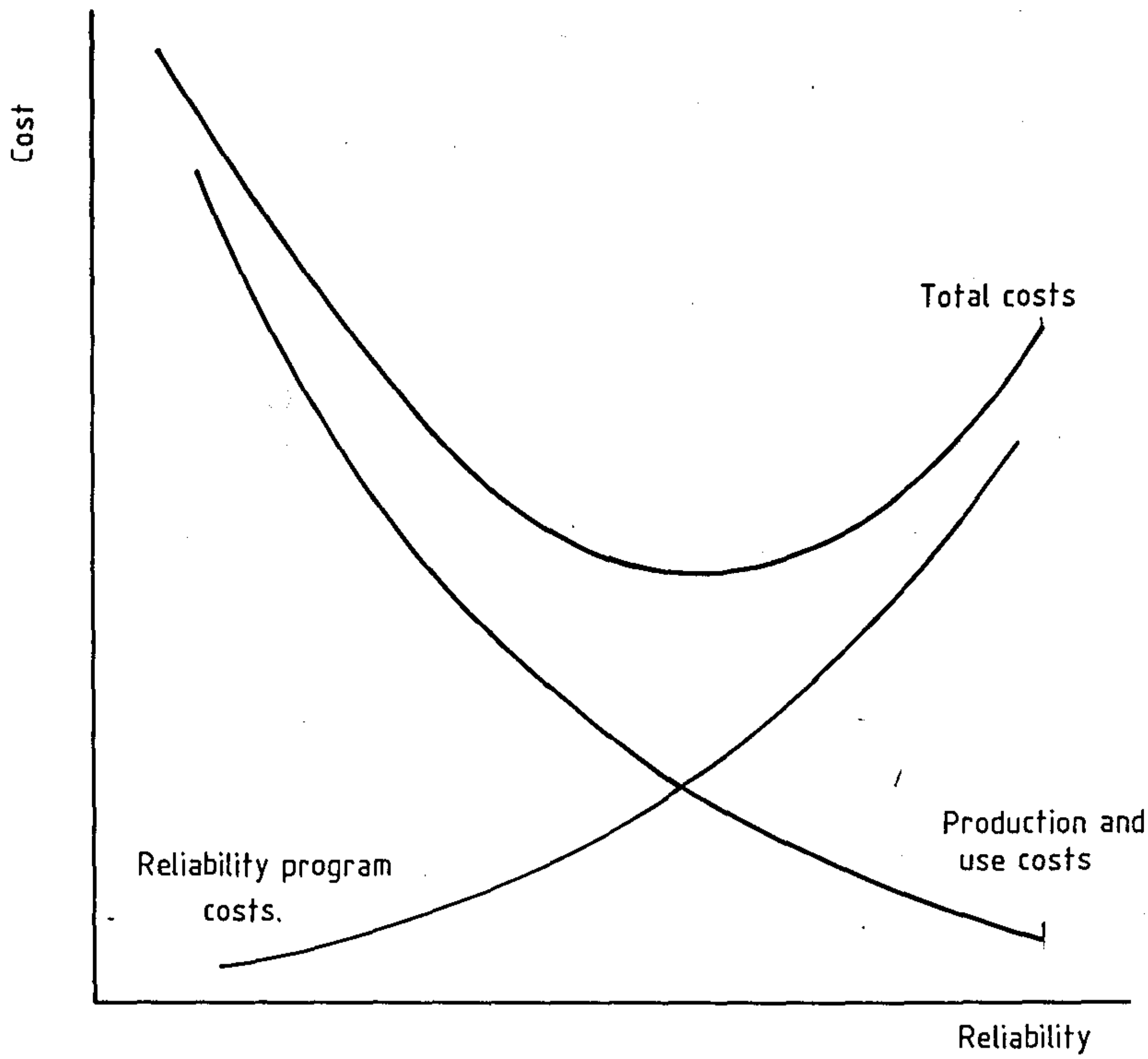


Fig. 1.6 The cost effectiveness of a reliability program.

It is far more economic to implement an effective reliability scheme than to need corrective action at a later production stage. Discovering and correcting a potential weakness at an early design stage may cost many times less than if it were found during testing of the production standard hardware.

1.2.4 Common Methods of Reliability Analysis

Reliability analysis can take many forms, however like most forms of experimentation it usually means applying one or more tests to the system and taking measurements. These measurements are then analysed to give information on the reliability of the system. Typically this might include some temperature stressing, raising the system to a given temperature for prolonged periods of time, temperature cycling or humidity and temperature stressing.

Measurements of these systems can be taken either continuously or at pre-specified time intervals. These are then analysed and such aspects as parametric drift, or catastrophic failures or whatever may be picked out, either by hand or using a computer statistics program such as SPSS/PC+ which is available at Loughborough.

A great deal of reliability experimentation involves simulation of conditions using various different test chambers (usually able to simulate one or more of temperature, humidity, vibration and pressure requirements). These chambers are commercially available in the U.K. The other significant part of this experimentation involves taking the measurements when and where needed either to be analysed on the spot, or later. Measurements may be taken by hand if small amounts of information are being gathered.

It may not be possible for measurements to be taken manually under the following circumstances.

(i) There is too much information to be measured.

(ii) The working environment does not permit direct human involvement (hazardous or inaccessible).

(iii) Measurements are to be taken at odd times or over very long or very short periods.

In these circumstances a form of automatic measurement and storage of results needs to be used, such as data logging.

1.3 DATA LOGGING

1.3.1 The Definition and the Uses of a Data Logging System

In its simplest form a Data Logger is a device for measuring and storing measurements. By such a definition Data Loggers have been around for a long time (e.g. a barometer with a pen chart recorder). Nowadays the picture has diversified greatly.

> "The ubiquitous microprocessor makes nearly every data gathering product a candidate for data acquisition discussion" [9]

Broadly speaking, the modern Data Logger is controlled by a small computer or a microprocessor. This controls one or more instruments and switches. It is usual for a Data Logger to use switches to look at devices sequentially.

To get an idea of what might constitute a Data Logger, there are two examples. The first one is a simple Data Logger that could be constructed in any laboratory without much difficulty (see Figure 1.7), and is typical of the type of device that might be used in an educational or research project [10,11] for storage of information and control of instrumentation.

The instrument is continuously measuring a parameter, which it outputs as an analogue voltage. This in turn is converted into a binary word by the analogue to digital converter (ADC) which outputs this voltage as a binary word. This can then be read into the computer using a parallel port (such as the parallel interface adapter incorporated on a BBC B microcomputer). This information from the instrument is continuously being sent to the computer. At appropriate, preprogrammed moments, the computer can sample the information, write it on the screen, store it on the disc and compare it for any further action.

Such a system represents a very simple straightforward example of a dedicated machine which has been set up to perform one task. It will do this effectively, but it is not capable of much more without being programmed again virtually from scratch.

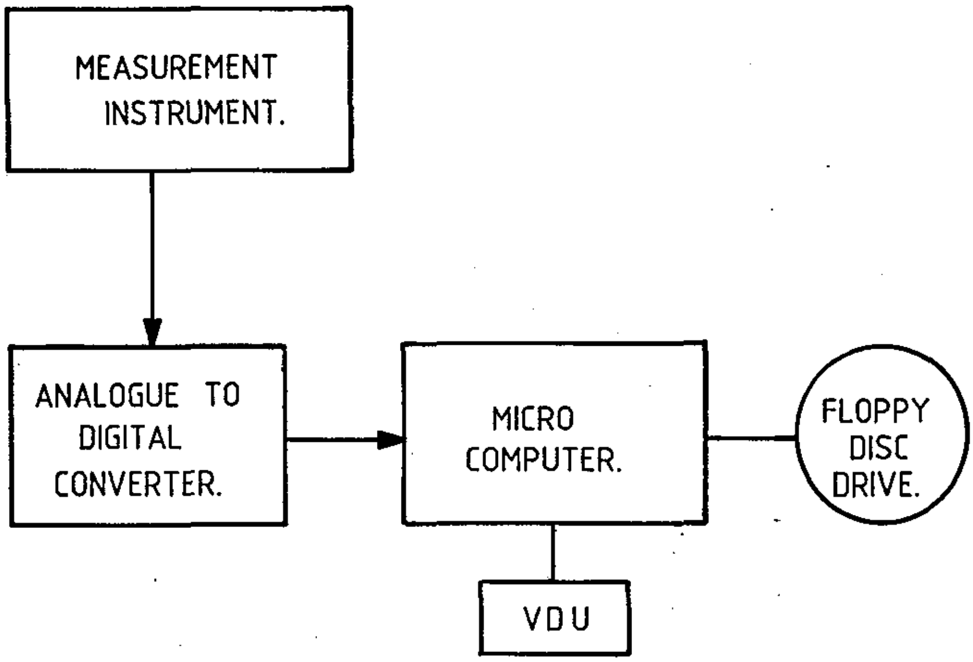


Fig 1.7 A simple data logger.

At the other end of the scale are the massive commercially available machines costing up to thousands of pounds. They will have been developed over a period of time by a design team and will feature many different abilities.

A top of the line Data Logger may have many input channels, interfaces, archiving ability and many other features. For instance it may be able to sample up to 30,000 [12] channels a second. This allows for practically continuous monitoring of a large number of inputs with one measuring device, (assuming it can measure at that speed). Appendix 1 gives details of some commercially available Data Loggers, showing their various features and costs. This is the alternative to building a Data Logger in house.

Typically, Data Loggers are used for gathering information. Two interesting examples have been taken from Automation magazine [13,14].

In the first example the stresses inside a ship were recorded. The ship carried bitumen at high temperature (165° Celsius), and this built up thermal stresses inside the ship's structure. The most efficient way of monitoring this was by the use of a Data Logger to be used over a journey. The results were used to help design new ships, armed with the knowledge of how thermal stresses developed.

The second example was using a Data Logger (Systematic Micro's CR7) on a train. In the British Rail experiments, which cover some of their latest diesel locomotives as well as electrical multiple units and high speed trains, the logger was used to capture data onto its built in cassette tape recorder. The data was processed and analysed using an onboard Hewlett-Packard HP9845 desk top computer, which could produce graphs or tables of data very rapidly.

The term Data Logger represents a very wide range of equipments. However they all basically retrieve and archive information, usually measurements.

1.4 COMPONENTS (PASSIVE AND ACTIVE)

Electronic components form the basic structure of any electrical circuit, they consist of passive devices such as resistors which restrict current flow, capacitors which store charge inductors, and other similar devices. A passive component can be defined as a component where the output impedence equals that of the input. They are usually two terminal devices.

Active devices started with valves. Nowadays almost all of the silicon and gallium arsenide devices produced are active devices. Active devices have three terminals and their input and output impedence are different. Under this definition a silicon diode is not classed as active. The diode is by definition a passive device, performing the role of a varialbe resistor. However, since the silicon diode is a pn junction, the basis of transistors and many active devices, it is usually considered to be an active device.

For the purposes of this discussion, an electrical component will be defined to be a device for transmitting or modifying electrical signals whose constituent parts cannot readily function alone.

1.4.1 <u>Component Reliability</u>

As detailed in the Appendix 2, components are divided into separate categories, each of which has its own typical reliability problems associated with it. To give a broad overview we have the following:-

1.4.1.1 Resistors

Resistors are probably the simplest case and have three basic ways that they can fail (failure modes). They are:-

(i) open circuit

(ii) closed circuit

(iii) change of resistance

Of these (iii) is the most vague, since a change of resistance in one application may mean failure (ceases to do what is required of it) while in another application this change may not constitute a failure, hence this is specific to the use of the resistor.

The failure mechanisms that can percipitate these modes are:

(i) mechanical

(ii) chemical/biological

(iii) temperature

(iv) electrical

(v) manufacture

(vi) misuse

Different types of resistors are susceptible to different ways of failing, but generally they can all be divided up into these headings or combinations of headings:-

Mechanical failure is usually brought on by vibration or shock. This is usually only a problem in environmentally severe conditions.

Chemical/Biological failures can be brought on by fungal growths in high humidity conditions. During encapsulation organic compounds may be encapsulated which subsequently attack a component. There are many possibilities for component failure involved [15,16].

Temperature failure, operating in temperatures above or below rated temperatures may mean that the components either stop functioning or change their properties. Resistance will generally increase with temperature increase [17].

Electrical failures are usually fairly obvious, 240 V across a 1 Ω , 1 Watt resistor will cause it to drastically overheat and probably catch fire giving failure.

Manufacturing failures. These divide up into two parts. Firstly there are failures because the way it was made means there is an intrinsic weakness. Secondly failures of the 'Monday morning' variety can occur (e.g. perhaps someone was a bit careless mixing the ceramics for this batch, or this resistor did not mould correctly).

Misuse if a resistor is put into a position that it was not designed for, then there is a good chance that it may fail. This represents a failure in one of the previous categories, but nevertheless is because of misuse.

1.4.1.2 Capacitors

Similarly to resistors, capacitors can suffer failure modes of:

(i) open circuit
(ii) closed circuit
(iii) parametric drift

Whether or not parametric drift constitutes a failure will again depend on the specific use of that component.

Again failure mechanisms are similar to the case of resistors, with perhaps the addition of humidity which can play an important part in capacitor reliability, particularly in wet capacitors süch as the electrolytic type where, for instance, a very dry or hot environment leads to failures due to the drying out of capacitors [18,19].

1.4.1.3 Other Passive Devices

Other passive devices include Inductors, (Passive Microwave), Connectors, Relays and Switches. These devices, especially the last three, all tend to be subject to failure of mechanical means. There is little literature on inductor reliability, but Jowett [15] gives a comprehensive list of conditions that may degrade inductors. These indicate that temperature, moisture and vibration factors need to be taken into account during design and manufacture.

Passive microwave devices will depend very much on the use these devices are going to be used for, as generally they are 'tailor made' for specific purposes.

1.4.1.4 Semiconductor Devices

For a complete discussion one can refer to "Failure Mechanisms in Semiconductor Devices" by E. A. Amerasekera and D. S. Campbell [20]. They state in the conclusions that:

> "It is not possible to present a tabulated list of failure mechanisms in an order of importance because the frequency of each failure mechanism is dependent upon
>
> (a) Operating and environmental conditions
>
> (b) Device technology (e.g. Bipolar, MOS etc.)."

However they go on to say that the most commonly quoted failure mechanisms are:-

(1) Electrical Overstress

(2) Contamination

(3) Package Related Failure Mechanisms

As for failure modes, there are many ways that a semiconductor can fail, depending on its use, its nature and the cause of failure. A list of possible failures is as follows:-

(1) Open circuit

(2) Closed circuit

(3) Illogical logic

(4) Degraded logic levels

(5) Total breakdown of function

(6) Partial breakdown of function

1.4.2 Components in General

The numbers of new components, and their complexity (especially in semiconductors) are increasing, while technology is producing better and more stable versions of simpler components.

It is debatable whether a microprocessor is a component or not, since once assembled it is fairly indivisible. On the other hand it contains a myriad of often sub-micron devices which themselves could be used to produce a different complex component, with a different use and function. It is for these devices that companies and research establishments will pay very large sums of money for automatic test equipment and highly complex Data Loggers.

1.5 SUMMARY

The reliability of a component is an important piece of information if that component is to be used successfully. It is therefore necessary to devise some means of collecting information to make that assessment.

To make this assessment there are two ways:

(i) collect field failure data

(ii) conduct experiments in a laboratory

In this chapter we have looked at reliability analysis, data logging and components to give a background for the second approach to assessing reliability, using the Data Logger that was developed by the author at Loughborough University of Technology.

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2. THE DATA LOGGER

2.1 INTRODUCTION

A small low budget Data Logger has been designed and built by the author at Loughborough University to help in the accelerated life testing of components. It is designed to enable accelerated life tests to take place involving large numbers of components in samples (typically around 100). This has enabled the Component Technology Group to produce work that is statistically very credible.

In 1983 the Component Technology Group at Loughborough purchased 10 Farnell Switching Boxes (IEEE-488 SWITCHING UNIT SWIB). These were to form the basis of a data logger that would be able to switch around from component to component using computer control, to measure the component and to log the results. This approach was decided on because the group had received a contract from the Ministry of Defence to work on Failure Studies in Electronic Components. This study had so far been using small samples, and it was felt that the use of a data logger provided an excellent opportunity to expand the work.

The Data Logger consists of:-

10	Farnell Switching Boxes
1	Solatron 7065 Digital Voltmeter

1 Keithley 617 Electrometer

1 Wayne Kerr 4120 LCR Bridge

2 Farnell Resistively Programmable Power Supplies

1 IEEE-488 General Purpose Interface Bus

1 Apple IIe Microcomputer

The equipment is arranged as in Figure 2.1.

2.2 DESIGN FEATURES OF THE DATA LOGGER

The Data Logger is designed to measure a wide variety of active and passive components. It can assess simple d.c. and low frequency a.c. (up to 10 kHz) parameters that may be of use in accelerated life testing.

Measurements of several components and several parameters may be made in any order. For simplicity's sake, usually the Data Logger will switch around from one component to the next taking measurements of several parameters in the most natural logical sequence.

The equipment is housed on a trolley (see Figure 2.2). The trolley has shelves to carry all the equipment, a filtered power supply and rides on castors. This allows the Data Logger to be wheeled up to an experiment with ease, to be connected and the appropriate measurement and logging programs to be run.

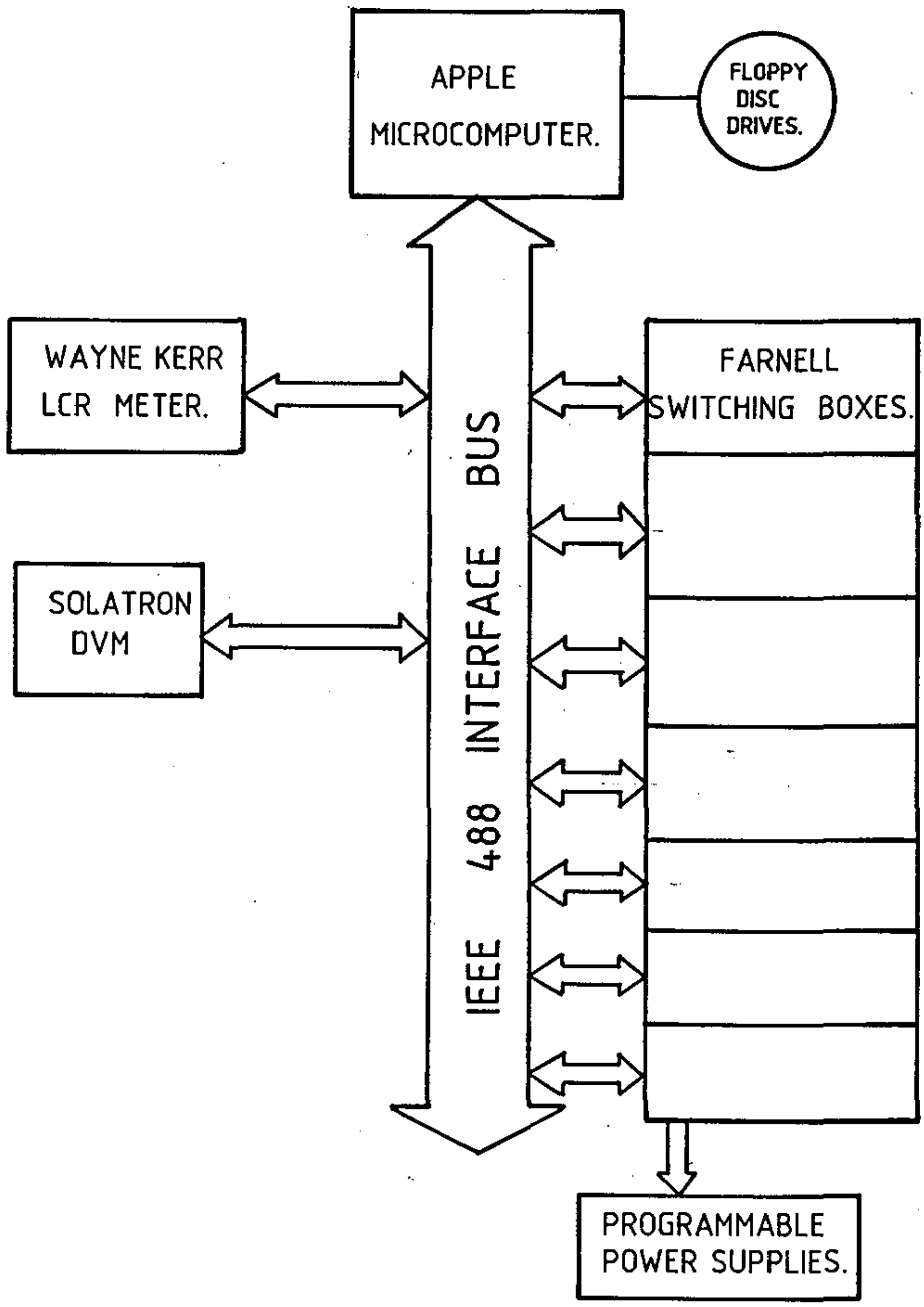


Figure 2.1 Schematic diagram of the data logger.

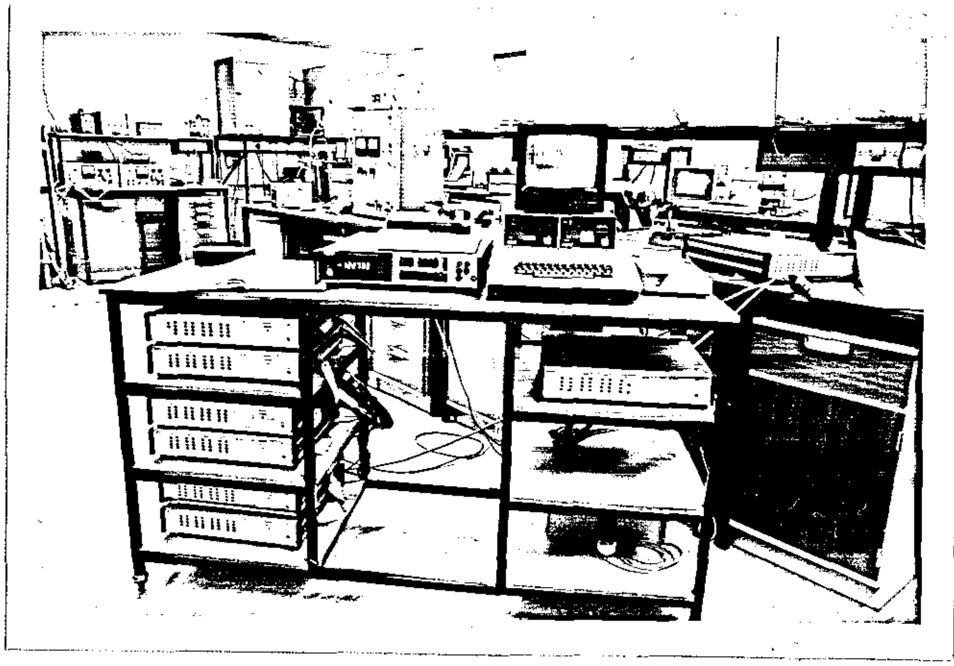


Figure 2.2 The Data Logger

All the separate instruments on the Data Logger were bought separately and may be commercially obtained, their total cost approaching £15,000 replacement value.

The beauty of buying separate instruments is that it makes the system very flexible. Any instrument which has IEEE-488 compatibility may be controlled by the Data Logger.

The main limitations on the system are:

(i) The Data Logger uses relays to connect to components. Any measurement will, by necessity, include measuring across a relay.

(ii) There is a limit to the speed the computer and IEEE interface can operate. For practical purposes a measurement will take about ½ second including any switching and processing. These considerations will be dealt with in Section 3.2.

Another aspect of the Data Logger that is worth briefly mentioning is the software (see Section 2.4). What can be done with the Data Logger is dependent to a large extent upon the software written. The software determines the switching sequences and all the measurements. This means that good software is important for the Data Logger to run effectively.

All software has been written in Basic because it is easy to change and alter on the spot, or to write new programs. It is also very easy to try ideas out using Basic as a command language and quickly develop them. However, compiled languages such as Pascal can be used.

The Data Logger has been designed to be flexible and versatile to respond to different requirements, and it undergoes a program of constant improvement. Its main function is to make repetitive simple measurements, but with clever programming it can do more subtle measurements.

2.3 HARDWARE

The hardware for the Data Logger consists of switching boxes power supplies, an IEEE bus, an Apple IIe microcomputer, several different measuring instruments, which may all be used together or separately, and a trolley which was built specially to hold all the apparatus together. Generally speaking they can all be used as stand alone instruments (with the exception of the IEEE bus and the switching boxes). Each instrument will be detailed separately.

2.3.1 The Apple IIe Microcomputer

The Apple IIe is based on the Rockwell 6502 microprocessor working at a 1.023 MHz clock rate [1]. This has 64 kilobytes of range giving it plenty of memory space for the purposes of the measurement programs run for the Data Logger.

The Apple also has 48 K of random access memory where programs and other information are stored to run the various programs.

In addition to the basic computer, the Apple also has six I/O ports which host the disc drives, a printer, an IEEE port (detailed later) and a 'Mountain' clock card. These devices can all be accessed to receive and transmit information. Further ports could be added if necessary, (e.g. a serial port) and there are many devices commercially available for these purposes.

Many similar microcomputers could have been used to do the job of controlling the Data Logger. However, there is not a great deal to choose between them, the choice being a matter of personal preference as much as anything. The Apple microcomputer was readily available.

2.3.2 The IEEE Bus

The IEEE bus or IEEE-488 general purpose interface bus is a standardised input/output (I/O) interface which has been developed since 1972 in an effort to provide a universal I/O device. A peripheral card, the Apple II GPIB card is plugged into a slot in the Apple IIe microcomputer. This conforms to the IEEE standard-488. Standard 24 way cables then connect from the card to all devices under the control of the IEEE.

The IEEE-488 standard interface began as the General Purpose Interface Bus (GPIB), which was developed by the Hewlett-Packard Corporation. In 1975 the IEEE adopted this interface as its standard [2]. The main advantages of the IEEE-488 bus as opposed to an RS232 link or using analog-to-digital converters and a parallel or serial port are:

(i) An ability to work in electrically noisy environments without picking up interference.

(ii) It has a bus structure allowing many devices to be interfaced to the same controller.

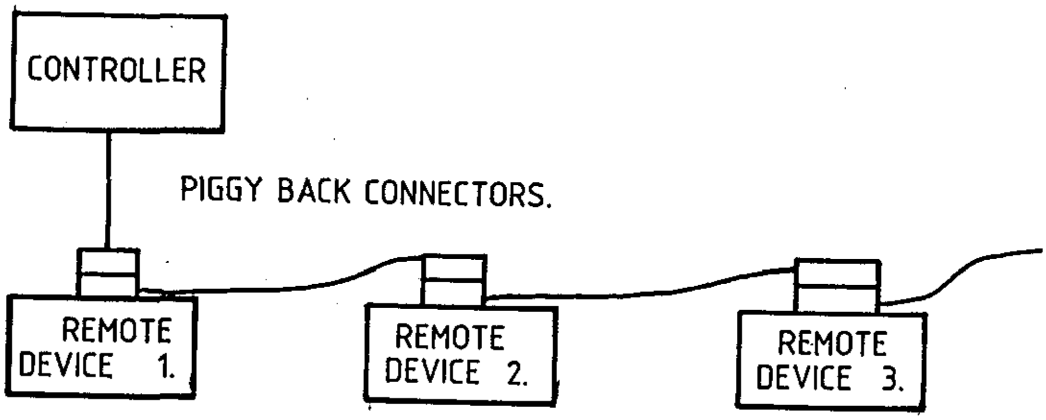
The IEEE bus uses eight data lines [3] and eight control lines to transfer commands and data to and from devices on the bus. The devices on the bus can be described in terms of their primary functions, controller, talker or listener.

A device is called a "talker" when its primary function is the transmission of data, e.g. a DVM taking measurements and passing them over the bus to the computer.

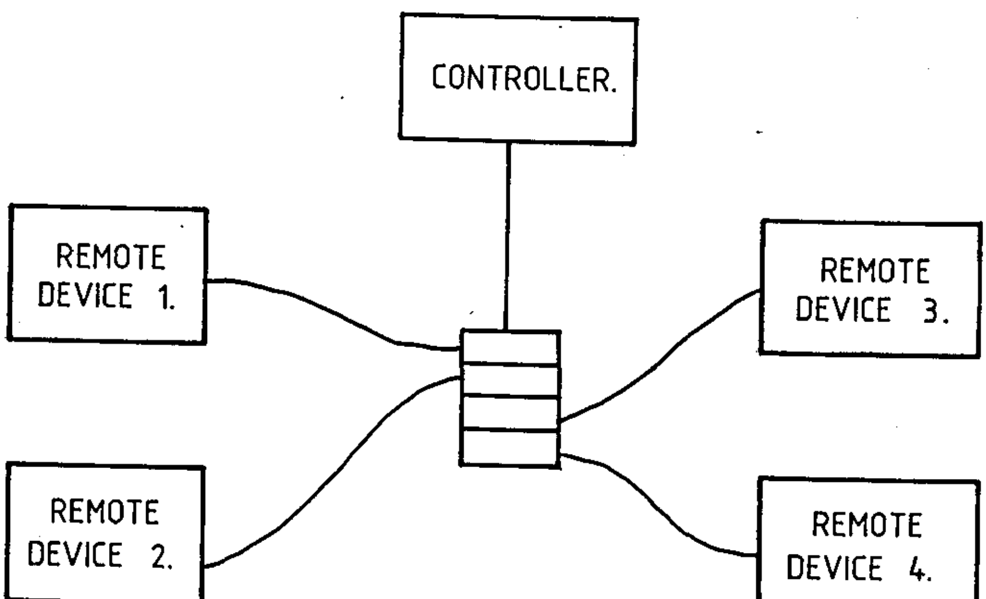
A device is called a "listener" when its primary function is to execute commands. An example of this is a switching box which sets its relays in the configurations demanded by the computer.

A "controller" is the device that arbitrates all transfer of data on the bus. The controller can turn on a listener for the transmission of data. The controller can turn on a talker for the reception of data.

The IEEE bus can control up to 14 external devices, and they may be connected in a star configuration or in a daisy chain configuration (see Figure 2.3). It must also not exceed 20 metres in total length.



Daisy chain configuration.



Star connected configuration.

Fig. 2.3 Configurations of the IEEE bus.

2.3.3 The Switching Boxes [4]

The switching boxes are Farnell SWIB switching boxes (SWIBS).

Each SWIB contains 32 change over relays which can be addressed and activated using the IEEE-488 bus. When a relay is selected this is indicated by a red light on the front panel of the SWIB.

Connection to the 32 relays is made via two 50 way Amphenol plugs.

The relays are mechanical and are of the type P.O. approved type 23. They can settle within 20 ms of the last bus command and may be scanned at a rate of up to 25 Hz.

This means that, assuming everything else is able to perform at this rate we can measure up to 25 different components in one second.

The maximum electrical ratings for the relay contacts are:

DC 110V 1A 30 Watts

AC 120V 2.5A 100 VA

These are important limitations on measurements. They may not be confidently exceeded. This must be considered when setting up a measurement program using the SWIBS.

2.3.4 Power Supplies [5]

It is possible to use any power supply with the Data Logger. However, the Data Logger does have two Farnell "S" series Stabilised Power Supply Units (PSUs).

These PSUs are mains driven d.c. stabilised output power supplies. They are capable of providing an output of between 0 and 45.00 volts in 0.01 volt increments.

These PSUs are resistively programmed, to produce the required output. A box of resistors plugs into a switching box and then by selecting relay combinations it is possible to determine the output voltage. This means that there are two power supplies which are capable of being controlled by the computer over the IEEE bus.

2.3.5 Solatron 7065 Digital Voltmeter [6]

This voltmeter is a high accuracy digital voltmeter with an IEEE interface. It is capable of measuring voltage, both a.c. and d.c., and resistance. The measurement facilities are:

DC voltage from 1 μV to 1 kV

AC voltage from 1 μV to 1 kV

Resistance from 1 mΩ to 14 MΩ

In addition to these basic measurements the meter is capable of filtering for a stabilised output. Filtering produces an averaged reading. It is possible to change the integration time of a measurement and the scale lengths. The integration time is the time that the meter uses to measure a signal. Integration times are chosen to be exact multiples of the mains supply frequency. This means that measurement remains unaffected by mains pick-up.

The voltmeter is highly accurate, generally to less than 0.01% over 24 hours.

2.3.6 Wayne Kerr 4210 LCR Bridge

The Automatic LCR Meter provides direct and accurate measurements on inductors, capacitors and resistors at any of three alternative frequencies (100 Hz, 1 kHz, 10 kHz). In addition to measuring the major term (inductance L, capacitance C, or resistance R), it can be switched to measure the resistive loss term of inductors and capacitors and any L or C term present with resistors. The bridge is also capable of measuring the dissipation factor D and Q factor of inductors. ($D = \omega R_s C_s$ and $Q = \omega L_s/R_s$ where ω = angular frequency, Rs = series resistance, Ls = series inductance and Cs = series capacitance [7]).

The instrument selects its own ranges. The range can be fixed to speed up measurement times. It also has the capability of sorting measurements into what are termed 'bins'. These bins can be selected either by % age deviation from a specific value or by absolute value. Ten bins are available.

The 4210 has an IEEE-488 bus. This allows total control by the Apple IIe on board the Data Logger.

The meter may read to an accuracy of 0.1%. At a speed of typically 650 ms. It can read:

Resistance (Q < 0.1)	0 to 990 MΩ resolving to 0.1 mΩ
Capacitance (D < 0.1)	0 to 990 mF resolving to 0.001 pF
Inductance (Q > 10)	0 to 9900 H resolving to 1 nH

Dissipation and Q factor can be measured with similar accuracies from the ranges 0.0001 to 9900 [8].

2.3.7 <u>The Keithley 617 Programmable Electrometer [9]</u>

The Keithley Model 617 Programmable Electrometer is used occasionally as an alternative instrument for measuring voltage, current, charge and resistance. It can be controlled using the IEEE-488 bus. The electrometer has an especially high input resistance. This means that it is capable of detecting very small currents and very high resistances. Typically it can detect currents as low as 0.1 fA

(10^{-16} A) and resistances up to 200 GΩ. This makes the instrument especially suitable for measuring insulation resistances.

2.4 SOFTWARE

2.4.1 Purpose of Software

The Data Logger is programmed to operate various tasks using the Apple II run under the Apple 3.3 operating system using the Basic language.

Basic is used because:

(i) it is simple to use

(ii) easy to write and alter

(iii) straightforward to edit while developing programs.

This makes programming very straightforward. The fact that it is an interpreted language means that it is easy to slow down parts of a program when waiting for measurements to settle. Errors are easy to trace and not needing excessive speed there is no great demand for compiled languages such as Forth or Pascal.

Typically a simple line of Basic takes about 1 or 2 milliseconds to be executed.

The software is used to direct the sequence of commands, to control and read instruments and then store this information in files in a readily accessible manner. The manner in which all this happens has been programmed. This is the flexible part of the Data Logger. What the instruments are capable of is fixed, but much can be achieved by imaginative software (see Figure 2.4).

We see that the software can allow us to communicate with every part of the system.

2.4.2 Programs Written for the Data Logger

A library of programs has been written, some for general use and some for specific uses. Listings of all programs are in Appendix 5.

2.4.2.1 General Programs

2.4.2.1.1 Subroutines

This contains all the subroutines needed to build a program for the Data Logger. It consists of a number of subroutines which may be called using the command GOSUB. It cannot operate by itself but forms the basis of the bigger measurement programs. It is useful because it helps reduce the time spent writing a new program.

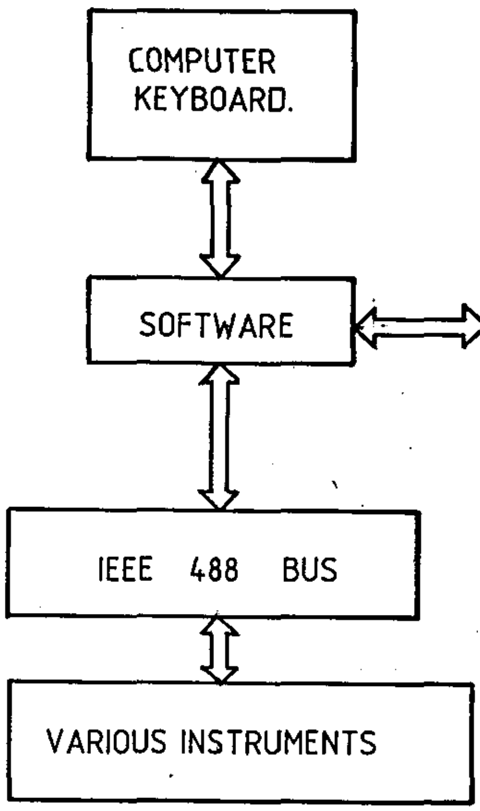


Fig. 2.4 Software control of the Data Logger.

2.4.2.1.2 Relay Control

This is a simple program for controlling the relays a step at a time. It is used to check relay combinations, for instance the stray capacitance of a circuit can be measured. Any relay combination may be programmed, programming a box at a time.

2.4.2.1.3 Fileread

A program for reading a text file, which can then be read on the screen or output to a printer has been written. The file is opened and the file length is read. All entries are copied into a string and the file is closed. Finally the string is output to the screen or the printer.

2.4.2.1.4 Meansd

This program is based on FILEREAD. It reads the file into an array. The mean and standard deviation are calculated discounting any data values that lie outside specified ranges. Out of range values are displayed by the computer. This allows rogue values to be spotted and to look at shifts in distribution for good data, from reading to reading. It does not consider the shape of a distribution of data and so is only used for preliminary data analysis.

2.4.2.2 Specialised Programs

Specialist programs have been written for use with specific experiments (see Chapter 3 for details of the experiments).

2.4.2.2.1 For Volta, Ctra, Sat Volta

These three programs are used for an experiment on accelerated life testing of optocouplers. Each is used to measure a particular parameter and to record the parameter values of the optocouplers in a text file on a floppy disc. The programs all select one optocoupler in turn via the relay boxes, take a measurement, then switch to the next optocoupler.

(i) For Volta - measures forward voltage of the light emitting diode of the optocoupler. This is measured for a given constant current supplied by an external source.

(ii) Ctra - measures the current transfer ratio of an optocoupler - the ratio of current through the transistor for a given current through the light emitting diode (L.E.D.). This is achieved by measuring the voltage drop across a resistor in series with the transistor and calculating the current and hence the current transfer ratio using Ohm's Law.

(iii) Sat Volta - this estimates the saturation voltage of the optocoupler's transistor by measuring transistor currents for increasing values of V_{CE}. It considers a graph of V_{CE} against I_C and calculates the gradient between the last two consecutive readings. When the gradient falls below a certain value (5 if I_C measured in mA, V_{CE} in volts) it uses that calculated gradient and the previous calculated gradient to estimate the value of V_{CE} that gives an instantaneous gradient of 5, using the Newton-Ralphson method [10]. This value of V_{CE} is called V_{SAT}, the saturation voltage.

2.4.2.2.2 Lookcer, Ceram*, Autoceram

As their names imply, these programs are concerned with the measurement of ceramic capacitors.

(i) Lookcer - this program, although used for ceramic capacitors, can be used more generally. It switches around from one capacitor to another measuring series resistance and displaying the results on the computer terminal. This is used in looking for devices that have catastrophically failed short circuit (characteristic of multilayer ceramic (MLC) capacitors in accelerated life tests [11]).

(ii) Ceram* - this program is a general program which uses the Wayne Kerr LCR bridge. It will measure up to ten different parameters and conditions, on up to 256 devices. The program asks the operator to type in the parameters and conditions for measurement. It then opens up a file for each different set of measurements and switches around from device to device, first measuring one parameter, writing the information to disc then the next parameter and so on until completion.

(iii) Autoceram - this program is built up from Ceram*. It makes use of a Mountain Clock Card, available for the Apple, enabling measurments to be made at any preprogrammed time. Autoceram consists of programs which call each other. The computer loads the information that normally an operator would type in from an information program. It then 'Watches the Clock' until the time it has to measure (as laid out in information). It then runs a program, also called Autoceram which executes the necessary commands, then returns to Watch the Clock. It can also change bias voltage at a given time, via the programmable power supplies.

The subprograms are self-explicitly called Hello, Information, Watch the Clock, Autoceram and Change Voltage.

This program will also reload itself in the event of a power failure and continue watching the clock until the next time for action.

The clockcard has a battery back up and so when the computer is switched off it continues to work.

2.4.2.3 Details of Subroutines, the Control Program

Subroutines is the program which contains all the essential subroutines used to control the Data Logger. As such this program will be discussed in some detail (see Appendix 5 for a complete listing).

100 to 345

These opening lines set up listening and talk addresses for the IEEE bus, it tells how many switching boxes are used on the bus, and it sets the string values that will determine whether a relay is on or off.

350 to 370

This will open a text file that is named by the operator. The text file can be used to store information retrieved by a program.

9000 to 9030 Turn on Relay J, Others Unaltered.

This sets relay J to the ON state by putting a 1 in the string R%(J) and calling another subroutine that actually sets the relay (GOSUB 9300).

9100 to 9130 Turn Off Relay J, Others Unaltered.

This sets relay J to the OFF state by putting a 0 in the string R%(J) and calling another subroutine that actually sets the relay (GOSUB 9300).

9200 to 9240 Turn on Relay J, Others Turned Off.

This uses the same technique as the above two subroutines except it switches off all the relays (using GOSUB 9500 which sends the string DFHL00 to all boxes causing all relays to go to the off state) before it switches relay J on.

9500 to 9590 Reset All Relays.

This sends the string DFHL00 to each box in turn causing the relays to be set to the off position.

9300 to 9370 Set Relay J

This converts the integer J. representing the Jth relay, into a string which can be sent to a particular box, altering that relay from on to off without affecting the other relays. The positions of all the relays are stored in a string R%(J) and so these strings for the boxes are calculated afresh each time a relay position needs to be changed.

9400 to 9427 Sets Up Electrometer to Measure Resistance.

This sends a string to the electrometer, at bus address 30, preparing it to measure resistance.

9430 to 9465 Measure with Electrometer

This takes a reading from the electrometer and places it into a string A$. It can then be stored in a file or used by the program.

9600 to 9640 Clear All Devices

This sends a message down the IEEE bus 'CA'. This literally will clear every device that is connected to the bus.

9700 to 9740 Write A$ to a File

This puts the string A$ and places it in the file F$ which was opened at the beginning of the program.

9750 to 9780 Initiate DVM and Set Ranges to Ohms

This clears the DVM and sets it to remote (i.e. controlled by the IEEE bus). It then sends a string to the meter, which in this case selects it to measure resistance.

9800 to 9880 Take a Reading into A$

This is similar to lines 9430 to 9465. It triggers the device at address 30 and takes a measurement. This is then sent over the bus to the controller and stored as a string A$.

9900 to 9960 Send A$ to Box Number BN

This is used for controlling the switching boxes. A string such as DnnFnnHnnLnn is sent to box number BN. The n's represent numbers which are interpreted as relay combinations similar to the way ASCII code represents binary combinations.

Additionally, there are subroutines which have been written to drive other instruments, the Wayne Kerr LCR bridge for instance. They are all very similar to the subroutines that are used to command the DVM or the electrometer, except that it will reside at a different address, and of course the command strings that the bridge needs are different, for instance in line 9770

```
9770 PRINT "WT";LA$;"M1RØT1"
```

this could be changed to

```
9770 PRINT "WT";LA$;"CA;PA;FU;ME;"
```

where	CA	Capacitance
	PA	Parallel
	FU	Frequency Upper (10 kHz)
	ME	Measure

i.e. "measure parallel capacitance at 10 kHz"

2.5 SUMMARY

The Data Logger has been built using separately available commercial instruments and switching boxes. Most of these are able to be used on their own, but have been combined to work together using an Apple IIe as a controller on an IEEE-488 general purpose interface bus.

The logger has been designed to be flexible and to measure a variety of different electronic components, being able to make and store measurements of Voltage, Current, Resistance, Capacitance and other parameters.

A suite of programs has been developed for this purpose and for any specific need a program can be written, using Apple Basic, by writing the necessary software and calling upon the subroutines and protocols that are already in existence in subroutines.

Applications of this Data Logger will be discussed in the next chapter.

2.6 REFERENCES

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3. APPLICATIONS OF THE DATA LOGGER

3.1 RELIABILITY SOURCE OF COMPONENTS

It is envisaged that in the future the Data Logger will be used to investigate the reliability of components using accelerated life techniques. It will obviously not be possible to investigate every single kind of component, so it is necessary to select those for study which are important.

In the Component Technology Group at Loughborough University a data base is being established [1] whose aim is to establish a set of dependable field failure data for components that have been shown to be the most likely causes of failure in equipments. The study will involve the collection of data from a wide range of sources. Using the information in this data base it will be possible to find out, using a Pareto Analysis [2] for instance, those components which are most troublesome. From that list it will be possible to choose those devices which are suitable for accelerated life testing and measure them using the Data Logger.

At present the Data Logger is being used to study two sets of components. Firstly, Multilayer Ceramic Capacitors are being studied. These were initially studied so that it would be possible to design and build the Data Logger using the capacitors as a case study. The capacitors were donated by STC. The results of the experiment were reported back to STC. This has been a valuable help in assessing the Data Logger.

The other component that the Data Logger is being used to study is the optocoupler. Studies at the Danish Academy of Engineering, under Professor J. Møltoft, have shown that the optocoupler is a 'troublemaker' [3] component and so 1,000 have been placed 'in the field' to be studied, and 1,000 are being studied under accelerated life test conditions at Loughborough University. The Data Logger is used for measuring.

Both these components and the experiments being conducted are discussed fully in Section 3.3.

3.2 GENERAL APPLICABILITY

This section will define the limits within which the Data Logger will satisfactorily operate.

The Data Logger is designed to operate in a benign laboratory environment. It is not suitable for use out of doors or in extremes of temperatures. Components are taken to the Data Logger for measurement rather than the other way round.

The two main factors which affect the performance of the Data Logger are the Apple IIe computer and the switching boxes. The Apple IIe dictates the speed at which processes can run, by virtue of the speed it can implement software. The SWIBs have the greatest effect on the minimum and maximum voltages, currents etc. that can be measured by virtue of the relays inside them. They also limit the complexity of a component that may be measured since there are a maximum of 256 switches available (admittedly this is usually not a problem).

The relays in the SWIBs have each a capacitance of 5 to 6 pF (series) when open and a dc resistance when closed which varies between 0.1 Ω and 0.2 Ω. This variation can be attributed to the fact that some relays will have been used more than others. The relay units are not sealed hermetically and therefore surface contamination and oxidisation of the contacts is to be expected, causing a temporary increase in resistance. The mechanical effect of the contacts closing together will help reverse this effect.

Therefore it is possible to measure capacitances to about 10 pF and to measure resistances to about 1 Ω with confidence. The voltage and frequency limitations are provided by the relays. The voltage and current across a relay should not exceed 110V, 1A dc, 30W or 120V 2.5A, 100VA a.c. Any applied voltages or currents should be below these values if they are likely to pass across the relays. Regarding frequency, the Data Logger is designed for low frequency and direct current measurements. It is not intended for high frequency measurements.

We can therefore formalise the limits to measurement of current, voltage, resistance and capacitance.

Current up to 1A dc

2.5A ac

Voltage up to 110V dc

120V ac

Resistance down to 1Ω

Capacitance down to 10 pF, this lower limit may be decreased by considering the relay capacitance as a systematic error.

The limits of measurements are otherwise limited by the instruments being used, and so it is possible to measure a resistance of Giga (10^9) Ohms using the Electrometer, and this would prove no problem for the Data Logger. Generally speaking the Data Logger is to be used for electrical measurements which would not be considered extreme in value.

3.3 SPECIFIC COMPONENTS

The Data Logger was developed and tested using an experiment with multilayer ceramic capacitors. This experiment is dealt with in Section 3.3.2. Since this experiment, which was used to develop the Data Logger, it is now being used for an optocoupler experiment, for measurements upon thick films and for surface mounted ceramic capacitors. These represent typical uses for the Data Logger.

The optocoupler experiment is described in depth in Section 3.3.2, and Section 3.3.3 describes experiments other than optocoupler and multilayer ceramic capacitor experiments which have used the Data Logger.

3.3.1 Multilayer Ceramic Capacitors

Multilayer Ceramic Capacitors (MLCs) were investigated using the Data Logger. The capacitors were provided free of charge by STC in return for which STC would be privy to our results. The capacitors were used for an accelerated life style experiment which was used as a test bed upon which to help develop the Data Logger and generally to uncover any weaknesses.

Screen printed multilayer ceramic capacitors (100 nF, 50 & 100V X7R type) were subjected to accelerated life tests. The tests used voltage and temperature overstress to investigate their effects upon lifetimes. The experiment also investigated the possibility of different failure mechanisms at different stress conditions. The Data Logger was used to take parametric measurements and to locate failures.

3.3.1.1 Outline of the Experiment

The experiment consisted of two different parts; (a) a series of step stress tests; (b) biasing capacitors at different fixed voltages and temperatures.

The step stress tests followed a regime of increasing stresses and looks for parametric drift and failures. One hundred and twenty capacitors were placed on test at maximum rated voltage and temperature (50 volts, 125°C) for 1,040 hours. Voltage was increased in steps for times given (see Figure 3.1) until approximately 20 capacitors had failed. Half the capacitors were then held at this voltage and temperature was stepped up in 10°C steps to 205°C for a time constant to the next voltage step time. The remaining half were all continued on the original test plan. The Data Logger was used to take regular measurements of parallel capacitance and resistance (at 1 kHz) and the dissipation factor, and hence to log all times to failure, using the program CERAM*.

In addition to this step stress, a series of tests were conducted at fixed combinations of temperature and voltage. These conditions are shown in Figure 3.2. These tests were conducted logging times to failure more accurately. This was achieved by monitoring leakage current and switching off the voltage bias when it exceeded 5 milliamps. A clock counted the number of hours voltage bias and this was also stopped when the voltage bias was switched off. A diagram of the circuit for this can be seen in Figure 3.3. In Figure 3.4 this circuit can be seen incorporated into the whole experiment.

When a failure occurs the clock and voltage bias are switched off, and it is necessary to remove or disconnect the faulty component. The Data Logger is connected to the batch of capacitors with the

Voltage (Volts)	Step	Time (Hours)	Accn	Factor
50	1	1,040	1	1
100	2	130	8	2
126	3	65	16	2.52
144	4	43.5	24	2.88
159	5	32.3	32	3.17
171	6	26	40	3.42
182	7	21.6	48	3.63
192	8	18.4	56	3.83
200	9	16.3	64	4.00
208	10	14.4	72	4.16
216	11	12.9	80	4.31
222	12	11.9	88	4.45
229	13	10.8	96	4.58
235	14	10	104	4.70

Fig. 3.1 Table of Voltages and Times for Accelerated Life Tests of Multilayer Ceramic Capacitors

Voltage	Temperature		
	125°C	160°C	200°C
100 volts	128 capacitors	128 capacitors	128 capacitors
400 volts	128 capacitors	128 capacitors	128 capacitors

Fig. 3.2 Conditions for Accelerated Life Tests at Fixed Conditions

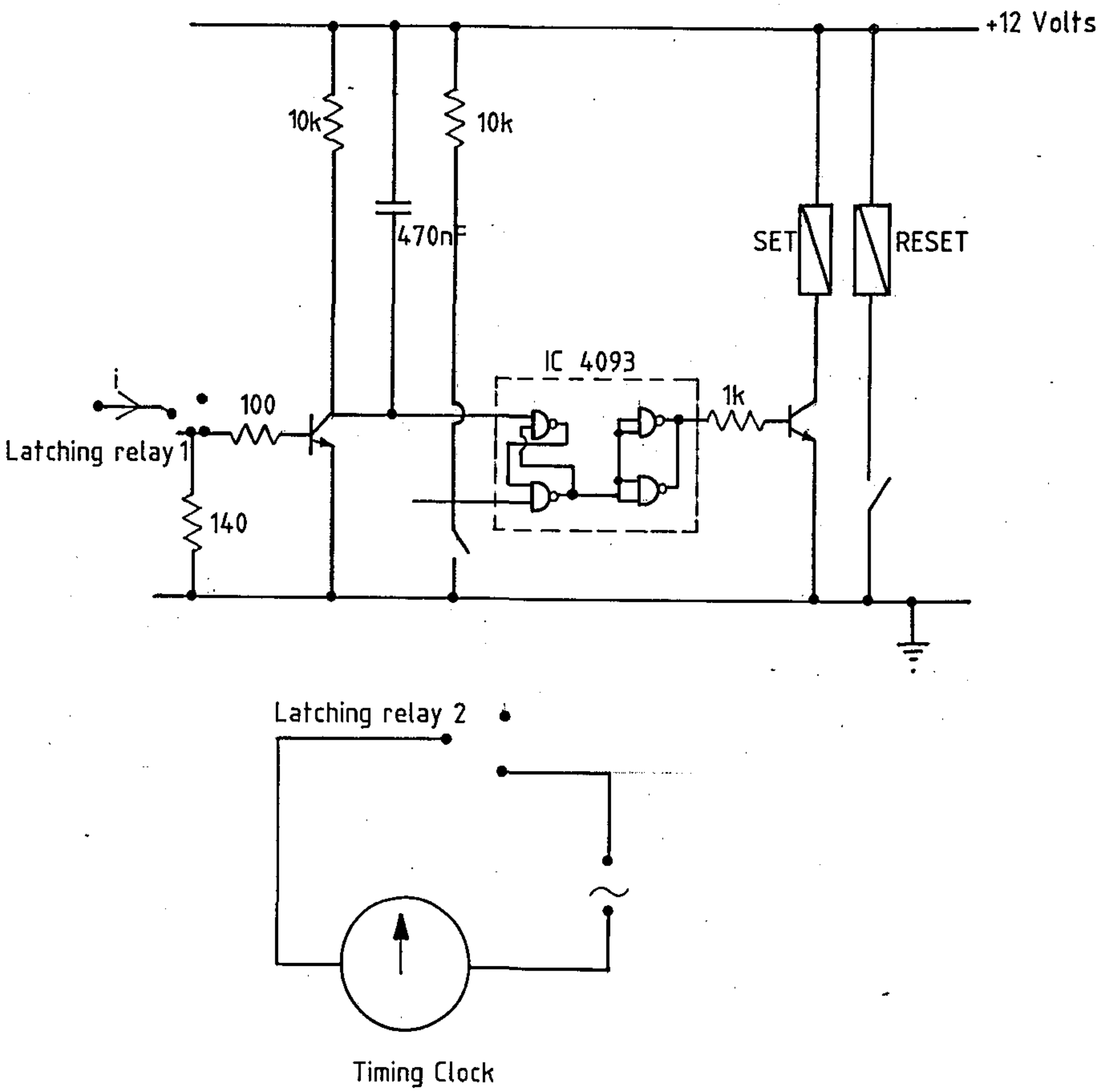

Fig. 3.3 Diagram of current leakage detection circuit.

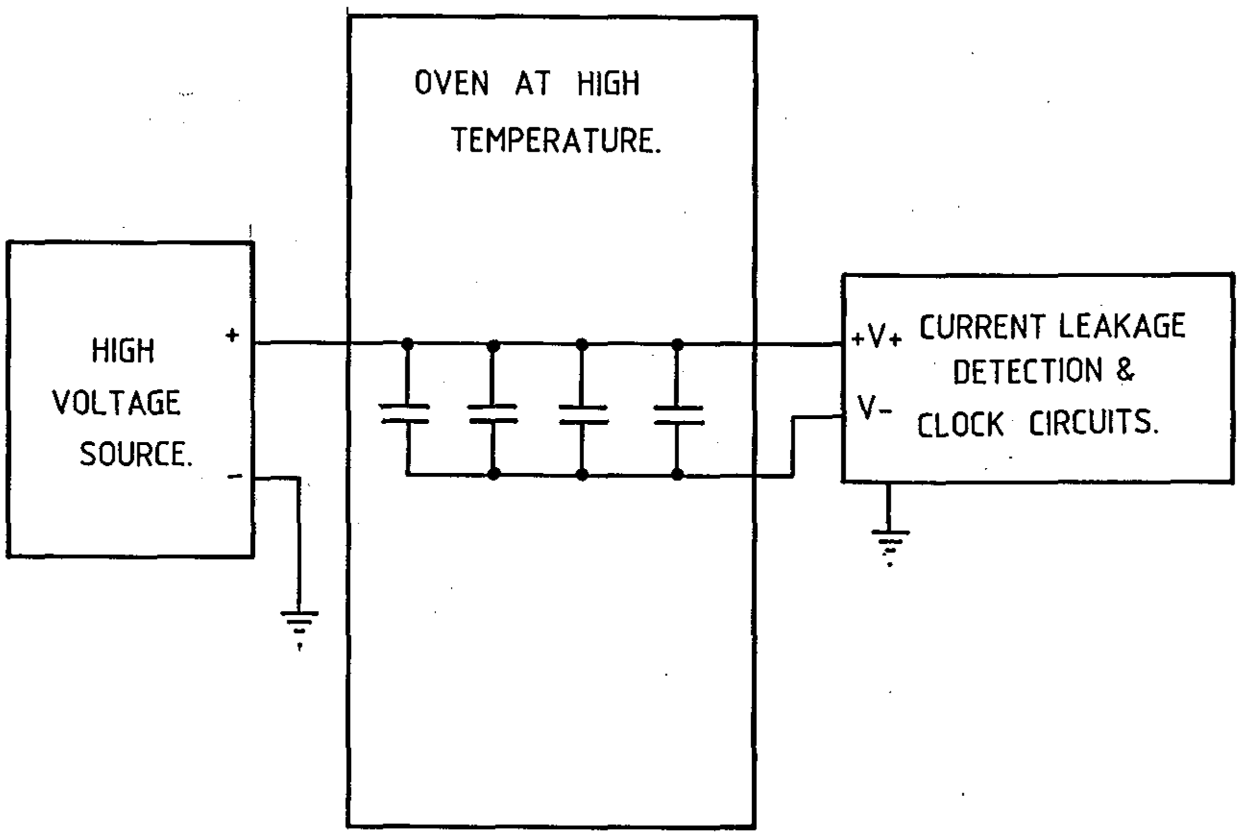

Figure 3.4 Circuit for testing capacitors.

failure. The program LOOKCER is run. This program switches the first relay on, measures the d.c. resistance and displays the result on the screen. The relay is then switched off and the process is repeated for the next relay. A low reading for resistance displayed on the screen corresponds to the failed capacitor.

The programs CERAM* and LOOKCER are listed in Appendix 5.

3.3.1.2 Results from Step Stress Program

The Results from the Step Stress Program were stored on disc and analysed. The results were used to assess the relationship between relative voltage stress and times to failure and to look at the effect of temperature upon degradation.

The first thing that was noticed was that all failures were due to the same failure mode, the drop in insulation resistance from an effective open circuit to an effective closed circuit (open circuit $R \cong 1\ G\Omega$, closed circuit $R \cong 10\ k\Omega$).

The results from this step stress are laid out in tabular form in Figures 3.5 and 3.6. If the parallel resistance of a capacitor fell below a certain value, then it was considered to have failed. If a capacitor's a.c. parallel resistance fell below 150 kΩ it was classed as a failure. 50 kΩ and 10 kΩ thresholds were also considered producing the same results and conclusions [4]. (The failure level is arbitrary, and in a piece of equipment would depend

No. Failures (/60)	Time (hours)	No. Steps	Non Acc. Time	% No. Failure Ranked
0	0	1		
2	718	1	718	2.81
3	1,082	2	1,375	4.47
3	1,109	2		
3	1,149	2		
3	1,197	3		
7	1,221	3	2,896	11.1
8	1,228	3	3,008	12.7
9	1,247	4	3,407	14.4
14	1,318	6	5.488	22.7
15	1,321	6	5,728	24.3
16	1,341	7	6.441	26.0
16	1,365	8		
17	1,390	9	9,162	27.6
18	1,443	13	13,510	29.3
18	1,448	14		
18	1,453	14		

Fig. 3.5 Results of Step Stressing, Voltage Increasing and Temperature Constant

No. Failures (/60)	Time (hours)	No. Steps	Time Real	% No. Failure Ranked
0	0	1	0	
0	718	1	718	
0	1,082	2	1,376	
4	1,109	2	1,592	6.13
5	1,149	2	1,912	7.78
6	1,197	3	2,512	9.44
9	1,221	3	2,896	14.4
9	1,228	3	3,008	
11	1,247	4	3,407	17.7
23	1,318	6	5,424	37.6
21	1,324	6	5,616	
24	1,341	6	6,160	39.2
25	1,365	7	6,928	40.9
27	1,390	8	7,728	44.2
28	1,446	10	9,520	45.8
32	1,462	10	10,032	52.4
34	1,482	11	10,672	55.8
41	1,505	11	11,465	67.4
39	1,510	12	11,568	
44	1,528	12	12,144	72.3
46	1,534	12	12,272	75.6
47	1,559	13	13,136	77.3
49	1,577	14	13,712	80.6
50	1,582	14	13,872	82.3

Fig. 3.6 Results from Step Stress with Voltage, Then Temperature

on the particular use of a component. This failure level will vary from use to use).

The results from the first part of the experiment, the step stressing, were used to investigate the Inverse Power Law which states:

> "When the life of a system is an inverse power function of the accelerating stress variable, the inverse power law is commonly used. The characteristic life is given by:
>
> $$\eta(V) = \frac{1}{KV^n} \qquad (1)$$
>
> where V is the accelerating stress and K and n are positive parameters characteristic of the material and test method."[5],[16]

From this equation we can say that the characteristic life at an accelerated voltage V_A will be given by

$$\eta_A = \frac{1}{KV_A^{\ n}} \qquad (2)$$

and the characteristic life at the usual voltage stress will be given by

$$\eta_U = \frac{1}{KV_u^{\ n}} \qquad (3)$$

Dividing equation (3) by equation (2) yields equation (4):

$$\eta_U = \eta_A (V_A/V_u)^n \qquad (4)$$

Using equation (4) the value of n is estimated graphically by plotting results of times to failure on Weibull [7] paper, see Figures 3.7 to 3.8. See Appendix 4 for a discussion on the Weibull distribution.

Figure 3.7 represents the times to failure for capacitors that were voltage step stressed at a constant temperature of 125°C. The times to failure are calculated assuming that the acceleration factor, n, (see equations 1 to 4) is equal to three. The graph is a reasonably straight line indicating that the acceleration factor of three is correct. An incorrect acceleration factor would bend the curve (upwards (n estimated too low) or downwards (n estimated too high)).

In Figure 3.8 an acceleration factor of three is again assumed. The graph again fits a straight line indicating the correct acceleration factor. Towards the top end of the graph it turns upwards. This corresponds to increasing temperature indicating that higher temperatures decrease characteristic lifetimes.

A detailed analysis of the results from phase 1 was carried out by Mr P. Crawley of STC Components, Gt. Yarmouth, whose conclusions were in accord with those above [8].

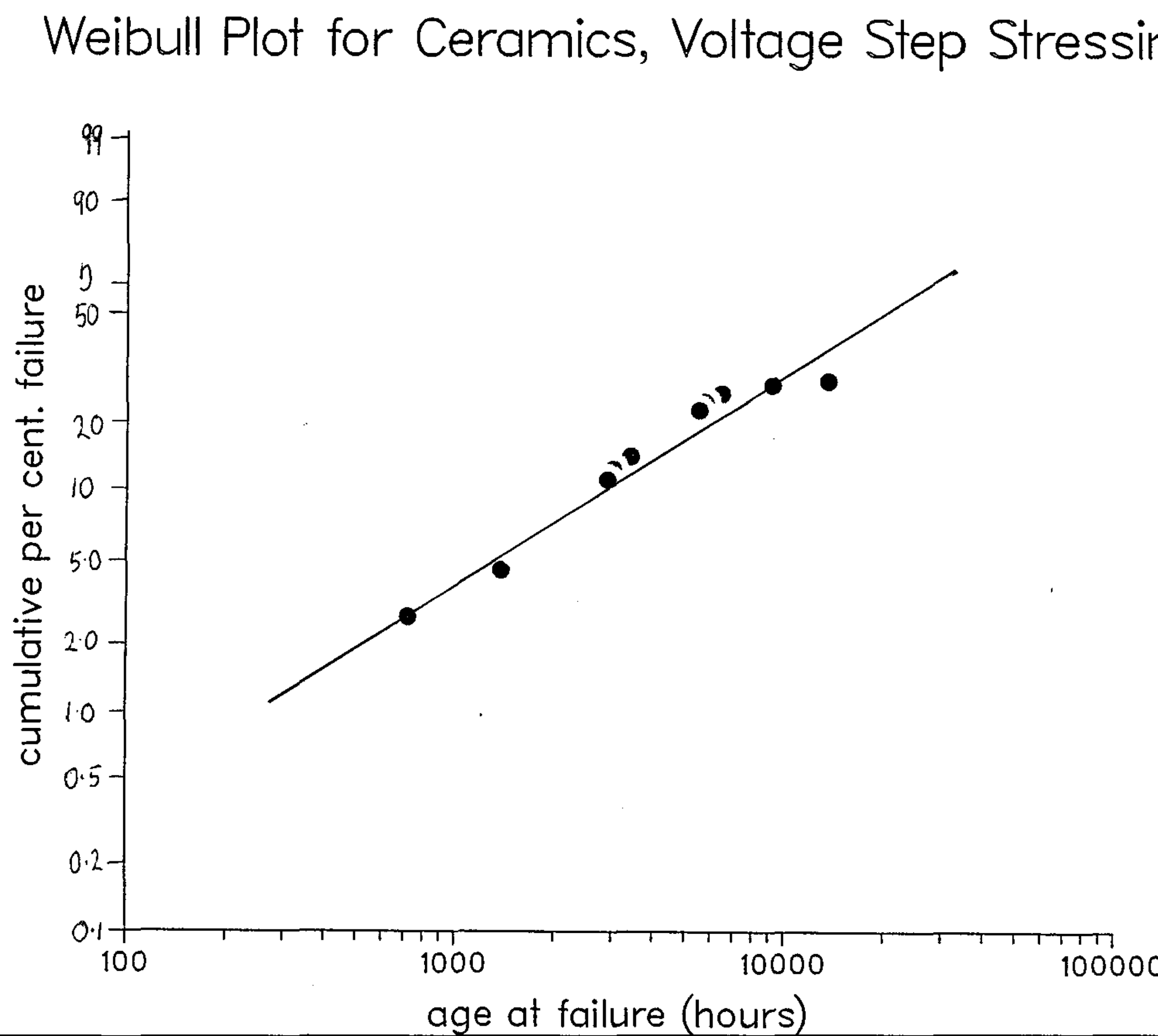

Fig. 3.7 Weibull Plot for Ceramics, Voltage Step Stressing

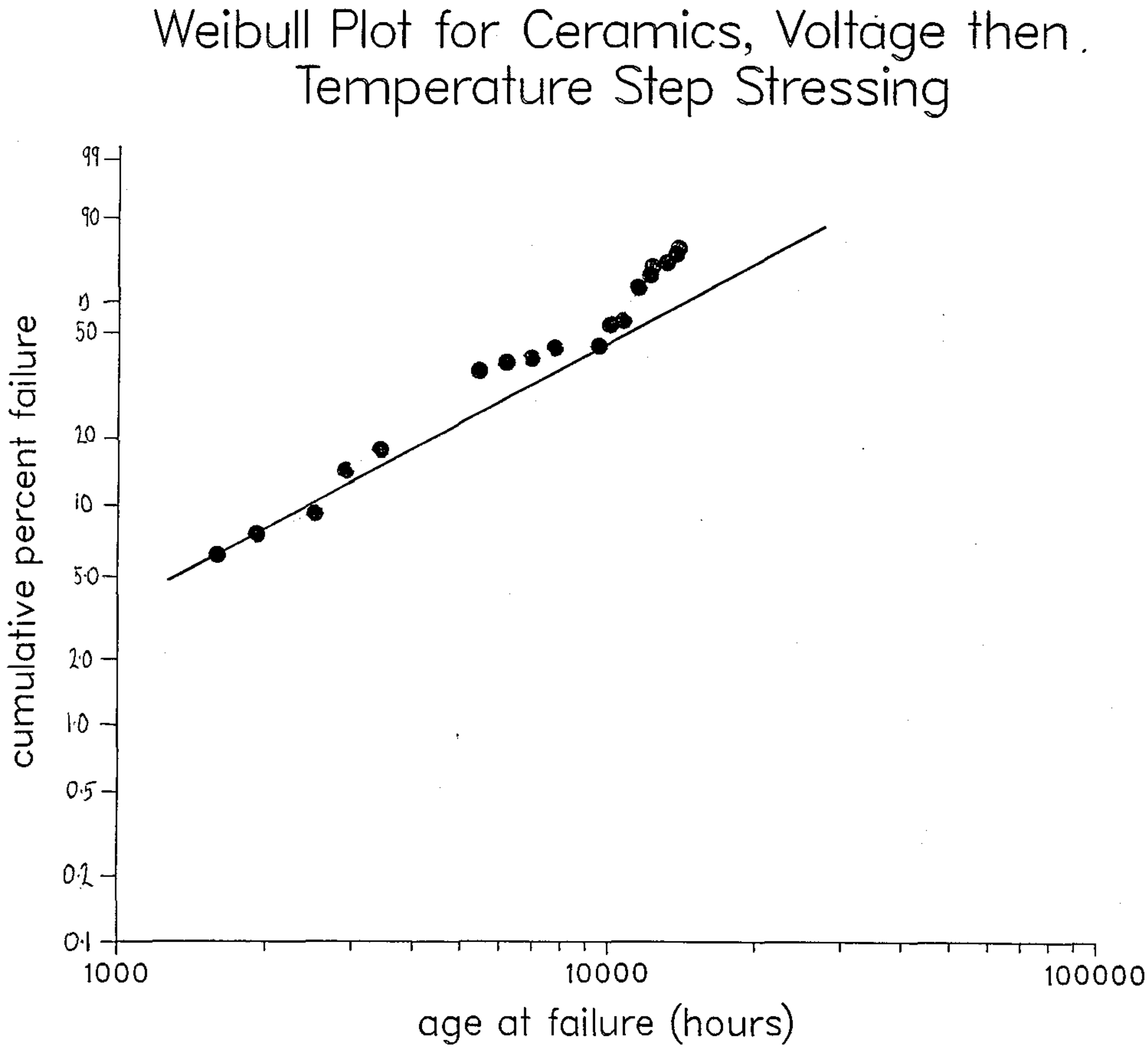

Fig. 3.8 Weibull Plot for Ceramics, Voltage Then Temperature Step Stressing

3.3.1.3 Results from the Matrix Life Tests

After the step stress was completed, further Life Tests were conducted. These tests were to give more accurate times to failure. Multilayer Ceramic Capacitors similar to those used in the step stress were used. The only difference was that these capacitors were rated to 100 volts as opposed to 50 volts.

The capacitors were mounted on boards made of the asbestos substitute 'Superlux'. Each board held 128 capacitors. Groups of capacitors were then placed on test, 128 capacitors in each group, at different sets of conditions, see Figure 3.9.

	125°C	160°C	200°C
100 volts	128 units	128 units	128 units
400 volts	128 units	128 units	128 units

Fig. 3.9 Conditions for Life Testing Multilayer Ceramic Capacitors

The times to failure for each set of conditions are given in Figure 3.10 together with the cumulative number of failures.

n	100 Volts			400 Volts		
Failures	125°C	160°C	200°C	125°C	160°C	200°C
1	265.0	67.8	7.6	0.45	1.0	0.01
2	1,036.5	137.8	14.6	3.8	2.9	0.1
3	1,227.3	166.8	15.8	4.3	3.7	0.1
4	1,656.0	246.7	19.5	6.2	5.5	0.4
5		272.3	21.4	6.5	7.6	0.8
6		470.3	23.8	28.9	9.5	1.1
7		530.7		31.1	11.4	1.2
8		623.5		36.3	11.5	1.2
9		1,090.1		43.9	12.1	1.4
10					13.0	1.9
11						2.4
12						2.5
13						2.5
14						2.8
15						3.2
16						3.45
17						3.45
18						3.5

All times to failure are in hours

Fig. 3.10 Times to Failure for Matrix Life Tests

All these results have been plotted on Weibull paper using ranked data [7]. From these results the characteristic life of the capacitors was estimated for each set of conditions. Arrhenius Plots were made by estimating the likely maximum and minimum characteristic lives from the Weibull graphs (Figures 3.11 to 3.18). From these graphs activation energies are estimated and the nature of the mechanisms causing failure are interpreted.

The likely maximum and minimum characteristic lives are shown in Figure 3.19, as estimated [7], the figure also includes the natural logarithms of these lifetimes.

From the Arrhenius Plots (Figures 3.17 and 3.18) it is possible to make an estimate of the activation energies. There appears to be more than one failure mechanism, (as discussed later in this section) but using the Arrhenius method of plotting failure rates or characteristic life against temperature (see Section 1.1.2) we can estimate the activation energy using the equation

$$E_A = k.\text{gradient} \qquad (5)$$

where k is Boltzman's constant = 8.625×10^{-5} eV/K and gradient is the gradient of the graph E_A is in electron volts.

It is possible to plot a straight line through both sets of data which would correspond to thermal runaway and to have another

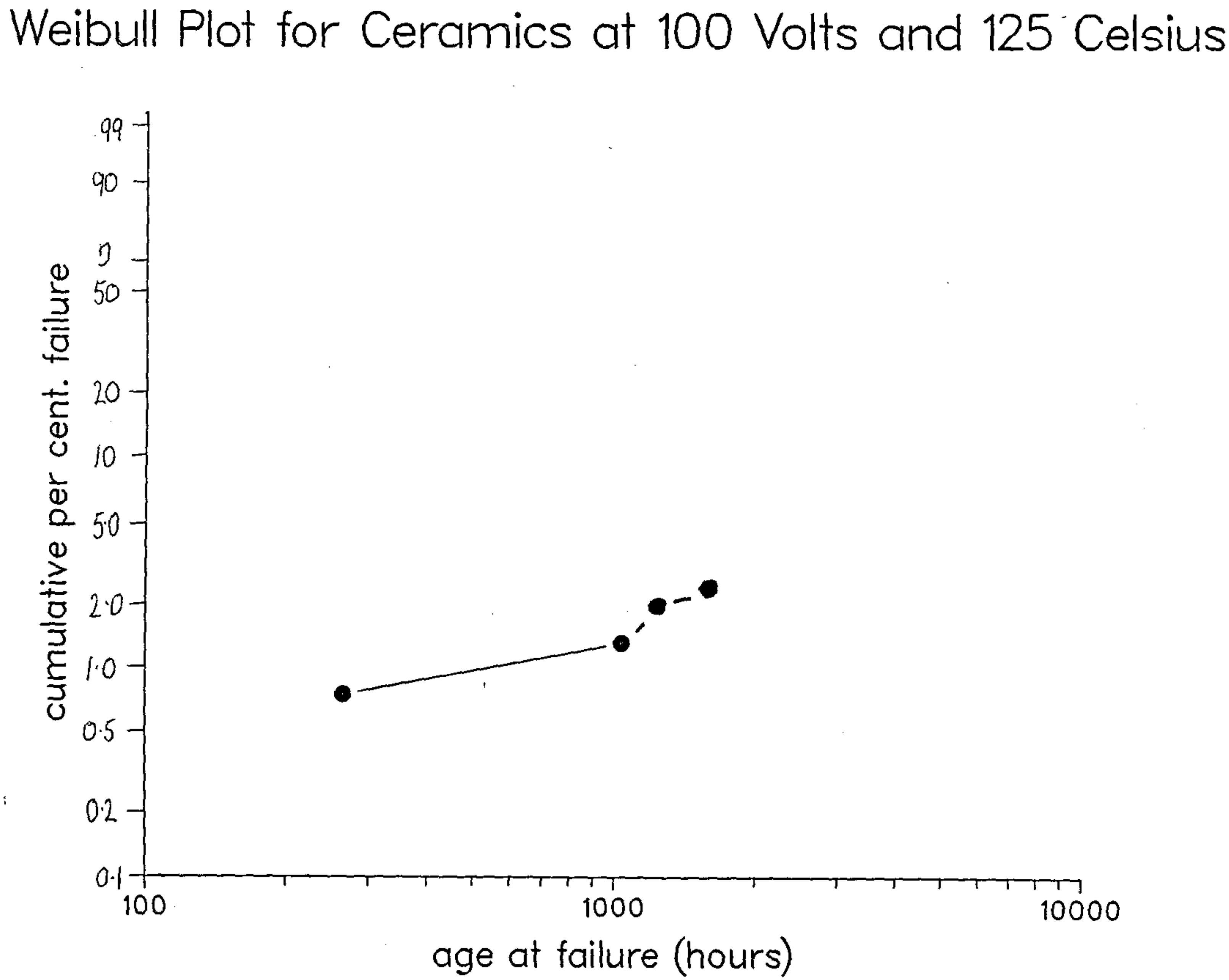

Fig. 3.11 Weibull Plot for Ceramics at 100 Volts and 125 Celsius

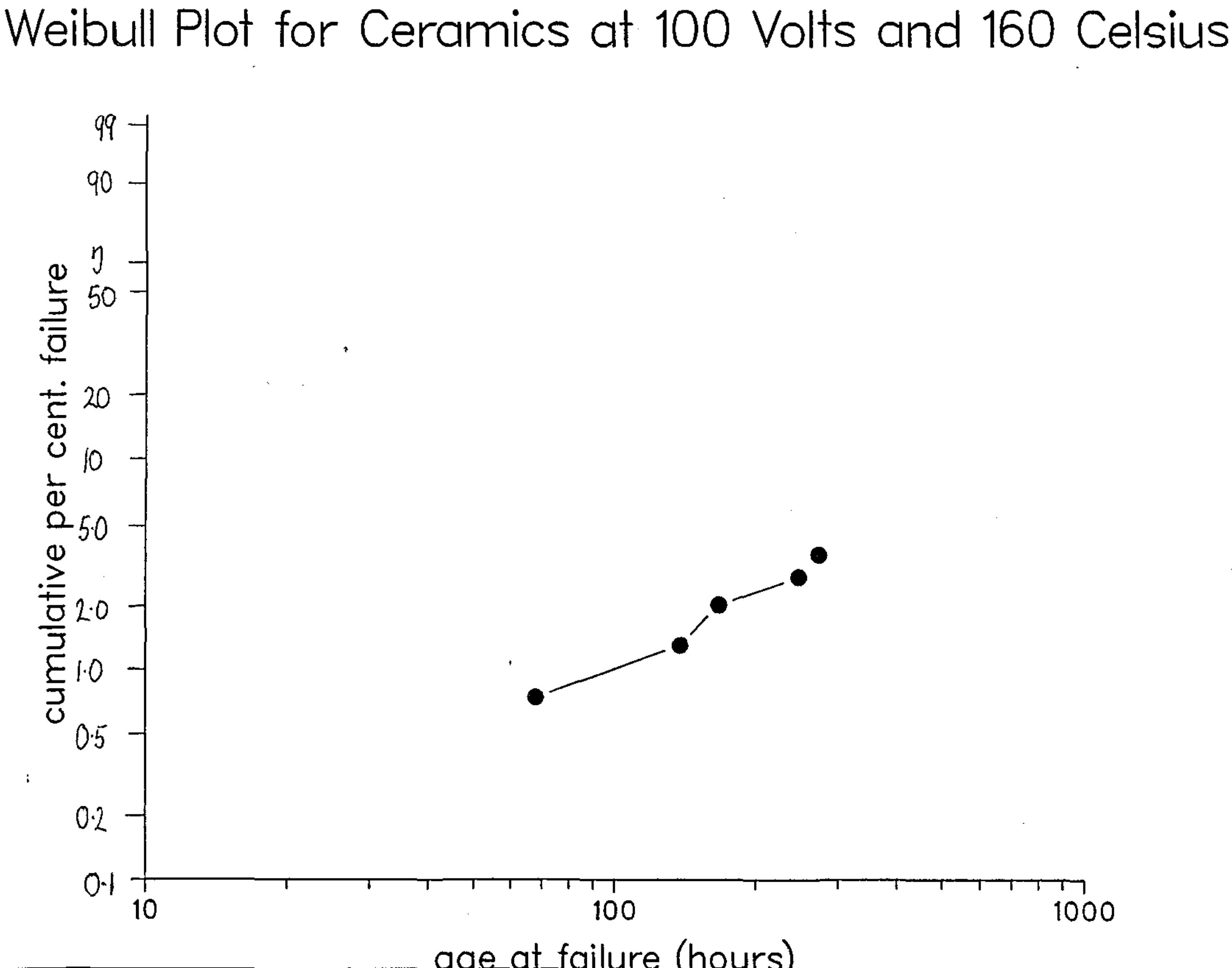

Fig. 3.12 Weibull Plot for Ceramics at 100 Volts and 160 Celsius

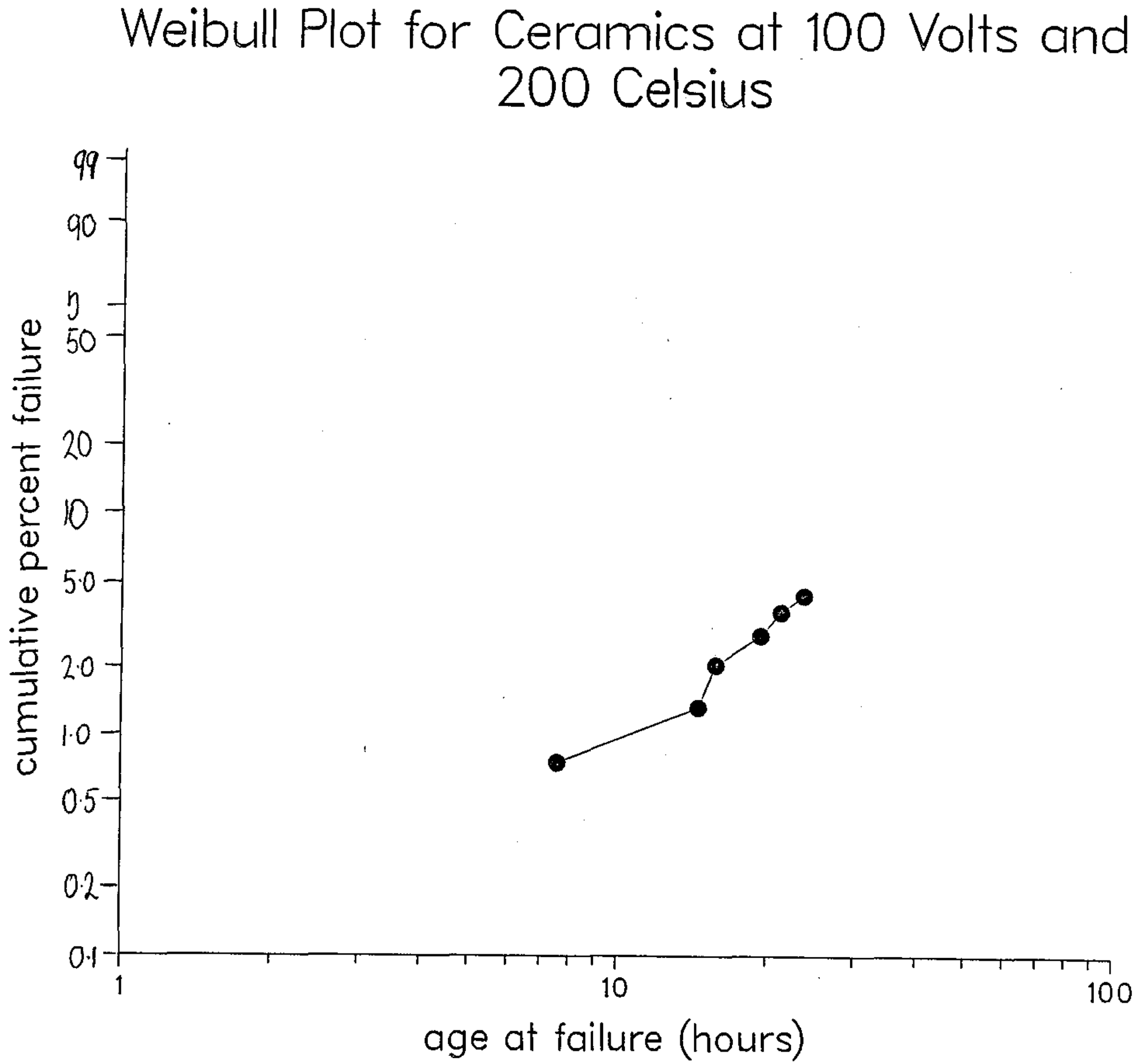

Fig. 3.13 Weibull Plot for Ceramics at 100 Volts and 200 Celsius

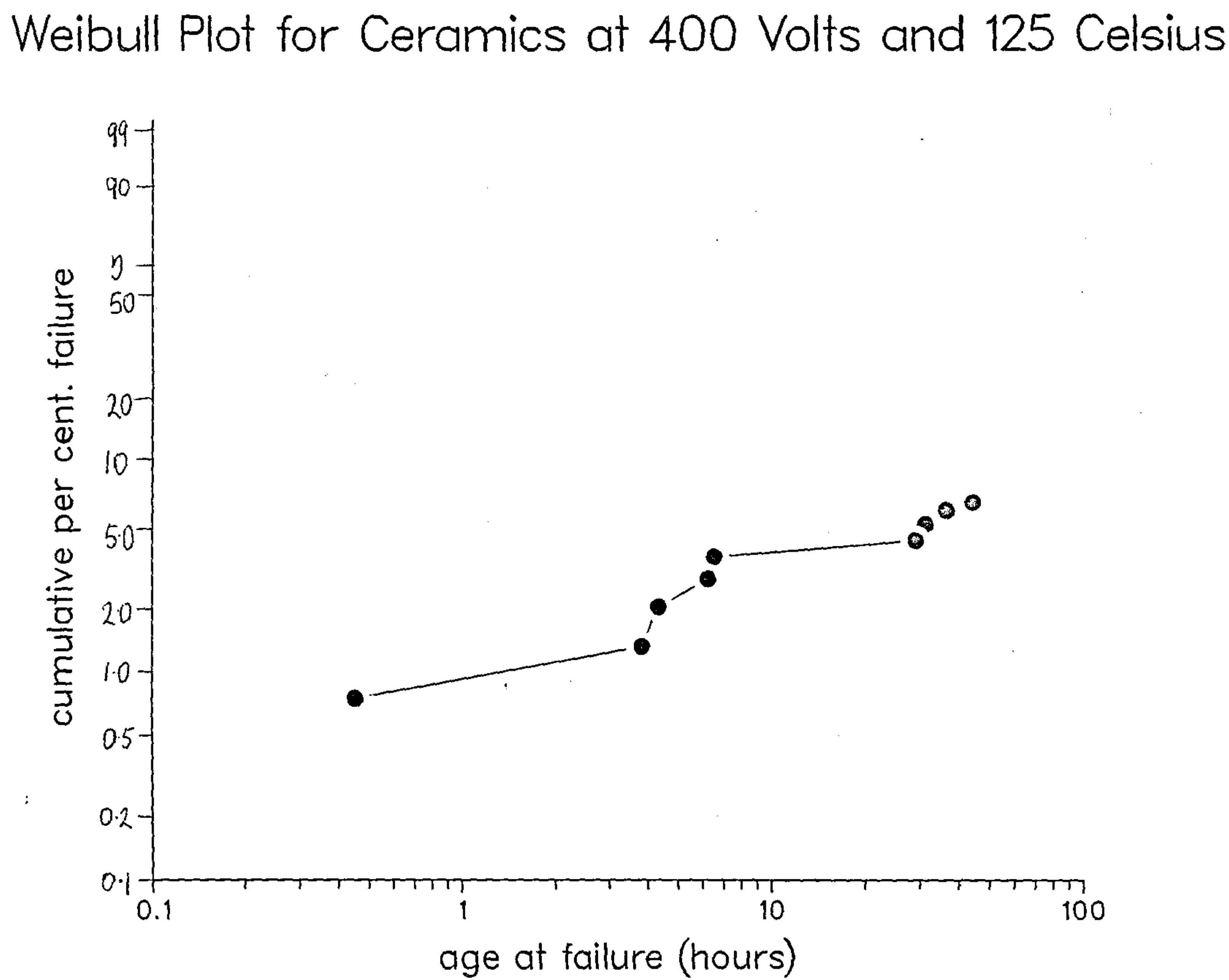

Fig. 3.14 Weibull Plot for Ceramics at 400 Volts and 125 Celsius

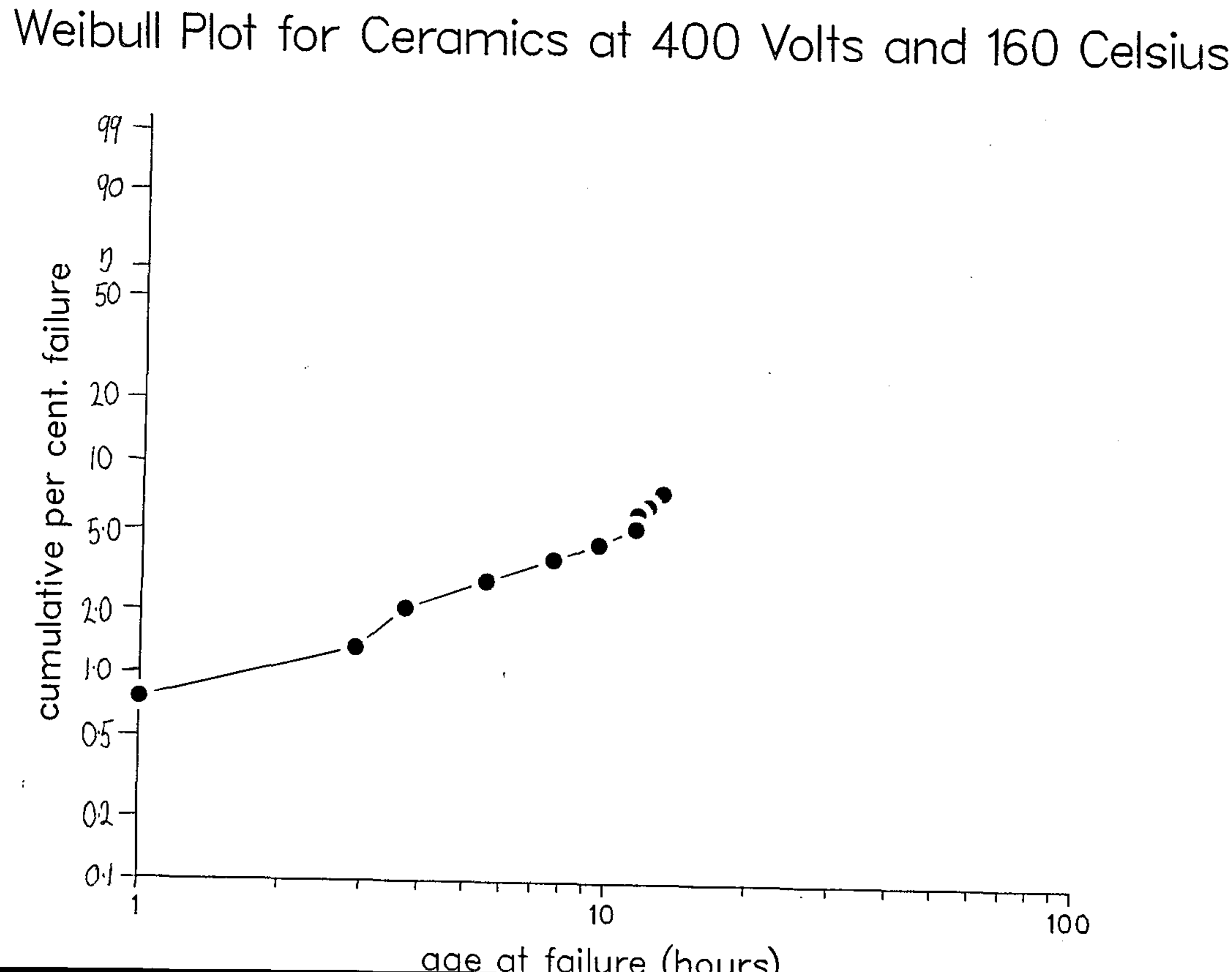

Fig. 3.15 Weibull Plot for Ceramics at 400 Volts and 160 Celsius

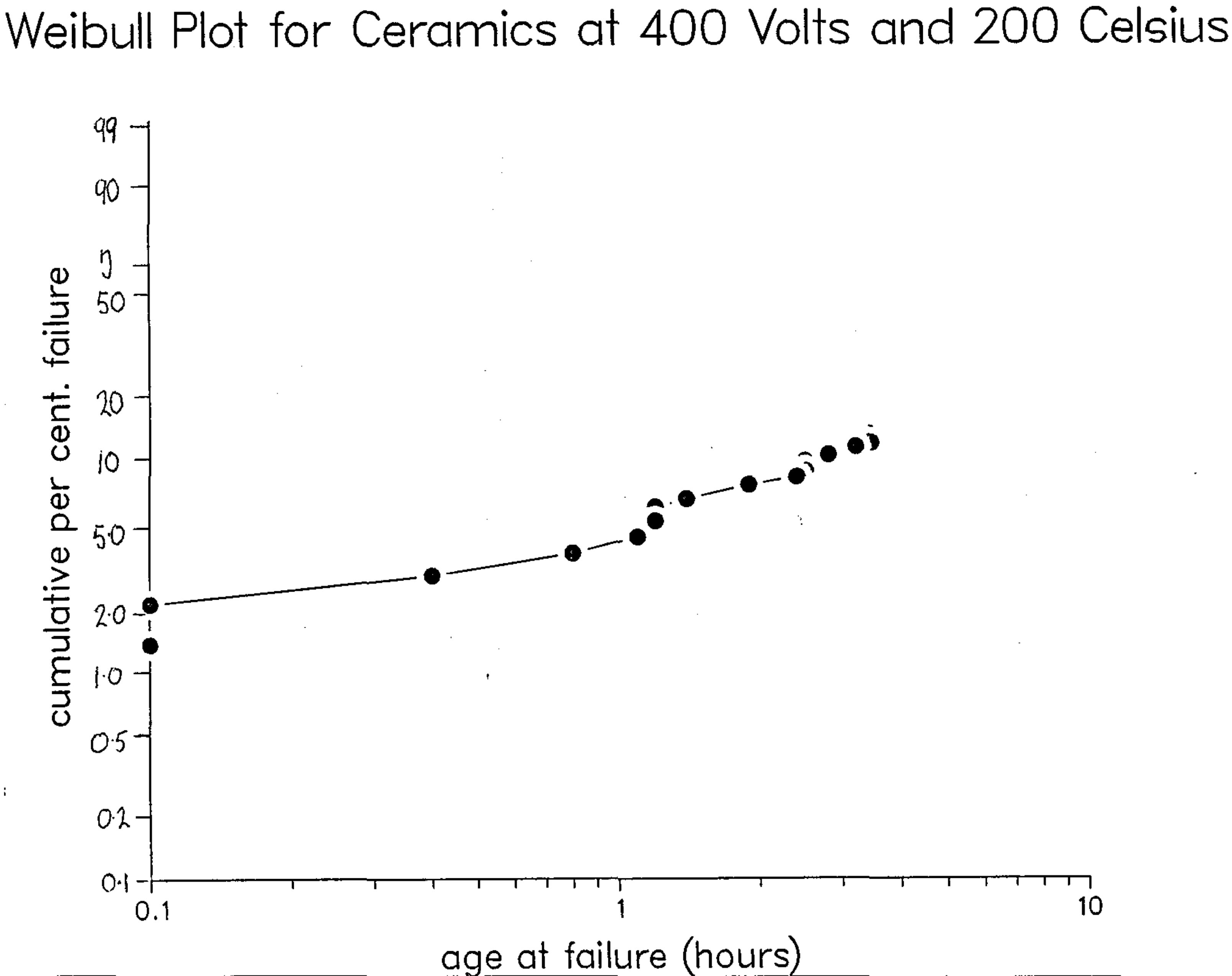

Fig. 3.16 Weibull Plot for Ceramics at 400 Volts and 200 Celsius

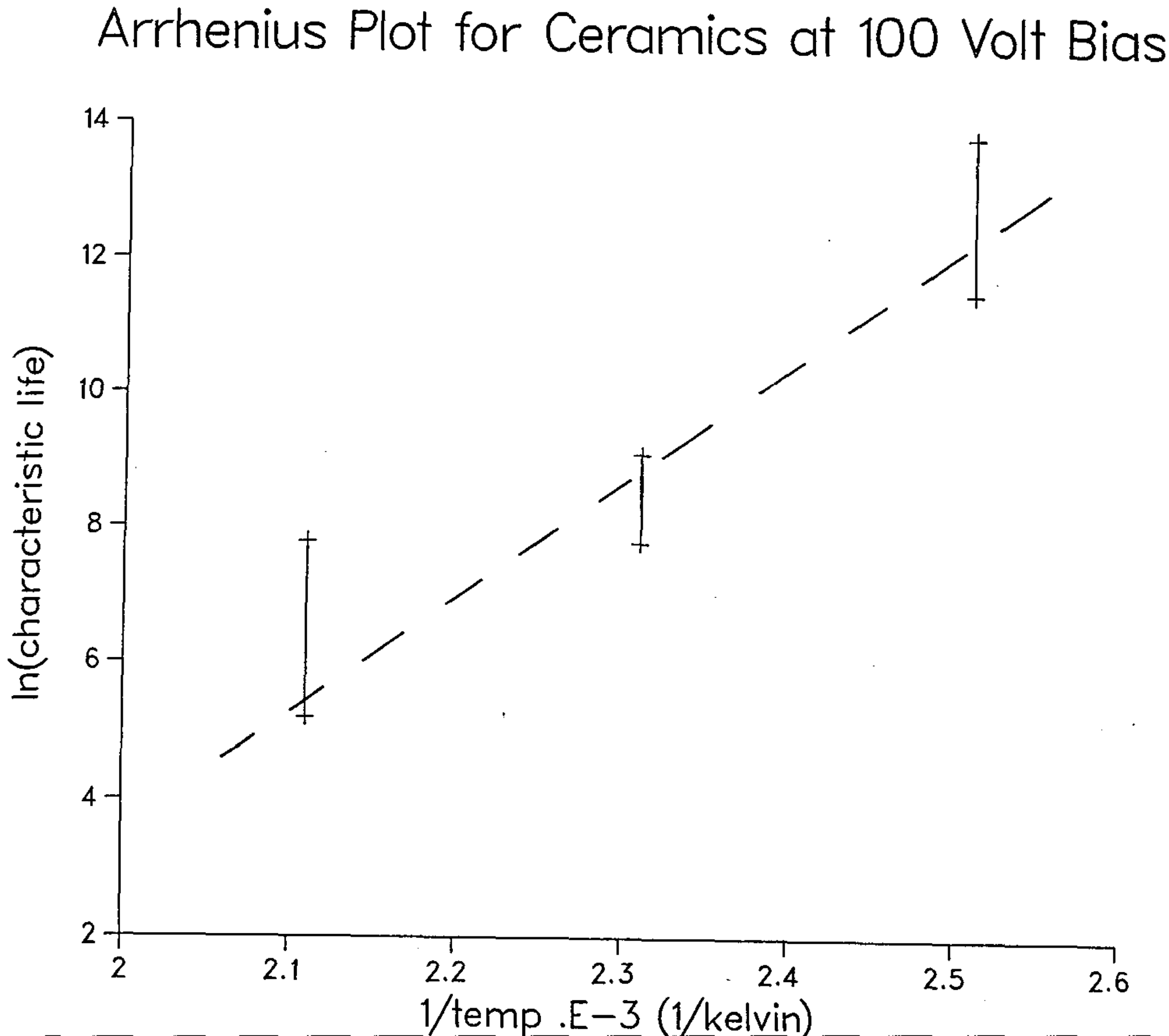

Fig. 3.17 Arrhenius Plot for Ceramics at 100 Volt Bias

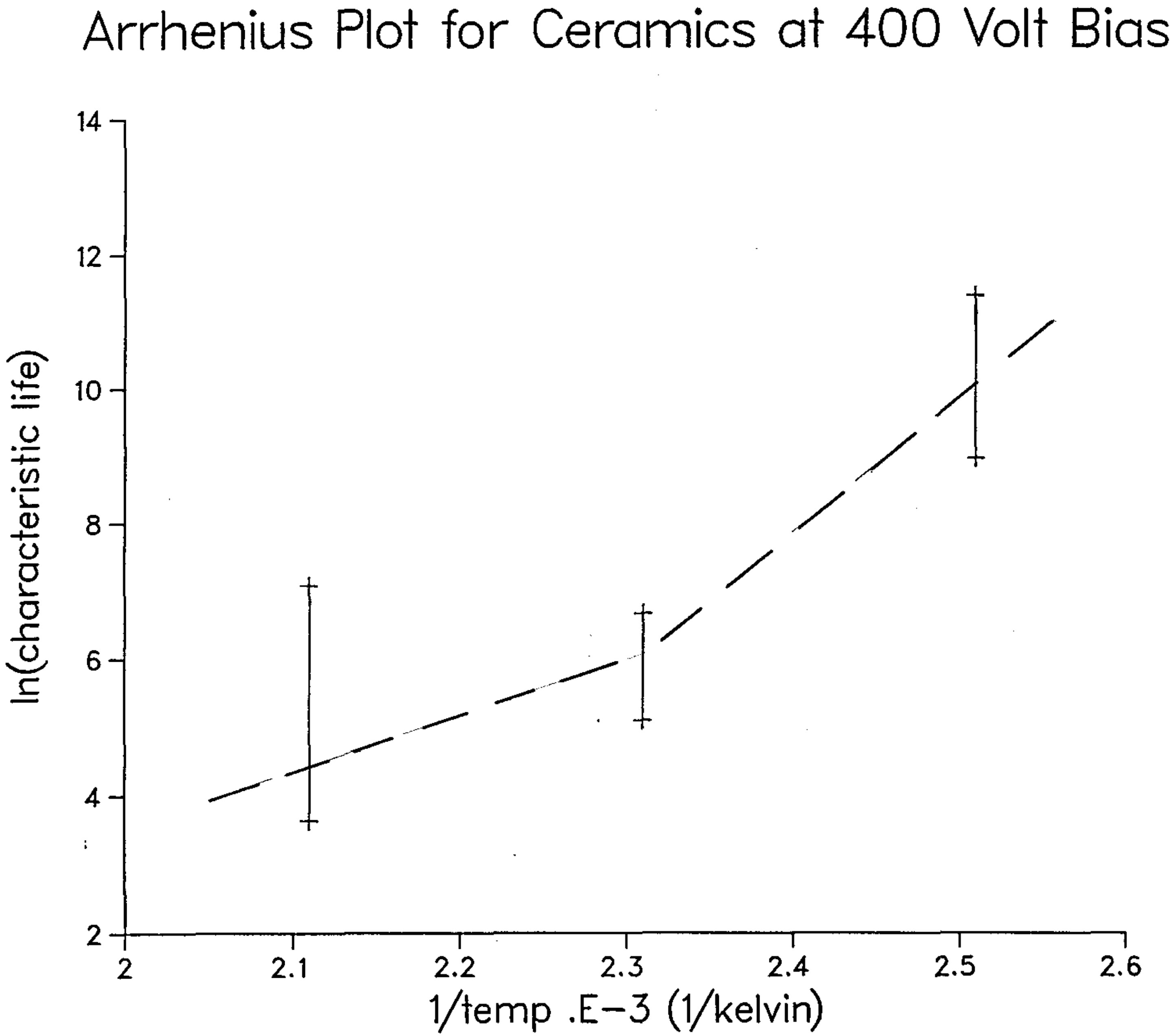

Fig. 3.18 Arrhenius Plot for Ceramics at 400 Volt Bias

	Voltage (Volts)	
	100	400
Temp. 125 (°C)	100,000-1,000,000 hrs. 11.512-13.815	8,000-90,000 hrs. 8.987-11.407
160	2,400-9,000 7.783-9.104	165-800 hrs. 5.105-6.684
200	180-2,400 5.192-7.783	38-1,200 hrs. 3.637-7.090

Fig. 3.19 Likely Maximum and Minimum Lifetimes for Multilayer Ceramic Capacitors Under Different Conditions (lower figures are natural logarithms of the times)

line for the avalanche breakdown on the 400 volt graph. This gives an estimate for the thermal runaway activation energy of 1.0 eV. The figure of 0.43 eV for the avalanche breakdown can not be regarded as being accurate due to the wide ranges of characteristic lives at higher temperatures. These values compare well with those obtained by L. C. Burton [8] and B. S. Rawal and N. H. Chan [9] in their own respective studies on multilayer ceramic capacitors.

The Weibull Plots, Figures 3.11 to 3.16, show two distinct failure patterns for the two different voltage stresses, with temperature affecting the times to failure rather than failure patterns. These indicates that for the 100 volt failures there is one failure mechanism. For the 400 volt failures there is more than one failure mechanism. This is borne out by the Arrhenius Plots, see Figures 3.17 and 3.18, the 100 volt failures produce a reasonably straight line, the 400 volt failures produce an obviously not straight line. The effect of high voltage stressing has been more severe than high temperature stressing.

It is known that degradation of insulation resistance is the primary failure concern for multilayer ceramic capacitors [10]. This has been observed in the experiments at Loughborough.

At high voltages the electric field across the dielectric is very high ($\cong 10^6$ volts/meter) [11]. There are two likely failure mechanisms, thermal runaway and avalanche breakdown [11]. Avalanche breakdown is prevalent at high field strengths. The dielectric for an X7R, 100 nF, 100V capacitor was approximately 4×10^{5} m or 40 μm thick. This means that a 400 volt bias produces a field of intensity of approximately 10×10^{6} V/m.

At lower voltages there appears to be only one failure mechanism, this could be thermal runaway.

The conduction mechanisms for barium titanate ceramics are beyond the scope of these experiments. However, previous work gives some clue as to the mechanism. Rawal and Chan [9] suggest that conduction is by electrons rather than ions. The likely current type is space charge limited emission for the degrading ceramic [10]. The likely mode of electron transport is small polaron hopping [10], [11]. Schottky currents or Poole-Frenkel currents are not considered likely current mechanisms [12].

3.3.1.4 Conclusions of Ceramic Capacitor Experiment

From the results obtained there are several important conclusions.

(1) The voltage acceleration factor is approximately three.

(2) Failure mechanisms depend on the applied voltage stress.

(3) Screen printed ceramics do not appear to differ significantly from other ceramics.

As a result of this work a paper has been written to be presented at CARTS-EUROPE in October 1987 at Brighton, see Appendix 6.

3.3.2 Optocouplers

Accelerated life tests are being undertaken on optocouplers (or optoisolators as they are otherwise known) at Loughborough University of Technology. This work is the result of pilot studies on optocouplers by Dr V. Williams at the University [13]. The optocouplers being studied are type CNY65 manufactured by Telefunken of Denmark.

3.3.2.1 Work Being Carried Out by the Danish Academy

The Danish Academy of Engineering, under Professor Jan Møltoft, are conducting a parallel study on optocouplers [14] which are individually identified, have been placed in equipments which are in use. Any failures of these optocouplers will be noted. It will therefore be possible to produce a picture of optocoupler reliability in commercial use.

The results from the work carried out by the Danish Academy of Engineering will be compared with the results from Loughborough University of Technology, and this will enable the accelerated life tests to be verified.

3.3.2.2 Reverse Recovery Times of Optocouplers

An optocoupler consists of a light emitting diode (L.E.D.) optically coupled to a photosensitive transistor. The reverse recovery time of a diode is a measure of the time that a diode will conduct if it has a reverse bias applied suddenly. The diode must have been in a steady state forward biased condition previously [15].

It has been suggested [15] by T. Takahashi et al. that the reverse recovery time of an optocoupler can be used as a screening method for removing bad optocouplers. With this in mind, reverse recovery times of optocouplers have been measured, using a reverse recovery meter built at Loughborough University of Technology. If it is possible to use reverse recovery times as a non-destructive screening method, then those optocouplers that fail first will correspond to those with the unusual reverse recovery times.

The accelerated life tests on optocouplers will be able to investigate whether it is possible to use this screening process effectively.

3.3.2.3 Accelerated Life Testing of Optocouplers

Optocouplers are being accelerated under ten different sets of conditions (two different L.E.D. currents and five different temperatures), see Figure 3.20.

The optocouplers, with 96 at each set of conditions, are aged in ovens which regulate to the required temperature. Periodically the optocouplers are removed from the ovens and allowed to cool to

20 mA 25°C F	20 mA 50°C G	20 mA 70°C H	20 mA 85°C I	20 mA 100°C J
8 mA 25°C A	8 mA 50°C B	8 mA 70°C C	8 mA 85°C D	8 mA 100°C E

Fig. 3.20 Table Showing Different Conditions for Accelerated Life Testing of Optocouplers

room temperature. They then each have 20 mA applied through the L.E.D. and 6.5 volts across the transistor. Under these conditions the following measurements are made.

V_F the forward voltage across the L.E.D. for a fixed diode current

CTR the ratio of current passed by the transistor for a given diode current

V_{SAT} the saturation voltage of the phototransistor for a given diode current.

The measurements are made initially before the tests begin and then at regular intervals, see Figure 3.21.

Measurements are taken more regularly at the beginning of the experiment because this will enable the times to failure of early failures to be calculated.

The optocouplers are mounted upon printed circuit boards. Each board holds 32 optocouplers and connections for applying bias to the optocouplers, and 34 way sockets which connect to the switching boxes for selecting specific optocouplers, see Figure 3.22.

Measurement Number	Times Between Measurements
1	0
2	1
3	1½
4	2½
5	4
6	7
7	11
8	19
9	30
10	50
11	80
12	130
13	200
14	350

Fig. 3.21 Table of Measurement Times for Optocouplers

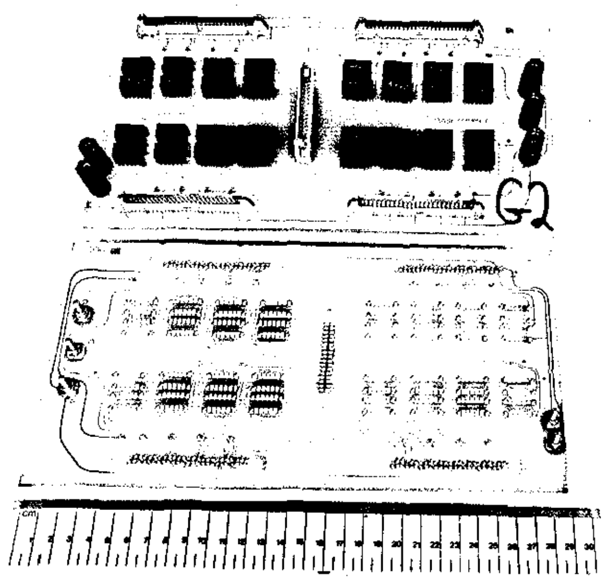

Fig. 3.22 Photograph of a Printed Circuit Board Holding Optocouplers for Accelerated Life Testing

In addition to the four 34 way d.i.l. sockets (female) which connect to the relays, there is another 34 way socket which is used to common all the connections to it during measurement. There are also five 4 mm banana plugs. Two provide positive and negative terminals for biasing the thirty-two optocouplers in series during the accelerated life tests. The remaining three banana plugs provide connections to the optocoupler's, annode, collector and ground terminals during measurements.

All the measurements are made using the Data Logger connected to a Solatron 7065 Digital Voltmeter. In order to measure current, as for measuring current transfer ratio and saturation voltages the voltage drop across a known resistance is measured. Current is then calculated using Ohm's Law.

When using the Data Logger to take the measurements of forward voltage, current transfer ratio and saturation voltage, the opto-couplers are connected to the relays as in Figure 3.23.

In order to measure forward voltages of the optocouplers relays 1 and 2 are closed. 20 mA is passed from the anode through the diode to ground, the voltage from anode to ground is measured and recorded as the forward voltage of that optocoupler. Relays 1 and 2 are opened and the process is repeated for the next optocoupler.

Unfortunately, owing to the complicated nature of the printed circuit boards which hold the optocouplers, it was not possible to have consecutive relays for consecutive optocouplers, and so the relay combinations are as in Figure 3.24.

In order to measure current transfer ratio the current is measured as it passes along the connection to the collector, a bias of 6.5 volts being applied between collector and ground. This value is converted to milliamps and divided by 20 (the current through the diode is 20 mA) to give a result for current transfer ratio.

For measurements of saturation voltage a similar procedüre takes place. However the collector current is measured for voltages

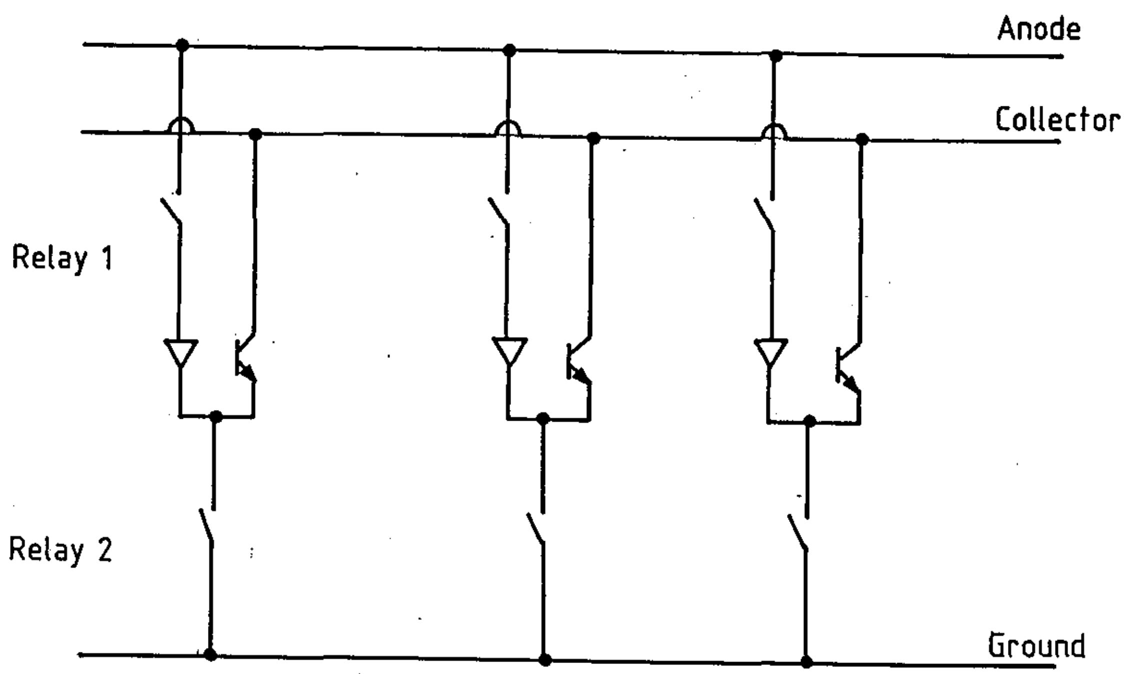

Fig. 3.23 Schematic diagram of relay connections when measuring optocouplers.

Optocoupler	Relay Combinations		Optocoupler	Relay Combinations	
1	1	2	17	33	34
2	10	11	18	42	43
3	3	4	19	35	36
4	12	13	20	44	45
5	5	6	21	37	38
6	14	15	22	46	47
7	7	8	23	39	40
8	16	25	24	48	57
9	17	18	25	49	50
10	26	27	26	58	59
11	19	20	27	51	52
12	28	29	28	60	61
13	21	22	29	53	54
14	30	31	30	62	63
15	23	24	31	55	56
16	32	41	32	64	9

Fig. 3.24 Relay Combinations to Select Optocouplers

across the collector to ground, starting at 0.3 volts and increasing in steps of 0.2 volts. The gradient of a graph of current (in mA) versus voltage (volts) is considered, and where the gradient would be 5 this is considered to be the saturation voltage. The actual point where the gradient equals five is calculated by considering the gradient on either side and using the Newton-Ralphson method of approximation, see Figures 3.25 and 3.26.

The results for forward voltage (V_F) are all 4% higher for the Data Logger. This is accounted for by voltage drop across relays and measurement leads. The figure of 4% difference has remained constant so far through the experiment (see Figure 3.27).

The differences in current transfer ratio are accountable to the fact that when a voltage is applied across the optocoupler's transistor it heats up. This means the impedance changes. With the Data Logger measurements are taken exactly at the same time after the voltage is applied. This is not possible when measuring by hand. Considering this difficulty the results for current transfer ratio are good.

3.3.2.5 Future Work with Optocouplers

Fourteen sets of measurements are planned to be taken for the optocouplers undergoing accelerated life tests. This corresponds to a period of about two years. Future work will include continuing these measurements.

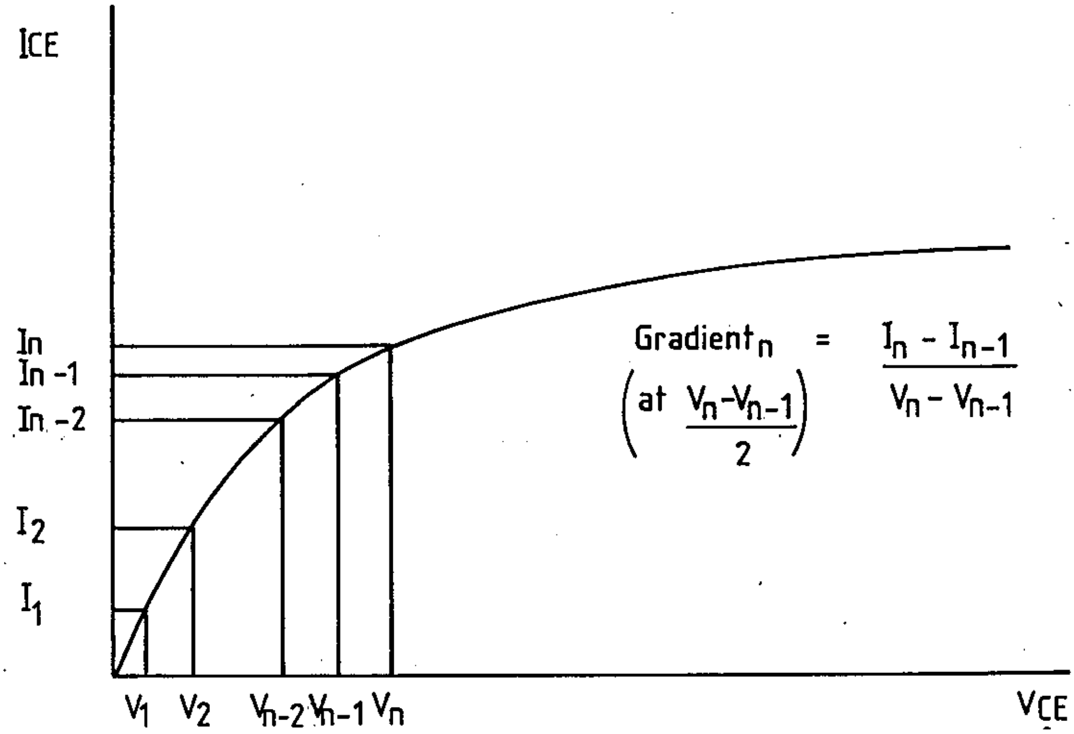

Fig. 3.25 Calculating Saturation Voltage (1)

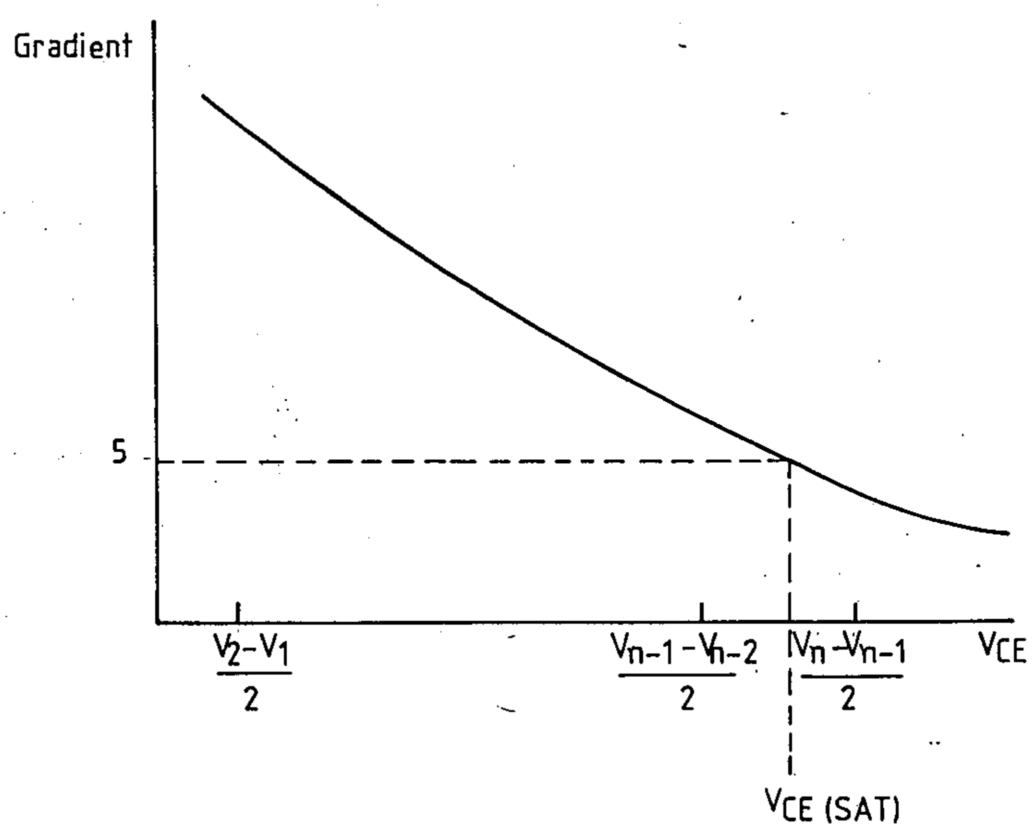

Fig. 3.26 Calculating Saturation Voltage. (2)

Bench Tests		Data Logger	
V_F (V)	CTR	V_F (V)	CTR
1.170	2.4	1.2178	2.025
1.172	2.9	1.2181	2.166
1.168	3.3	1.2149	2.624
1.177	3.0	1.2213	Not available
1.164	3.5	1.2092	2.742
1.174	2.0	1.2207	1.726
1.169	3.2	1.2162	2.482
1.171	3.7	1.2175	2.757

Fig. 3.27 Results from Data Logger Compared with Same Measurements Taken by Hand

The IBM PC AT is being used to archive all the information in two forms. Firstly each set of measurements is stored as a file.

e.g. AFOR.003

this means measurements of forward voltage upon the A block of opto-couplers (8 mA, 25°C acceleration conditions), third set of readings (i.e. after 1½ day aging period).

Secondly a file is also being kept for each optocoupler's measurements, which records how a certain parameter will vary with time.

e.g. C58.CTR

this records the values of current transfer ratio that were measured and their respective times under accelerated conditions in hours, for the 58th optocoupler of the C block (8 mA, 70°C acceleration conditions).

Analysis of results will be undertaken using this archive of information and results can be compared with those achieved by Dr V. Williams [4]. It will be possible to compare accelerated life test results withs results from the field, from Denmark [5].

It may be possible to develop other models for optocoupler degradation. It is anticipated that specialist statistical advice may be needed for the correct analysis of such a large amount of data. (Approximately 40,000 separate results when all measurements are taken).

3.3.3 Other Components

The Data Logger is currently (as of February 1987) being used to take measurements for other components. The Component Technology Group at Loughborough is conducting research on thick film resistors and surface mount technology. The Data Logger is used by other members of the group to take measurements on these components, using the equipment and ideas that have been detailed here.

3.4 SUMMARY

The Data Logger has been designed to help make measurements on components that have been shown to be troublemakers. These troublemakers may be spotted using the component data base at Loughborough.

Many different components can be measured using the Data Logger. The Data Logger is best measuring simple components.

The Data Logger has been used to take measurements for an experiment on accelerated life testing of ceramic capacitors. The results from this experiment has yielded information about the behaviour of ceramic capacitors and shown that the Data Logger is capable of being used as a research tool. This has lead to it being used for another bigger accelerated life testing experiment on opto-couplers. The Data Logger is now also used by other members of the Component Technology Research Group.

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4. CONCLUSIONS

4.1 DESIGN

The Data Logger was designed to measure discrete electronic components, to be used in a laboratory for research work. It has met these needs by drawing on available research tools and instruments. They have been combined together to produce a data logger. A trolley has been built to carry the hardware, and the switches were purchased to be used specifically with the Data Logger. The trolley provides space to hold the hardware, a flat top for a working space, and it is on castors so that it may be wheeled about the laboratory.

The Data Logger is a very flexible system. It can be used for a variety of applications (see section 4.3). Instruments which are IEEE compatible can be easily added or removed, as and when necessary.

The Data Logger runs from a 240 volt a.c. supply which is filtered from the mains to protect the sensitive computer and measuring equipment from surges and sudden variations in the supply. The IEEE-488 interface is used for the control of instruments. The interface is a fixed standard which is recognised worldwide and used extensively [1].

The IEEE interface and the use of a trolley make it very easy to tailor the Data Logger to a particular requirement as it is easy to change instruments around.

4.2 SOFTWARE

The software for the Data Logger has been written in Basic.

Basic was used for two reasons:

(i) It is easy to use as a development language, being very easy to alter and run a program and immediately alter again and re-run.

(ii) It was well understood by the author.

Unfortunately, using Basic means that a program will not run very fast. It is also very important that the software is well commented, otherwise it becomes difficult to understand. A large program written in Basic tends to be very difficult to follow and to write without making mistakes. It is also laborious to store the information from the Data Logger on an Apple format disc and then to have to transfer it to the IBM PC for analysis.

In order to solve these problems an IBM compatible personal computer is going to replace the Apple. It will use Pascal as a programming language. This means that the data stored by the Data Logger will be stored in IBM format. Pascal is a better language to use for an established system as it uses procedures. Procedures are like miniature programs. This suits the idea of having a library very well.

Apart from this the software has worked well. Measurement programs and simple analysis programs have been written using the library of software to cover several different applications of the Data Logger. This approach has shown itself to be simple, easy to use and can be applied to many different situations.

4.3 COMPONENT APPLICATION

The Data Logger has been used with a variety of different electronic components. It has worked well with all of them. Clearly it is best suited to taking simple measurements on large numbers of components that have just a few terminals, otherwise switching arrangements can become very complicated. It is not suited to very specialised measurements, for instance measurements at very high frequencies.

If a data logger were needed which was for a very specific purpose, then it would be possible to use the architecture and ideas incorporated into this Data Logger but using appropriate instruments and tailoring the necessary fine details.

The Data Logger has shown itself to be effective at laboratory measurements of large numbers of components. In this respect it does what was intended of it.

4.4 IMPROVEMENTS

Following from the initial design and development of the Data Logger, some improvements have been planned for the Data Logger.

The two major areas for improvement of the Data Logger are:

(i) Replacing the Apple IIe with a more powerful computer capable of being more directly compatible with the IBM PCAT.

(ii) Using a programming language other than Basic which would be faster and more efficient.

In order to achieve these aims an Advance 88d personal computer with an IEEE card is to replace the Apple IIe. The Advance is directly compatible with the IBM PCAT. Instead of using Basic as a control language Turbo Pascal will be used. Turbo Pascal is a compiled language and runs at a much faster pace. It also uses procedures which are called to execute different tasks. This makes it an ideal language for using with a library of existing software, especially in a mature system. The basic language has been useful to develop the Data Logger. Now this has been achieved a more sophisticated language can be used.

In terms of hardware there are no immediate improvements to be made. However, if measurements were needed that required a high degree of accuracy then a set of very low impedance switches could be useful. Apart from that there is little needed.

4.5 SUMMARY

The Data Logger has been assembled onto a trolley. It has used instruments that are all readily available, and they are all controlled to act as a Data Logger by the Apple IIe computer. Information is conveyed to various parts of the Data Logger over the IEEE-488 interface. The machine is programmed using the Basic computer language.

The Data Logger has been designed to measure discrete electronic components. It has been shown to be capable of this. It is most suitable for taking large numbers of very simple repetitive measurements.

An experiment on life testing of ceramic capacitors has taken place. This experiment used the Data Logger to locate failures. The experiment has provided information on those types of ceramic capacitors. It has also shown that the Data Logger is a useful research tool which has a practical use. The Data Logger is now being used for a larger experiment investigating the degradation of optocouplers.

It has been found that the Data Logger works effectively. The Data Logger is going to be improved. This will be achieved by replacing the Apple IIe with an IBM PC compatible computer, and by implementing a library of software which will need to be programmed in Turbo Pascal. This will mean that the Data Logger will work faster and be directly IBM compatible, which will speed up the analysis of results.

4.6 REFERENCES

1. T. R. Clune. 'Interfacing for Data Acquisition'. Byte, pp. 269-282 (February 1985).

APPENDIX 1

Automation Data Loggers Survey

Automation, pp. 36-43, October 1984.

automation DATA LOGGERS SURVEY

		Action Instruments Europe APAC	Advanced Instrumentation HR14	Advanced Instrumentation KET 512	Advanced Instrumentation KDD 32	Analogue Devices Macsym 150	Analogue Devices Macsym 350	Analogue Devices Micromac 5000	Ancom Scana 3000
Software	Logger is preprogrammed with essential software supplied (Key part 1)	●	●	●	●	—	—	—	●
	Programming language used by the logger (2)	c	bc	bc	c	c	c	c	—
	Logger is totally programmable by the user	●	●	●	●	●	●	●	—
	Data logging & analysis software is supplied (4)	●	●	●	●	—	—	—	●
Analogue	How many bits can the system resolve [illegible]	12	14	12/14/16	8/12/14/16	12	12/16	14	12
Logger Inputs	Basic number of analogue inputs (6)	376	4	16	8	192	512	12	8
	Basic number of digital inputs (7)	216	—	16	24 or 64	96	256	8	0
Expansion	How many expansion/slave units can be driven from the basic system (8)	—	16	a	a	15	14/[illegible]	6	—
	How far remote can the expansion unit be from the basic system (9)	—	1.8m	1.8m	1.8m	60m	60m	0.6m	—
Transducers/inputs that can be connected directly to the system	Number of types of thermocouple including cold junction compensation & linearisation (10)	120	□	□	□	□	□	8	6
	RTDs including linearisation? (11)	120	●	●	●	—	●	●	●
	Strain gauges? (12)	80	●	●	●	—	●	●	●
	Pulse counter inputs (15)	●	●	●	●	—	●	●	—
	Flow meters (16)	●	●	●	●	a	●	●	—
	Status (17)	●	●	●	●	—	●	●	—
	Event (18)	●	●	●	●	—	●	●	—
	BCD (19)	●	●	●	●	●	●	●	—
Technical specification	Accuracy of measurement	0.1%	±0.3%	±0.003 ±0.06%	0.005% ±1%	0.025%	0.024%	0.04%	0.1%
	What speed of logging and recording can be achieved (Channels per second)	250	4000+	1000-30,000	2-20,000	1000+	6000	50	20
Recording medium	Type of magnetic tape/disc used (22)	ae	e	e	e	—	—	—	—
	Separate reader or transfer unit available with RS232C interface	—	●	●	●	—	—	—	—
	System uses solid state recording	●	—	●	●	●	●	●	—
	Number of raw/processed readings that can be recorded using solid state	6k	8k	128k	8k	30k	30k	10k	—
	How many readings can be recorded with optional memory cards	50k	128k	350k	128k	94k	94k	12k	—
Interfaces	Logger interfaces (27)	ad	acd	acd	acd	ac	ac	ac	a
	Number of control outputs (28)	432dig 40An	8	16	24/64	96	256	8	—
	Number of outputs that can be used with the logger when using expansion/slave units (29)	—	128	160	512	3840	3840	136	—
Fault finding	System has self check mode or diagnosis programme	●	●	●	—	●	●	●	—
Cost	Cost of the basic system including all modules to store basic inputs, display, and relay via a RS232C interface	£4000	£1500+	£2500+	£500+	£7152	£10391	£2070	£1100
	Cost of input channel block (32)	£576 18 ch	a	a	a	£568An £289dig	£610	£182	—
Delivery	Delivery time for basic system (33)	0-6 wks	2-6 wks	2-6 wks	2-6 wks	6 wks	6 wks	8 wks	3 wks
Enquiries	For more information enter	500	501	502	503	504	505	506	507

Ancom Scana 5000	Astech DA80	Auriema (Kaye Instruments)	Auriema (Daytronic)	Canberra Imacs 50	Carel Acurex Autograph 700 & 800	Carel Acurex Autodata 10/50	Computing Techniques down hole data logger	Control & Readout CRL 703	Christie CD6	Christie CD248	Datron Logpac 2001	Digital Power 2000	Data & Research Services PDL7
●	●	9	●	●	●	●	●	●	●	●	●	—	●
b	bc	c	h	c	ch	ch	b	—	—	—	c	ehl	g
●	●	●	●	●	●	●	●	—	—	●	●	●	—
●	●	a	●	—	●	●	—	●	—	—	●	●	—
12	16	16	16	12	14	16	8	12	10	12	18	12	—
c	4096	16-48	1000	192	90	120	1	99	12	96	200	256b	1/2/8
c	1024	—	1000	432	90	120	—	—	6	96	—	256b	1/2
—	16	128	3	31	256	1000	—	—	—	—	1	256	—
—	100m	1km	1km	1km	1.5km	—	—	—	—	—	100m	3km	—
6	□	8	—	8	7	7	—	25	—	4	6a	6	—
●	●	2	—	5	3	3	—	4	—	1	1	8	—
●	●	—	—	2	—	1	±5v	□	—	—	2	4	—
b	●	●	1/card	18	●	●	—	—	20ma	0.1%	0-50 kHz	12	1/2
c	●	●	1/card	18	●	●	—	—	6	6	—	8	1/2
b	●	32	8/16	432	●	●	—	—	6	●	—	24	—
b	●	—	—	48	●	●	—	—	8	●	—	24	●
a	●	●	●	—	●	●	—	—	4	●	—	8	●
0.1%	0.005%	±0.003%	0.02%	0.1%	0.01%	0.01%	±0.5%	±0.25%	0.5%	0.1%	0.003%	0.05%	—
20	20	8	—	3000	60	60	—	10/ch	4	6	10	10k	—
—	bdef	f	f	ef	d	d	f	b	b	bg	ce	ef	f
—	—	●	—	—	●	●	●	●	●	●	●	●	●
—	—	—	●	●	●	●	●	—	—	—	—	●	●
—	4k	—	64k	30k	—	—	6k	—	—	—	—	8k	2716
—	64k	—	—	2	50k	50k	—	—	—	—	—	32k	—
acd	acd	ae	ac	ab	a	a	ac	ad	—	a	c	ad	—
16+	16An 1024dig	16	—	32	120	120	—	—	1	1	24	80	—
7256	16An 1024dig	48	a	72	120An 1000dig	120An 1000dig							
●	●	●	●	●	●	●	●	●	●	●	—	●	—
£3000+	£4000	£3600	£10-12k	£4500	£6000+	£6000+	£1200	£5k	£3k	£1470	£800	£2700	£1200
£250	£340	£500	£500	£830	£700	£700	a	£30/ch	150	£21/ch	300	260	—
8 wks	4 wks	4 wks	10-12 wks	12 wks	8-10 wks	8-10 wks	6-8 wks	12 wks	6-8 wks	4-6 wks	8 wks	8 wks	14 wks
508	509	510	511	512	513	514	515	516	517	518	519	520	521

automation DATA LOGGERS SURVEY

		Dyneer Technitron Tacit	Emerson Digitec Magnum PC	Emerson Digitec 1100	Euro Electronics Drawetz 2000	Field Electronics Digital Data Unit System	Fluke PTI/front end	Fluke 2383A/2393A	Fluke 2200B
Software	Logger is preprogrammed with essential software supplied (Key part 1)	●	●	—	●	●	●	●	●
	Programming language used by the logger (2)	h	ch	—	h	c	m	m	m
	Logger is totally programmable by the user	●	●	●	●	●	●	●	●
	Data logging & analysis software is supplied (4)	●	●	—	●	●	●	●	●
Analogue	How many bits can the system resolve	12/16	16	12	8	12	12	12	12
Logger Inputs	Basic number of analogue inputs (6)	32/mod		40	64b	1/8/16	20	20	60
	Basic number of digital inputs (7)	32/mod		—	64b	8	—	—	—
Expansion	How many expansion/slave units can be driven from the basic system (8)	b	110	—	1024	255	2	2	1
	How far remote can the expansion unit be from the basic system (9)	a	300m	—	—	1km	2m	2m	15m
Transducers/inputs that can be connected directly to the system	Number of types of thermocouple including cold junction compensation & linearisation (10)	4	9	7	—	5	11	11	4
	RTDs including linearisation? (11)	●		●	—	3	5	5	4
	Strain gauges? (12)	●		—	—	●	—	—	—
	Pulse counter inputs (15)	—	5kHz	—	—	●	—	—	—
	Flow meters (16)	—	5kHz	—	—	●	—	—	●
	Status (17)	—		—	●	●	—	—	—
	Event (18)	—		—	●	●	—	—	—
	BCD (19)	—	5	—	—	—	—	—	●
Technical specification	Accuracy of measurement	0.1%	±0.005%	±0.05%	—	±0.1%	—	—	0.01%
	What speed of logging and recording can be achieved (Channels per second)	2k	100	1	1k	10	0.5	0.5	12
Recording medium	Type of magnetic tape/disc used (22)	bcde	e	f	—	ef	—	—	g
	Separate reader or transfer unit available with RS232C interface	●	●	●	●	●	—	—	●
	System uses solid state recording	●	—	—	●	●	—	—	—
	Number of raw/processed readings that can be recorded using solid state	128k	—	—	—	4k	—	—	—
	How many readings can be recorded with optional memory cards	—	—	—	—	12k	—	—	—
Interfaces	Logger interfaces (27)	acd	acd	ac	—	a	acd	acd	acd
	Number of control outputs (28)	—	1000	—	—	2048	—	—	—
	Number of outputs that can be used with the logger when using expansion/slave units (29)						—	—	—
Fault finding	System has self check mode or diagnosis programme	●	●	—	●	—	●	—	—
Cost	Cost of the basic system including all modules to store basic inputs, display, and relay via a RS232C interface	£5-60k	£11k	£2.5k	£7-9k	£1700	£1600	£2800	£3200
	Cost of input channel block (32)	—	£50/ch	£15/ch	—	£520 8An £302 8dig	£280	£278	£210
Delivery	Delivery time for basic system (33)	12-16 wks	8 wks	6 wks	6-8 wks	3 wks.	6 wks	6 wks	6 wks
Enquiries	For more information enter	522	523	524	525	526	527	528	529

Fluke 2240C	Fluke 2280A	Fluke 2400B	Fluke 2452 MCS	Harlyn 3700	Hewlett Packard 3054A	Intercole Spectra	Instem Link-on 2100 stations	Intersil Datel Multidas	Keithley	Lucas Logic	Martron AD5312	Microdata M1682 SOLOG	Microdata M1600
●	●	●	—	—	●	●	—	—	●	a	●	●	●
m	h	f	co	—	c	cen	c	d	c	o	m	h	h
●	●	●	●	●	●	●	●	●	●	●	●	●	●
●	●	—	●	—	●	●	—	—	—	●	●	●	●
12	12	16	16	12	12/16	12/16	12	12/14/16	12/14	8	12	12	12
60	100	60	60	◇	100	256	16/s	4096	136/272	36	25	20	40
—	100	192	192	◇	80	832	24/s	72	160	144	—	20	40
8	15	10	10	—	8	4	16/1	10	—	—	—	—	2
15m	100m	1.2km	1.2km	—	25m	1km	1km	—	—	1.2km	—	—	1m
11	11	12	12	□	7	6	5	7	7	□	7	6	6
2	3	●	●	●	●	●	●	—	●	□	●	●	●
—	●	●	●	—	●	●	●	—	●	●	—		
—	●	●	●	●	●	●	●	72	●	●	—	●	●
●	●	●	●	●	—	●	●	72	●	●	—	●	●
—	●	●	●	●	●	●	●	72	—	●	—	●	●
—	●	●	●	—	●	●	●	72	●	●	—	●	●
●	●	●	●	●	—	●	●	72	●	●	—	●	●
0.01%	0.005%	0.002%	0.002%	◇	0.007%	0.025%	—	0.025%	0.038%	0.004%	0.03%	0.2%	±0.2%
12	20-70	25	257	◇	40	35	12	20k	500	60	[illegible]	50	80
g	d		e	—	e	e	g	ef	g	ef	f	f	c
●	●	●	●	—	—	—	—	●	◇	●	—	●	●
—	—	●	●	—	●	●	●	—	●	●	—	●	●
—	—	—	—	—	100	800	—	57k	53k	256k	—	4-16k	4-16k
—	—	32k	—	—	—	1200	—	77k	>500k	—	—	12-48k	8-32k
acd	acd	ac	acd	ac	ac	ac	a	acd	f	acd	ac	acd	ac
—	100	160	192	—		52	12	72	160	48	—	16	16
—	1500	1024	1024	—	1360	260	192	4096	—	192	—	—	32+
—	●	●	●	—	●	—	●	●	—	—	●	—	—
£5k	£5k	£4200	£12500	—	£9087	£3500	£400+	£8k	£3k	£10k	£1500	£3k	£6500
£210		£500	£500		£470	£350	£400+	£340	£300	£250	£300	—	
6 wks	6 wks	6 wks	6 wks	4-6 wks	10 wks	4-6 wks	4-6 wks	6-8 wks	4-6 wks	a	6 wks	4 wks	4 wks
530	531	532	533	534	535	536	537	538	539	540	541	542	543

automation DATA LOGGERS SURVEY

		Microtrol DLS 200	Microtrol DLS 20	Newport Electronics Pyroscan	Oxford Automation Flexilogga	PPM Compuscan	Process Measurement Systems Dataline 256	Pye Unicam PR2011	Rapco Rapllog
Software	Logger is preprogrammed with essential software supplied (Key part 1)	●	●	—	●	●	●	●	●
	Programming language used by the logger (2)	b	b	—	k	c	c	h	h
	Logger is totally programmable by the user	—	—	—	●	●	●	●	—
	Data logging & analysis software is supplied (4)	●	●	—	●	●	●	●	—
Analogue	How many bits can the system resolve?	12	12	12	12	12/16	12	12/16	8/12
Logger Inputs	Basic number of analogue inputs (6)	—	—	100	256	180	4096	256	16/32
	Basic number of digital inputs (7)	—	—	—	256	240	4096	512	16/32
Expansion	How many expansion/slave units can be driven from the basic system (8)	256	256	—	15	9	256	—	—
	How far remote can the expansion unit be from the basic system (9)	2km	2km	—	5km	100m	10km	—	—
Transducers/inputs that can be connected directly to the system	Number of types of thermocouple including cold junction compensation & linearisation (10)	5	5	9	5	8	7	5a	4
	RTDs including linearisation? (11)	2	2	●	●	●	●	●	●
	Strain gauges? (12)	a	a	—	—	●	●	●	●
	Pulse counter inputs (15)	—	a	—	●	●	●	●	●
	Flow meters (16)	b	b	—	●	●	●	●	●
	Status (17)	a	a	—	●	●	●	●	●
	Event (18)	a	a	—	●	●	●	●	●
	BCD (19)	a	a	—	●	●	●	●	●
Technical specification	Accuracy of measurement	0.25%	0.25%	—	0.1%	0.02%	½%	—	0.5%
	What speed of logging and recording can be achieved (Channels per second)	30	30	2	25.6	1-15	96	—	10
Recording medium	Type of magnetic tape/disc used (22)	e	—	f	e	bce	ef	b	e
	Separate reader or transfer unit available with RS232C interface	●	—	—	●	—	●	—	●
	System uses solid state recording	—	●	—	●	—	●	—	●
	Number of raw/processed readings that can be recorded using solid state	—	8k	—	—	—	—	—	60k
	How many readings can be recorded with optional memory cards	—	3200	—	—	—	—	—	250k
Interfaces	Logger interfaces (27)	acd	acd	—	a	ac	a	ac	ac
	Number of control outputs (28)	—		—	—	100/10	4096		—
	Number of outputs that can be used with the logger when using expansion/slave units (29)	192	192	—	—	1000/100	4096	—	—
Fault finding	System has self check mode or diagnosis programme	●	●	—	●	●	●	●	●
Cost	Cost of the basic system including all modules to store basic inputs, display, and relay via a RS232C interface	£13k	£1800	—	£10k	£5310	£15k	£2810	3-9k
	Cost of input channel block (32)	£190	£190	—	—	£230	£50	£905	—
Delivery	Delivery time for basic system (33)	12 wks	6 wks	4 wks	8 wks	4 wks	18 wks	6-8 wks	a
Enquiries	For more information enter	544	545	546	547	548	549	550	551

Rosemount Digitrend 235	Rosemount Dataport 236	Rosemount Dataport 277	Rosemount Minitrend 205	Rostol 1470	Seltek ADP 65	Seltek MDL 1000	Seltek MDP 82	Shawcity Molytek 2702	Sintrom Dian DMS 550/561A	Sintrom Omnilogger	Sintrom Micrologue	Solartron Orion	STC Keithley 192
●	●	●	●	●	●	●	●	●	●	●	●	●	—
b	◇	—	—	—	c	h	c	h	ac	a	b	c	—
●	●	—	●	●	●	●	●	●	●	●	●	●	●
●	—	—	—	●	●	●	●	—	—	●	●	—	—
16	16	16	12	8/16	12/16	12/16	12/16	8	12	12	8/12	16	—
100	100	40	36	16	60	50	30/mod	32	16/mod	5	8	600	1
96	96	—	—	16	300	64	64/mod	—	16/mod	—	—	200	—
5	5	8	—	20	5	5	19	[illegible]	14	—	—	[illegible]	—
1.5km	1.5km	1.5km	[illegible]	a	6m	6m	4km	[illegible]	4.6m	[illegible]	—	4m	—
9	9	7a	8	7	4	4	4	13	—	3	0	6	—
●	●	●	●	●	●	●	●	●	—	a	—	●	—
—	●	—	—	●	●	●	—	—	—	a	—	●	—
—	—	—	—	●	●	●	●	—	—	—	—	●	—
—	—	—	—	—	●	●	●	—	—	—	—	●	—
●	●	—	—	—	●	●	●	—	—	—	—	●	—
●	●	—	—	●	●	●	●	—	—	—	—	●	—
●	●	—	—	●	●	●	●	—	—	—	—	●	—
0.035%	0.035%	0.005%	0.25%	0.1-2%	0.05%	0.5%	0.05%	[illegible]	0.1%	2.5%	1%	0.005%	—
3-14	3-14	[illegible]	[illegible]	50	10	10	37	[illegible]	250k	[illegible]	—	10/40	—
—	—	—	—	ce	bc	b	—	—	—	f	e	c	—
—	—	—	—	—	●	●	—	—	—	—	—	●	—
—	—	—	—	●	●	—	◇	—	—	●	●	—	●
—	—	—	—	—	1000	1000	—	—	—	4k	8k	—	100
—	—	—	—	—	—	—	—	—	—	—	—	—	—
ac	a	a	a	ac	ac	acd	ac	a	ac	a	a	ac	c
—	—	—	—	8	156	16	30	—	64	—	—	200	—
64	64	—	—	16	156	16	600	—	>100	—	—	—	—
●	●	—	●	○	●	—	—	—	●	●	—	—	●
£3400	£2145	£1665	£2360	£1000+	£4536	£4500	£1400/mod	£2725	£1100	£410	£900	£5900	£1355
£850	£850	£850	£430	—	£241	£241	£1400/mod	—	£100	—	—	£440	—
2 wks	2 wks	2 wks	2 wks	8 wks	4 wks	4 wks	6 wks	4 wks	stock	2 wks	10 wks	12 wks	stock
552	553	554	555	556	557	558	559	560	561	562	563	564	565

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automation DATA LOGGERS SURVEY

		STC Thurlby 1905A	STC Iwatsu SC7501	Stonefield Omicrom Captain	Systematic Micro CR7	Systron-donner Minilogger Maxilogger	Tecquipment MA 1000/ UC15	Technitron Tacit III	Wellman Dlog 2
Software	Logger is preprogrammed with essential software supplied (Key part 1)	—	—	●	●	●	—	●	●
	Programming language used by the logger (2)	—	—	i	h	a	c	j	cd
	Logger is totally programmable by the user	●	●	●	●	●	●	●	●
	Data logging & analysis software is supplied (4)	—	—	●	●	●	●	●	—
Analogue	How many bits can the system resolve	—	—	12	16	12	12	12	12
Logger Inputs	Basic number of analogue inputs (6)	1	12	10	98	50	128	◇	10/20
	Basic number of digital inputs (7)	—	—	16	28	—	256	◇	—
Expansion	How many expansion/slave units can be driven from the basic system (8)	—	18	10Ana 16dig	1	10	32	◇	—
	How far remote can the expansion unit be from the basic system (9)	—		1.6km	8km	—	1.2km	2m	—
Transducers/inputs that can be connected directly to the system	Number of types of thermocouple including cold junction compensation & linearisation (10)	—	5	100	4	6	128	◇	—
	RTDs including linearisation? (11)	—	—	●	●	●	●	◇	—
	Strain gauges? (12)	—	—	—	●	—	□	◇	—
	Pulse counter inputs (15)	—	—	50	●	—	128	◇	—
	Flow meters (16)	—	—	●	—	—	128	◇	—
	Status (17)	—	—	●	—	—	256	◇	—
	Event (18)	—	—	●	—	—	256	◇	—
	BCD (19)	—	—	●	—	—	256	◇	—
Technical specification	Accuracy of measurement	—	—	0.1%	0.02%	±0.05%	0.01%	0.01%	0.1%
	What speed of logging and recording can be achieved (Channels per second)	—	—	100	100	96	200	10k	1
Recording medium	Type of magnetic tape/disc used (22)	—	f	abcd	a	b	e	de	e
	Separate reader or transfer unit available with RS232C interface	●	●	●	●	●	●	—	—
	System uses solid state recording	●	—	—	●	●	●	●	◇
	Number of raw/processed readings that can be recorded using solid state	100	—	—	6k	100	65k	12k	◇
	How many readings can be recorded with optional memory cards	—	—	—	10k	1k	374k	◇	◇
Interfaces	Logger interfaces (27)	c	c	a	a	acd	acd	acd	◇
	Number of control outputs (28)	—	—	256	—	—	256	◇	◇
	Number of outputs that can be used with the logger when using expansion/slave units (29)	—	—	256	—	—	—	◇	◇
Fault finding	System has self check mode or diagnosis programme	—	—	●	●	—	●	●	—
Cost	Cost of the basic system including all modules to store basic inputs, display, and relay via a RS232C interface	£325	£2750	£1000	£6000	£3095	£2000+	£10k+	£350
	Cost of input channel block (32)	—	—	£200-£2500	£500	£133	£100-£400	£1500	—
Delivery	Delivery time for basic system (33)	stock	stock	8 wks	4-6 wks	10-12 wks	4 wks	16-20 wks	4-6 wks
Enquiries	For more information enter	566	567	568	569	570	571	572	573

[illegible] DATA LOGGERS SURVEY

Action Instruments
St James Works
St Pancras, Chichester
West Sussex
Tel: 0243 774022

Advanced Instrumentation Systems (AIMS)
400 Woodstock Rd
Oxford
Tel: 0685 511484

Analog Devices
Central Avenue
East Molesey, Surrey
Tel: 01 941 0466

Ancom
Devonshire St
Cheltenham
Tel: 0242 513861

Astech Electronics
73 Castle St
Farnham, Surrey
Tel: 0252 725585

Auriema
442 Bath Rd
Slough, Berks
Tel: 06286 4353

Canberra Instruments
5 Pioneer Rd
Faringdon, Oxford
Tel: 0367 20868

Carel Components
24 Endeavour Way
London
Tel: 01 946 9882

Computing Techniques
Brookes Rd
Billingshurst,
West Sussex
Tel: 0403 813171

Control & Readout
Goring by Sea
Worthing, West Sussex
Tel: 0903 502599

Cristie Electronics
Rodney Hse
Church St
Stroud, Gloucestershire
Tel: 04536 79821

Datron Instruments
Hurricane Way
Norwich
Tel: 0603 404824

Digital Power Ltd
34 3rd Avenue
Hove, Sussex
Tel: 0273 727073

DRS Data & Research
14/16 Kilnfarm Ind. Estate
Milton Keynes
Tel: 0908 567114

Dyneer Technitron
Doman Rd
Camberley, Surrey
Tel: 0276 26517

Emerson Electronic Equipment
6c Furlong Rd
Bourne End, Bucks
Tel: 06285 28944

Euro Electronics
Twynan Hse
31 Camden Rd
London
Tel: 01 267 5416

Field Electronics
Gill Hse
Conway St
Hove, East Sussex
Tel: 0273 724361

Fluke (GB)
Colonial Way
Watford, Herts
Tel: 0923 40511

Harlyn Automation
27 North St
Congleton, Cheshire
Tel: 026 023099

Hewlett Packard
9 Mile Rd
Wokingham, Berks
Tel: 0344 773100

Instem Computer Systems
Walton Industrial Estate
Stone, Staffs
Tel: 0785 812131

Intercole Systems
Avenger Close
Chandlers Ford Ind. Estate
Eastleigh, Hampshire
Tel: 04215 4727

Intersil Datel
Belgrave Hse
Basing View,
Basingstoke
Tel: 0256 69085

Keithley Instruments
1 Boulton Rd
Reading, Berks
Tel: 0734 861287

Lucas Logic
Welton Rd
Wedgnock Ind. Estate
Warwick
Tel: 0926 59411

Martron
Park St
Princes Risborough,
Bucks
Tel: 08444 4321

Microdata
Monitor Hse
Station Rd
Radlett, Herts
Tel: 09276 3333

Microtrol
11 Church St
Kidderminster, Worcs
Tel: 0562 742244

Newport Electronics
Maxwell Rd
Stevenage
Tel: 0438 65671

Oxford Automation
Lakelands North
Milton Keynes, Bucks
Tel: 0908 613691

PPM Instrumentation
Hermitage Rd
St Johns
Woking, Surrey
Tel: 04867 80111

Process Measurement Systems
Holmethorpe Industrial Estate
Redhill, Surrey
Tel: 0737 713355

Pye Unicam
York Rd
Cambridge
Tel: 0223 358866

Rapco
10 Joule Rd
Basingstoke, Hants
Tel: 0256 25454

Rosemount Engineers
Heath Place
Durban Rd
Bognor Regis,
West Sussex
Tel: 0243 863121

Rostol
Liysons Avenue
Ash Vale
Aldershot, Hants
Tel: 0252 512469

Seltek Instruments
High St
Stanstead Abbots, Herts
Tel: 0920 871094

Shawcity
Units 12/13 Pioneer Rd
Faringdon, Oxon
Tel: 0367 21675

Sintrom Electronics
14 Arkwright Rd
Reading, Berks
Tel: 0734 8564

Solartron
124 Victoria Rd
Farnborough, Hants
Tel: 0252 544433

STC
West Rd
Harlow, Essex
Tel: 0279 29522

Stonefield
13 Demme Parade
Horsham, West Sussex
Tel: 0403 51366

Systematic Micro
Index Hse
Ascot, Berks
Tel: 0990 23377

Systron Donner
St Mary's Rd
Leamington Spa
Warwicks
Tel: 0926 35411

Tecquipment
Bonsall St
Long Eaton, Nottingham
Tel: 0602 721696

Technitron
Doman Rd
York Town Ind. Estate
Camberley, Surrey
Tel: 0276 26517

Wellmen Microtechnology
Roberts Hse
Cornwal Rd
Warley, West Midlands
Tel: 021 565 2766

DATA LOGGER SURVEY EXPLANATORY KEY

1. Is logger preprogrammed with essential software supplied?
a Optional

2. Programming language used by the logger:
a ASCII
b Assembler
c Basic
d Pascal
e Fortran
f Highlevel
g Machine code
h Menu driven
i Micro Vera
j Microcode
k PLM
l ASM80
m Push button
n Other
p Optional

4. Is data logging & analysis software supplied?
a Optional

6. Total number of analogue inputs in the basic system:
a As required
b Analogue plus digital

7. Total number of digital inputs in the basic system:
a As required
b Analogue plus digital

8. How many expansion/slave units can be driven from the basic system?
a Various
b Unlimited

9. How far remote can the expansion unit be from the basic system?
a Not answered

10. Number of types of thermocouple including cold junction compensation & linearisation:
a Plus customized fits

11. RTDs including linearisation:
a any

12. Strain gauges including excitation voltage:
a To special order
b Any

15. Pulse counter inputs
a Available to special order
b As required

15. Flow meters
a Digital or BCD outputs
b Available to special order
c As required

16. Status
a Available to special order
b As required

18. Event
a Available to special order
b As required

19. BCD
a As required

22. Type of magnetic tape/disc
a Audio cassette
b ECMA34
c ECMA46
d DC100A
e Floppy disc
f Other
g External

27. Logger interfaces
a RS232C/V24
b RS422
c GPIB/IEEE 488
d parallel
e 20mA loop
f IBM bus

28. How many control outputs may be used with the logger?
a Expandable

29. Number of outputs that can be used with the logger when using expansion/slave units:
a Any number if analogue channel capability not exceeded

32. Cost of input channel block:
a No extra cost

33. Delivery time for basic system
a Varies

ABBREVIATIONS

● Yes	Analogue	Ana
— No/not applicable	Digital	Dig
□ All	Relay	Rel
◇ User specified function	Per Card	/Card
	Per Module	/Mod
	Per channel	/Ch

APPENDIX 2

GENERIC DESCRIPTION OF COMPONENTS

CAPACITORS

Aluminium, foil

Aluminium foil, solid electrolyte

Aluminium, sintered, solid electrolyte

Tantalum, foil

Tantalum, sintered, solid electrolyte

Tantalum, sintered, liquid electrolyte

Mica, metallised

Mica, foil

Mica, button

Ceramic multilayer

Ceramic disc

Ceramic barrier layer

Glass

Paper, foil

Paper, metallised

Paper, foil and plastics

Paper, metallised and plastics

	Polystyrene, foil
	Polyester (PTP), foil
	Polyester (PTP), metallised
	Polycarbonate, foil
	Polycarbonate, metallised
	Polypropylene, foil
	Polypropylene, metallised
(variable)	Tuning/Trimmer
	Preset

RESISTORS

(a) FIXED	Carbon
	Carbon film
	Carbon ceramic
	Metal Oxide
	Wirewound
	Metal foil
	Metal film
	Thick film
	Conducting plastic
	Cermet thin film
	Tantalum nitride film

Networks of thick film resistors

Networks of thin film resistors

(b) VARIABLE — Carbon

Carbon film

Metal oxide

Wirewound

Metal foil

Metal film

Thick film

Conducting plastic

(c) NON LINEAR — Thermistors (-ve temp. coeff.)

Thermistors (+ve temp. coeff.)

Varistors

Strain gauges

Pressure transducers

<u>TRANSFORMERS</u>

Transformers

Air cored transformers

Pulse transformers

INDUCTORS

Air cored inductor

Loaded inductor

PASSIVE MICROWAVE

DEVICES

Wave guides)
)   TRANSMISSION
Strip lines)
)   LINES
Micro strip)

Couplers

Attenuators

Isolators)
)
Circulators) FERRITES
)
Phase shifters)

Filters

Cavities

Microwave switches

CONNECTORS

(non-permanent)

Rectangular

Edge

Cylindrical

Optical fibre

RELAYS

Coil activated

Coil activated/mercury wetted

Reed

SWITCHES

Push button

Rocker

Keyboard

Rotary

Proximity

DISCRETE SEMICONDUCTORS

(a) DIODES

pn Junction

Varactors

Avalanche

Tunnel

Impatt

Shottkey barrier

Gunn

PIN

(b) TRANSISTORS

Bipolar

JFET

MOSFET enhancement

MOSFET depletion

CCD

MESFET

(c) OPTOELECTRONIC DEVICES

Photosensitive diodes

L.E.Ds

Displays

Optoisolators

INTEGRATED CIRCUITS

To be classified in the following 5 categories

(a) BIPOLAR

This group to contain all TTL, DTL, ECL and TIL devices

(b) MOS

To include all metal oxide semiconductor microcircuits which includes NMOS, CMOS and MNOS fabricated on various substrates such as sapphire, polycrystalline or single crystal silicon.

(c) BIPOLAR/MOS

To include combinations (if any) of both groupings

(d) JFET

To include any JFET Logic circuits

(e) MESFET

To include any GaAs microcircuit devices

HYBRID SUBSYSTEMS

All hybrid subsystems

APPENDIX 3

RELIABILITY DEFINITIONS

Reliability

The ability of an item to perform a required function under stated conditions for a stated period of time.

Redundancy

The existence of more than one means for accomplishing a given function. Each means of accomplishing the function need not necessarily be identical.

Failure

The termination of the ability of an item to perform a required function.

Observed Failure Rate

For a stated period in the life of an item, the ratio of the total number of failures in a sample to the cumulative observed time in that sample. The observed failure rate is associated with particular and stated time intervals (or summation of intervals) in the life of an item, and under stated conditions.

Observed Mean Time to Failure

For a stated period in the life of an item, the ratio of the cumulative time for a sample to the total number of failures in the sample during the period under stated conditions.

APPENDIX 4

THE WEIBULL DISTRIBUTION AND WEIBULL ANALYSIS

The Weibull distribution was developed by the Swedish scientist Waloddi Weibull who used it to describe the breaking strength of materials and the life properties of ball bearings [1]. He published papers on its application in the 1940's and 1950's [2]. The distribution is used widely in reliability as it is suitable for modelling to a variety of situations involving catastrophic failures [3].

A.4.1. Statistical Basis of the Distribution

The Weibull distribution function is described in terms of the reliability function as:

$$R(t) = 1 - F(t) = e^{-\left(\frac{t - t_o}{\eta - t_o}\right)^{\beta}} \tag{1}$$

where

$F(t)$: the cumulative distribution function

β : the shape parameter

η : the characteristic lifetime

t_o : the time location parameter

t : time

This expression can be transformed into the two parameter Weibull distribution by using the transformation $t := t - t_o$, $:= - t_o$ giving:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (2)$$

and

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (3)$$

Differentiating (3) we get the probability density function, f(t).

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (4)$$

and the hazard rate, h(t) is

$$h(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \qquad (5)$$

Manipulating (2) we get

$$\ln\ln\left[\frac{1}{1 - F(t)}\right] = \beta\ln(t) - \beta\ln\eta \qquad (6)$$

If the lifetimes are Weibull distributed then plotting the results on Weibull paper, where the ordinates are scaled in accordance with (6), will yield a straight line. Comparing (6) with the equation

$$\eta = mx + c \qquad (7)$$

we can see that the gradient is equivalent to β and that η corresponds to the time t for when $F(t) = 62.3\%$.

In lifetesting the lifetimes of components are measured and a cumulative distribution is formulated. It is important that the data is ranked (1) in order to compare the sample of results with the whole population. This is achieved using the median rank formula which states:

$$\hat{F}(t) \cong \frac{i - 0.3}{n + 0.4} .100\% \qquad (8)$$

where $\hat{F}(t)$: best estimate of $F(t)$ for the whole population

i : rank of component

n : total size of sample

A.4.2 Two Examples of the Use of the Weibull Distribution

Two examples are used here to illustrate how the Weibull distribution can be used to estimate characteristic lifetimes and to interpret these graphs. Both examples are hypothetical but typical of results from lifetesting.

Example 1

In this example 20 components are tested and times to failüre (t.t.f.) are recorded as in Figure A.4.1.

n	t.t.f. (hours)	Rank Order (%)
1	24	3.43
2	70	8.33
3	120	13.2
4	160	18.1
5	230	23.0
6	280	27.9

Fig. A.4.1 Results from Lifetest on 20 Components

The rank order is calculated from equation (8). These results are then plotted on Weibull paper, Figure A.4.2. From the graph in Figure A.4.2 we can draw a straight line through the points plotted, this indicates the data is Weibull distributed. It is now possible to estimate η, the characteristic life of these components and β the Weibull shape parameter.

The characteristic lifetime is estimated by extrapolating the line drawn through the data points so that it is possible to estimate the age at failure for a 62.9% cumulative failure, this age is called the characteristic life η. For these components $\eta \cong 900$ hours.

The Weibull shape parameter β, which determines the shape of the Weibull curve (see equations (1) and (2)), is estimated by calcu-lating the gradient of the graph. On some graph paper there is an estimation point. A tangent to the line through the data is drawn

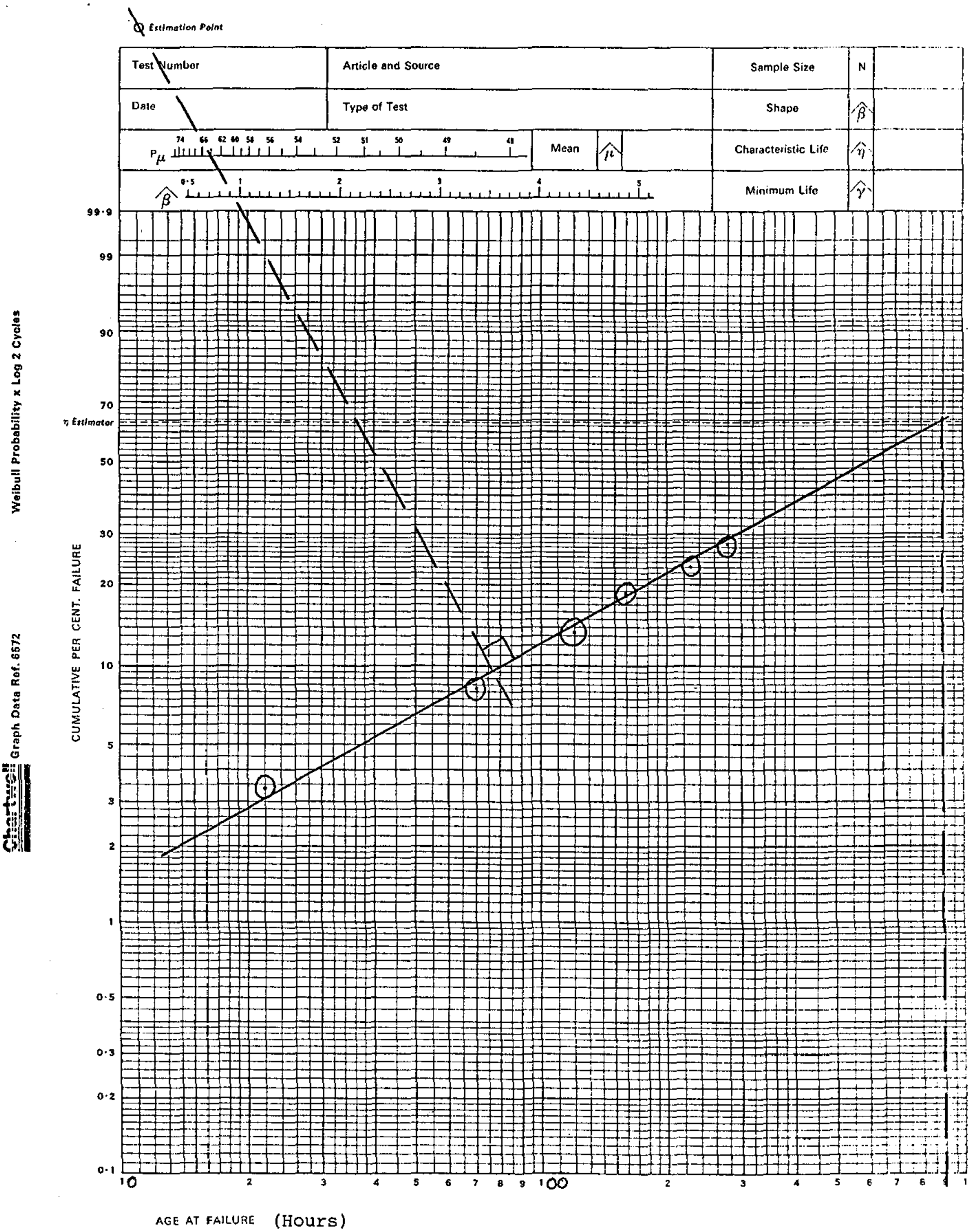

Fig. A4.2 Weibull Plot of Results from Lifetest on 20 Components which passes through the estimation point. β is read off a scale. For these components $\beta \cong 0.9$.

Example 2.

In this example 100 components are tested and times to failure are recorded as in Figure A.4.3. Once again the rank order is calculated from equation (8) and the results are then plotted on Weibull paper, Figure A.4.4.

When the data is plotted it is immediately apparent that the data does not easily fit to a single straight line. This is because there is more than one distribution within the data. (For a classic example of this see 'Behind the "Bathtub" Curve, a New Model and Its Consequences' by J. Møltoft [4]).

n	t.t.f. (hours)	Rank Order (%)
1	20	0.697
2	33	1.69
3	42	2.69
4	47	3.68
5	84	4.68
6	93	5.67
7	102	6.67
8	107	7.66
9	108	8.66
10	110	9.66

Fig. A.4.3. Results from Lifetest on 100

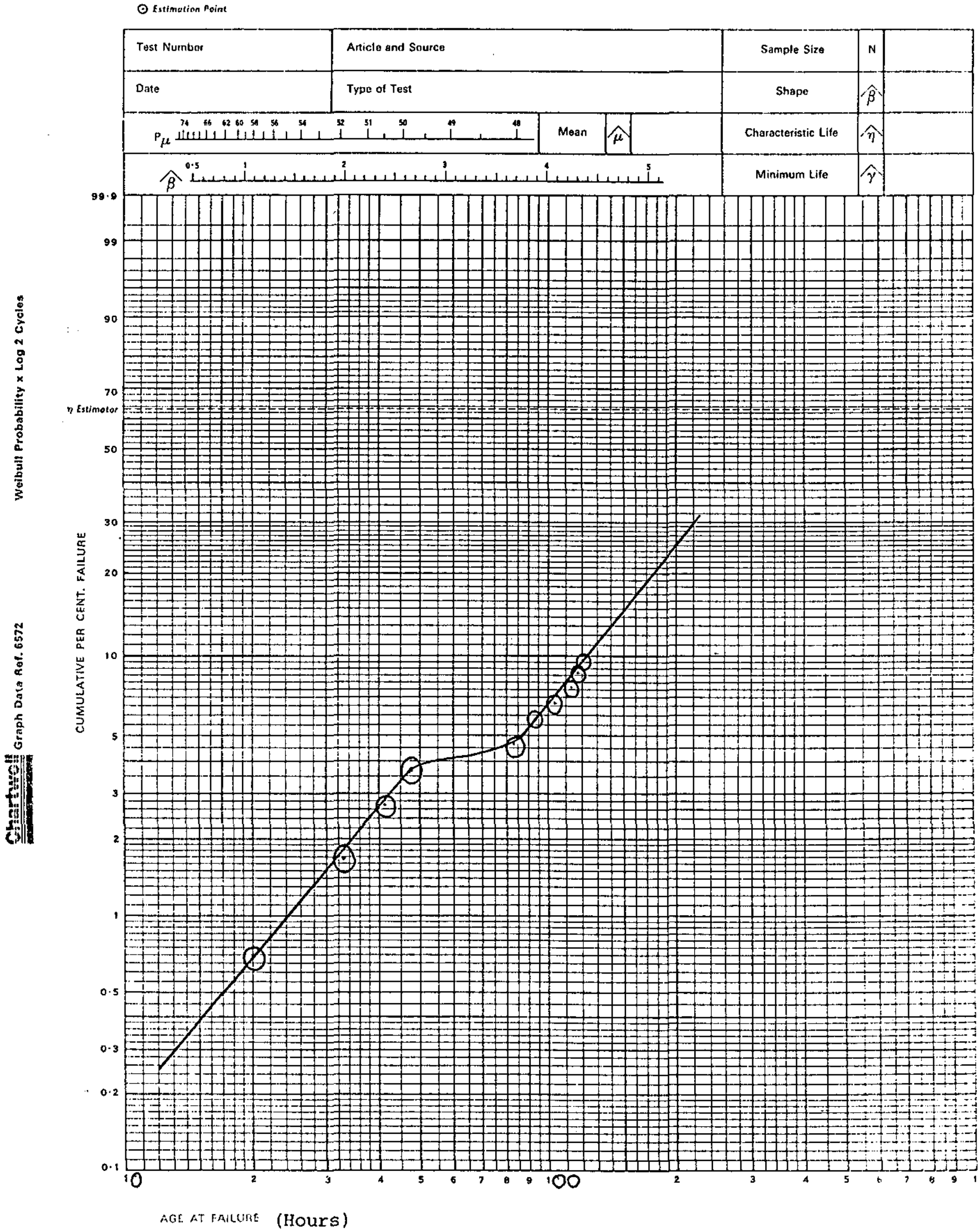

Fig. A4.4 Weibull Plot of Results from Lifetest on 100 Components

The graph shows an 'S' shape characteristic of two distributions. The data can be split up into two separate Weibull distributions [4]. The physical significance of an 'S' shape result is that in the sample under test there are two different batches of components, with different failure rates and characteristic lifetimes. This could correspond to a weak population of components within a normally strong population.

REFERENCES AND FURTHER READING

1. F. Jensen and N. E. Petersen. 'Burn In', Pub. Wiley, London (1982).

2. W. J. Weibull. 'Statistical Distribution Function of Wide Application'. J. App. Mechanics, Vol. 18, pp. 293-297 (1951).

3. M. Shooman. 'Probabilistic Reliability: An Engineering Approach', Pub. McGraw-Hill, New York (1968).

4. J. Møltoft. 'Behind the "Bathtub" Curve a New Model and Its Consequences'. Microelectron. Reliab., Vol. 23, No. 3, pp. 489-500 (1983).

APPENDIX 5

Software - Listings of Data Logger Programs

```
1  REM  RELAY CONTROL
2  PRINT
3  PRINT
4  HOME
5  VTAB 6: HTAB 15
6  PRINT " RELAY CONTROL "
7  VTAB 8: HTAB 1
8  PRINT " THIS PROGRAM CAN BE USED TO CONTROL"
9  PRINT "THE RELAYS WITHIN THE SWITCHING BOXES"
10  PRINT "INDIVIDUALLY"
15  PRINT
16  PRINT
100  REM  SET UP
110 D$ = "": REM  CTRL-D
120 Z$ = "": REM  CTRL-Z
121  PRINT "WHICH BOX"
122  INPUT BN: IF BN > 8 THEN  GOSUB 1000: IF BN > 10 THEN  GOTO 121
123 LA$ =  CHR$ (32 + BN): REM  LISTEN ADDRESS
131 LA$ = LA$ + Z$
132  PRINT
140  PRINT
150  PRINT "INSTRUCTION?"
160  INPUT A$
200  GOSUB 9900
299  PRINT
300  PRINT
301  PRINT "ANOTHER BOX"
302  INPUT A$
303  IF A$ = "N" THEN  GOTO 700
304  PRINT
305  PRINT
306  GOTO 100
700  HOME
710  VTAB 12
715  FLASH
720  PRINT "RETURNING TO MAIN MENU"
721  NORMAL
730  PRINT D$;"RUN HELLO"
1000  PRINT ""
1001  IF BN = 9 THEN  GOTO 1005
1002  IF BN = 10 THEN  GOTO 1010
1003  PRINT "THERE ARE ONLY 10 BOXES"
1004  PRINT "1-8 ARE FOR SWITCHING;9 AND 10 ARE CONTROL": RETURN
1005  PRINT "THIS IS THE CONTROL BOX"
1006  PRINT "ARE YOU SURE YOU WISH TO ALTER THIS?"
1007  INPUT Y$
1008  IF Y$ = "Y" THEN  RETURN
1009  GOTO 1
1010  PRINT "THIS BOX CONTROLS THE POWER SUPPLIES"
1011  PRINT "ARE YOU SURE YOU WANT TO CONTINUE?"
1012  INPUT N$
1013  IF N$ = "Y" THEN  RETURN
1014  GOTO 1
9900  REM  SEND A$ TO SWIB
9901  PRINT D$;"PR#4"
9930  PRINT "RM";LA$
9940  PRINT "WT";LA$;A$
9950  PRINT D$;"PR#0"
9955  PRINT D$;"IN#0"
9960  RETURN
```

RELAY CONTROL

```
100  REM  IEEE SWIB2
101  REM
102  REM
103  REM   L  IS A LOCAL VARIABLE, USED IN THE SUBROUTINES.
104  REM
105  REM
110 D$ = "": REM  CTRL-D
120 Z$ = "": REM  CTRL-Z
130 NB = 10: REM  NUMBER OF BOXES
140 NR = NB * 32: REM  NUMBER OF RELAYS
150  DIM LA$(NB): REM  LISTEN ADDRESSES FOR BOXES
160  DIM R%(NR): REM  STATES OF THE RELAYS
170  REM  IF R%=1 THEN RELAY IS ON
180  REM  IF R%=0 THEN RELAY IS OFF
200  FOR BN = 1 TO NB: REM  SET UP BOX ADDRESSES
210 LA$(BN) =  CHR$ (32 + BN) + Z$: REM  CHARS STARTING AT "!", I.E. HEX 2
    1
220  NEXT BN
230 BL$(0) = "D":BL$(1) = "F":BL$(2) = "H":BL$(3) = "L": REM  BLOCK CODES
240 LB$ = "4"
250 TB$ = "T"
260 LB$ = LB$ + Z$
270 TB$ = TB$ + Z$
331 LA$ = ">" + Z$
340 TA$ = "P": REM  TALK ADDRESSES FOR DVM
341 TA$ = "^" + Z$
345  GOTO 1200
350  PRINT "WHAT IS THE NAME OF THE OUTPUT FILE"
360  INPUT F$: REM  OUTPUT FILE NAME
370  PRINT D$;"OPEN ";F$
9000  REM  TURN ON RELAY J IN ADDITION TO OTHERS
9010 R%(J) = 1
9020  GOSUB 9300
9030  RETURN
9100  REM  TURN OFF ONLY RELAY J, OTHERS UNALTERED
9110 R%(J) = 0
9120  GOSUB 9300
9130  RETURN
9200  REM  TURN ON ONLY RELAY J, OTHERS OFF
9210  GOSUB 9500: REM  RESET ALL RELAYS
9220 R%(J) = 1
9230  GOSUB 9300
9240  RETURN
9300  REM  SET RELAY J
9305 BL% = (J - 1) / 8: REM  BLOCK NUMBER STARTING AT 0
9310 B% = BL% / 4: REM  BOX NUMBER STARTING AT 0
9315 S% = BL% * 8 + 1: REM  START OF THE BLOCK OF EIGHT RELAYS
9320 BL% = BL% - 4 * B%: REM  LOCAL BLOCK NUMBER 0..3
9325 C1% = 0:C2% = 0
9330  FOR L = 3 TO 0 STEP  - 1
9331  REM  SET UP HEX CODES FOR THE RELAY PATTERN IN THE BLOCK.
9335 C1% = C1% * 2 + R%(S% + L)
9340 C2% = C2% * 2 + R%(S% + L + 4)
9345  NEXT L
9350 A$ = BL$(BL%) +  CHR$ (C1% + 48) +  CHR$ (C2% + 48)
9351  REM  INSTRUCTION TO BE SENT TO SWIB
9355 BN = B% + 1: REM  BOX NUMBER STARTING AT 1
9360  GOSUB 9900: REM  SEND A$ TO BOX BN
9370  RETURN
```

<u>SUBROUTINES</u>

```
9400  REM  SET UP ELECTROMETER FOR RESISTANCE (USES SAME ADDRESS AS DVM)
9405  PRINT D$;"PR#4"
9410  PRINT "CL";LA$
9415  PRINT "RM";LA$
9420  PRINT "WT";LA$;"F2D0X"
9425  PRINT D$; PR# 0
9427  RETURN
9430  REM  MEASURE WITH ELECTROMETER
9435  PRINT D$;"PR#4"
9440  PRINT D$;"IN#4"
9445  PRINT "RD";TA$;Z$;: INPUT "";A$
9450  PRINT D$;"PR#0"
9455  PRINT D$;"IN#0"
9460  PRINT A$
9465  RETURN
9500  REM  RESET ALL RELAYS
9510  FOR L = 1 TO NR
9515 R%(L) = 0
9520  NEXT L
9530  PRINT D$;"PR#4"
9540  FOR L = 1 TO NB
9550  PRINT "RM";LA$(L)
9560  PRINT "WT";LA$(L);"DFHL00"
9565  NEXT L
9570  PRINT D$;"PR#0"
9580  PRINT D$;"IN#0"
9590  RETURN
9600  REM  CLEAR ALL DEVICES
9610  PRINT D$;"PR#4"
9615  PRINT "SC1"
9620  PRINT "CA"
9630  PRINT D$;"PR#0"
9640  RETURN
9700  REM  WRITE A$ INTO THE FILE
9710  PRINT D$;"WRITE ";F$
9720  PRINT A$
9730  PRINT D$: REM  CANCELS WRITE
9740  RETURN
9750  REM  INIT DVM & SET RANGES TO OHMS
9755  PRINT D$;"PR#4"
9760  PRINT "CL";LA$
9765  PRINT "RM";LA$
9770  PRINT "WT";LA$;"M1R0T1"
9775  PRINT D$;"PR#0"
9780  RETURN
9800  REM  TAKE A READING INTO A$
9810  PRINT D$;"PR#4"
9820  PRINT D$;"IN#4"
9840  PRINT "RM";LA$
9850  PRINT "TG";LA$
9860  PRINT "RD";TA$
9870  INPUT A$
9875  PRINT D$;"PR#0"
9876  PRINT D$;"IN#0"
9880  RETURN
9900  REM  SEND A$ TO BOX NUMBER BN
9910  PRINT D$;"PR#4"
9920  PRINT "RM";LA$(BN)
9930  PRINT "WT";LA$(BN);A$
9940  PRINT D$;"PR#0"
9950  PRINT D$;"IN#0"
9960  RETURN
```

```
5  DIM A$(200): DIM A(200)
10 D$ = ""
20  DATA  "AFOR","BFOR","CFOR","D
     FOR","EFOR","FFOR","GFOR","H
     FOR","IFOR","JFOR"
22  DATA  "ACTR","BCTR","CCTR","D
     CTR","ECTR","FCTR","GCTR","H
     CTR","ICTR","JCTR"
24  DATA  ASAT,BSAT,CSAT,DSAT,ESA
     T,FSAT,GSAT,HSAT,ISAT,JSAT
28  PRINT
30  READ F$: PRINT F$
40  PRINT D$;"OPEN";F$
50  PRINT D$;"READ";F$
60  INPUT A$
70  FOR I = 1 TO  VAL (A$)
80  INPUT A$(I)
90  NEXT I
100  PRINT D$;"CLOSE";F$
110  PRINT "LOWER LIMIT ON DATA I
     S 0.05"
120 MN = .05
130  PRINT "UPPER LIMIT ON DATA I
     S 6.00"
140 MAX = 6
150  FOR I = 1 TO  VAL (A$)
160 A(I) =  VAL (A$(I))
165  NEXT I
170 N = 1
180  FOR I = 1 TO  VAL (A$)
190  IF A(I) < MN THEN 230
200  IF A(I) > MAX THEN 230
210 A(N) = A(I)
220 N = N + 1: GOTO 240
230  PRINT "OUT OF RANGE",I,A(I)
240  NEXT I
250 N = N - 1
260 SUM = 0: REM  CALC MEAN
270  FOR I = 1 TO N
280 SUM = SUM + A(I)
290  NEXT I
300 MEAN = SUM / N
310  PRINT "MEAN IS ",MEAN
320 SUM = 0: REM  CALC SD
330  FOR I = 1 TO N
340 SUM = SUM + ((A(I) - MEAN) ^
     2)
350  NEXT I
360 VAR = SUM / (N - 1)
370 SD = VAR ^ .5
380  PRINT "SD IS ",SD
390  GOTO 28
```

<u>MEANSD</u>

```
5  DIM A$(200)
10 D$ = ""
20  PRINT "INPUT FILENAME"
30  INPUT F$
40  PRINT D$;"OPEN";F$
50  PRINT D$;"READ";F$
60  INPUT A$
70  FOR I = 1 TO  VAL (A$)
80  INPUT A$(I)
90  NEXT I
100  PRINT D$;"CLOSE";F$
110  FOR I = 1 TO  VAL (A$)
120  PRINT A$(I)
130  NEXT I
140  END
```

<u>FILEREAD</u>

```
50  ONERR  GOTO 6000
100  HOME : VTAB 12
110  PRINT " BEFORE USING THIS PR
     OGRAM IT IS "
120  PRINT "NECCESARY TO BOOT THE
      DISC,THIS WILL BE"
130  PRINT "DONE AUTOMATICALLY IF
      REQUIRED"
140  NORMAL
150  FOR K = 1 TO 1000
160  REM  WAIT
170  NEXT K
180 T =  PEEK (116) * 256 +  PEEK
     (115)
190  IF T = 34235 THEN  GOTO 270
200  FLASH : VTAB 20: PRINT "BOOT
     ING THE DISC"
210  PRINT : PRINT "ENSURE DISC I
     N DRIVE ONE": NORMAL
220 D$ = "": REM  CTRL-D
230  PRINT D$;"PR#6"
240  REM  WAIT
250  NEXT G
260  FLASH
270  VTAB 20: PRINT "THE PROGRAM
     WILL RUN WITHOUT BOOTING"
280  NORMAL
290  FOR G = 1 TO 1000
300  REM  IEEE SWIB2
310  DIM ME$(10): REM  DIMENSION
     ME$ AS 10
320  DIM P$(10): REM  DIM FILE AD
     DITIVE
330  REM   L  IS A LOCAL VARIABLE
     , USED IN THE SUBROUTINES.
340  DIM F$(10): REM  DIMENSION F
     ILE NAMES
350  REM
360  DIM WHOLE$(10): REM  STRING
     FOR BRIDGE"
370 D$ = "": REM  CTRL-D
380 Z$ = "": REM  CTRL-Z
390 NB = 09: REM   NUMBER OF BOXE
     S
400 NR = NB * 32: REM  NUMBER OF
     RELAYS
410  DIM LA$(NB): REM  LISTEN ADD
     RESSES FOR BOXES
420  DIM R%(NR): REM  STATES OF T
     HE RELAYS
430  REM  IF R%=1 THEN RELAY IS O
     N
440  REM  IF R%=0 THEN RELAY IS O
     FF
450  FOR BN = 1 TO NB: REM  SET U
     P BOX ADDRESSES
460 LA$(BN) =  CHR$ (32 + BN) + Z
     $: REM  CHARS STARTING AT "!
     ", I.E. HEX 21
470  NEXT BN
480 BL$(0) = "D":BL$(1) = "F":BL$
     (2) = "H":BL$(3) = "L": REM
      BLOCK CODES
490 LB$ = "4"
500 TB$ = "T"
510 LB$ = LB$ + Z$
520 TB$ = TB$ + Z$
530 LA$ = ">" + Z$
540 TA$ = "P": REM  TALK ADDRESSE
     S FOR DVM
550 TA$ = "^" + Z$
560  GOSUB 2240: REM  RESET RELAY
     S
570  HOME : FLASH : VTAB 12
580  PRINT " ENSURE THAT THERE IS
      A DATA DISC IN"
590  PRINT "DRIVE 2 TO RECIEVE DA
     TA"
600  NORMAL
610  FOR K = 1 TO 2500
620  REM  WAIT
630  NEXT K
640  HOME
650  PRINT
660  PRINT " MEASUREMENT OF CERAM
     IC CAPACITORS"
670  VTAB 6
680  PRINT " THIS PROGRAM MEASURE
     S UP TO 10 SPECIFIC"
690  PRINT "ASPECTS OF THE 120 CE
     RAMIC CAPACITORS"
700  PRINT "AND WRITES THE DATA T
     O A FILE LABELED"
710  PRINT "WITH THE NATURE OF TH
     E DATA"
715  VTAB 23: HTAB 35: PRINT "CER
     AM*"
716  VTAB 11: HTAB 1
720  PRINT "HOW MANY CAPACITORS":
      INPUT D
730  IF D > 256 GOTO 2490
740  HOME :M = M + 1
750  PRINT "====================
     ================="
760  PRINT
770  PRINT "ENTER ONE OF THE FOLL
     OWING MEASUREMENT"
780  PRINT "CODES AFTER THE PROMP
     T "
790  VTAB 9: HTAB 10: PRINT "PARA
     METER": HTAB 29: VTAB 9: PRINT
      "CODE"
800  VTAB 10: HTAB 10: PRINT "---
     ---------------------------"
810  HTAB 10: PRINT "RESISTANCE"
820  VTAB 11: HTAB 30: PRINT "R;"
830  HTAB 10: PRINT "CAPACITANCE"
840  VTAB 12: HTAB 30: PRINT "C;"
850  HTAB 10: PRINT "INDUCTANCE"
860  VTAB 13: HTAB 30: PRINT "L;"
870  HTAB 10: PRINT "DISSIPATION"
880  VTAB 14: HTAB 30: PRINT "D;"
```

CERAM*

```
890  HTAB 10: PRINT "Q FACTOR"
900  VTAB 15: HTAB 30: PRINT "Q;"
     : PRINT
910  PRINT "ALSO ENTER SERIES(SE;
     ) OR PARALLEL(PA;)"
915  PRINT "FREQUENCY RANGE CAN A
     LSO BE SELECTED"
916  PRINT "ENTER SELECTED FREQ A
     S PART OF INPUT"
917  PRINT "IF D OR Q SELECTED FO
     RMAT IS "
918  PRINT "C;D; OR L;Q;"
930  PRINT
940  PRINT "ENTER CODE NOW
950  INPUT WHOLE$(M)
960 ME$(M) =  LEFT$ (WHOLE$(M),5)

970  HOME : VTAB 12
980  PRINT "DO YOU WANT TO MAKE A
     NOTHER MEASUREMENT"
990  INPUT Y$: IF Y$ = "Y" THEN  GOTO
     740
1000  HOME : VTAB 12
1010  PRINT "DO YOU WANT TO NAME
     THIS FILE"
1020  PRINT "DEFAULT WILL STORE I
     T AS CAP 'STRING'!"
1030  INPUT Y$
1040  IF Y$ = "Y" THEN  GOTO 1080

1050  GOSUB 1700: REM  READ TIME
     FROM CLOCK
1060 G$ = "CAP" + T$
1070  GOTO 1100
1080  PRINT "NAME OF FILE"
1090  INPUT G$
1100  FOR U = 1 TO M
1110  IF ME$(U) = "C;SE;" THEN P$
     (U) = "CAPSER"
1120  IF ME$(U) = "C;PA;" THEN P$
     (U) = "CAPPAR"
1130  IF ME$(U) = "R;SE;" THEN P$
     (U) = "RESSER"
1140  IF ME$(U) = "R;PA;" THEN P$
     (U) = "RESPAR"
1150  IF ME$(U) = "L;SE" THEN P$(
     U) = "INDSER"
1160  IF ME$(U) = "L;PA;" THEN P$
     (U) = "INDPAR"
1170  IF ME$(U) = "C;D;" THEN P$(
     U) = "DISSIP"
1180  IF ME$(U) = "L;Q;" THEN P$(
     U) = "QFACT"
1210 F$(U) = G$ + " " + P$(U) + "
     ,D2"
1220  PRINT D$;"OPEN";F$(U)
1230 F$(U) = G$ + " " + P$(U)
1240  NEXT U
1250  HOME : VTAB 12: PRINT "MEAS
     UREMENT PROCEEDING--PLEASE W
     AIT"
1260 CO = 0: REM  START MEASUREME
     NT HERE
1270  FOR U = 1 TO M
1280 J = 0
1290  FOR K = 1 TO D:J = J + 1
1300  IF J = 31 THEN J = 33
1310  IF J = 63 THEN J = 65
1320  IF J = 95 THEN J = 97
1330  IF J = 127 THEN J = 129
1340  IF J = 159 THEN J = 161
1350  IF J = 191 THEN J = 193
1360  IF J = 223 THEN J = 225
1370  IF J = 255 THEN  GOTO 1580
1380 B$ = WHOLE$(U)
1390 A = J:J = 270: GOSUB 2030:J =
     A
1400  GOSUB 1950: REM  RELAY ON
1410 A = J:J = 270: GOSUB 1990:J =
     A
1420 N = N + 1
1425  IF J = 1 THEN  GOSUB 6300
1430  GOSUB 1770: REM  INIIT AND
     MEASURE
1440 C = C + 1: IF C = D THEN C =
     0
1450  VTAB 18: HTAB 10: PRINT "NU
     MBER DONE SO FAR:-"
1460  VTAB 20: HTAB 10: PRINT "ME
     ASUREMENT "U
1470  VTAB 20: HTAB 24: PRINT "CO
     MPONENT "C" "
1480  VTAB 22: HTAB 10: PRINT "NU
     MBER REMAINING "(M * D) - N"
     "

1490  GOSUB 1840: REM  READING TO
     A$
1500 DA$ = A$ + " " + ME$(U)
1510  PRINT D$;"WRITE"F$(U): REM
     WRITE TO FILE
1520  PRINT DA$
1530  PRINT D$: REM  CANCELS WRIT
     E
1540  GOSUB 1990
1550  NEXT K
1560  NEXT U
1570  HOME : VTAB 12
1580  PRINT " MEASUREMENTS COMPLE
     TE---RUN LOOKCER TO"
1590  PRINT "READ DATA"
1600  FOR U = 1 TO M
1610  PRINT D$;"CLOSE";F$(U)
1620  NEXT U
1630  PRINT
1640  PRINT "DATA STORED IN FILES
     :-"
1650  FOR U = 1 TO M
1660  PRINT F$(U)
1670  NEXT U
1680  GOSUB 2520
1690  PRINT D$;"LOCK CERAM,D1"
1695  END
```

CERAM* (continued)

```
1700  REM  TEMPORAL INFO TO T$
1710  PRINT D$;"IN#1"
1720  PRINT D$;"PR#1"
1730  INPUT T$
1740  PRINT D$;"IN#0"
1750  PRINT D$;"PR#0"
1760  RETURN
1770  REM  INIT BRIDGE AND MEASUR
     E
1780  PRINT D$;"PR#4"
1790  PRINT "CL";LB$
1800  PRINT "RM";LB$
1810  PRINT "WT";LB$;B$
1820  PRINT D$;"PR#0"
1830  RETURN
1840  REM  TAKE READING TO A$
1850  PRINT D$;"PR#4"
1860  PRINT D$;"IN#4"
1870  PRINT "RM";LB$
1880  PRINT "TG";LB$
1890  PRINT "RD";TB$
1900  INPUT A$
1910  PRINT "LO";LB$
1920  PRINT D$;"PR#0"
1930  PRINT D$;"IN#0"
1940  RETURN
1950  REM  TURN ON
1960 R%(J) = 1
1970  GOSUB 2080
1980  RETURN
1990  REM  TURN OFF ONLY RELAY J,
      OTHERS UNALTERED
2000 R%(J) = 0
2010  GOSUB 2080
2020  RETURN
2030  REM  TURN ON ONLY RELAY J,
     OTHERS OFF
2040  GOSUB 2240: REM  RESET ALL
     RELAYS
2050 R%(J) = 1
2060  GOSUB 2080
2070  RETURN
2080  REM  SET RELAY J
2090 BL% = (J - 1) / 8: REM  BLOC
     K NUMBER STARTING AT 0
2100 B% = BL% / 4: REM  BOX NUMBE
     R STARTING AT 0
2110 S% = BL% * 8 + 1: REM  START
      OF THE BLOCK OF EIGHT RELAY
     S
2120 BL% = BL% - 4 * B%: REM  LOC
     AL BLOCK NUMBER 0..3
2130 C1% = 0:C2% = 0
2140  FOR L = 3 TO 0 STEP  - 1
2150  REM  SET UP HEX CODES FOR T
     HE RELAY PATTERN IN THE BLOC
     K.
2160 C1% = C1% * 2 + R%(S% + L)
2170 C2% = C2% * 2 + R%(S% + L +
     4)
2180  NEXT L
2190 A$ = BL$(BL%) +  CHR$ (C1% +
     48) +  CHR$ (C2% + 48)
2200  REM  INSTRUCTION TO BE SENT
      TO SWIB
2210 BN = B% + 1: REM  BOX NUMBER
      STARTING AT 1
2220  GOSUB 2420: REM  SEND A$ TO
      BOX BN
2230  RETURN
2240  REM  RESET ALL RELAYS
2250  FOR L = 1 TO NR
2260 R%(L) = 0
2270  NEXT L
2280  PRINT D$"PR#4"
2290  FOR L = 1 TO NB
2300  PRINT "RM";LA$(L)
2310  PRINT "WT";LA$(L);"DFHL00"
2320  NEXT L
2330  PRINT D$;"PR#0"
2340  PRINT D$;"IN#0"
2350  RETURN
2360  REM  CLEAR ALL DEVICES
2370  PRINT D$;"PR#4"
2380  PRINT "SC1"
2390  PRINT "CA"
2400  PRINT D$;"PR#0"
2410  RETURN
2420  REM  SEND A$ TO BOX NUMBER
     BN
2430  PRINT D$;"PR#4"
2440  PRINT "RM";LA$(BN)
2450  PRINT "WT";LA$(BN);A$
2460  PRINT D$;"PR#0"
2470  PRINT D$;"IN#0"
2480  RETURN
2490  PRINT "THAT IS TOO GREAT "
2500  PRINT "RESTART PROGRAM"
2510  END
2520  REM  SET UP NAME STORE
2530  PRINT "ADD THESE FILENAMES
     TO NAME STORE?"
2540  INPUT Y$
2550  IF Y$ = "N" THEN  GOTO 1690

2560  PRINT "ADDING FILES TO NAME
      STORE"
2570  PRINT D$;"OPEN NAMESTORE,L3
     6"
2575  GOSUB 2639
2579 H = 1
2580  FOR Y = S TO S + (U - 2)
2590 U$ =  STR$ (D)
2600 F$(H) = F$(H) + "      " + U$
2610  PRINT D$;"WRITE NAMESTORE,R
     ";Y
2620  PRINT F$(H)
2625 H = H + 1
2630  NEXT Y
2633  PRINT D$;"CLOSE NAMESTORE"
2635  RETURN
2639  REM  READ INPUT DATA
2700  PRINT D$;"OPEN NAMESTORE,L3
     6"
2701  HOME : PRINT "HAS NAMESTORE
      BEEN CREATED BEFORE": INPUT
      Y$: IF Y$ = "N" THEN  GOSUB
      5000
```

CERAM* (continued)

```
2710  PRINT D$;"READ NAMESTORE,R0
"
2720  INPUT A$
2730 A =  VAL (A$)
2735 S = A
2740 A = A + M
2750 A$ =  STR$ (A)
2760  PRINT D$;"WRITE NAMESTORE,R
0"
2770  PRINT A$
2790  RETURN
5000  REM  SET UP USABLE NAMESTOR
E
5005 J$ = "1"
5010  PRINT D$;"WRITE NAMESTORE,R
0"
5020  PRINT J$
5025  RETURN
6000  REM  ERROR CATCH
6010  HOME : PRINT "============
=========================="
6030  VTAB 5: HTAB 20: FLASH : PRINT
 "ERROR": NORMAL
6031  PRINT : PRINT : PRINT : PRINT
 : PRINT
6032  PRINT ""
6035 Q =  PEEK (218) + 256 *  PEEK
(219)
6036 C =  PEEK (222)
6040  PRINT "ERROR AT LINE "Q
6050  PRINT "ERROR CODE IS "C" TH
IS CAN BE FOUND IN"
6060  PRINT "RELEVANT REFERENCE M
ANUUALS"
6070  POKE 216,0
6080  PRINT "HIT RETURN TO RESTAR
T AFTER CHECKING BUS"
6090  GET H$
6095  ONERR  GOTO 6000
6100  GOTO 7000
6200  END
6300  REM  SWITCH BOUNCE CHECK
6310 J = 2: GOSUB 1990:J = 1
6320  RETURN
7000 D$ = "": REM  CTRL-D
7001  PRINT D$
7002  PRINT D$;"RUN CERAM*,D1"
```

CERAM* (continued)

```
1  ONERR  GOTO 500
2  HOME
3  PRINT
4  PRINT "THIS PROGRAM CAN BE USED TO READ DATA "
5  PRINT "COLLECTED BY THE CERAM PROGRAM"
6  PRINT
7  PRINT
10 D$ = "": REM  CTRL D
11  PRINT " OUTPUT TO SCREEN(SC) OR PRINTER(PR)"
12  INPUT P$
13  PRINT "WHICH DISC DRIVE CONTAINS DATA"
14  INPUT DD: IF DD = 1 THEN  GOTO 17
15  IF DD = 2 THEN  GOTO 17
16  PRINT "OUT OF RANGE ERROR": GOTO 13
17  PRINT D$;"SAVEQ,D";DD
20  INPUT "NAME OF TEXT FILE?";Z$
30  PRINT "HOW MANY COMPTS ARE THERE"
40  INPUT N
45  IF P$ = "PR" THEN  PRINT D$;"PR#1"
50  PRINT D$;"OPEN";Z$
60  PRINT D$;"READ";Z$
70  FOR I = 1 TO N
80  INPUT A$
85 B$ = A$
90  PRINT I"     "B$
100  NEXT I
110  PRINT D$;"CLOSE";Z$
111  IF P$ = "PR" THEN  PRINT D$;"PR#0"
120  PRINT D$;"DELETE Q,D";DD
125  PRINT "ON WHICH DRIVE IS SYSTEM DISC"
126  INPUT OD: IF OD > 2 THEN  GOTO 125
130  PRINT D$;"SAVEQ,D";OD
140  PRINT D$;"DELETEQ,D";OD
145  END
500  HOME : VTAB 12: HTAB 15: PRINT "ERROR"
501  PRINT : PRINT : PRINT : PRINT "PRESS ANY KEY TO RESTART:
502  GET Y$
503  POKE 216,0
504  GOTO 2
```

LOOKCER

```
5  REM  GREETINGS PROGRAM CALLED
   HELLO
6 D$ = "": REM  CTRL D
10  VTAB 12
20  PRINT "FOR USE WITH SWIB SYST
    EM FOR MEASUREMENT OF COMPON
    ENTS"
30  FOR T = 1 TO 1000
35  NEXT T
40  PRINT D$;"MAXFILES 10"
41  HOME : VTAB 12: FLASH
42  PRINT "NO. OF I/O BUFFERS SET
     TO TEN"
43  FOR T = 1 TO 2000
44  NEXT T
46  NORMAL
50  PRINT D$;"RUN INFORMATION"
60  END
```

HELLO

```
100  REM  THIS PROGRAM IS CALLED
     WATCH THE CLOCK
110 D$ = "": REM  CTRL-D
120  REM  TEMPORAL READINGS TO TI
     ME$
130  PRINT D$;"IN#1"
140  PRINT D$;"PR#1"
150  INPUT TIME$
160  PRINT D$;"IN#0"
170  PRINT D$;"PR#0"
180  FOR T = 1 TO 25
190 TIME$ =  RIGHT$ (TIME$,17)
200  IF TIME$ = T$(T) THEN  GOTO
     270: IF TIME$ = TV$(T) THEN
      GOTO 300
210  NEXT T
220  HOME : VTAB 12: HTAB 15: PRINT
     "TIME IS "TIME$
230  VTAB 5: HTAB 15: INVERSE : PRINT
     "DO NOT SWITCH OFF"
240  VTAB 19: HTAB 15: PRINT "DO
     NOT SWITCH OFF"
250  NORMAL
260  GOTO 100
270  HOME : VTAB 12: PRINT "MEASU
     REMENTS PROCEEDING"
280  PRINT D$;"BLOAD CHAIN,A520"
290  CALL 520"AUTOCERAM"
300  HOME : VTAB 12: PRINT "VOLTA
     GE BEING STEPPED UP"
310  PRINT D$;"BLOAD CHAIN,A520"
320  CALL 520"CHANGE VOLTAGE"
330  END
```

WATCH THE CLOCK

```
1  REM  THIS PROGRAM IS CALLED IN
   FORMATION
3  REM  DIMENSIONS OF ARRAYS AND
   VARIABLES
5  DIM T$(25): DIM TV$(25): REM
   T$=MEAS. TIMES , TV$=CHANGE
   VOLTAGE TIMES
10  DIM WHOLE$(10)
15  DIM P$(10)
16  DIM ME$(10)
17  DIM DA$(25)
18  DIM F$(10)
19  DIM R%(320)
20  DIM LA$(10)
21  DIM VOLTS$(10)
100  REM  PROGRAM FOR TIMED SWITC
     HING
110 D$ = "": REM  CTRL-D
120  HOME : VTAB 2
130  PRINT "PROGRAM FOR TIME CONT
     ROL OF CERAM"
140  FOR W = 1 TO 1000
150  REM  WAIT
160  NEXT W
170  HOME : VTAB 12
200  REM  MEASUREMENT TIMES , E.G
     . T$(N)="11/27/84 14;19;56"
201 T$(1) = "12/18/84 12;09;00"
202 T$(2) = "12/16/84 10;00;00"
250  REM  VOLTAGE TIMES , SAME FO
     RMAT AS ABOVE
251 TV$(1) = "..............."
280  REM  MEAS. TO BE MADE , E.G.
      WHOLE$(N)="C;PA;"
281 WHOLE$(1) = "C;PA;"
282 WHOLE$(2) = "R;PA;"
283 WHOLE$(3) = "C;D;"
300 D = 120: REM   NO. OF CAPACI
     TORS
310 M = 3: REM  NO. OF PARAMETERS

330  NORMAL
340  PRINT D$;"BLOAD CHAIN,A520"
350  CALL 520"WATCH THE CLOCK"
360  END
```

INFORMATION

```
100  REM   L  IS A LOCAL VARIABLE
     , USED IN THE SUBROUTINES.
110  REM
120 D$ = "": REM  CTRL-D
130 Z$ = "": REM  CTRL-Z
140 NB = 09: REM   NUMBER OF BOXE
    S
150 NR = NB * 32: REM  NUMBER OF
    RELAYS
160  REM  IF R%=1 THEN RELAY IS O
    N
170  REM  IF R%=0 THEN RELAY IS O
    FF
180  FOR BN = 1 TO NB: REM  SET U
    P BOX ADDRESSES
190 LA$(BN) =  CHR$ (32 + BN) + Z
    $: REM  CHARS STARTING AT "!
    ", I.E. HEX 21
200  NEXT BN
210 BL$(0) = "D":BL$(1) = "F":BL$
    (2) = "H":BL$(3) = "L": REM
     BLOCK CODES
220 LB$ = "4"
230 TB$ = "T"
240 LB$ = LB$ + Z$
250 TB$ = TB$ + Z$
260 LA$ = ">" + Z$
270 TA$ = "P": REM  TALK ADDRESSE
    S FOR DVM
280 TA$ = "^" + Z$
290  GOSUB 820: REM  READ TIME FR
    OM CLOCK
300 G$ = "CAP" + T$
310  FOR U = 1 TO M
320 ME$(U) =  LEFT$ (WHOLE$(U),5)

330  IF ME$(U) = "C;SE;" THEN P$(
    U) = "CAPSER"
340  IF ME$(U) = "C;PA;" THEN P$(
    U) = "CAPPAR"
350  IF ME$(U) = "R;SE;" THEN P$(
    U) = "RESSER"
360  IF ME$(U) = "R;PA;" THEN P$(
    U) = "RESPAR"
370  IF ME$(U) = "L;SE" THEN P$(U
    ) = "INDSER"
380  IF ME$(U) = "L;PA;" THEN P$(
    U) = "INDPAR"
390  IF ME$(U) = "Q;SER;" THEN P$
    (U) = "QFACSE"
400  IF ME$(U) = "Q;PA" THEN P$(U
    ) = "QFACPA"
410  IF ME$(U) = "C;D;" THEN P$(U
    ) = "DISSIP"
420  IF ME$(U) = "L;Q;" THEN P$(U
    ) = "QFACT"
430 F$(U) = G$ + " " + P$(U)
440  PRINT D$;"OPEN";F$(U)
450 C = 0
460  IF ME$(U) = "C;PA;" THEN  GOSU
     1650
470  IF ME$(U) = "C;SE;" THEN  GOSU
     1650
480  NEXT U
490  FOR U = 1 TO M
500  FOR K = 1 TO D:J = J + 1
510  IF J = 31 THEN J = 33
520  IF J = 63 THEN J = 65
530  IF J = 95 THEN J = 97
540  IF J = 127 THEN J = 129
550  IF J = 159 THEN J = 161
560  IF J = 191 THEN J = 193
570  IF J = 223 THEN J = 225
580  IF J = 255 THEN  GOTO 760
590 B$ = WHOLE$(U)
600 A = J:J = 270: GOSUB 1150:J =
     A
610  GOSUB 1070: REM  RELAY ON
620 A = J:J = 270: GOSUB 1110:J =
     A
630 N = N + 1
635 J = K
640  IF J = 1 THEN  GOSUB 1690
650  GOSUB 890: REM  INIIT AND ME
     ASURE
660  GOSUB 960: REM  READING TO A
     $
670 CA =  VAL (A$): REM  REMOVE S
     TRAYS
680 CA = CA - C
690 A$ =  STR$ (CA)
700 DA$ = A$ + " " + ME$(U)
710  PRINT D$;"WRITE ";F$(U): REM
      WRITE TO FILE
720  PRINT DA$
730  PRINT D$: REM  CANCELS WRITE

740  GOSUB 1110
750  NEXT K
755 J = 0
760  NEXT U
770  FOR U = 1 TO M
780  PRINT D$;"CLOSE";F$(U)
790  NEXT U
800  GOTO 1610
810  END
```

AUTOCERAM

```
10  REM  THIS PROGRAM IS CALLED "
     CHANGE VOLTAGE"
15  REM  INCREASES VOLTAGE UNTIL
     JUST ABOVE REQUIRED LEVEL
20 U = 0
30 U = U + 1
40  GOSUB 7900
50  GOSUB 9800
60 PU2 = 1
70  IF TV(U) >  VAL (A$) THEN 30
80 PU2 = PU2 + 1
90  GOSUB 6035
100 BN = 10: GOSUB 9900
110  GOSUB 9800
120  IF  VAL (A$) < TV(U) THEN 15
    0
130  GOTO 80
150  PRINT D$;"BLOAD CHAIN,A520"
160  CALL 520"WATCH THE CLOCK"
170  END
6035  REM  CONVERTS REAL NO PU2 I
     NTO STRING (MUST LIE BETWEEN
      0 AND 99.99)
6040 V% = PU2
6041 V = V%:W = PU2 * 100
6042 W% = W
6043 W = W%
6044 W = W - (V * 100)
6050 V$ =  STR$ (V):W$ =  STR$ (W
    )
6064  IF  LEN (V$) = 1 THEN V$ =
    "0" + V$
6065  IF  LEN (V$) = 0 THEN V$ =
    "00"
6066  IF  LEN (W$) = 1 THEN W$ =
    "0" + W$
6067  IF  LEN (W$) = 0 THEN W$ =
    "00"
6070 A$ = "D07F85H" + V$ + "L" +
    W$
6071 BN = 10
6075  RETURN
6080  REM  READS DVM AND CONVERTS
     TO A REAL NO. RES
6090  GOSUB 9800: REM  DVM RESD I
    NTO A$
6100 RES$ =  RIGHT$ (A$,14)
6110 RES =  VAL (RES$)
6120  RETURN
7900  REM  INITIALISE DVM AND SET
     RANGES
7901  PRINT D$;"PR#4"
7920  PRINT "CL";LA$
7930  PRINT "RM";LA$
7940  PRINT "WT";LA$;"M0R0T1"
7950  PRINT D$;"PR#0"
7960  RETURN
```

CHANGE VOLTAGE

```
1   HOME
2   PRINT
3   PRINT
4   PRINT
5   PRINT "MEASUREMENT OF OPTOCOUP
     LERS"
6   PRINT
7   PRINT
8   CLEAR
9   DIM COM(192): REM   RELAY COMB
     INATIONS
10  FOR I = 1 TO 64
11  READ COM(I)
12  NEXT I
13  DATA  1,2,10,11,3,4,12,13
14  DATA  5,6,14,15,7,8,16,25
15  DATA  17,18,26,27,19,20,28,29

16  DATA  21,22,30,31,23,24,32,41

17  DATA  33,34,42,43,35,36,44,45

18  DATA  37,38,46,47,39,40,48,57

19  DATA  49,50,58,59,51,52,60,61

20  DATA  53,54,62,63,55,56,64,9
21  FOR I = 65 TO 128
22 J = I - 64
23 COM(I) = COM(J) + 64
24  NEXT I
25  FOR I = 129 TO 192
26 J = I - 128
27 COM(I) = COM(J) + 128
28  NEXT I
100  REM  IEEE SWIB2
101  REM
102  REM
103  REM   L  IS A LOCAL VARIABLE
     , USED IN THE SUBROUTINES.
104 Q = 1
105 P = 0
110 D$ = "": REM  CTRL-D
120 Z$ = "": REM  CTRL-Z
130 NB = 7
140 NR = NB * 32: REM  NUMBER OF
     RELAYS
150  DIM LA$(NB): REM  LISTEN ADD
     RESSES FOR BOXES
160  DIM R%(NR): REM  STATES OF T
     HE RELAYS
170  REM  IF R%=1 THEN RELAY IS O
     N
180  REM  IF R%=0 THEN RELAY IS O
     FF
200  FOR BN = 1 TO NB: REM  SET U
     P BOX ADDRESSES
210 LA$(BN) =  CHR$ (32 + BN) + Z
     $: REM  CHARS STARTING AT "!
     ", I.E. HEX 21
220  NEXT BN
230 BL$(0) = "D":BL$(1) = "F":BL$
     (2) = "H":BL$(3) = "L": REM
      BLOCK CODES
240 LB$ = "4"
250 TB$ = "T"
260 LB$ = LB$ + Z$
270 TB$ = TB$ + Z$
331 LA$ = ">" + Z$
340 TA$ = "P": REM  TALK ADDRESSE
     S FOR DVM
341 TA$ = "^" + Z$
350  PRINT "WHAT IS THE NAME OF T
     HE OUTPUT FILE"
360  INPUT F$: REM  OUTPUT FILE N
     AME
370  PRINT D$;"OPEN ";F$
1501  PRINT
1502  PRINT
1503  PRINT "  PLEASE ENSURE THAT
      ALL EQUIPMENT IS SWITCHED O
     N, ESPECIALLY SWITCHING BOXE
     S AND POWER SUPPLIES. IF NOT
     , SWITCH OFF MAINS SUPPLY, S
     WITCH ON DEVICES, SWITCH ON
     MAINS AND RESTART PROGRAMME.
     "
1504  PRINT "
            PLEASE ENTER THE NUM
     BER OF OPTOCOUPLERS TO BE TE
     STED"
1505  INPUT N
1506  PRINT
1507  PRINT "PLEASE NOTE ERRORS S
     ET AT 0.01 FOR V(F)"
1508  PRINT
1510  IF N > 256 THEN  GOTO 9999
1600  PRINT D$;"WRITE";F$
1610  PRINT N
1620  PRINT D$
2000  REM  Vf for N optoisolators

2005  GOSUB 9500: REM  RESETS REL
     AYS
2070  GOSUB 7900: REM GET DVM REA
     DY
2080  FOR Z = 1 TO N: REM  TAKE R
     EADINGS
2085 J = Z * 2
2087 J = COM(J)
2090  GOSUB 9000
2095 J = (2 * Z) - 1
2097 J = COM(J)
2100  GOSUB 9000
2105  GOSUB 9800
2107 A$ =  MID$ (A$,4)
2110  GOSUB 9700
2115  GOSUB 9100
2120 J = Z * 2
2123 J = COM(J)
2125  GOSUB 9100
2130  NEXT Z
2250  GOSUB 9500: REM  CLOSING DO
     WN
2255  PRINT D$;"CLOSE";F$
2260  HOME
2261  VTAB 12: FLASH
2262  PRINT " RETURNING TO MAIN M
     ENU"
2263  NORMAL
2264  PRINT D$;"RUN MENU,D1"
```

FOR VOLTA

```
1  HOME
2  PRINT
3  PRINT
4  PRINT
5  PRINT "MEASUREMENT OF OPTOCOUP
     LERS"
6  PRINT
7  PRINT
8  CLEAR
9  DIM COM(192): REM  RELAY COMBI
     NATIONS
10  FOR I = 1 TO 64
11  READ COM(I)
12  NEXT I
13  DATA  1,2,10,11,3,4,12,13
14  DATA  5,6,14,15,7,8,16,25
15  DATA  17,18,26,27,19,20,28,29

16  DATA  21,22,30,31,23,24,32,41

17  DATA  33,34,42,43,35,36,44,45

18  DATA  37,38,46,47,39,40,48,57

19  DATA  49,50,58,59,51,52,60,61

20  DATA  53,54,62,63,55,56,64,9
21  FOR I = 65 TO 128
22 J = I - 64
23 COM(I) = COM(J) + 64
24  NEXT I
25  FOR I = 129 TO 192
26 J = I - 128
27 COM(I) = COM(J) + 128
28  NEXT I
100  REM  IEEE SWIB2
101  REM
102  REM
103  REM   L  IS A LOCAL VARIABLE
     , USED IN THE SUBROUTINES.
104 Q = 1
105 P = 0
110 D$ = "": REM  CTRL-D
120 Z$ = "": REM  CTRL-Z
130 NB = 7
140 NR = NB * 32: REM  NUMBER OF
     RELAYS
150  DIM LA$(NB): REM  LISTEN ADD
     RESSES FOR BOXES
160  DIM R%(NR): REM  STATES OF T
     HE RELAYS
170  REM  IF R%=1 THEN RELAY IS O
     N
180  REM  IF R%=0 THEN RELAY IS O
     FF
200  FOR BN = 1 TO NB: REM  SET U
     P BOX ADDRESSES
210 LA$(BN) =  CHR$ (32 + BN) + Z
     $: REM  CHARS STARTING AT "!
     ", I.E. HEX 21
220  NEXT BN
230 BL$(0) = "D":BL$(1) = "F":BL$
     (2) = "H":BL$(3) = "L": REM
      BLOCK CODES
240 LB$ = "4"
250 TB$ = "T"
260 LB$ = LB$ + Z$
270 TB$ = TB$ + Z$
331 LA$ = ">" + Z$
340 TA$ = "P": REM  TALK ADDRESSE
     S FOR DVM
341 TA$ = "^" + Z$
350  PRINT "WHAT IS THE NAME OF T
     HE OUTPUT FILE"
360  INPUT F$: REM  OUTPUT FILE N
     AME
370  PRINT D$;"OPEN ";F$
1501  PRINT
1502  PRINT
1503  PRINT "  PLEASE ENSURE THAT
     ALL EQUIPMENT IS SWITCHED O
     N, ESPECIALLY SWITCHING BOXE
     S AND POWER SUPPLIES. IF NOT
     , SWITCH OFF MAINS SUPPLY, S
     WITCH ON DEVICES, SWITCH ON
     MAINS AND RESTART PROGRAMME.
     "
1504  PRINT "
               PLEASE ENTER THE NUM
     BER OF OPTOCOUPLERS TO BE TE
     STED"
1505  INPUT N
1506  PRINT
1507  PRINT "Please note errors s
     et at 5.00 for Ic"
1508  PRINT
1510  IF N > 256 THEN  GOTO 9999
1520  PRINT "Input shunt resistan
     ce across the voltm
                              eter, in
     ohms."
1530  INPUT SHUNT
1600  PRINT D$;"WRITE";F$
1610  PRINT N
1620  PRINT D$
2070  GOSUB 7900: REM GET DVM REA
     DY
2190  FOR Z = 1 TO N: REM  TAKE R
     EADINGS
2195 J = Z * 2
2197 J = COM(J)
2200  GOSUB 9000
2205 J = (2 * Z) - 1
2207 J = COM(J)
2210  GOSUB 9000
2212  GOSUB 9800
2213 AZ$ =  RIGHT$ (A$,14):AZ =  VAL
     (AZ$)
2215 AZ = (AZ / (.02 * SHUNT))
2217 A$ =  STR$ (AZ)
2220  GOSUB 9700
2225  GOSUB 9100
2227 J = Z * 2
2230 J = COM(J)
2235  GOSUB 9100
2240  NEXT Z
2250  GOSUB 9500: REM  CLOSING DO
     WN
2255  PRINT D$;"CLOSE";F$
2260  HOME
2261  VTAB 12: FLASH
2262  PRINT " RETURNING TO MAIN M
     ENU"
2263  NORMAL
2264  PRINT D$;"RUN MENU.01"
```

CTRA

```
1  HOME
2  PRINT
3  PRINT
4  PRINT
5  PRINT
6  PRINT
7  PRINT
8  CLEAR
9  DIM COM(192): REM  RELAY COMBI
     NATIONS
10  FOR I = 1 TO 64
11  READ COM(I)
12  NEXT I
13  DATA  1,2,10,11,3,4,12,13
14  DATA  5,6,14,15,7,8,16,25
15  DATA  17,18,26,27,19,20,28,29

16  DATA  21,22,30,31,23,24,32,41

17  DATA 33,34,42,43,35,36,44,45
18  DATA  37,38,46,47,39,40,48,57

19  DATA  49,50,58,59,51,52,60,61

20  DATA  53,54,62,63,55,56,64,9
21  FOR I = 65 TO 128
22 J = I - 64
23 COM(I) = COM(J) + 64
24  NEXT I
25  FOR I = 129 TO 192
26 J = I - 128
27 COM(I) = COM(J) + 128
28  NEXT I
100  REM  IEEE SWIB2
101  REM
102  REM
103  REM    L  IS A LOCAL VARIABLE
     , USED IN THE SUBROUTINES.
104  REM
105  REM
110 D$ = "": REM  CTRL-D
120 Z$ = "": REM  CTRL-Z
130 NB = 7: REM   NO. OF BOXES

140 NR = NB * 32: REM  NUMBER OF
     RELAYS
150  DIM LA$(NB): REM  LISTEN ADD
     RESSES FOR BOXES
160  DIM R%(NR): REM  STATES OF T
     HE RELAYS
170  REM  IF R%=1 THEN RELAY IS O
     N
180  REM  IF R%=0 THEN RELAY IS O
     FF
200  FOR BN = 1 TO NB: REM  SET U
     P BOX ADDRESSES
210 LA$(BN) =  CHR$ (32 + BN) + Z
     $: REM  CHARS STARTING AT "!
     ", I.E. HEX 21
220  NEXT BN
230 BL$(0) = "D":BL$(1) = "F":BL$
     (2) = "H":BL$(3) = "L": REM
      BLOCK CODES
240 LB$ = "4"
250 TB$ = "T"
260 LB$ = LB$ + Z$
270 TB$ = TB$ + Z$
331 LA$ = ">" + Z$
340 TA$ = "P": REM  TALK ADDRESSE
     S FOR DVM
341 TA$ = "^" + Z$
1000  HOME
1010  PRINT
1020  PRINT
1030  PRINT
1040  PRINT
1050  PRINT "Measurement of Satur
     ation Voltage of Optocoupler
     s."
1060  PRINT
1070  PRINT
1080  PRINT
1090  PRINT
1095  GOSUB 9500: REM  All relays
      set to off position
1097  DIM I(150): DIM V(150): DIM
     VC(150): DIM SLOPE(150)
1100  PRINT "How many optocoupler
     s are you measuring?"
1110  INPUT NOP: REM  number of o
     ptocouplers is 'NOP'
1115  IF NOP > 256 GOTO 10000
1120  PRINT "Please type in the v
     alue of the shunt resistance
     , across the DVM, in ohms."
1130  INPUT SHUNT
1132  PRINT "What is the name of
     the output file?"
1133  INPUT F$: REM  Output file
     name
1134  PRINT D$;"OPEN ";F$
1135  PRINT D$;"WRITE";F$
1136  PRINT NOP
1137  PRINT D$
1138  PRINT "   MEASURING......"
1139  GOSUB 7900: REM   INITIALIS
     ES THE VOLTMETER
1140  FOR Z = 1 TO NOP: REM  TAKE
      READINGS
1143  GOSUB 9500: REM   ALL RELAY
     S SET TO OFF POSITION
1144 J = Z * 2:J = COM(J)
1145  GOSUB 9000
1146 J = (2 * Z) - 1:J = COM(J)
1148  GOSUB 9000
1150 PU2 = 0.3
1160  GOSUB 6035
1170  GOSUB 3900: REM  voltage fr
     om power supplies is now on
1190  GOSUB 9800: REM   voltmeter
      read, value is 'RES'
1200 N = 1:I(1) = 0
1205 A$ =  MID$ (A$,4):RES =  VAL
     (A$)
1210 I(N) = RES / SHUNT: REM  giv
     es Ic
```

SAT VOLTA

```
1215 I(N) = I(N) * 1000: REM  CON
     VERT TO MILLI-AMPS
1220 V(N) = PU2 - RES: REM  gives
      Vce
1230 N = N + 1
1240 PU2 = PU2 + 0.2
1250  GOSUB 6035: REM  converts P
     U2 to a string
1260  GOSUB 9900: REM  voltage ch
     anged
1280  GOSUB 9800: REM   voltmeter
     read, value is 'RES'
1285 A$ =  MID$ (A$,4):RES =  VAL
     (A$)
1290 I(N) = RES / SHUNT
1295 I(N) = I(N) * 1000
1300 V(N) = PU2 - RES: REM  gives
      Vce
1310 SLOPE(N) = (I(N) - I(N - 1))
      / (V(N) - V(N - 1)): REM  c
     alculates position of Vce(N)

1320  IF SLOPE(N) > 20 THEN  GOTO
     1230
1330 VC(N) = (V(N) + V(N - 1)) /
     2: REM  calculates position
     of Vce(N)
1340 VC(N - 1) = (V(N - 1) + V(N -
     2)) / 2: REM  calculates pos
     ition of Vce(N-1)
1345  IF SLOPE(N) = SLOPE(N - 1) THEN
     SRN = 0: GOTO 1360
1350 SRN = VC(N) + (VC(N - 1) - V
     C(N)) * (5 - SLOPE(N)) / (SL
     OPE(N - 1) - SLOPE(N)): REM
      calculates saturated voltag
     e
1360 A$ =  STR$ (SRN)
1380  GOSUB 9700: REM  informatio
     n written to file
1383  GOSUB 9100
1385 J = Z * 2:J = COM(J)
1387  GOSUB 9100
1390  NEXT Z
1393  PRINT D$;"CLOSE ";F$
1395  PRINT " MEASUREMENTS OVER.
     DATA IN FILE "F$" RUN A LOOK
      PROGRAM TO READ"
1400  GOSUB 9500: REM  all relays
      reset
1410  END
```

SAT VOLTA (continued

APPENDIX 6

A RELIABILITY ANALYSIS OF MULTILAYER CERAMIC CAPACITORS UNDER VOLTAGE AND TEMPERATURE ACCELERATION

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SUMMARY

Reliability analyses have been carried out on type X7R multilayer ceramic capacitors, manufactured using a screen printing process. The initial purpose of this work was to establish the validity of the 3rd power law under voltage acceleration for capacitors manufactured with this technique. In addition, temperature and temperature/voltage acceleration effects have been investigated.

The preliminary test programme involving temperature and voltage step stressing establishes the existence of a 3rd power law for voltage acceleration. The importance of temperature as an acceleration factor is also highlighted.

The second phase of the work, based on the results of the preliminary programme, involved accelerated life studies of multilayer ceramic capacitors at fixed voltage and temperature combinations.

Results from these experiments have been analysed making use of Weibull analysis techniques to investigate activation energies, characteristic lifetimes and possible failure mechanisms under voltage and temperature acceleration.

At high voltage stress levels (400 volts) two temperature dependent failure mechanisms, thermal runaway and avalanche breakdown, are postulated.

Screen printed type X7R multilayer ceramic capacitors used under rated conditions are shown to have characteristic lifetimes of possibly 25 years.

INTRODUCTION

The reliability of multilayer ceramic capacitors has been well researched in recent years. Many papers have been written on these studies [1-5]. These studies have generally used the model proposed by Prokopowicz and Vaskas [6] when investigating the behaviour of multilayer ceramic capacitors under temperature and voltage acceleration.

The model states:

$$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n \exp\left(\frac{Ea}{k}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]\right) \quad (1)$$

where t is time to failure, V is applied d.c. voltage, T is the absolute temperature at the test condition, k is Boltman's constant, Ea is the pseudo-activation energy and n is the voltage acceleration factor.

Calculations of times to failure can thus be made for different combinations of temperature and voltage, assuming that the failure mechanism does not change.

Values of n, the acceleration factor, have been reported between 2 and 4 for medium "K" and high "K" barium titanate based dielectrics [4]. A value of 3 is generally accepted in the industry. Similarly different values of Ea, the pseudo-activation energy, have been reported. However, a value of 1 eV is generally assumed by many researchers [7].

The major concern in the failure of multilayer ceramic capacitors is the degradation of insulation resistance [5]. In accelerated life testing this is monitored directly as insulation resistance, or more usually as a leakage current. Typically a device might be considered a failure if the leakage current exceeds 5 mA.

This paper describes the results of accelerated life test experiments on multilayer ceramic capacitors which have undergone a manufacturing process change. It was consequently of interest to study the general reliability of these components, and to assess to what extent the model stated in equation 1, still held.

The capacitors were manufactured using a new screen printing technique, where both the dielectric and the ceramic were screen printed, one after the other, building up a block of multilayers which could then be cut and fired in the usual manner.

A programme of work was established which consisted of two phases:

(I) A step-stress programme to determine whether the established third power law of voltage acceleration still held for multilayer ceramic capacitors manufactured by this different process. The effect of temperature would also be investigated.

(II) A larger scale voltage/temperature test matrix based on the results of phase I.

Experimental Details

Phase I of the work involved:

(a) Placing 60 capacitors initially on test at maximum rated voltage and temperature (50 V, 125°C) for 1,040 hours. At the end of the 1,040 hours the voltage was increased in steps, as shown in Table 1. The test times at each voltage were reduced in proportion to $(V_{test}/V_{rated})^3$ in order to investigate the validity of the third power law.

(b) A further 60 capacitors underwent the same voltage step-stress programme as outlined in (a). When approximately 15% of these capacitors had failed, at the end of stage 5 (159 V, 32.3 hours), the remainder were held at this voltage i.e. 159 volts and then subjected to a temperature step-stress programme which involved increasing the temperature in 20°C steps and holding the capacitors at each stage for 26 hours.

Phase II of the work consisted of a test matrix involving both voltage and temperature acceleration as shown in Table 2. 128 Capacitors were placed on test at each of the voltage-temperature combinations.

Table 1.

Voltage-Time Step-Stress Test Program

Voltage (Volts)	Time (Hours)	Step Number
50	1,040	1
100	130	2
126	65	3
144	43.5	4
159	32.3	5
171	26	6
182	21.6	7
192	18.4	8
200	16.3	9
208	14.4	10
216	12.9	11
222	11.9	12
229	10.8	13
235	10	14

Table 2.

Accelerated Life Tests at Fixed Temperatures and Voltages

	125°C	160°C	200°C
100 volts	128 capacitors	128 capacitors	128 capacitors
400 volts	128 capacitors	128 capacitors	128 capacitors

Measurement Techniques

In order to measure the desired parameters of the components undergoing life test, a data logger system was constructed. This consisted of an Apple IIe microcomputer, which controlled, via an IEEE interface, a number of switching boxes and the various measuring instruments. During Phase I measurements of insulation resistance, dissipation factor and capacitance were made at various time periods using this system.

During the second phase of the work it was necessary to determine the times to failure more accurately. This was achieved by means of a trip circuit. The total current through the 128 capacitors, connected in parallel, was monitored and the circuit was designed to trip out when this exceeded 5 mA. The effect of tripping was to disconnect the bias voltage and to stop a clock. Using the data logger the bank of capacitors could be measured individually to locate the failed capacitor or capacitors.

Results from Phase I

The results from the two tests in phase I, (a) and (b), are shown respectively in Tables 3 and 4. The non accelerated times shown in these tables are the times to failure converted to the 50 V base level, assuming the third power law holds.

Table 3.

Results of Voltage Step-Stress

Tests at Constant Temp. (125°C)

Number of Failures (Out of 60)	Time (Hours)	Step	Non Accld. Time (Hours)	% Cumulative Failures (Ranked)
0	0	1		
2	718	1	718	2.81
3	1,082	2	1,375	4.47
3	1,109	2		
3	1,149	2		
3	1,197	3		
7	1,221	3	2,896	11.1
8	1,228	3	3,008	12.7
9	1,247	4	3,407	14.4
14	1,318	6	5,488	22.7
15	1,324	6	5,728	24.3
16	1,341	7	6,441	26.0
16	1,365	8		
17	1,390	9	9,162	27.6
18	1,443	13	13,510	29.3
18	1,448	14		
18	1,453	14		

Table 4.

Result of Combined Voltage and

Temperature Step-Stress Test

Number of Failures (Out of 60)	Time (Hours)	Step	Non Accld. Time (Hours)	% Cumulative Failures (Ranked)
0	0	1	0	
0	718	1	718	
0	1,082	2	1,376	
4	1,109	2	1,592	6.13
5	1,149	2	1,912	7.78
6	1,197	3	2,512	9.44
9	1,221	3	2,896	14.4
9	1,228	3	3,008	
11	1,247	4	3,407	17.7
23	1,318	6	5,424	37.6
21	1,324	6	5,616	
24	1,341	6	6,160	39.2
25	1,365	7	5,928	40.9
27	1,390	8	7,728	44.2
28	1,446	10	9,520	45.8
32	1,462	10	10,032	52.4
34	1,482	11	10,672	55.8
41	1,505	11	11,465	67.4
39	1,510	12	11,568	
44	1,528	12	12,144	72.3
46	1,534	12	12,272	75.6
47	1,559	13	13,136	77.3
49	1,577	14	13,712	80.6
50	1,582	14	13,872	82.3

The results in Tables 3 and 4 have been plotted on Weibull paper. These are shown in Figures 1 and 2. Assuming that the failures are occurring in the constant failure part of the bathtub curve and increasing voltage does not take them into a wearout situation, a straight line relationship should be obtained on a Weibull plot with a β value = 1 for the third power law to hold. Within the limits of experimental error it is possible to construct a straight line through the points in Figure 1 with a β value approximately = 1. This shows the third power law is approximately correct for capacitors manufactured using screen printing.

The results in Table 2 are shown plotted in Figure 2. The failures in the first part of the test which involved only voltage acceleration account for approximately 20% of the accumulated failures. Up to this stage a straight line can be constructed as in Figure 1 with β approximately = 1. After this point a curve showing increasing failure rate is observed. This is due to the increased temperature stressing. It should be noted that the times to failure are converted to the 50 V baseline from the elevated voltage i.e. 159 V only. No correction is made for the increased temperature stresses. The figure is shown merely to illustrate that these results indicate the importance of temperature as an accelerating agent.

All failures recorded in Tables 3 and 4 were due to the breakdown in insulation resistance of the capacitor.

Results from Phase II

The observed failure time for each of the temperature-voltage combinations in Phase II are shown plotted in Table 5(a) and 5(b). The results are plotted on Weibull paper and are shown in Figures 3 to 8.

Table 5(a).

Number of Failures Versus Time as a Function of Voltage and Temperature

100 Volts

Number of Failures	125°C	160°C	200°C
1	265.0	67.8	7.6
2	1,036.5	137.8	14.6
3	1,227.3	166.8	15.8
4	1,656.0	246.7	19.5
5		272.3	21.4
6		470.3	23.8
7		530.7	
8		623.5	
9		1.090.1	

All times to failure are in hours

Table 5(b)

Number of Failures Versus Time as a Function of Voltage and Temperature

400 Volts

Number of Failures	125°C	160°C	200°C
1	0.45	1.0	0.01
2	3.8	2.9	0.1
3	4.3	3.7	0.1
4	6.2	5.5	0.4
5	6.5	7.6	0.8
6	28.9	9.5	1.1
7	31.1	11.4	1.2
8	36.3	11.5	1.2
9	43.9	12.1	1.4
10		13.0	1.9
11			2.4
12			2.5
13			2.5
14			2.8
15			3.2
16			3.45
17			3.45
18			3.5

All times to failure are in hours

Maximum and minimum characteristic lifetimes have been estimated and the results are shown in Table 6.

Table 6.

Estimated Maximum and Minimum Characteristic Lifetimes in Hours

		Voltage (Volts)	
		100	400
Temp. °C	125	100,000-1,000,000	8,000-90,000
	160	2,400-9,000	165-800
	200	180-2,400	38-1,200

Arrhenius plots of these results are shown in Figures 9 and 10. In Figure 9 a straight line is obtained and the activation energy is calculated to be 1.0 eV. In Figure 10 there is no obvious straight line which can be drawn through all three points.

However, based on the work of Rawal and Chan [4], it is postulated that two lines may be drawn as shown, corresponding to thermal runaway and at lower temperatures and avalanche breakdown at higher temperatures. The activation energy for thermal runaway again being 1.0 eV and estimated as 0.4 eV for avalanche breakdown. The maximum and minimum values of characteristic lifetimes are shown on this graph and the values of activation energy are calculated from the best lines drawn considering the associated spread at each point.

CONCLUSIONS

From this work on screen printed type X7R multilayer ceramic capacitors the following important factors have been established:

(i) Screen printed multilayer ceramic capacitors do not differ significantly from those manufactured by traditional methods.

(ii) The voltage acceleration factor, n, is shown to be approximately equal to 3.

(iii) Temperature acceleration has been demonstrated. A more detailed programme is necessary to quantify the situation.

(iv) An activation energy of 1.0 eV is shown for failures due to thermal runaway, predominant at lower voltage stress levels.

An activation energy of 0.4 eV has been estimated for avalanche breakdown failure, which tends to predominate at high voltage and temperature.

(v) Used under rated conditions type X7R screen printed multilayer ceramic capacitors have calculated characteristic lifetimes of 25 years.

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Fig. 1.

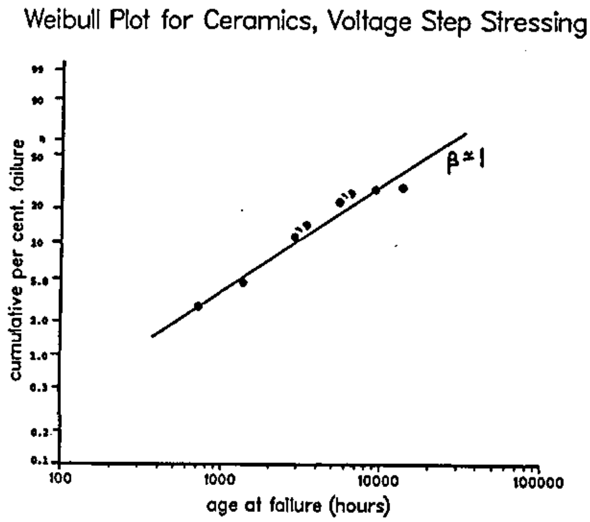


Fig. 3.

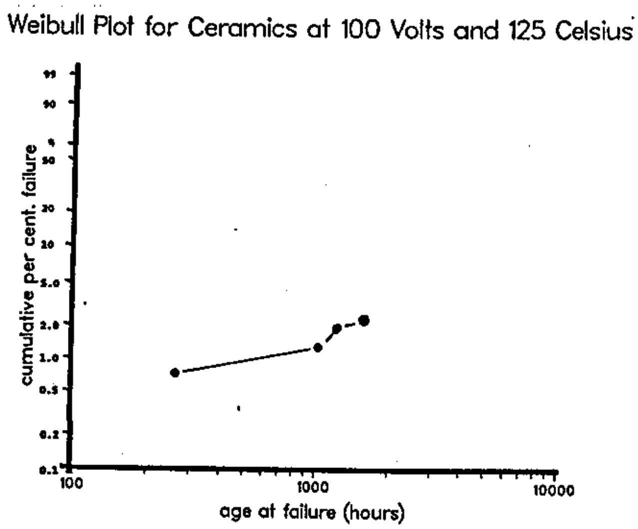
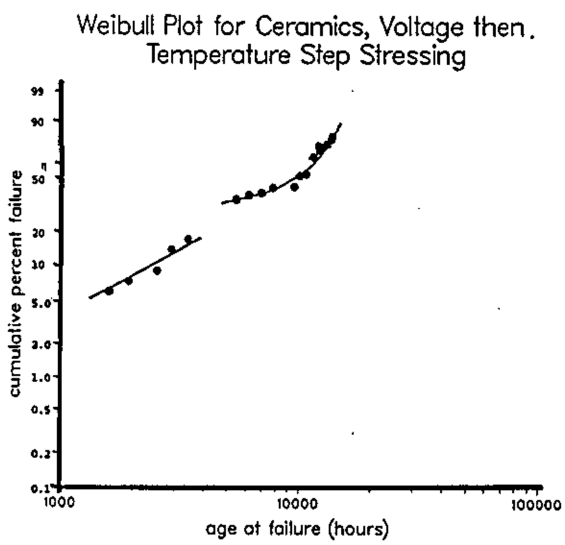


Fig. 2.



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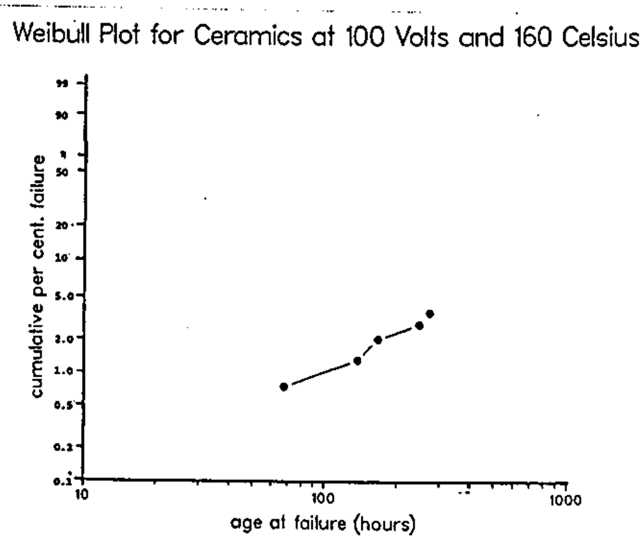
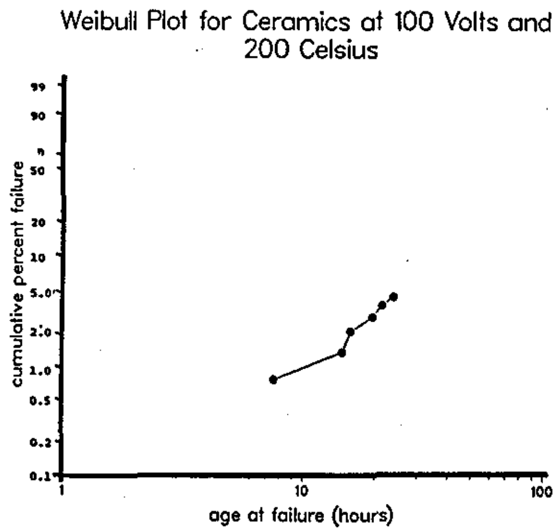


Fig. 5.



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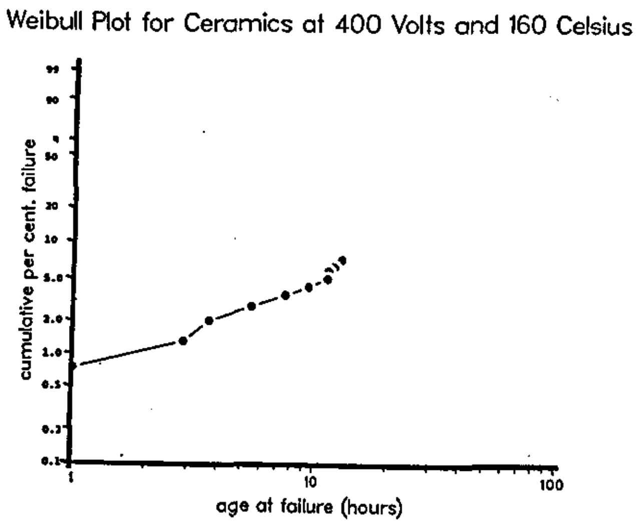


Fig. 6.

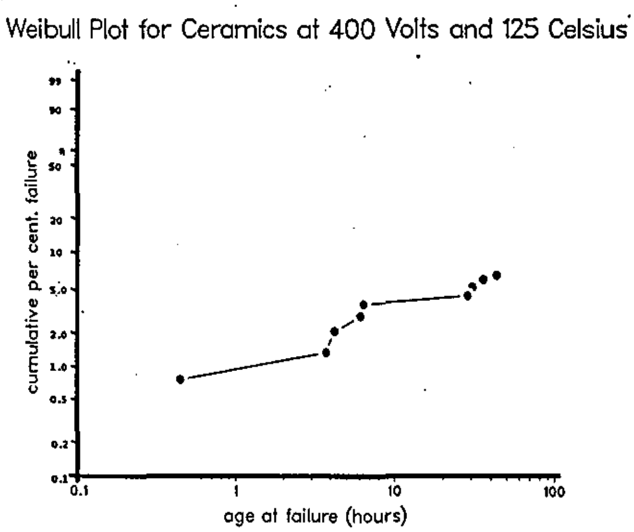


Fig. 8.

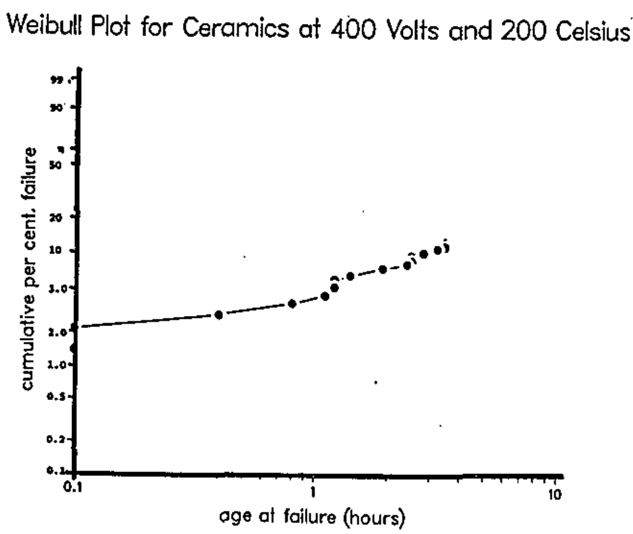


Fig. 9.

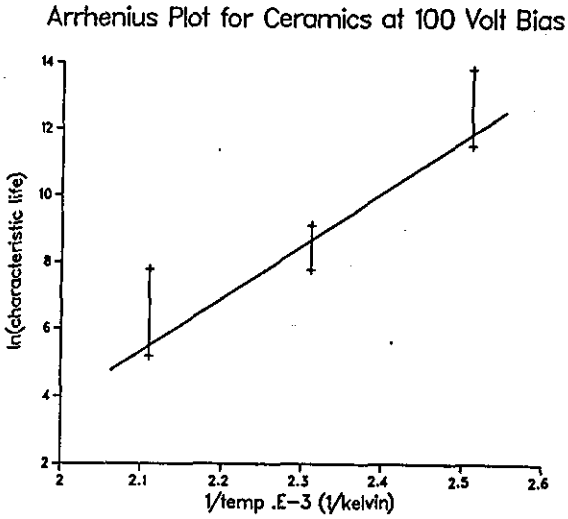
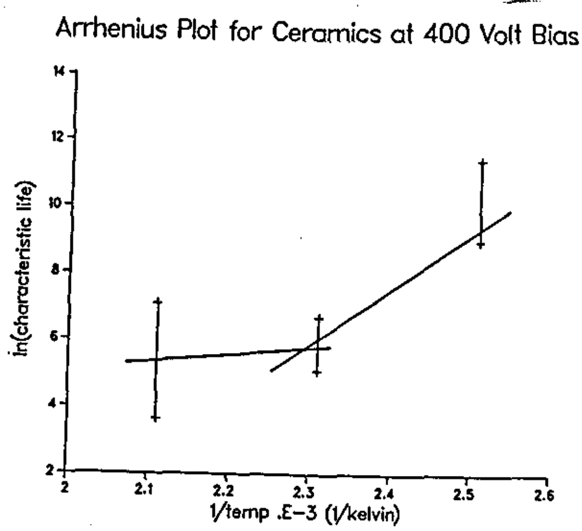

Arrhenius Plot for Ceramics at 100 Volt Bias
ln(characteristic life)
1/temp .E-3 (1/kelvin)

Fig. 10.


Arrhenius Plot for Ceramics at 400 Volt Bias
ln(characteristic life)
1/temp .E-3 (1/kelvin)