SPRING CONTACT PROBES, WEAR CHARACTERISTICS TESTING FOR ELECTRICAL AND MECHANICAL PARAMETERS

by

MICHAEL ELSTON

A Master's Thesis submitted in partial fulfilment
of the requirements for the award of Degree
of Master of Philosphy of the
Loughborough University of Technology

January 1990

ACKNOWLEDGEMENTS

The author wishes to thank Professor I. R. Smith, Head of the Department of Electronic and Electrical Engineering for permission and encouragement to complete the project. I am also most grateful to Dr R. Jones of the Department of Manufacturing Engineering for his choice of subject advice and guidance throughout the unsupervised study. An acknowledgement is extended to Multiprobe Ltd., Bollington, Cheshire for help and advice received. I would like to acknowledge the help given by Mr D. Walters for his advice and assistance on the Epic Computer and to Mr J. T. W. Smith with respect to Photography and Metrology during the assessment of the effects of wear on the mechanical parameters. Acknowledgements are due to Mr A.D. Bailey for his advice and help in low resistance measurement, to Mr F. Page for the work on the (SEM), to Mr D. W. Hurrell for help during the lengthy experimental programme and to Mr D. Womersley for advice and encouragement throughout.

My final thanks are extended to my wife for her great efforts and tenacity in overcoming the hidden gremlins within the wordprocessor software and also for her sustained support and encouragement from the early stages of the project.

Thesis Title:

Spring Contact Probes, Wear Characteristics Testing for Electrical and Mechanical Parameters.

Synopsis.

The study considers the development and evaluation of spring contact probes used for automated testing of printed circuit boards (PCBs) and assemblies. It considers the evolution of circuit technology which originated from the introduction of the thermionic valve at the beginning of the century. Since the introduction of the integrated circuit in the 1960's, the industry has seen considerable advances in integrated and printed circuit miniaturisation with its associated effect on the testability of the completed assembly. The close spacing between the tracks and pads within the printed circuit board, which is possibly loaded on both sides with integrated circuits and other components with fine pitch termination spacings, has initiated the rapid development of a specialised electronic test industry to ensure product quality.

Automated test equipment (ATE) has evolved to satisfy the demand for rapid testing of printed circuit boards which are becoming loaded with more sophisticated and complex components. The ATE system is computer based, controlling a range of signal injection and measurement units, thus replacing signal generators, oscilloscopes and meters and enabling faults to be rapidly located down to component level.

In order to identify and locate faults rapidly, a connection between the ATE and the PCB must be established for each land or termination point on the unit under test (U.U.T.). This interface normally comprises of a wiring harness and test fixture, loaded with spring probes enabling rapid repetitive contact onto the test point of each U.U.T.

There are often problems encountered during automated testing of PCBs, the majority of which are due to spring loaded test probes not establishing a repetitive low impedance contact onto the U.U.T. test lands. This may be caused by a number of factors such as probe wear or contamination and misalignment. Unfortunately no standards have been established for the specification of test probes. This study analyses the operation and performance of the probes and an experimental method for the evaluation of probe characteristics during life cycle tests has been developed.

Extended life tests were conducted on a range of probe samples with the results showing the breakdown of probe resistance values during the life cycle. The work emphasises the significant effect of interfacial contact insulating layers developing on contact surfaces, and its effect on the variability of the results.

CONTENTS

Page

CHAPTER 1: INTRODUCTION

CHAPTER 2: THEORETICAL APPROACH

CHAPTER 3: THE DEVELOPMENT AND MANUFACTURE OF THE OF THE EXPERIMENTAL TESTING MACHINE

CHAPTER 4: EXPERIMENTAL PROCEDURE

CHAPTER 5: RESULTS

CHAPTER 6: DISCUSSION

CHAPTER 7: CONCLUSIONS AND FURTHER WORK

LIST OF FIGURES

CHAPTER 1

1 INTRODUCTION

1.1 ELECTRONIC CIRCUIT DEVELOPMENTS

One of the earliest electronic devices to be mass produced was the radio receiver in the 1920s. In those days the active devices used in the circuits were thermionic valves, which were some-what larger than the transistors and integrated circuits used today. The electronic circuits of the early radios were generally constructed by using a metal chassis onto which all the main components were fixed. The chassis was also used as a ground plane for shielding, incorporating a common ground earth return path. The connections between the terminals of the main components were achieved by wiring, which was supported by insulated stand offs known as tag strips. Small components such as resistors,capacitors, and inductors could be soldered between the terminals of the main components and the tags or tag strips. If a number of wires took the same route, they would be bound together by lacing cord to form a wiring harness to give better rigidity and tidiness. By using insulated clips the wiring harness would be secured to the chassis using screws. As all the wiring was carried out by hand, there were generally some variations between wiring systems which made it necessary to introduce variable components, such as trimming resistors, capacitors and inductors to achieve the exact component values specified in the design.

Chassis built electronic circuits became standard throughout the world for consumer domestic equipment, as well as industrial electronic instruments and military equipment, until the introduction of the printed circuit around 1940. Routine checking of wiring relied on resistance and insulation testing before most of the components were inserted to minimise alternate parallel paths within the circuitry. Tested components were used to ensure that the circuit was likely to work first time, provided the correct value components had been inserted in the right positions.

Circuit assembly methods using the chassis as a base for components and wiring were not well suited to automated production, for they were labour intensive, requiring soldering and testing to be done by hand. A number of wiring faults related to human error would be unavoidable, as each unit was wired individually, tracking down and correcting faults would be expensive for it would require skilled electronics technicians after the final test routine. By comparison the printed circuit design, once tried and tested, would continue to produce a high percentage of quality circuit boards, each circuit produced being an exact copy of the original design. Automation can be used in most if not all of the production processes,for example, soldering, component insertion and testing.

1.1.1 The Introduction and Development of Printed Wiring Boards

Todays acceptance and widespread use of the printed wiring or circuit board, has caused a revolution in the manufacture of electronic wiring and component assemblies in the electronic manufacturing industry. Its introduction has made it possible to manufacture more complex electronic circuits, while at the same time achieving increased miniaturisation. In 1969 Draper stated, that in the future printed wiring would be considered to be one of the major advances of the 20th Century. Without printed wiring there would be little advance in the electronics industry (1).

The initial ideas relating to the printed circuit were conceived between the years 1923 - 1939. During that period a large number of patents were granted describing different methods, including stamping out metal foil, the pouring of low melting point metal into grooves, metal spraying, die casting, electro- deposition and the chemical etching of metal foil. Around 1940 Dr Paul Eisler became interested in the etched foil technique and a number of patents were subsequently granted, however, practical exploitation of this technique was delayed until after the second world war, due to lack of interest from industry and government (2).

Dr Eisler claimed to be the inventor of printed circuit wiring, although this has been contested. He could claim that the impetus which his work gave to the development of printed wiring was significant. It is evident that miniaturisation of electronic assemblies, could not have been achieved without the development of printed wiring (1-3). Dr Eisler is said to have produced the first printed circuit with Parker in 1942, followed by a further 48 in 1943. The circuits produced were radio assemblies using thermionic valves. The British Government and the radio industry showed little interest despite the impetus provided by the Second World War. Unfortunately, some of the early attempts to produce printed circuits, concentrated on printing almost all of the components in one operation, including all the connecting wiring, which further delayed the development of the printed wiring system in use today (2). In 1947, it was revealed that the U.S. industry had used the principles of printed wiring and had applied them in military projects during the Second World War. One of the first applications was for proximity fuses for a mortar shell, the circuit was printed in silver on a ceramic base by means of a stencil screen process. The circuit contained resistors and capacitors in addition to the printed wiring. Mass production of the printed circuit boards began in 1945, and eventually production rates of 5000 assemblies a day were achieved (2-4).

Until 1947 it appeared that no UK firm or government department had used printed circuit board technology in production. The 1947 release of information brought about a significant change in attitude, allowing printed circuits to become established as an important feature of products in the armaments and consumer industry. In the U.S.A, the Bureau of Standards undertook a study of printed circuit applications, issuing two publications in succession. The second being the proceedings of the first technical symposium on printed wiring boards, held on October 15th 1947, in Washington DC. The proceedings did not cover earlier development work carried out by Eisler in the UK (4). The etched foil technique which differs very little from the conventional process of engraving, has become the most well established method of producing the majority of printed circuits, however, other techniques were gaining popularity, notably plated circuits (2).

After 1947 there was a rapid development in printed circuits, followed by the invention of the point contact transistor by Bardeen and Brattain (5-6-7). A year later William Shockley working in the Bell research laboratories, invented the junction transistor (8). The transistor was significantly smaller than the thermionic valve and was therefore more suited to PCB application, its use resulted in considerable reduction in circuit size. It is worth noting, that soon after the transistor became established as the active device in the majority of electronic circuits, virtually all electronic manufacturers started using printed wiring assemblies. The transistor radio receiver introduced in the 1950's was the first device using only transistors, rather than a mixture of transistors and valves. During the transitionary period circuits were designed, using both valve and transistor technology in the same circuit, but by using only transistors, significant miniaturisation was achieved. Reduced power consumption greatly extended battery life on portable equipment, as there were no cathodes which required heating. In addition most thermionic valves had only a relatively short life time, compared with the transistor which was more robust.

1.1.2 Wired Circuit Boards

Alternative techniques to printed wiring boards have been tried, but have not become established as a viable alternative. One example is known as strip wiring where a punched metal strip is used, having teeth which are pushed into holes in the insulating board, thus securing the strip to the board. The components are then inserted and clinched over the strips before dip or wave soldering. Another technique is wrapped wiring; component leads are wrapped around a rectangular tag in the form of a U or I shape, while interconnecting wire is wrapped around the tags to form connections between circuit components. The pierced matrix board is another method in use, today, mainly as a prototype bread board system (this has been used in the past for production). Double or single sided pins are inserted into the holes to support the components and interconnecting wiring joints are hand soldered. This method allows components to be mounted on both sides of the board between the double sided matrix pins. The circuit acquires a rather bulky appearance compared with the double sided printed circuit board due to the components being spaced off the board by the pins. Another method of constructing circuits is by using matrix board where the component leads are inserted through the holes, thereby soldering component and interconnecting wires on the lower side of the board, leaving components on the upper side only. A further method of circuit construction, is the use of strip board usually known as "vero board", its structure is based on an insulating substrate with parallel copper tracks pierced at fixed points, ready for component lead insertion before soldering. Individual circuits are formed by cutting and bridging the tracks with jump wires to form the desired circuit configuration, it is in use today for one off prototype wiring systems. Probably one of the most sophisticated methods of board production is the multiwire system where a special machine lays down insulated wires onto a board covered in "glue". Many wires can be overlaid with the interconnection provided by drilled holes. This method is expensive but allows a high degree of flexibility particularly for prototype work (9).

From 1950 progressive development in component miniaturisation has taken place, resulting in increased circuit and component density. Some of the more notable developments are: the double sided printed circuit board; followed by the plated through hole process; the multilayer circuit boards; surface mounting of components on both sides of the board. It should be noted at this stage that the developments in printed wiring boards has resulted in more complex circuits, which also means that considerable skill is required to test them.

1.1.3 Printed Circuit Production Processes

Most processes start with a copper-clad insulating substrate material. Early circuits used paper or paper/cloth impregnated with phenolic resin, which is still in use today. Other materials more recently introduced, are the range of glass reinforced plastics (GRP). In the form of woven cloth, glass is combined with phenolic, polyester, epoxide, melamine or silicone resins. Epoxide/glass cloth laminates offer the best compromise between mechanical, thermal and electrical properties at reasonable cost. The good dielectric loss characteristics and high insulation resistance are maintained under high humidity (10). These materials in general, have better electrical and mechanical properties, but tend to be more expensive.

A number of methods have been used for producing the conductive tracks, the most crude have been mechanical methods, where the foil was cut with a sharp knife and the copper stripped off by hand (11). Mechanical engraving has been used for "one-offs" and small production runs where shallow grooves, just deep enough to remove the foil, are cut by means of a rotary tool similar to an end mill, the width of the groove being equal to the diameter of the tool (11).

The etched foil process first used in Britain in the early 1940s by Eisler is now the most established process in use today. Etching is a chemical process whereby, all the unnecessary copper is removed chemically from the laminate, while the copper which is protected by an etch resist is retained and forms the conductor pattern itself (12-13).

There are various methods of depositing an etchant resist pattern on the copper surface of the board, some using printing as a basis for the transfer of an image, others using photo sensitive resist coatings in the form of a varnish or a polymer film. The screen printing technique is the oldest and simplest method of printing an etchant resist circuit pattern on the copper clad board, it is necessary to print a positive image on the copper foil. It may be used to deposit either a conducting paint, or alternatively, an etchant resisting paint or ink. Various other printing methods have been used e.g. wood block, offset-litho, but they have not resulted in much success in production. Stencil screen superiority lies principally in its ability to provide a deposit of adequate thickness, resulting from hand or photographic preparation of the stencil. The resolution achieved by screen printing is inadequate for boards with narrow conductors and close spacing (12).

In order to overcome the limitations imposed by screen printing, photo resist methods are now established for the production of the majority of circuit boards. The technique of forming an etchant resist by exposure to light, has a long history and in common with many systems now used in the electronics industry, owes its beginning to the pioneers of photography and printing. In 1824 Nuephore Nie'pce found that a natural bitumen was sufficiently light sensitive to harden under exposure to light, the non exposed areas being dissolved away with solvent. Fifteen years later, Mungo Ponton discovered, that a potassium dichromate would produce an image by exposure and this principle was used by Fox Talbot, for his "photographic engraving process" in 1852 (14-15).

Current photo resists in use are based on solvent soluble copolymers in the form of liquid varnish, or a dry polymer film, which is applied to the board as a thin film. Commonly used photo resists are negative acting and polymerise on exposure to ultraviolet light, becoming insoluble to the solvent developers which dissolve away the areas of non polymerised film, leaving a bare copper pattern ready to be etched away, the rest of the pattern being protected by the resist film. Image transfer is from a photo sub master, using ultraviolet light transferred to the board, using contrast printing techniques. Photo mechanical processes are economical, provide excellent line definition with good dimensional stability, and are considered technically the best processes available (11).

1.2 INTEGRATED CIRCUIT DEVELOPMENT

The development of the monolithic integrated circuit was a natural progression from the invention of the junction transistor by William Shockley in 1948, and by using the newly discovered diffusion processes it was found possible to diffuse more than one active device on a single silicon wafer. Semiconductor junctions were built up by the diffusion of P and N type impurity atoms into a silicon wafer using a tubular furnace, containing impurity atoms in a gas phase within the furnace tube. Further development allowed the epitaxial growth of an impurity doped silicon crystal layer from a vapour phase of gases, containing a silicon compound with impurity atoms. In the process, silicon along with impurity atoms rained down on the silicon substrate interlocking with the crystalline structure of the impurity doped substrate. By using diffusion, epitaxial growth and ion implantation layers of P and N type silicon can be built up, to form any type of semiconductor device from a diode or transistor to a thyristor. The conductivity of the silicon can be changed from an insulator to a conductor, by the amount of impurity diffused or grown in the crystal lattice, enabling conductive interconnecting networks to be formed within the silicon structure.

Electrical isolation of separate components within the structure can be achieved by diffusing or growing a reversed biased PN or NP junction, by using a PNP or NPN sandwich, isolation would be achieved in both directions equivalent to a back to back diode configuration. Low resistance conductive networks can also be produced by evaporating a metal (usually aluminium) in a vacuum, where condensation occurs on the surface of the silicon wafer, leaving a conductive metallic layer. By using masking, photo resists, and etching, a conductive network can be formed on the surface of the wafer. Insulating layers within the silicon wafer are formed by oxidising the surface of the wafer, before epitaxial crystal growth of the next layer. Windows etched into the oxide layer will form semiconductor junctions between the P & N type layers, furthermore the windows are also used to diffuse P & N type impurity atoms into a silicon substrate or epitaxial layer, enabling the fabrication of a semiconductor device. Resistors and small capacitors can be formed by diffusing or growing isolated strips or layers of doped P or N type silicon. Resistivity is controlled by doping levels.

Resistors and capacitors use relatively large amounts of space on the silicon wafer compared with semiconductor junctions, restricting their use in the circuit design. By using more semiconductors and less resistors and capacitors, circuit dimensions can be minimised, although some external larger components may be required. Very large numbers of individual circuits are manufactured on one silicon slice, in the region of 50 to 100 mm diameter. Every circuit on the entire wafer is tested and the defective ones marked. The wafer is then scribed by a diamond stylus or a laser and broken into hundreds or thousands of individual chips. Wafers may alternatively be sawn into chips by means of a diamond saw. Individual chips are called dice (singular die) and are now ready for bonding onto the aluminium termination pads of the silicon wafer.

Before the bonding process takes place, the silicon wafer has to be mounted into a termination package, industry standards are now reduced to two main types, which include the less popular TO5 can type package and the dual in line flat pack. Connections are now made from the metallised pads on the silicon wafer, to the pin outs on the TO5 package, or the dual in line lead frame assembly in the flat pack version.

Integrated circuits can be bonded by a wide variety of techniques using ultrasonics, thermosonics, soldering, thermocompression, epoxy bonding insulating or conductive (16). Bonding the wafer to the header or package, is followed by the bonding of the outgoing connections to the package terminals, using wires, pads or fingers. A number of monolithic circuits can be fabricated in one package to produce one integrated circuit, although todays trend is towards producing all the circuits on one chip. The monolithic circuit is particularly attractive for application, where identical circuits are required in relatively large quantities, and have substantial advantages over their discrete component counterparts, and represent at least a 1000 fold reduction in size.

1.2.1 Hybrid Circuits

The hybrid circuit is one in which separate component parts are attached to a ceramic substrate, and interconnected by means of either, a metallisation pattern or wire bonds (17). It is possible for a hybrid circuit to contain one or more monolithic dice, plus a number of thick or thin film circuits in one encapsulation. In addition it could also contain individual component parts as required for circuit function.

Hybrid technology is more suited to small quantity custom designed circuits, because the circuit can be fabricated from readily available mass produced circuits, married together to produce the desired circuit functions without incurring the initial design and production costs. It is entirely conceivable that, as the state of the art progresses, this technique will be superseded entirely by the monolithic process.

A hybrid circuit could contain component circuits using thin or thick film technology. The manufacture of thick film circuits is an adaption and refinement of the ancient art of silk screen printing. Conductors, resistors and less commonly capacitors, are produced by this technique. Discrete components such as ceramic chips, capacitors, diodes, transistors or integrated circuits, may be attached to the passive thick film circuit to complete its functional capability (18). Thick microcircuits are produced by depositing conductor and passive component films onto a passive substrate. The thick film circuit process uses a paste screening system, similar to silk screen printing, followed by a firing process at a temperature of around 1000 C, causing the paste to adhere to the substrate as a permanent thick film approximately 1mm thick. Repeating the screening and firing processes adds layers of conductive dielectric, or resistive films, which need to be trimmed afterwards to obtain tolerances of less than 5%. Active and passive circuit components are attached to the substrate ready for the circuit to be encapsulated in plastic, ceramic or metal packages.

The alternative process to thick film, is the use of vacuum deposition to lay down a thin metallic layer on a glass, alumina or beryllia substrate known as a thin film circuit. It is primarily used for the production of resistor networks where small size close tolerances, and precise definition are required. Many different materials are used, but nicrome for resistors, and gold for conductors are the most commonly used. The circuit designs are produced on masks, similar to those used for thick film circuits, using photoresists to produce an etchant resist pattern. Electron beam, sputtering or evaporation may be used in the vacuum process. One of the most difficult tasks, is making contact with the thin film element, which must form a low resistance junction. Care is required to avoid reactions between the contact metal film and resistor film, which when heated during contact deposition, may produce undesirable compounds that will prevent the contact from being ohmic. Once the circuit is complete, discreet devices are added to the circuit which may include monolithic chips, transistors, inductors and capacitors.

1.3 PRINTED CIRCUIT TESTING.

Almost all electronic equipment is built on printed circuit boards (PCBs). Manufacturers dealing with large numbers of these boards, either as a user or a manufacturer, have reason to test them. If quantities are large enough, the best way to do this is by using computer based automatic test equipment (ATE).

Computer based testers contain standard electronic test instruments and can be programmed to quickly test boards for faults and function. Depending upon the product they are testing they can be complex and expensive items. The tester gains access to the PCB through either the edge connector or to individual node points by means of a bed of nails fixture (Fig.1.1). The bed of nails fixture contains spring loaded probes (Fig.1.2) which make individual contacts and they can be used for testing bare or populated boards. They are available or can be designed for use with test equipment, ranging from simple panels of lamps to sophisticated electronic systems tied to mainframe computers. The board configuration, test parameters, and ATE interface requirements determine the design of the test fixture and the type of probes to be used.

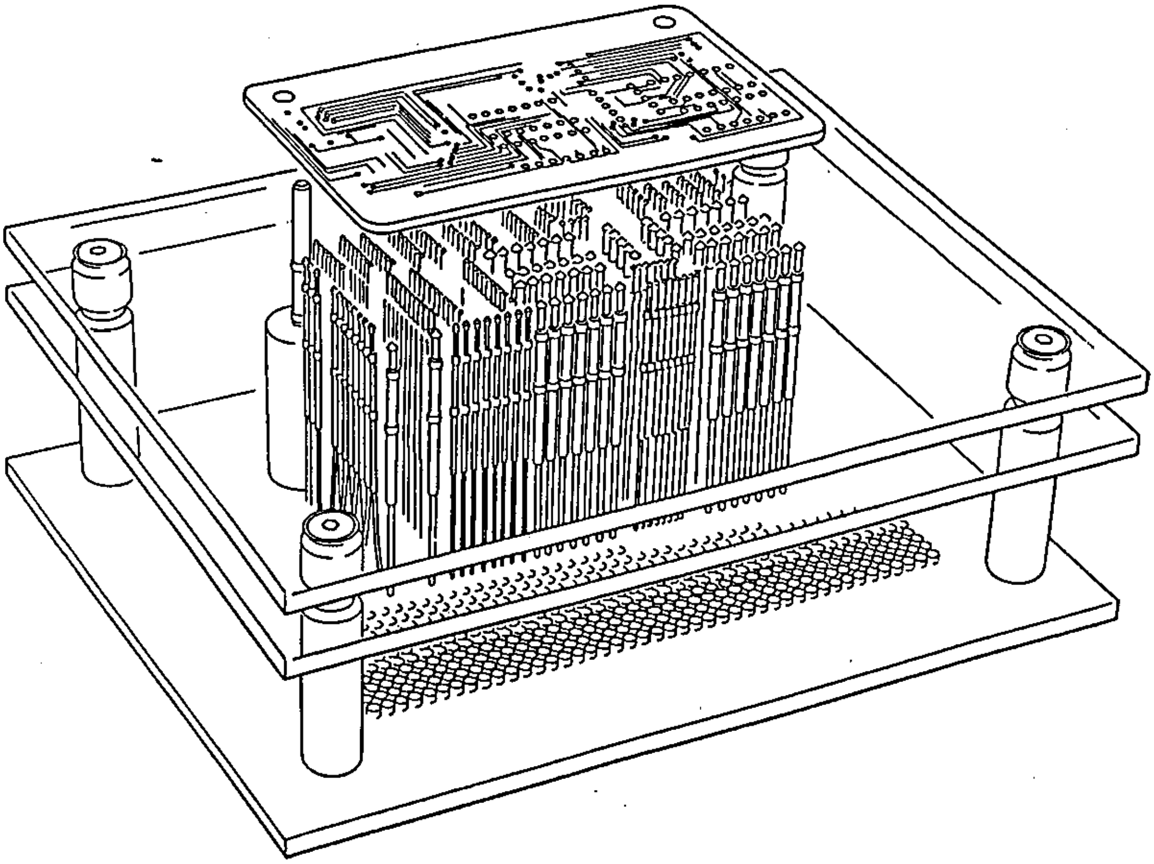


Fig. 1. 1 BED OF NAILS FIXTURE.

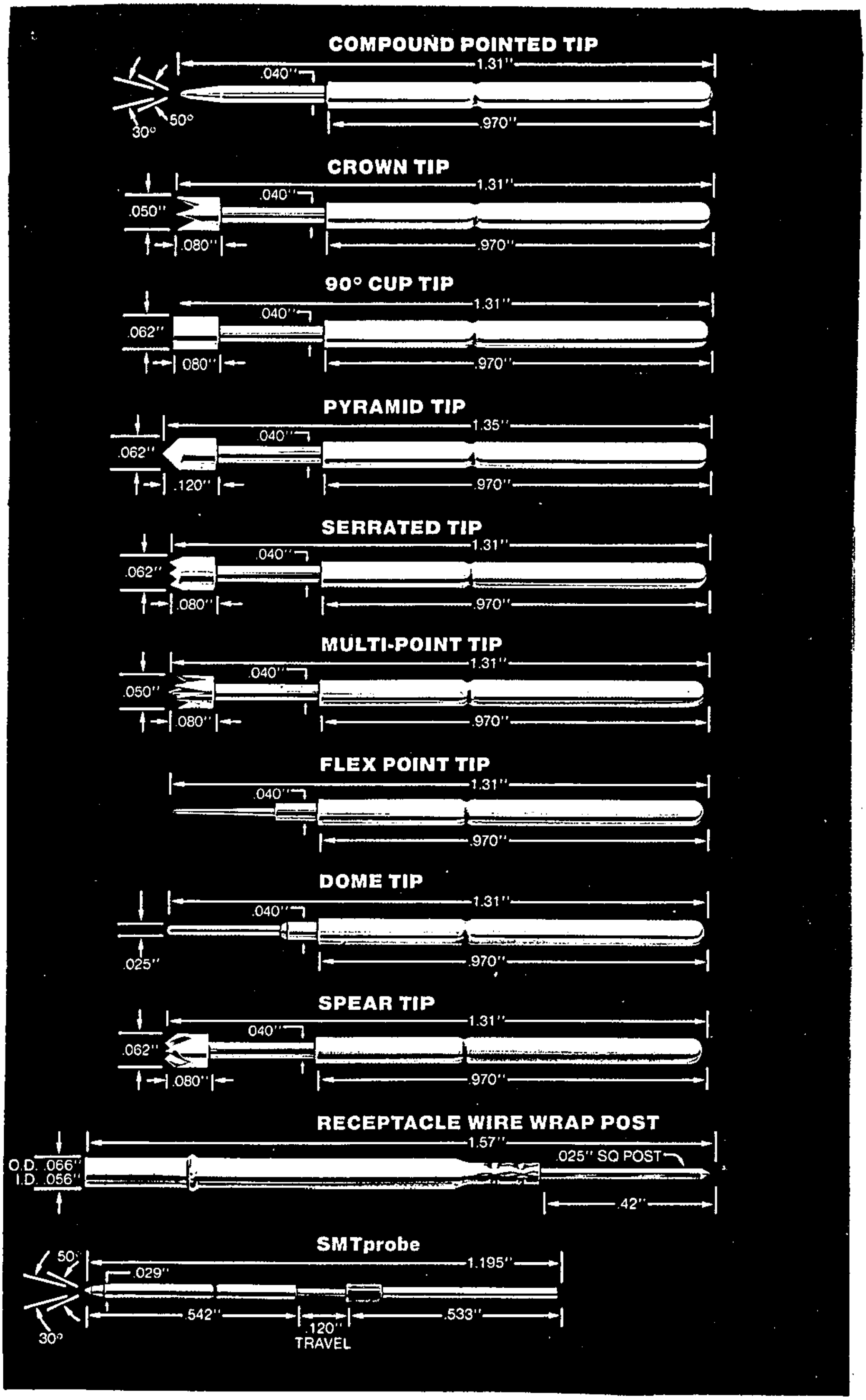


Fig. 1. 2 SPRING LOADED PROBES AND RECEPTACLE.

There is now much greater pressure for manufacturers to test circuit boards during and after the production processes, as greater cost savings may be achieved by eliminating faults at an early stage, since it is much easier to identify and rectify faults early in production, due to the increasing product complexity as it passes through progressive stages of manufacture.

Testers are available to locate specific types of faults as quickly as possible, or alternatively, a tester may be designed to contain the whole spectrum of faults on one machine. The number and type of testers required, will depend on the number of faults produced in various categories over the fault spectrum. For instance if faults produced by a process were 99% solder shorts, then the only tester required would be a shorts and opens tester. Another factor effecting the choice of tester would be the number of products requiring testing, for instance, a manufacturer producing occasional batches of circuits every few days would require a tester to cover the whole spectrum of possible circuit faults. However, companies using their process lines continuously, could have a predominant number of faults developing in part of the spectrum, requiring a specific type of tester to overcome the problem.

An important factor for consideration is the ability of the range of testers chosen to detect the highest possible percentage of faults in the minimum time. It is possible due to changing conditions on the production line (with different component suppliers feeding into the system) for the fault spectrum to change on a daily or weekly basis thus needing a change in the order which different types of testers are used. With complex circuit designs certain faults may become masked by other components within the circuit design, resulting in a small percentage of unverifiable faults for the ATE system used in the process line.

In the past low cost, low density boards could be scrapped if the cost of testing and repair approached the cost of the board, but with todays high density double sided boards, their value will often be too high for them to be discarded. The amount of time spent on fault identification will therefore increase.

In the 1960s and 1970s, most of the testing and repair work was done by skilled technicians using a wide variety of test equipment. This often comprised of parts of the product along with conventional electronic test instruments, sometimes interconnected using a buss, controlled by a small computer (19). By 1975, there was a range of purpose designed testers available, using a computer as an operating system controlling the various test instruments.

The range of testers available include testers designed for only one specific type of testing, for example, the bare board shorts and opens tester, or the functional circuit board tester, being capable of performing only one test function. Other testers such as the combinational tester, as its name implies, can perform a combination of tests using only the one tester. This type of tester would be found to be more useful in a production unit operating well below its maximum capacity, as its flexibility with increasing use could cause it to become a bottle neck. Circuit board testing ensures better quality while at the same time monitors production plant processes, so avoiding more costs in diagnostic and rework activity at a later stage.

1.3.1 Automated Test Equipment Fault Coverage

While studying a circuit schematic diagram, it is often found that components are masked from fault detection, by one or more of the different types of testing used by the ATE but detectable by another. In a small minority of cases, it may be found that faults are undetectable on a loaded PCB (20) which is why it may be desirable to test at various stages of manufacture. An indication of fault coverage is confirmed by the results of fault detection at later stages of testing, assuming the testers used, are capable of detecting the fault. Fault coverage in testing may be effected by whether the board is digital or analog or a combination of the two, as well as relating to the complexity of the circuitry to be tested.

Fault coverage claims by tester manufacturers are surprisingly high, figures of between 80% and 98% are given for functional testers compared with 85% to 96% for in-circuit testers (21). The time taken in test execution and programming is an important consideration when considering the merits of various types of ATE. The in-circuit tester uses three levels during testing, short circuits, unpowered component testing, followed by powered component testing. Using this approach, damage to components can be minimised during the testing of faulty boards, as the first two stages of testing will identify serious damaging faults before power is applied. There may be long diagnostic times with functional board testers, due to operator intervention, followed by further probing required to localise faults.

1.3.2 Unverifiable Faults

The number of unverifiable faults , although relatively small in percentage terms (around 2% at the moment), is bound to increase with increased board density and complexity. ATE will therefore need to become more sophisticated and faster, if it is to maintain or reduce unverifiable fault levels. As mentioned earlier, it is possible that components in a part of a circuit may mask certain types of faults, but other unverifiable faults may be due to problems in the ATE interface connection to the circuit boards or unit under test (UUT). Connection difficulties may be caused by contaminated solder pads on the PCB or the spring loaded test probes used to make contact with the PCB. The probes may become contaminated with flux or other material used on the PCB, or become bent, or misaligned. Internal springs within the probe may become broken or worn or cause the test probe to jam. Another problem is that the springs often become weak after considerable use and do not exert the required force to produce a low ohmic contact.

Wear debris within the probe may also be responsible for this type of defect developing, causing unreliable intermittent contact to the UUT. A suitable choice of appropriate style test probe heads, which should be compatible with the PCB contact target, will minimise unverifiable faults. Almost 80% of all faults found in manufacturing circuit boards are process errors. These faults, which include opens; shorts; components that are incorrect; defective; incorrectly positioned; missing, can be easily found by measuring their impedance signature. A procedure which is much more cost effective than that needed to identify the 20% or so of faults that are dynamic or functional in nature. A tester designed for this purpose is the manufacturing defects analyzer, developed to find faults at one quarter to one tenth the cost of in circuit testers. About 90% of all faults can be found with in circuit testing, while the final 10% require functional testing (22).

About half of all board defects are due to shorts and opens. However, depending on specific manufacturing processes and complexity of the circuit board, each board will have a slightly different fault distribution. Defects are introduced into the circuit boards as they travel through the production process. Typical figures quoted for production defects in electronic manufacturing journals are, boards with no defects 74%, boards with one defect 22.2%, boards with 2 defects 3.3%, and boards with three defects 0.3% (22).

1.3.3 Fault Spectrum

The fault spectrum is the distribution of the different types of defects that occur on a board, on a collection of boards, or from an entire production process. Defect categories consist of many kinds of faults such as solder shorts, missing components, wrong value components and timing race conditions. While there are literally hundreds of defect categories, they all fall into three fault classes. Which are:- (1). Device Faults; (2). Assembly Faults; (3). Operational Faults.

Device faults include defect categories associated with the components themselves on or off the board. Examples of device faults are, out-of-tolerance components, "non-working devices, mismarked packages, broken leads etc..

Assembly faults arise from defects which occur to components and to the sub-assembly itself as it proceeds through various stages of manufacture, solder shorts, mis-inserted or missing components and cold solder joints are typical assembly defects.

Operational faults are problems which cause functional failures on the board , that cannot be traced by the test system in use to a particular device or an assembly problem. In other words, the board has no identifiable construction defects but it still will not work. Timing race conditions between different sections of the board, tolerance build up (where all the components in a circuit are within their specified tolerance, but perhaps all at one end of the tolerance bond such that the entire circuit falls out of specification) are typical operational faults.

1.3.4 The Test Fixture, a Preliminary Description

The Bed of Nails test fixture (23), which interfaces a PCB to the ATE often represents the true limit of test capability. The fixture may introduce electrical and mechanical parameters which limit the ATEs ability to locate faults accurately down to component level.

There are three main type of test fixture: Vacuum; mechanical and pneumatic. The major difference is in the way in which they are actuated. Vacuum fixtures are the most widely used (Fig.1.3). Air is evacuated from a sealed chamber between the boards and the probe matrix then draws the board onto the probe tips. Mechanical fixtures sometimes known as manual fixtures, push the board down onto the probe tips by a manually operated pressure plate (Fig.1.4). Pneumatic fixtures are similar in many respects to mechanical fixtures, but they force the board down onto the probe tips by air cylinders rather than arm power and a lever (Fig.1.5).

The test probe is perhaps the most important component in an ATE system. It is the probe which makes the physical and electrical contact with the board, and through which information flows from the board to the ATE. Therefore the probes must be totally suited for the specific application.

The important probe characteristics are its electrical properties, contact shape, length and diameter, they are available in both long and short stroke length, as required. The probe diameter is more critical, because it controls the minimum allowable centre spacing and maximum current carrying capacity.

VACUUM OPERATED TEST FIXTURE – GENERAL ASSEMBLY

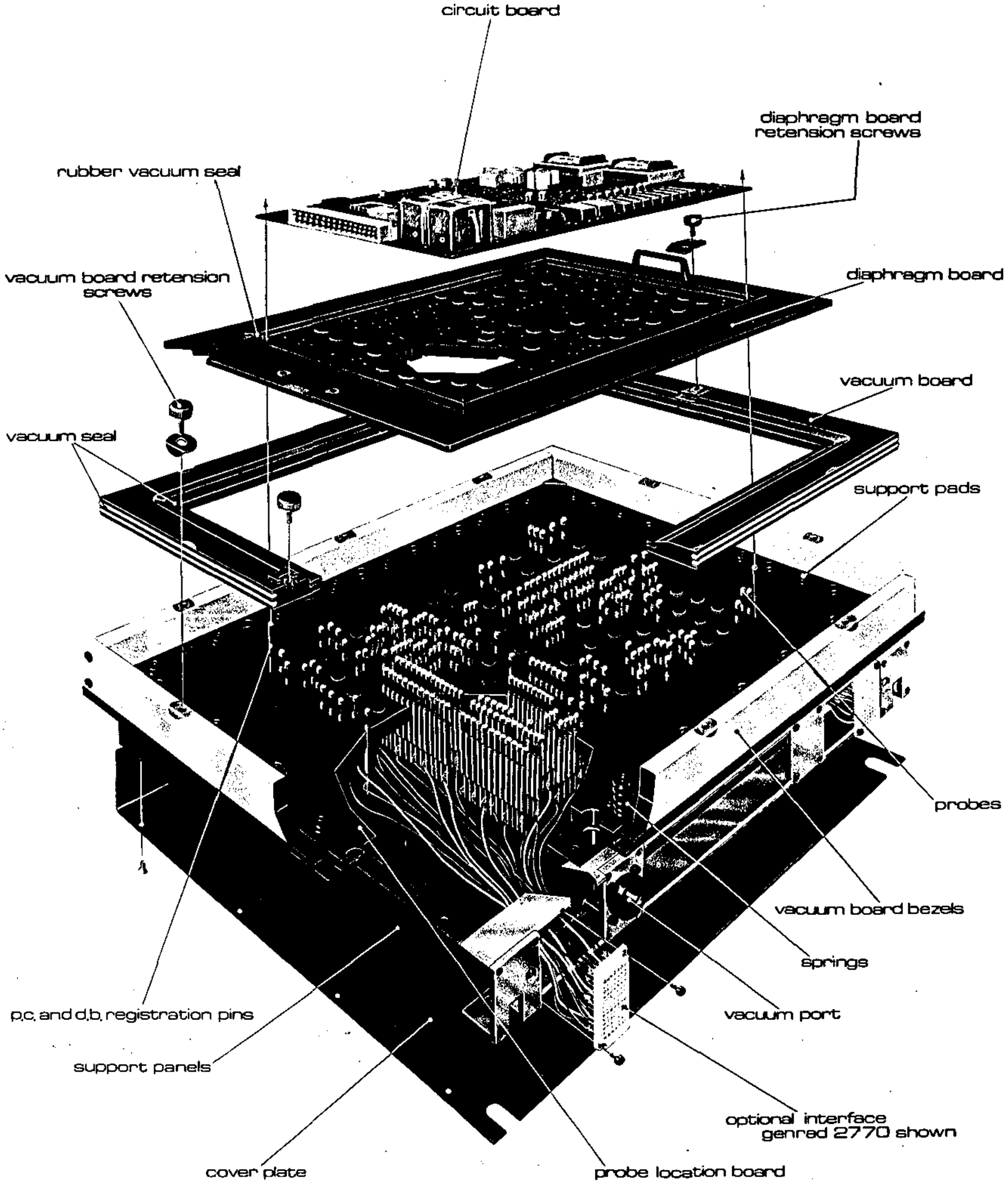


Fig. 1. 3 VACUUM FIXTURE.

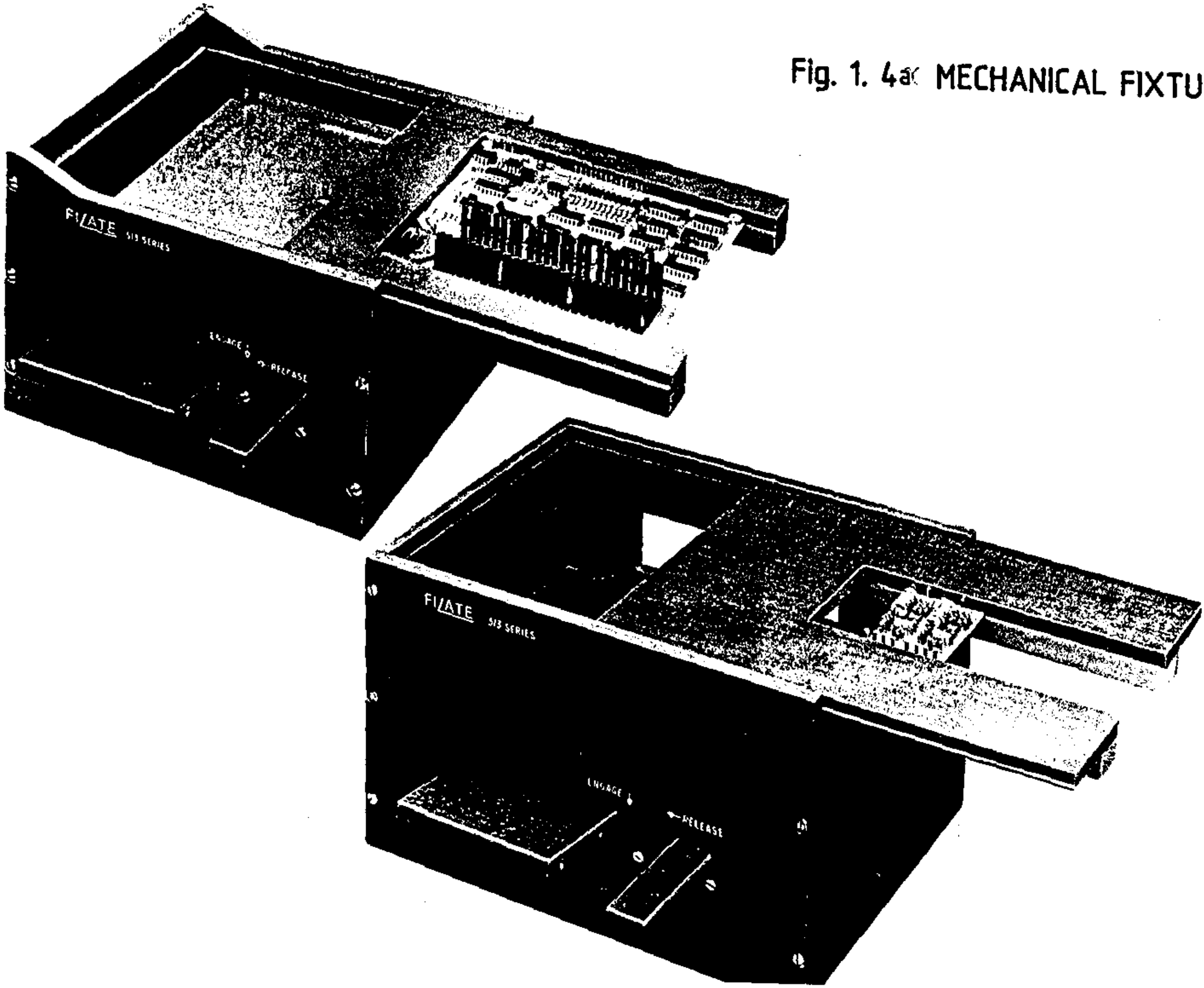


Fig. 1. 4a MECHANICAL FIXTURES.

Manual Test Fixture

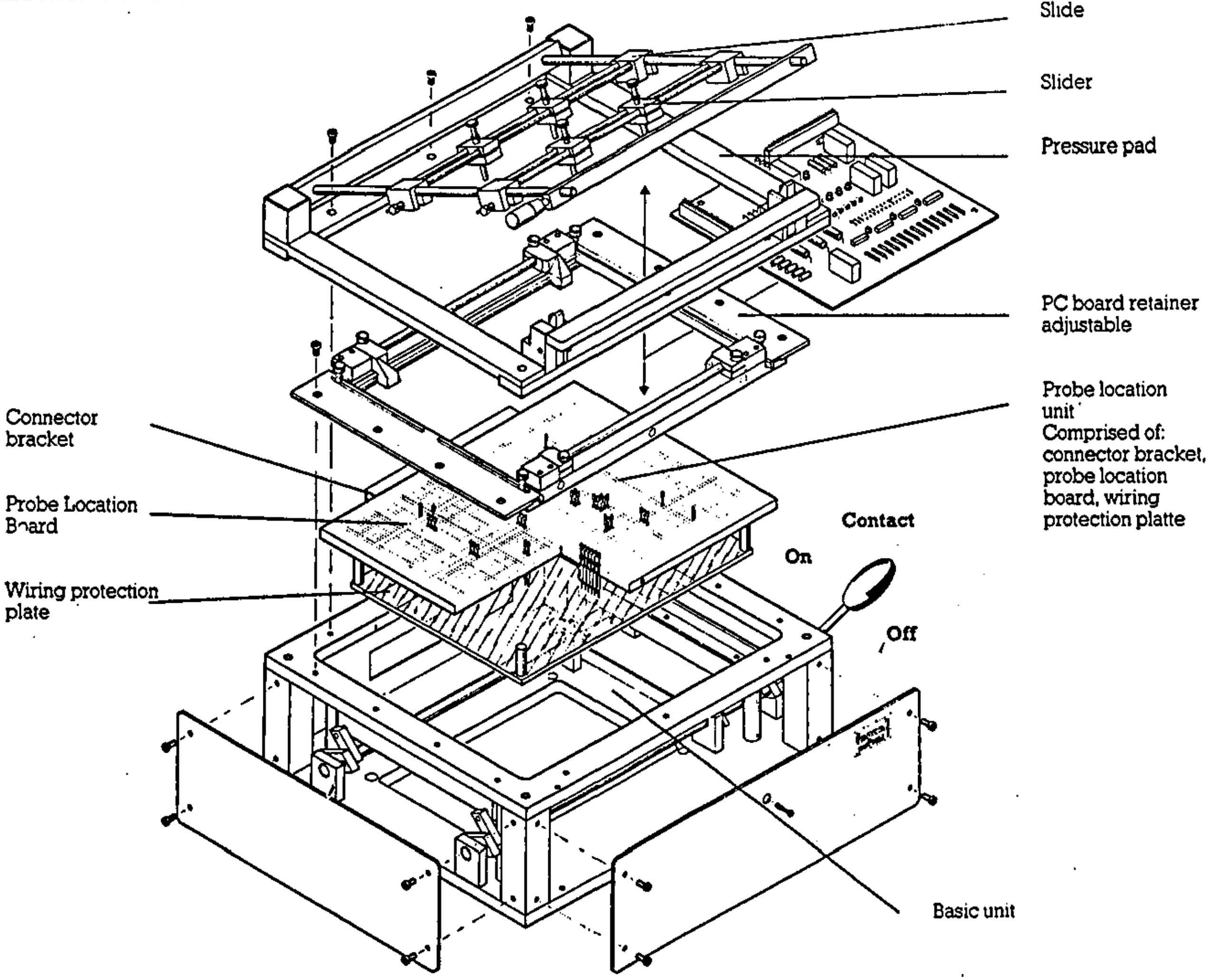


Fig. 1.4b Mechanically activated fixture.

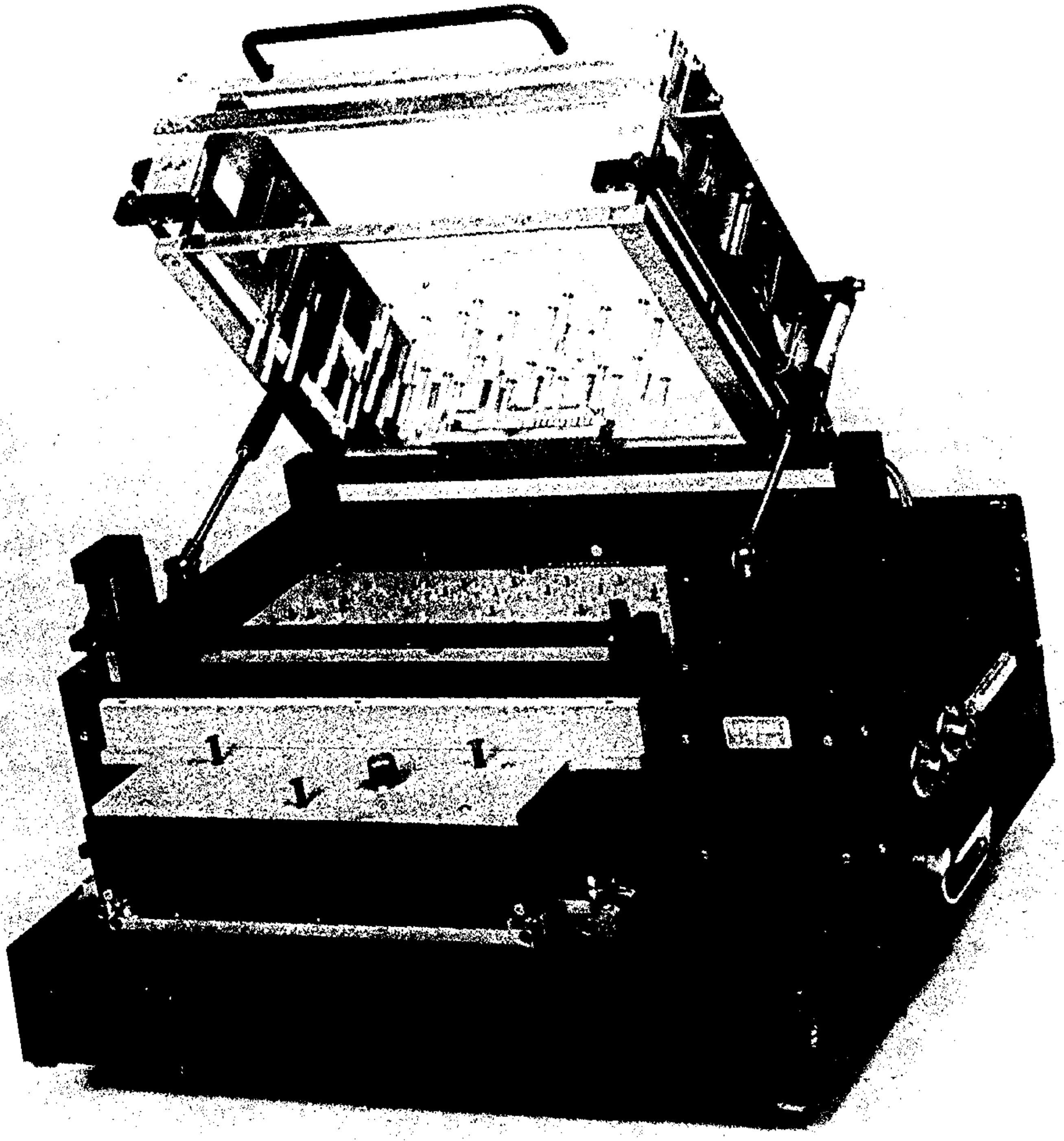


Fig. 1.5a Pneumatic Test Fixture.

rsion for contacting from both sides and
mbined in-circuit and functional testing
obe Location Unit with integrated
erface for interfacing to the HP panel
essure pad system can be lowered manu-
y and pneumatically

Pneumatic Test Fixture

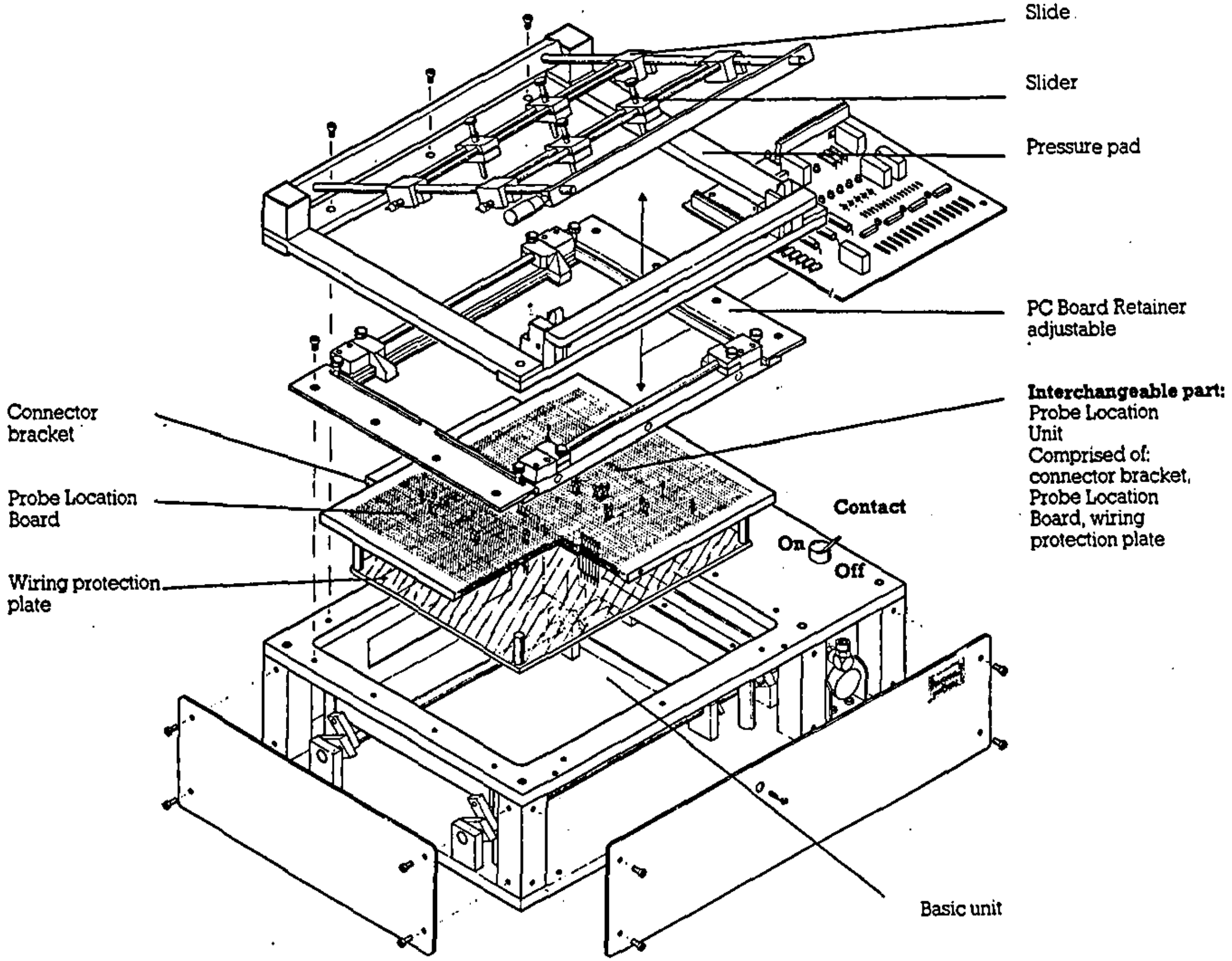


FIG. 1.5b

1.3.5 Test Probe Construction

The main parts of a probe, are the barrel, plunger and spring (Fig.1.6), with variations available in each. The barrel acts as a housing for the entire probe assembly, and also as a bearing surface for the sliding portion of the plunger. Barrels are generally made of phosphor-bronze tubing, although other materials may be used to give desired probe characteristics.

The probes spring can only provide a certain number of operating cycles at a precise load at fully compressed operating pressures, however, manufacturers usually guarantee probes for a certain number of cycles, a typical value being one million. Heat treated beryllium copper, which offers excellent bearing characteristics is used for the moving plunger section. Hard gold plate over a nickel preplate, provides the corrosion resistance, copper creep restraint, and the electrical conductivity characteristics required for a good connection.

To make probe removal easier for cleaning and replacement, each is housed in a receptacle, which is wired into a matrix on the bottom of the board. It is important that the receptacles hold the test probes firmly in place at specific test points within the fixture, receptacles are connected to the ATE interface by hand wiring. There are four main methods of connecting wires to the receptacles: (1) wire wrapping; (2) soldering; (3) crimping; (4) plugging. Wire wrapping is the most widely used technique, as it provides an excellent mechanical and electrical connection, which is economical whilst being removable, without damaging the receptacle. Soldering is the second most popular method being stronger than wire wrapping, but has the disadvantage of being permanent. Crimping, like wire wrapping is economical, provides a good electrical contact, but where there are dense pin fields on close centres there is little space to use a crimping tool, and is time consuming. It is much faster and easier to wire pins with a wire wrapping tool, because once crimped, removal or replacement of the wire is almost impossible. Plugging as a wiring option has almost fallen into disuse, because it does not provide a good connection either mechanical or electrical. However it does offer a replacement connection and may possibly be used for closely spaced probes.

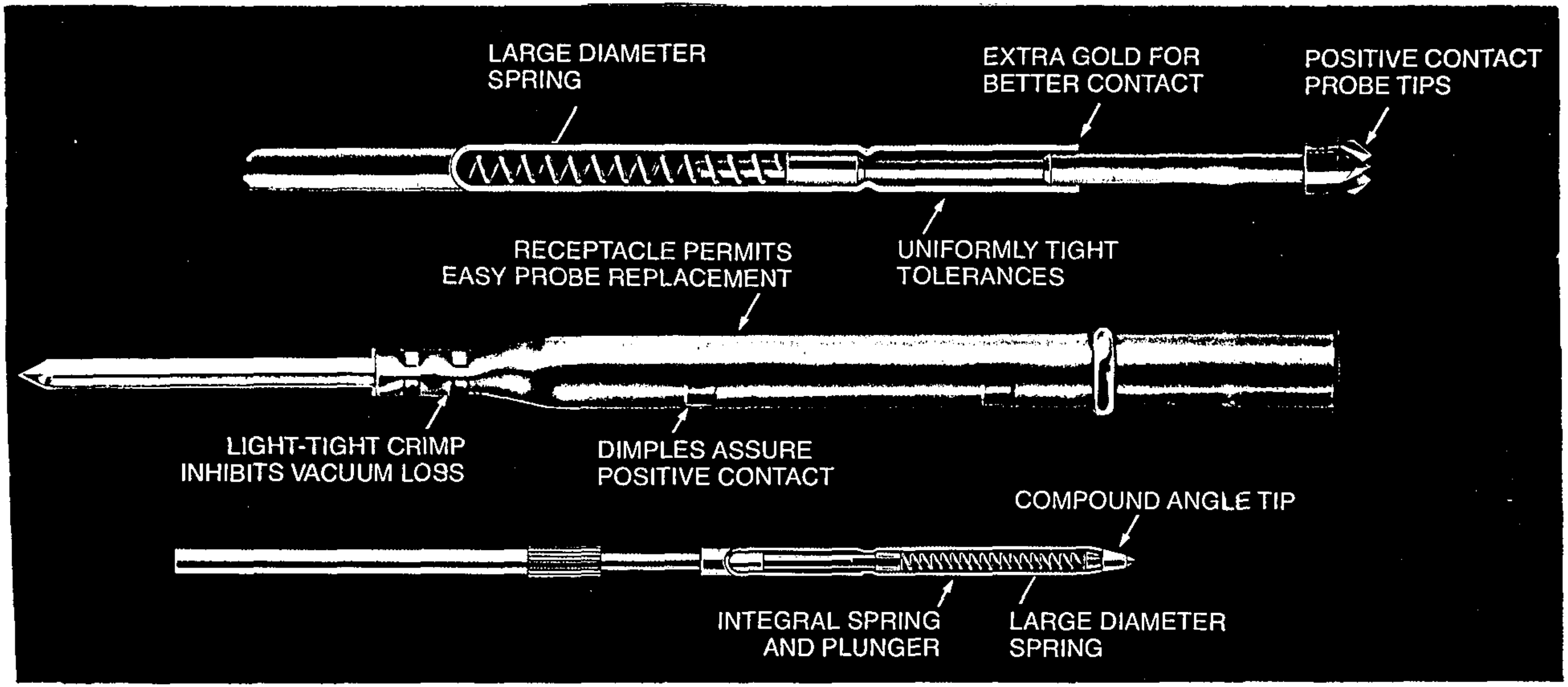


Fig. 1. 6 COMPONENT DIAGRAM OF PROBE ASSEMBLY.

1.3.6 Surface Mounting on Both Sides of the PCB

The practice of mounting components on both sides of the PCB is now well established. Instead of using holes through the board for component leads to be anchored to solder pads on the opposite side of the board, epoxy adhesive is used to secure the component to the PCB dramatically reducing the number of holes required. Components are therefore held by the solder bond to the tracks as well as the epoxy bond to the PCB. This eliminates the majority of holes, and means that both sides of the board can be used for circuit tracks and mounted components, greatly increasing circuit and component density.

The trend towards surface mounting of components however, leads to problems when trying to test a completed PCB. There is the possibility of tracks, pads and component terminals being inaccessible to test probes, partly due to chip component connections made on the underside of the component. There is also the further problem of the surface mount components on both sides of the circuit board which requires access by the test probes to the tracks and pads both sides of the PCB simultaneously.

The effect of increased component density and miniaturisation is to increase the amount of precision required in the test fixture. In order to overcome obscured PCB pads, tracks, and component terminals, additional test pads need to be designed into the initial design to overcome some of the problems encountered.

1.3.7 Reasons & Problems Encountered in the Testing of PCBs & Components

Most electronic manufacturers use a wide variety of test activities that can be divided into three general categories: (1). incoming inspection testing of parts; (2). testing of assembled circuit boards; (3). final system test when the product is completely assembled and ready for dispatch. Because of the increasing complexity of electronic components assembled into more complex units, testing is becoming one of the more important aspects of the production cycle. It is necessary to test at all stages of manufacture to eliminate defects at an early stage and identify defective processes and increase product yield.

The advantages of adopting a total quality approach are now well known and lead to an improved reputation and business image. The costs of introducing and implementing a suitable quality system, are far out-weighed by the savings made in reduced operating expenses and product failure costs. Productivity can often be increased, by the monetary savings translated into increased R & D expenditure or improved production techniques (24).

Nowhere has the increasing complexity and cost of manufacturing electronic products become more apparent than at the circuit board test stage, because new technology keeps demanding new test approaches.

1.4 ECONOMIES OF QUALITY ASSURANCE

Printed circuit board testing is now well accepted as an important tool in helping to achieve improvements in product quality. By being able to determine the presence of faults, computer controlled test equipment has made it possible to report back, so that production faults can be corrected at source. Testing is therefore, an aid in the quest for improved quality and it has to be recognised, that fundamentally these reporting and data analysis processes are only useful, as long as the basic test and diagnosis facilities are capable of isolating a large percentage of faults. Design for testability has always been important for electronic companies wishing to minimise manufacturing cost and improve production quality. A great deal of time and money can be saved by taking a little extra care during the design and lay out of any PCB. New production processes are required to accommodate the rapid progress to higher levels of integration in semiconductor circuits. Increased integration affects both the components of the electronic assembly, as well as the techniques used to assemble and test the completed circuit. However new processes are emerging, which lend themselves to and in many cases demand automation. The benefits of new technology are many, greater circuit density, smaller product size, better performance, product reliability, and ultimately resulting in lower production costs.

In many cases, traditional in-process inspection and probing/fixturing techniques for electrical testing are no longer effective or applicable. Visual inspection is becoming less efficient as circuits become more complex with narrower tracks and smaller spaces. This is unfortunate since in many cases not only is the basic integrity of the circuit important, but consistency of line widths and spaces are critical to the function of a high speed assembled circuit (25).

As circuit integration progressively increases, so does the demand for improved circuit board quality with the ability to eliminate faults at the earliest possible stage in the production line. Testing is often left until all the components have been assembled and soldered into the circuit board, greatly increasing the costs of fault detection. Due to increased miniaturisation, a larger proportion of faults will be caused by inadequate circuit board quality. J. Page-Walton states, that typical yield in PCB manufacturing is said to be between 85% and 90%, depending on pattern complexity. Since the X10 rule states that with each step of the manufacturing process, the value of the product increases by ten, inspecting the bare board at the earliest stage is one of the cheapest ways in which to detect errors (26).

Consideration should therefore be given to bare board testing and inspection, where track thickness and spacings are fine. Electrical testing will find existing causes of failure, but not potential causes of failure such as protrusions, undersized lines, track bites, or registration problems. Optical inspection would detect potential weakness which would go undetected using electrical test methods, and which might not become evident until the board had passed through several more processes, and had increased in value. In the worst case the fault could find its way out into the product, failing after weeks, months or years of service.

Another method being considered to improve PCB quality is high voltage testing, designed to "weed" out potential shorts likely to appear when the board is powered up during final testing, or in operation.

Poor quality PCBs can cause considerable increases in cost, as board faults would be assumed to be due to component or soldering defects. Loaded board testing would mask any faults existing in the printed wiring board, and would probably show up as component faults and could mean extensive fault finding time by a skilled technician, with resultant increased costs.

Printed circuit board quality can be adversely affected during the soldering process, if the process control conditions are not set or maintained to suit the board being soldered. Automated soldering processes have been used to solder components into printed wiring boards for the last thirty years, but once again, as with PCB testing, fine lines and spaces have put greater strain on the soldering process.

Poor quality joints can be caused by oxide coating on the PCB or the component leads, furthermore a poor quality PCB design can lead to soldering defects. For high quality production, solderability tests should be carried out on all PCBs, components, and connections before they find their way into the production line. Better quality in production can save money in the long term by cutting the cost of testing, rework, and scrap production.

According to D.Elliott there are 2000 defective solder joints for every million joints soldered. At this rate, the industry is producing 400 million defective solder joints per year. The Institute for Interconnecting and Packaging Electronic Circuits (IPC), reports that 26% of the cost of assembling PCBs, is for repair and rework plus another 30.2% for testing. When one includes the cost of field repairs and the number of times that an assembly must be tested and retested, it can cost a surprising $1.00 - $2.00 for each defective joint. This equates to $400 million dollars per year (27).

The aims of any electronic manufacturer must be to achieve a near zero defect soldering programme, to eliminate solder repairs and reduce in-circuit testing. Circuit board handling should be kept to a minimum throughout all the production processes, as greasy fingerprints due to handling, may cause increased soldering defects which would probably be incorrectly attributed to the soldering machine. Most latent solder defects are not detectable by the usual test routines employed, but are mainly attributed to cold or oxidized solder joints. Most latent faults will occur during the early mortality phase after a short period of thermal cycling, leaving a small percentage of mature failures over a much longer period, in the order of months or years. A large percentage of latent faults can be detected by rapid power and temperature cycling in an environmental test cabinet. From the quality cost and reliability view-point, it is better to concentrate on eliminating solder defects, rather than detect and repair soldering faults that may occur.

Bateson states that the cost of correcting faults after PCB assembly and soldering, ranges from $3.99 to $6.50. The cost of correcting a fault at system test ranges from $30.00 to $65.00. Further, correcting a defect in the field costs between $300.00 to $650.00 at 1985 prices. Obviously, it is economically advantageous to find and rework faults at the earliest possible point in the production process (28).

Soldering faults are included in the faults that can be induced by the manufacturing process, other faults in this category are: components which are wrong, missing or wrongly polarised; leads that are missing, broken or bent; wiring that is missing, broken or wrong. Manufacturing process faults account for 50% of all faults with 30% static assembly and component faults, leaving 10% each for dynamic component faults and dynamic unit faults (29).

Although defect free manufacturing will probably be unattainable, electrical testing has proved its ability to raise the quality of the delivered product, and reduce the cost of manufacture. Quality control is basically the supervision of a product throughout its production and up to delivery to the consumer. The product must meet basic minimum standards through each phase of the production processing cycle, assuring quality and long term reliability in the final product.

1.5 METHODS OF TESTING COMPONENTS & PCBs

Component testing is the only way of ensuring a supply of high quality components despite overall component quality improvements, it is only in more recent years that the failure rates on even the most common components were generally known. Increasing quality awareness and the competitive need to make products more reliable, has led to a better understanding by the user, and further improvement from the components manufacturers. Although vendor quality assessment schemes have helped to reduce received goods inspection in general, at the moment there is no indication that component failure rates are becoming so low that the user does not need to test.

Electronic equipment manufacturers have to be more aware of the reliability of the devices they manufacture, by screening out marginal components that may cause intermittent faults causing the product to fail early in its life. As more complex and expensive assemblies become common, they are at the same time becoming difficult to repair and yet too costly too discard, furthering the need for incoming component testing over a wider range of products. Companies may now have to turn to incoming testing of all components in an effort to increase quality and reduce production costs. In circumstances where component quality can be proved to be very high, switching to batch sample testing may prove to be more economic, although allowing a very small number of faulty components onto the production line.

Goods inward testing, can be automated by the use of automatic handling machines in conjunction with the component tester. This may take the form of an automatic L.C.R. bridge for testing passive components such as: resistors, capacitors or inductors, or in-circuit testers configured to test either passive, active or integrated circuits of all types. Automated testing of components may require the use of a fairly simple test fixture, to make contact with the device pins or wire leads, but some testers have a range of test heads suited to the types of components to be tested. There is often little or no difference in the testers used for goods inwards testing, and testers used in production testing.

Large users of high technology devices, are using sophisticated ATE for incoming inspection purposes in an attempt to increase quality, and reduce the number of units that have to be discarded as scrap.

The increasing use of surface mount components with more complex and dense packaging, can often mean that a component can be near impossible to replace, or several devices may have to be replaced, because the ATE cannot diagnose a fault to component level. Component testing before assembly may save considerable time and money, leading to a more reliable and better quality product. In an ideal environment one could test every item entering the production line, or better still with 100% quality there would be no need to test them at all. Unfortunately, component testing is still necessary as a method of assuring quality and reducing the amount of rework after final testing. In the case of consumer domestic products, it may be considered impractical or uneconomic to test every component used in a product, therefore, testing only a small percentage of each batch delivered. It may be worth while considering BS 6001 with respect to sampling, inspection and testing of components (30).

With the ever increasing use of automatic test equipment, the cost per parameter for each device is far less than a bench test or post- production rework. Automatic test equipment can perform the primary tasks of receiving inspection testing in a matter of seconds to assure acceptable parameters (31).

1.5.1 PCB Board Testing

Printed circuit board testing can be divided into a number of categories, the first being, bare board testing where the circuit board is tested without components. The objective being, to locate any faults caused by the printed circuit board manufacturing processes, as it is a much easier task to locate circuit board faults at this early stage of the production process. At this early stage all faults will either be shorts or opens, detected by electrical or vision methods of inspection. Faulty boards can be inspected after testing to locate and rectify faults, or alternatively, automated testers will indicate fault locations by directing a flashing light or laser beam to pin point the exact position. Bare board testing may pay economic dividends by reducing the cost of testing and reworking loaded boards, which have become high value added near the end of the production processes. Bare board testing techniques range from hand held probes, to bed of nails test fixtures as a method of making contact with the board under test.

Another system in use, uses computer driven moving probes that access any point on the bare boards testing for shorts opens and high resistance leakage. The moving probes eliminate the need for expensive dedicated test fixtures, but the system's sequential nature limits the test speed to a rate of 350 points per minute. It has been shown that up to 50% of all circuit board faults can be found at bare board level (32). The most obvious method of testing is with two moving probes, using continuity to detect open circuits, but by using this method the time could become prohibitively long to test a complex board. Using another concept, both shorts and opens can be uncovered by using capacitance for detection, and resistance for verification. Some testers use a two or four probe configuration and can provide access to both sides of a double sided board. Visual methods of inspection do not functionally test a board but they do identify design rule violations e.g. narrow tracks, which may cause breakdown in service.

The manufacturer of printed circuit boards dates from the post war years, but electrical testing of bare boards has only had serious consideration since the late 1960s or early 1970s, mainly due to higher circuit density and miniaturisation. With technology producing more complex components packaged on even smaller circuit boards with finer line configurations, its value has become increasingly high and the need for suitable test methods has increased.

Today it is becoming more generally accepted, that printed circuit boards are supplied tested, especially the double sided fine line designs. However, there is still a large number of manufacturers that do not test before delivery, in spite of the speculation that failure rates on some PCB lines may initially be as high as 50%.

Loaded board testing is required to detect the whole range of faults, which may be in the circuit board, components, or faults induced by manufacturing defects within the production system. The ideal test system is one that finds the largest range of fault classes at the smallest cost. There may be a justification in the argument that detecting component and assembly faults at the earliest possible stage, by relatively simple equipment, will result in the downstream test costs being reduced. A general figure quoted in journals is that 80% of the faults at the first test are assembly related.

In use today are four categories of circuit board tester, the first being, the bare board tester mentioned earlier, the others being, in circuit, functional and the loaded board shorts tester sometimes known as the pre screen tester.

In a situation where shorts are the predominant process fault, it may be cost effective to use a loaded-board shorts tester as a pre screener, before in-circuit or functional testing. This screening improves the test capability, which in turn increases the production throughput. A loaded board shorts tester will rapidly identify shorts in a single pass, and will produce failure messages to guide rework. Alternatively, an in-circuit analyzer may be used to rapidly test for shorts, resistance, capacitance and semi conductor junctions on an unpowered PCB. The in-circuit analyzer may be used independently or as a screener before in circuit or functional testing, thereby producing a very cost effective method of increasing the product fault coverage, improving the finished unit yield throughput, by first testing for shorts and secondly testing for component failures.

In order to cover the full range of circuit board faults. The in-circuit tester is necessary , using a guarding principle to measure the performance of individual components by electrically isolating them from the surrounding circuitry. It is also capable of detecting shorts and opens as well as testing passive components on an unpowered PCB. At the next stage of testing, power is applied to enable active component testing. In circuit testers can cover a larger fault spectrum, displaying specific failure messages. The tester may be used independently, or as a screener before the functional tester. It can be a cost effective method of increasing the product fault coverage, thereby increasing throughput and the finished unit yield, but the test and diagnostic time is considerably faster than that of other testers considered. In-circuit testers are capable of identifying multiple faults within each of its levels of test hierarchy.

Functional testing of a circuit board is the only way to prove that all the manufacturing and component induced faults have been eliminated at the end of the manufacturing processes. In order to prove that the circuit board can achieve all of its design functions, it is subjected finally, to the functional board tester, which has the largest fault coverage capability by simulating all the operating conditions. In testing, it produces stimuli measuring the response of the PCB in the final product environment. The functional tester is essentially independent of the rest of the test systems, but has an extremely rapid go/no go test time with an extremely slow diagnostic time, it produces general failure messages which may require some interpretation. The functional tester is designed for general purpose use and not for a specific range of boards. In addition the programming costs associated with functional testing can be high and the programming time lengthy.

1.6 ADVANTAGES OF ATE

The objective of electronic production engineering is to optimise product quality, while at the same time try to maximise throughput of the production line, both in the most cost effective manner possible. Increasing the throughput beyond a certain point may lead to increased production, but at a loss of product quality. There is a need to employ automated test equipment to reduce costs, increase profits, increase productivity, reduce the need for skilled labour, and increase product reliability. The cost of detecting and reworking a PCB fault increases significantly as the production process advances, optimising in field service and repair on the customers premises under product warranty. Automated Test Equipment includes the whole range of circuit board testers from the bare board testers, the loaded board shorts tester, the in circuit tester, the in circuit analyzer, the in-circuit and functional board tester, being the whole range of test equipment in use today. ATE is now beginning to play an increasing role in the field service and repair environments as a way of reducing costs, reducing the need for skilled and experienced technicians leaving only circuit board replacement in the customers premises. In the PCB production environment, testing ensures subassembly quality and monitors the manufacturing processes to avoid more costly diagnostic rework, at a later stage.

There may be certain circumstances where, not testing a circuit board may be a sound economic decision. For instance, where the PCB is extremely simple and has a very high pass yield, or extremely low volume. Manual testing is quite common in small companies with low volume PCB production requirements. Testing consists of a technician using an array of bench instruments following a routine test procedure to verify correct circuit function, followed by defective PCBs being further diagnosed by a higher level technician. Test cost per PCB is usually very high because of the labour intensive nature of the operation.

There are a number of less automated ATE systems in use, where a group of IEEE 488 bussed instruments are connected to a PCB test fixture, and are controlled by a micro processor or mini computer. This type of ATE is sometimes known as "rack and stack", and offers a large degree test configuration with flexibility at a moderate cost. Unfortunately, the set up time is long and requires a test engineer and skilled technician. Test quality will depend on the skill of the programmer with a fairly high unit test cost. Rack and stack testing is common in small to medium size companies for low volume testing.

When considering the set of test functions performed automatically, most of the testing operations would be performed simultaneously. Print outs would be produced more rapidly with near 100% accuracy, other advantages are the ability to store data for further use at a later date. The elimination of human error with very little operator judgement is an added advantage. PCB units with marginal performance are easily removed from the production line for further diagnosis and rework. There may be circumstances where it may be desirable to test also for variable parameters in a system to be tested. Variable parameters may readily be controlled electrically more easily than manually, with logic matrices replacing mechanical switches, or relays replacing switches. These functions are more rapidly performed automatically, and thus contribute to test time reduction. In most cases, electrical control is more efficient than mechanical methods.

Tracking down malfunctions within a complex system, is a demanding and time consuming operation. A fast overall operational check, eliminates much of these time consuming fault location procedures, saving time and labour to free skilled personnel for more important work. Unfortunately in complex electronic systems, it is possible to arrive at inaccurate fault diagnosis if manual testing is used, but with the use of ATE, faulty diagnosis is more unlikely.

ATE will produce a higher quality and consistency of test results, therefore redundancy and over-testing is minimised, and sometimes is virtually eliminated. Automation can save money in all phases of its operation and offers the advantage of 100% repeatability with mistakes in timing, measurement reading, and sequencing, which are all likely occurrences with manual equipment, largely avoided in an automated programme. Controlled equipment has the inherent capacity to provide the collection and storage of test data on a cumulative basis. Such a capacity is particularly valuable in a failure mode analysis, where the individual parameters monitored may be too numerous for effective manual observation. ATE can determine the failure and record the cause, allowing a test system to be set up whereby the units are sorted as they are tested, resulting in a higher salvage rate than could be obtained by a manual process.

Inspection testing is a significant production expense and can no longer be treated as a manufacturing after-thought. It is evident, that fully automated testing is emerging as a vital factor in manufacture, and a way of controlling the line processes for optimum quality and production rates. Testing costs therefore can be considered as a profit factor, rather than a production burden.

1.7 FIXTURING METHODS AND PROBLEMS

Any item of ATE equipment can only be effective and reliable if it is able to make consistent and reliable connections onto the PCB under test.

One of the methods used to make contact with the board under test, is to make use of the finger connectors on the circuit board, the test interface being a wiring harness with plugs and sockets, making contact with the ATE and the circuit board being tested. Unfortunately, this type of test interface would be only suitable for functional testing of the PCB, since the diagnosis of faults down to component level would require test points available down to every node on the PCB.

In order to facilitate node access, a test fixture is used to register the PCB in a fixed location, whilst accurately positioned test probes are used to give reliable repetitive contact to every board being tested. Test fixtures are mainly vacuum actuated, using spring loaded test probes to make contact with the PCB test points. In the majority of cases, an individual test fixture is required for each circuit board to be tested, but universal fixturing can be used to a limited extent if PCB circuits are designed on a standard grid pattern. Generally test fixture probes access the board from one side only, however a "clam shell" or "toaster" type fixture can be used for double sided board testing. This type of fixture is designed to make contact with both sides of the board simultaneously and is primarily used for boards with surface mounted components (Fig.1.7).

In general, test fixture systems are classified by the method of actuation: manual, mechanical, vacuum or pneumatic. Each type of fixture system is then subdivided into fixed or interchangeable test heads, and fixed or removable probes. The vacuum fixture with interchangeable test heads and removable probes is used almost exclusively by the in-circuit market. The board under test is seated on a probe field by a vacuum, drawn down by a neoprene rubber diaphragm, a movable top plate, or a fixed top plate with flexible gasketing. Each type has its own advantages & disadvantages for different applications. The vacuum is drawn from the test head, either by a hose or a manifold. The probe density is a function of the probe pressure, measured at 75% of its travel with the vacuum pumps employed (33).

In the smaller companies with low throughput, in house built mechanical fixtures may be used, which may be hand or semi automatically operated depending on production line requirements. Test fixtures can be designed as a single or two stage fixture with probes of different lengths, the first set for in-circuit, followed by the second for functional testing of the same PCB. Double vacuum or pneumatic actuating systems are used to make contact to the appropriate set of circuit nodes.

Test fixtures for earlier generations of PCBs with wide lines and spacing between tracks and pads, did not present too many problems for the PCB fixture designer, but for todays PCBs with increased integration and component packing density, the design of test fixtures has

FIG. 1.7 A CLAM SHELL DOUBLE SIDED FIXTURE

become more difficult. The use of more double sided PCBs with surface mounted components on both sides of the board, has made testing and fixture design progressively more expensive. With pin spacing on I.C. components steadily getting closer, there is a greater need for more precision and accuracy in the test fixture.

Surface mounted components on both sides of the PCB may obscure tracks, nodes, and pads preventing access by the test probes. However, this problem may be overcome by the design of test pads in the PCB layout using redundant space that may be available.

Manufacturers may offer a kit to build PCB fixtures. The user drills the fixture and inserts the probe receptacles, wire, gasket, etc. The fixture kit can reduce the typical finished fixture turn around time of 4 to 6 weeks, to 1 to 2 weeks. In many cases the NC drill tape or the bare PC board will serve as a template. Many manufacturers send the fixture plates to the manufacturers of their PC boards for drilling since they have the necessary hole coordinate information.

The advantage of universal fixtures is a reduction in fixturing costs and test head storage. The disadvantage is that if the main portion of the universal fixture malfunctions, the whole test system is down for a considerable time. There is also a high initial cost, equivalent to 4 to 10 individual custom test fixtures. It now appears, that the test fixture is becoming the product of high precision engineering. The accuracy and tolerances that are being demanded to meet todays high technology test applications, can only be achieved by using very high precision machine tools and CNC drills. Fixturing for functional test equipment is considered comparatively simple, because in general, only an edge connector is required to interface the tester to the board to be tested.

For bare board, in-circuit, prescreen, combinational and some functional testers, a more complicated approach is required. Each test point on the board needs to be accessed by a probe, which in turn is connected to a test channel in the system. A bed of nails fixture is used and has to be dedicated to the board type to be tested. It may need to be connected to automatic handling and loading equipment, and in most cases, the fixture needs to be removable so that other board types can be tested.

The concept of the universal fixture was first developed for the bare board testers in the early 1980s. The idea was to build a bed of nails fixture from a number of reusable parts, such as the base plate, frame and probes. The fixture can be easily built, broken down and rebuilt, thus saving time and expense. A top plate dedicated to the board under test is drilled to accept the correct combination and location of probes from the bed of nails. For small board design, only a small bed of nails needs to be installed. Each board type has a personality plate drilled to the correct configuration for the probes. Wire terminals are installed in the contact bed and wired to the probes. When the vacuum fixture is activated, the required probes are raised to make contact with the board under test. Once installed, the fixture allows the user to reprogram the fixture for different PCBs, by changing the personality plate.

The base plate is drilled to a standard grid pattern, but for off grid design, a pitch adaptor plate is also incorporated. There seems to be a small, but growing trend towards designing in a standard grid pattern. Some journals report that at present around 90% of all designs are made off a standard grid. There is increasing pressure for all PCBs to be designed for testability where the increasing use of surface mount components may make a PCB untestable. Double sided test fixtures are not required if all the test points are brought through to one side of the board at the design stage. Typically in any double sided board design, 70% to 80% of all test points will appear on one side. It takes little extra effort to ensure, at the design stage, that all remaining test points are brought through to the same side of the PCB.

The problems of accessing densely packed components or fine tracks and via holes can be solved at the design stage. The designer must regard a test point pad as an essential component and design it into the circuit design. Typically, the inclusion of test pads for the probes would take up about 1% of board space, but there is often up to 20% of unused board space on a design. To enable accurate probing, test pads should be no closer than 0.1" minimum spacing between test points. There are a range of fine probes available for the more miniaturised precision testing applications. Finer probes are required because the lead pitch of SMDs, has reduced the traditional 0.1" to 0.05" currently preferred by the American component manufacturers, and 0.040" favoured by the Japanese.

However, components on 0.030", 0.025" and 0.020" pitches are being manufactured with the forecast of further reductions in the near future. Device availability, shape, pitch and terminations, are all design restraints and affect the production equipment needed for assembly, soldering, test and repair. Target size determination becomes a critical issue when dealing with close centre testing, therefore, it is essential for the circuit design engineer to define a minimum size target area for probing. The relationship of tooling location pins, used to align the unit under test and the test pad pattern with respect to the aligned edges of the PCB, must be carefully assessed. For example, the expected error encountered in drilling the fixture test head, generated by inaccuracies in the CNC drill machine, drill bit flexibility and material properties, can be anything between 0.05 to 0.1 mm. This fixturing error represents the absolute minimum ideal condition and does not indicate any mechanical errors in the probe itself. The recommended target pad size of 0.85 mm may be larger than the available board space will allow. A more practical dimension, such as 0.5 X 0.5 mm would generally work well because the chances of all the tolerances being in the same direction are minimal. Based on experience, an average size of 0.64 X 0.64 mm has proven to be adequate, but if space permits, an 0.85mm target may avoid any probe target misses. In addition, other testability related problems have surfaced: such as fixture and tooling pin tolerances; circuit pad and track spacing; probe tips style; mechanical probe tolerances and probe electrical specifications. The maximum component height will effect the design of the test fixture and selection of test probes, as the probe may have to be extended above the probe plate, to compensate for the difference (34).

It is important to keep all test pads at least 9.66mm from tall components when possible, and group tall components together in case relief cavities are needed in the test head. To make a test, the product to be tested is placed on top of the rubber gasket inside the product dam, which is close fitting to produce a good seal. Air is then evacuated from the space between the probe plate and the support plate, effectively causing the support plate to move down and bring the product in contact with the spring probes, thus allowing the tester to scan the PCB in the test mode required.

1.8 SPRING TEST PROBES

The effectiveness of automatic test equipment used in the testing of printed circuit boards depends on making a reliable reproducible low impedance contact onto the printed circuit board, in order to prevent degradation of the test signals to and from the ATE system. In the majority of cases this connection to the PCB nodes is achieved using spring loaded telescopic test probes fitted to the test heads. Unless careful consideration is given to these test probes, production delays may occur due to poor connections between the UUT and ATE system, thus making expensive reworking necessary.

Many different types of probes are now available to suit most testing requirements. The first logic boards to be produced were manually tested, but this was a time consuming operation that was also very costly and did not support high volume production. As the complexity of boards increased, manual testing was replaced by automatic testing, and with the introduction of computer based ATE, diagnostic software became available. The early single sided boards with widely spaced tracks were easy to inspect visually, but ATE was developed as double-sided boards, multiple-layer boards and reduced track spacing were introduced.

The first ATE was developed from testers that were originally used for checking backplanes and wiring looms. The equipment was fitted with a platen containing a number of test probes, known colloquially as a bed of nails. The bed of nails technique for contacting PCBs is used for loaded boards and bare board testing, but a higher density of probe concentration is necessary for the latter, due to the need to check each track end to end and prove track continuity. The flat surface of the PCB permits the use of probes with shorter plunger movement, than are required for loaded boards where the surfaces to be contacted are not of uniform height. Test heads for PCBs with relatively few test points i.e. 150 to 200, and low volume production are usually operated manually, depending on the total amount of spring pressure that is required. The maximum theoretical vacuum force available is 14 lbs/in2. but typically it is 15in of mercury (about 7.5lb/in2). A typical loaded board probe needs 6 - 8oz spring pressure, therefore the 7.5lb/in2 available would limit the probe density to a maximum of 15 - 20 probes per square inch. However, the use of smaller probes with lower spring pressure would allow more densely populated probe field. High initial vacuum leakage occurs before the board has sealed itself down, some leaks are due to holes in the board, so the vacuum pump has to have sufficiently large capacity to accommodate such leakage.

Similar problems exist when testing bare boards, but in order to prevent air leakage through the holes the boards are not used as a sealing device. A pressure plate is fitted over the boards, forcing them hard down on the platen contacting the exposed probes. Pneumatically operated test heads are used in circumstances where the probe density and total spring pressure exceeds that recommended for manual or vacuum operated heads. The fixture can be similar to a manual fixture, but is operated by pneumatic cylinders, which can exert more force on the board than is possible when using the other methods of operation.

The first test probes (35) were ordinary sewing needles which slid up and down inside brass ferrules and springs produced by factory model shops. These probes were fitted into the test fixture permanently, and worked well where the test requirement was undemanding. However, the major problems with this style of probe included their large size, which limited the closeness of spacing, and the wire connection. With the latter soldered to the probe needle the up and down movement, which occurred when the probe was depressed, eventually fractured the joint. These probes were used almost exclusively on single sided PCBs with large test pad areas.

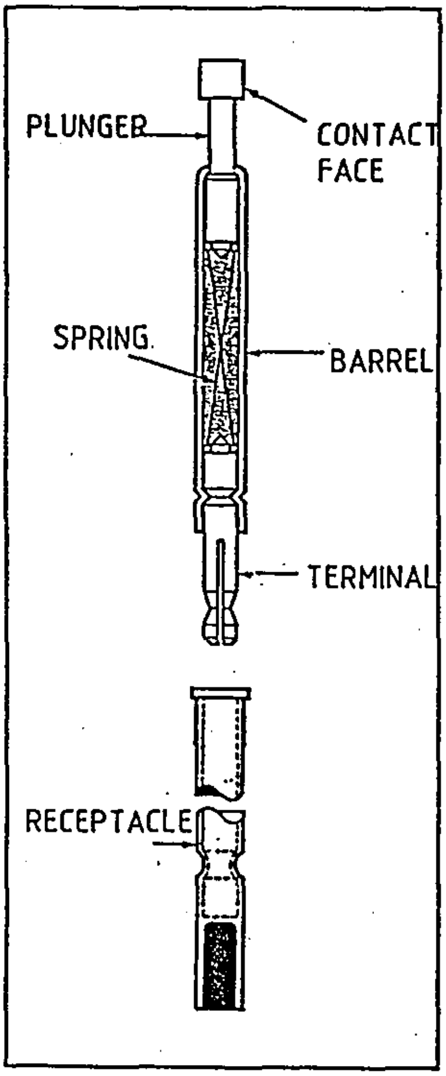
The arrival of integrated circuits and a later, more specific, requirement to perform in-circuit testing to see whether components were correctly fitted or, indeed, there at all, made it necessary to probe along ic legs and other components with test points close to each other. The old type of probe was therefore unsuitable and several manufacturers designed ranges of probes using an integral spring. Because it was desirable to have a range of tip styles to cope with various contact surfaces, these probes tended to be of an interchangeable design, consisting of the spring probe assembly and a receptacle into which the probe could be inserted and removed if required.

An illustration of one style is shown in (Fig.1.8). However, one manufacturer produced an integrated range of five sizes, later expanded to seven, to a common design standard, each size having a range of tip styles with in it. Additionally a choice of two spring rates was available, the higher pressure items being useful in helping to cut through various types of test point contamination. This range was so satisfactory that the designs were widely copied, and now form a useful core of established designs that allow more or less complete interchangeability between probes and receptacles from a number of different manufacturers.

Other early probes used in ATE test fixtures were comparatively large, fitted with external springs, with wires connected directly to the plunges. These connecting wires were continuously flexed as the probes were operated, and often fractured. In areas where the probe density was concentrated, the wires fouled each other causing frequent delays.

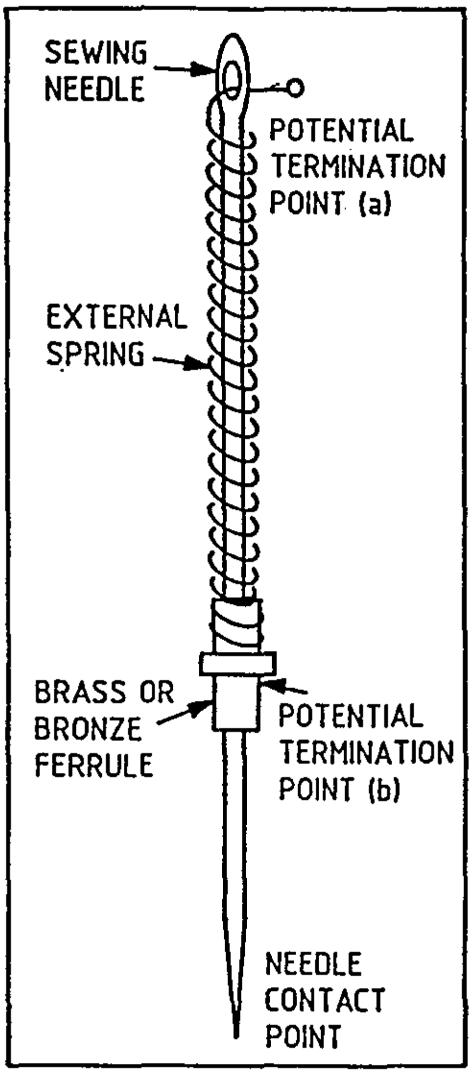
The original probes used, were pointed and proved to be satisfactory with defined test pads, eventually the test pads were omitted as component density increased and it became necessary for the probes to access the stub ends of component leads. It would therefore appear, that with the introduction of surface mounted devices which require test pads that the technology has gone "full circle".

These probes (Fig.1.9) have now been displaced by two part assemblies, consisting of probe and receptacle (See Fig.1.8). The probes were originally designed for a 0.1 in pitch and a stroke of 0.16" and could readily access ICs and most components which was not possible with the original probe with its external spring. Probes were continuously developed to provide longer throws, consistent with testing more difficult boards with badly cut leads and terminal posts.



INTERCHANGEABLE PROBE AND RECEPTACLE

FIG. 1.8



EARLY TEST PROBE DEVELOPED BY MARCONI, USING AN EXTERNAL SPRING ON A SEWING NEEDLE

FIG. 1.9

A variety of different style probe heads (Fig.1.10) became available to cope with the many different types of problems encountered in testing. Some probes had heads with inverted cups to capture cut through leads, flat heads for large terminals, or triangulated known as pyramid heads for contacting via holes. Heads were developed for penetrating the flux and oxide deposits present on contaminated boards, such heads including tulip, crown, super crown and flexible. The flexible probe has a spring which will operate with a low pressure with a surgical sharp needle designed to pierce flux contamination. Its flexibility enables it to return to a normal shape after making contact with a misaligned component. Tulip and crown heads with centre points but lower outer points were developed to contact wide spread lead throughs, with their deep set serration to pierce the contamination, without the troughs of the heads filling and reducing the efficiency of the probe.

Rotating probes have now been developed for testing severely contaminated boards. These are manufactured with a small helix which caused the plunger to turn through 90 degrees, when the probe is subject to compression, and therefore cut through the contaminating material. Early test fixtures were dedicated to a specific design of PCB and were assembled by the user, but as probe densities increased, more precision was required to ensure correct drilling and alignment of the assembly.

Localised heating reduces probe life, therefore, the largest probes possible should be used on given spacing in order to increase the current carrying capacity of the probe. The larger probes are more robust and will last longer. Several probes connected in parallel to the same track or node will reduce probe current density by dividing the current by the number of probes used. By minimising the current density per probe, spring degradation and internal damage may be reduced or avoided. It is necessary to ensure that the probe is stationary during the application of current, to prevent variations in contact resistance occurring within the probe. Small changes in resistance caused by relative internal movement, can have significant effects with large current density, and apart from contributing to earlier failure, they reduce the accuracy of measurement.

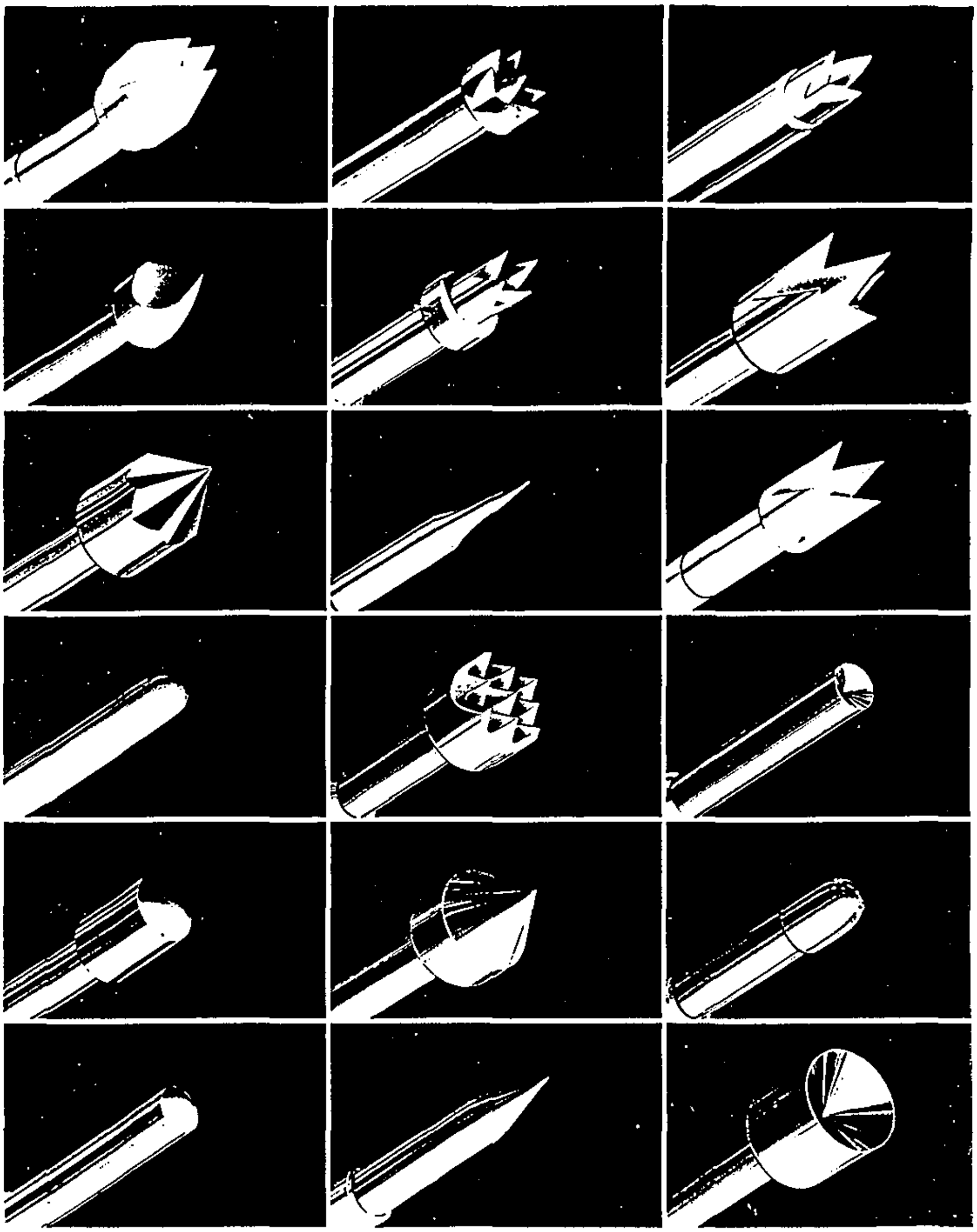


Fig. 1. 10 DIFFERENT STYLE PROBE HEADS.

It is also important to consider the effects of low probe currents in connection with the probe contact resistance, as these can seriously effect the accuracy of measurement when the test current is only of the order of a few micro amps. Probes of different sizes can be mixed providing the stroke length is the same for each type of probe. There is no problem in this respect when testing bare boards, but where boards contain different terminal profile components, they may introduce the need for probes of different stroke lengths. Although this difference may be small perhaps 0.010 inch when it is related to a large number of operations during the life of the probe, it can be seen there will be significant differences between the total distances travelled by the probe plungers, with a related reduction in life of the probes subjected to the greatest movement.

Reasonable uniformity of probe life in the test fixture can be preserved if the platen is drilled to depths related to the differences in plunger travel before fitting the probe receptacles. The platen should be drilled with the first board or with a common template, to ensure that the probe location in the test fixture is accurately aligned with the target areas of the boards. It is recommended that PC boards are cleaned before testing, but probe tips which are specially designed for the penetration of flux and oxide residues may be selected. Maximum penetration of the surface is achieved by using probes which operate with the highest spring pressure, but it is important that the total force required to compress all of the probe springs in the test fixture is considered when making this choice.

If a certain type of probe has been chosen for testing a bare board measuring 8" X 12", and containing 3000 holes, then the total compression force on the test head has to be evaluated. Initially, reference to the probe manufacturers data shows that these probes are available with two values of spring force, the first being 80g and 155g. There is also a plus or minus 20% tolerance on all spring pressures. Selecting the highest spring pressure (155g) for maximum penetration and allowing for the worst case, gives a total compression force of 3000 (5.4 + 20%) 16 X 2240 = 0.55 tons (558.16 kg). This emphasises the need for overall consideration of the test fixture parameters.

For vacuum fixtures the holes in PCBs must be blocked (except tooling holes) to preserve vacuum integrity, as just six plated through holes left open can prevent fixture operation. Special sealing methods are available from some fixture manufacturers, but failure to seal holes can result in a reduced probe density due to loss of available vacuum.

1.8.1 Probe Performance

It is desirable to achieve a consistent probe performance throughout its life, where the probe behaves as a fixed resistor of low ohmic value. A variable resistance characteristic would adversely affect the reliability and accuracy of the ATE system as a whole. The performance of a test unit is only as good as the quality of the simple test probe making contact with the PCB under test. A very time intensive investigation into the tester board interface is undertaken, but most of the blame is usually allotted to the spring probes due to the effects of mechanical wear.

Investigations into the test probe head "zone of contact" shows it is not by any means the actual contact area, and as the electron is only a very small particle, only 10^{-24}g in mass, it cannot jump very far. So when two pieces of metal make contact with each other as in a connector, the actual electronic junction is made over a minute area, known as an "asperity". An analogy is to turn upside down a range of hills and mate them with the same hills the right way up, therefore very few tips would be in contact with each other, this being the situation with all metal to metal contacts. Bringing the tips together creates friction, making cold welds over minute areas. These areas are where the electrical contact is made and although small, are sufficient for the electrical connection.

Comparing the specified zone of contact and the real contact area, shows an amount of redundancy which is a feature of every electrical connection (Fig.1.11). The principle factors for consideration, are heating due to the passage of current through the closed contact resistance, and erosion of material from the active contact surface of the probe, leading to an inevitable increase in resistance. Other considerations are the mechanical force applied, the shape of contact faces, and the condition of such faces with respect to surface contamination due to coatings used on PCBs, and the formation of oxides with their associated affect on contact resistance (Fig.1.12), (Fig.1.13), (Fig.1.14).

Looking at the probe more closely, it is possible to divide the probe into four separate resistors, two variable and two fixed. (1). The fixed probe outer barrel to receptacle resistance. (2). The variable plunger to outer resistance. (3). The fixed resistance of inner probe plunger. (4). The variable resistance of the probe target contact. This analogy is shown in (Figs.1.15a & 1.15b).

Resistance values of the fixed elements within the probe should remain reasonably constant over the probe life time, with the remaining two variables showing an average gradual increase, as seen in manufacturers sales literature (Figs.1.16a & 1.16b). However, there are random reductions and increases in values over the probe life due to the build up of wear debris and fluctuating spring pressure within the probe assembly. Preliminary tests have already shown that probes may become solid after extensive use, leaving the spring unable to exert the necessary force to return the probe to its extended position. It is possible for the probe to remain permanently jammed or sometimes revert back to normal operation, often resulting in part of a batch being rejected by the ATE adding extra cost and time to the production process.

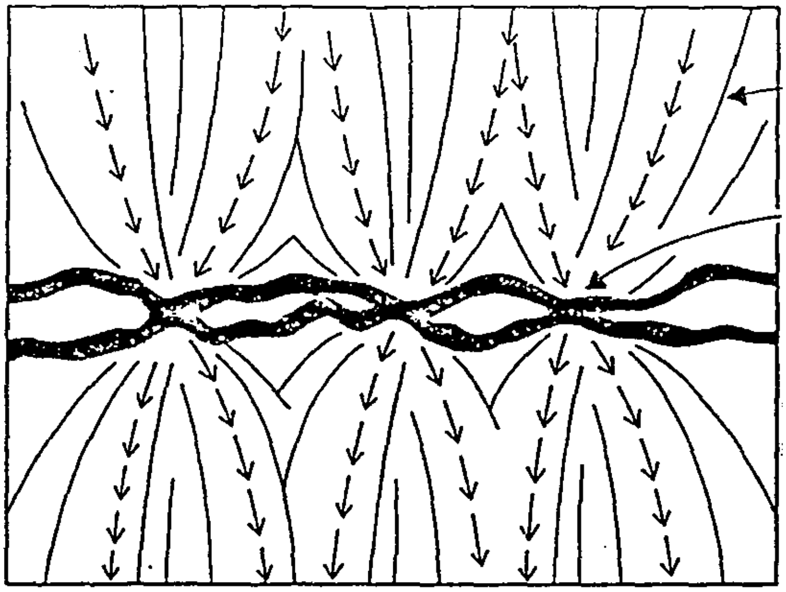


Fig. 1. 11 CONTACT SURFACE ASPERITIES.

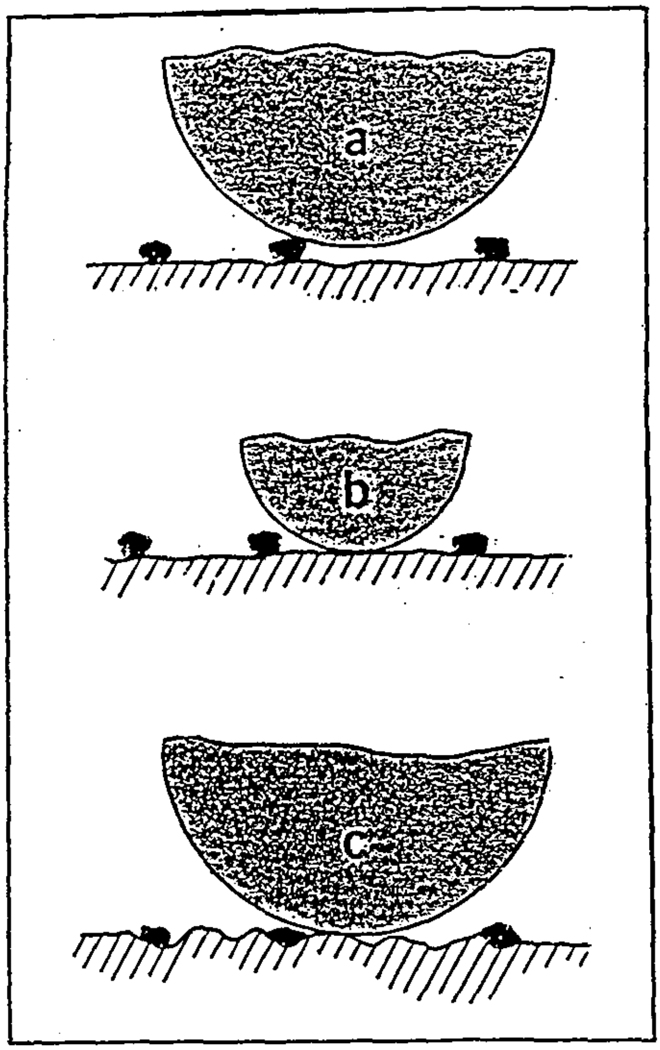
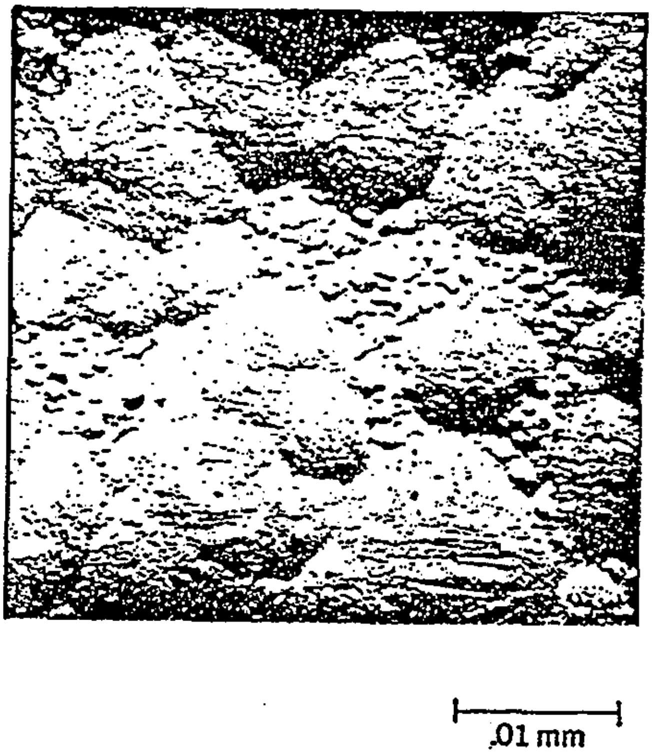
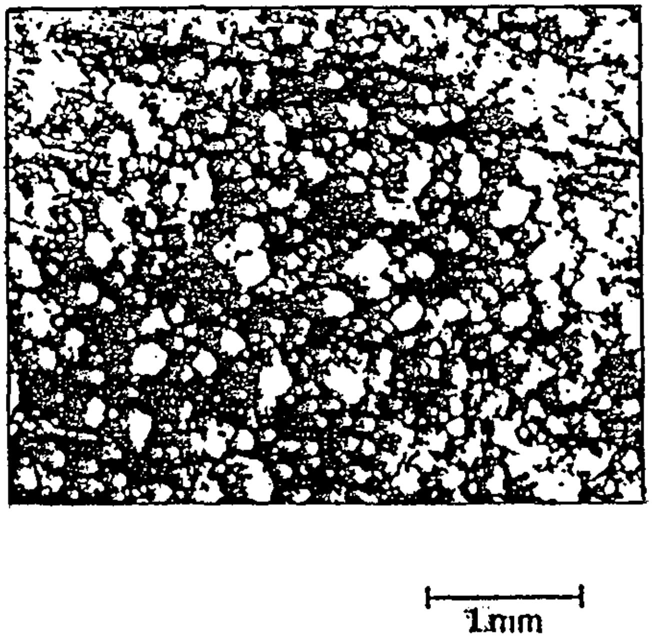


Fig. 1. 12 CONTACT CONTAMINATION.



Surface of electroplated gold contact.

Fig. 1.13



Corrosion solids on porous gold-plated nickel after exposure

Fig. 1.14

PROBE RESISTANCE

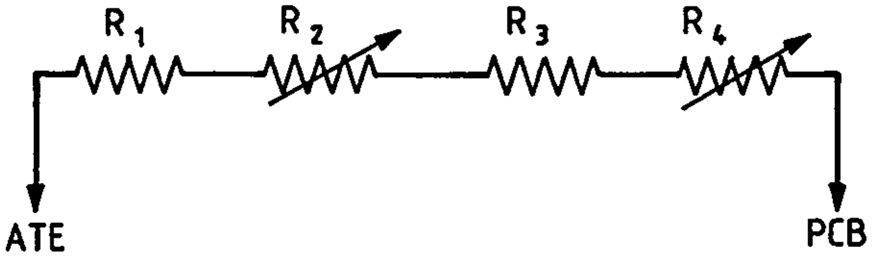
RESISTANCE ELEMENTS WITHIN THE STRUCTURE

R_1 PROBE BARREL HOUSED IN RECEPTACLE

R_2 MOVING CONTACT RESISTANCE OF BARREL TO PLUNGER

R_3 FIXED RESISTANCE OF INNER PLUNGER

R_4 VARIABLE RESISTANCE OF PROBE TIP TO TARGET

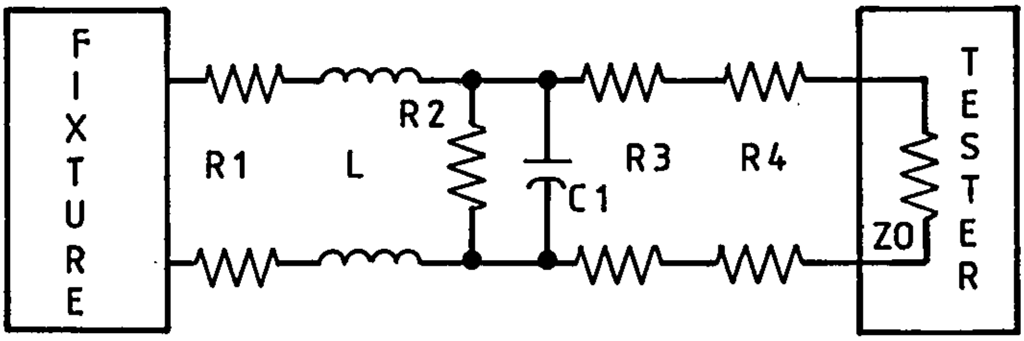


R_1 and R_3 FIXED VALUE

R_2 and R_4 VARIABLE

Fig. 1.15a

PCB - ATE INTERFACE



R1. R4 = CONTACT RESISTANCE.
R2 = ISOLATION IMPEDANCE.
R_3 = LINE RESISTANCE.
L = LINE INDUCTANCE
C1 = COUPLING CAPACITANCE
ZO = CHARACTERISTICS IMPEDANCE

Fig. 1.15b

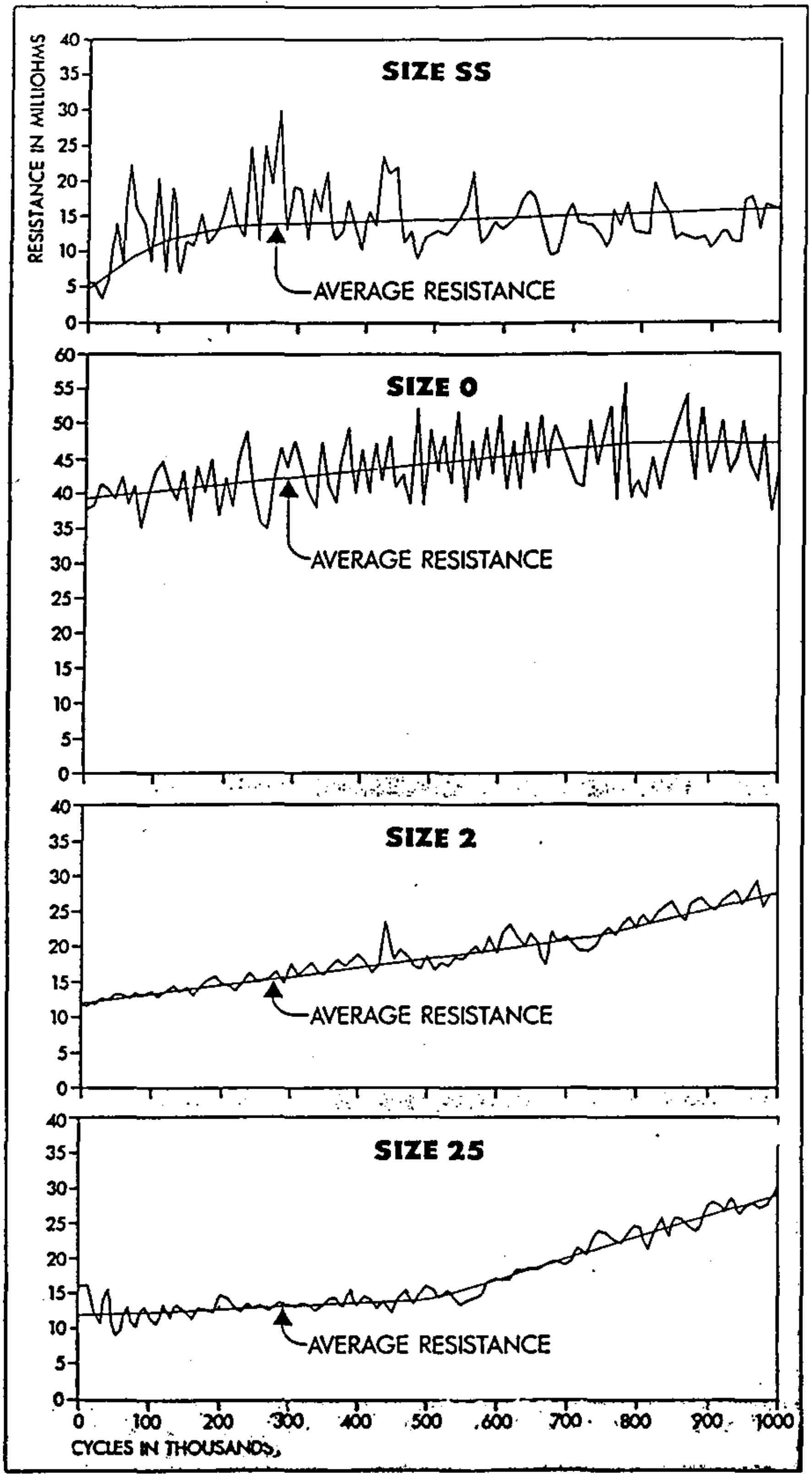
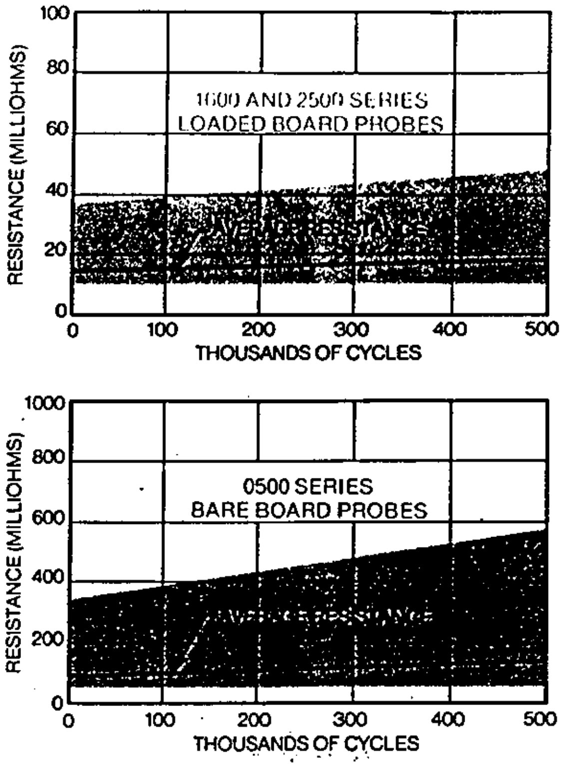


Fig. 1. 16a PROBE MANUFACTURERS AVERAGE RESISTANCE PROJECTIONS.

Performance Data.



Each of the above graphs are based upon 128 randomly selected probes which were mechanically cycled and tested according to the specification below. Over a 500,000 cycle test, each probe was measured at 2,000 cycle intervals, giving 32,000 data points for each graph. It should be noted that all of the data falls within the shaded regions and that the average probe resistance is represented by the dark lines.

Test stroke:	(1600 series) .130 inches/3.3mm
	(2500 series) .170 inches/4.3mm
	(0500 series) .045 inches/1.14mm
Test current:	100 milliamperes max.
Test voltage:	2.50 volts max.

Fig. 1. 16b PROBE MANUFACTURERS AVERAGE RESISTANCE PROJECTIONS.

1.8.2 Route Taken by the Current in the Probe Assembly

From the electrical view point the probe has become a spring loaded, telescopic cylindrical connector, comprising of two fixed resistance elements with another two which are variable, all connected in series. As in all electrical circuits the current will take the path of least resistance with little current flowing through the spring, due to its greater resistivity and longer length. But it is possible, as the sliding cylindrical assembly becomes worn with associated increase in resistance, there will be a greater percentage of current flowing through the spring causing increased heating.

The accumulation of oxidised wear debris between the sliding cylindrical contacts, which is continuously being moved by probe action, will cause random variable values of resistance which is also due to a looser fit of the probe components. This effect was developed and used in the old telephone carbon microphone, where variable pressure waves in the air were converted to variable electric currents by carbon particles between two electrodes.

Lateral forces between the two loose fitting cylindrical contacts, have the effect of pushing the mating contact surfaces either closer together or further apart, depending on the relative co-axial position of the internal probe surfaces and the lateral force applied by the probe target. The result being substantial changes in resistance values over successive probe operations, ranging from low values to open circuit over several circuit board engagements. In circumstances where the relative co-axial position within the probe, remains unchanged for a long period, the surface gold coating becomes completely worn away on specific areas of the probe, resulting in further variation of test values.

1.8.3 Probe Head to Target Resistance

Considerable variations in values may be measured due to several factors, one being, the inability of the probe head to penetrate oxide and other coatings, due to wear of the probe point or points. Another factor may be insufficient or variable spring pressure affecting contact pressure between the probe head and the PCB target, as contact pressure is a function of contact resistance (36). A better connection can be achieved where there is a substantial voltage gradient available, to break down resistive coatings on both contacts with a moderate current to initiate a cold weld. Where test voltages and currents are very low, problems often arise in making a good connection to the PCB, because of the lack of energy available to initiate the current.

1.8.4 The Mechanical Effects of Probe Wear

As the probe becomes worn, its concentric components become loose, resulting in a reduction in its pointing accuracy, with a greater chance of the probe tip missing or shorting its target pads or pins. This is now of greater importance due to increased probe field density with smaller probes and closer spacings. The effect of tolerance build up through the fixture, probes, and the PCB leads to more unnecessary board failures on test.

1.8.5 Spring Materials

As probe size continues to decrease and working loads increase, material selection for the spring becomes more critical. The most commonly used materials for this application are music/piano wire, stainless steel and beryllium copper. Each material has good and bad characteristics which should be evaluated in terms of the users design requirements.

Music/piano wire is the strongest of the three materials, it is high carbon steel wire which may be obtained in diameters as small as 0.004" and is known for its consistency and strength. Stainless steel derives its strength from cold working and is available in fine wire diameters. It is frequently used in high temperature applications and corrosive environments. Although its tensile strength is somewhat less than music wire, it fatigue prolongation is excellent. Because it is corrosion resistant, processing consists of passivating and stress relieving.

Beryllium copper is the weakest of the three materials. Its strength is derived by heat treating to spring temper, but has a much lower electrical resistance (37).

CHAPTER 2

2 THEORETICAL APPROACH

2.1 GENERAL

The investigation of the electrical & mechanical parameters of PCB test probes was undertaken using a test machine to simulate as close as possible the conditions experienced by probes in a typical test fixture. To evaluate the probes parameters, it is necessary to state the objectives of the probes performance during normal routine PCB testing. The characteristics required for a perfect probe, looking in the first instance from the electrical viewpoint, is a probe with low internal resistance which has little or no variation in value throughout the probes life cycle. Interfacial contact resistance measured from the probes receptacle to the PCB contact target should in ideal circumstances be low and constant in value, but during testing values may increase due to insulating layers developing on contact surfaces. Test probe points are designed to access a range of PCB targets and penetrate any insulating layers or contamination, (Fig.2.1). Ten experiments were conducted using ten sets of near identical style probes (100 probes in total) and resistance measurements were logged every 10,000 cycles with a probe deflection rate of 123 cycles per minute and measurements taken at 80 minute intervals, thus producing results of the probes resistive performance as part of the test circuit. These experiments were conducted between two to three million cycles on average. Probe life is guaranteed by manufactures up to one million cycles and so accordingly probes were assessed for performance at 1.2 million.

One of the principle objectives of this study, is the analysis of electrical contact reliability. Most probe manufacturers give data related to probe life resistance performance measured usually to an ideal target, which does not include any detrimental effects experienced in the field of manufacture and testing (See Fig.1.16).

As the probe is one of the most important parts within the test interface, its electrical resistance is measured on a regular basis during life simulation for the analysis of electrical contact reliability. The two factors affecting contact reliability are: (1). the wear and debris

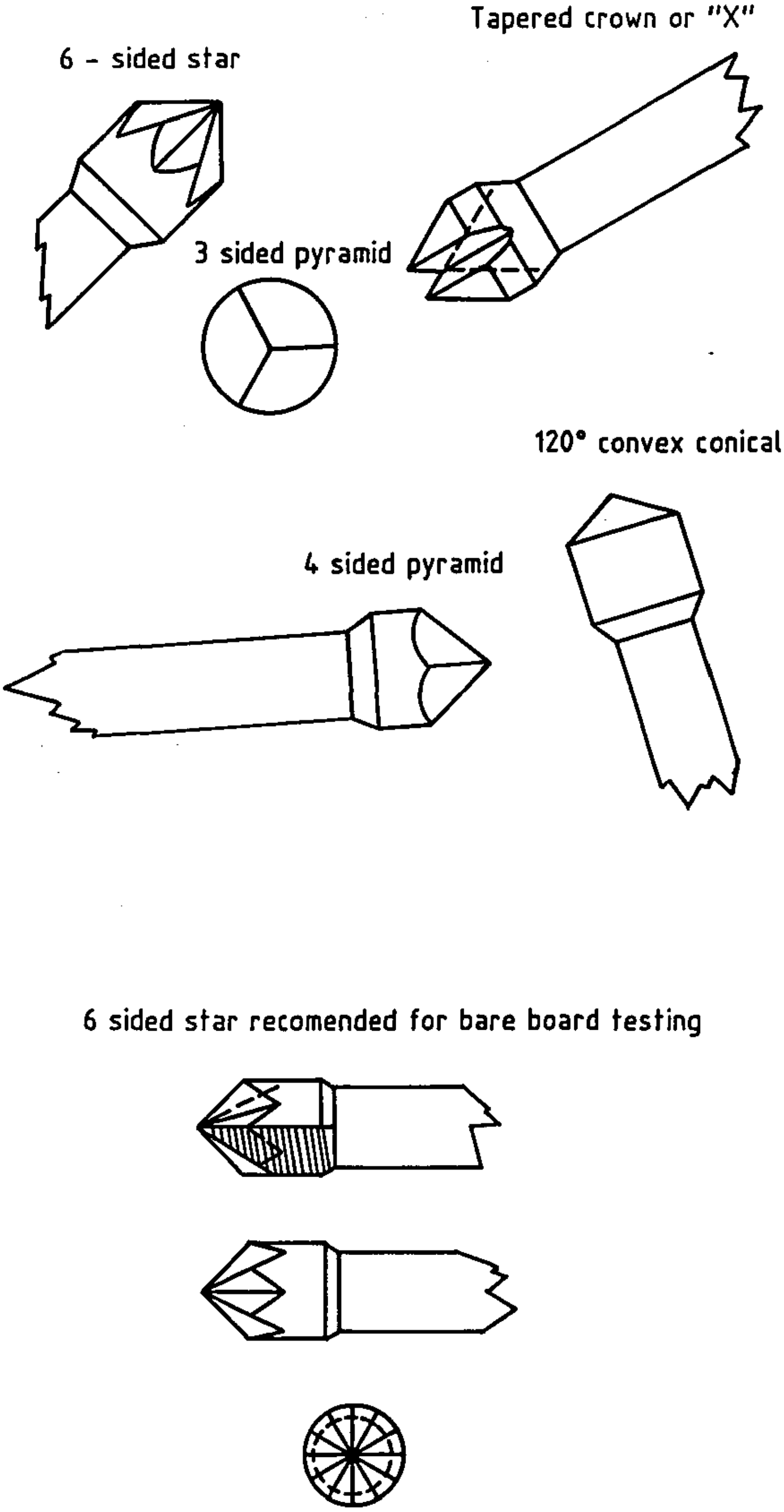


FIGURE 2.1(a) TEST PROBE POINTS

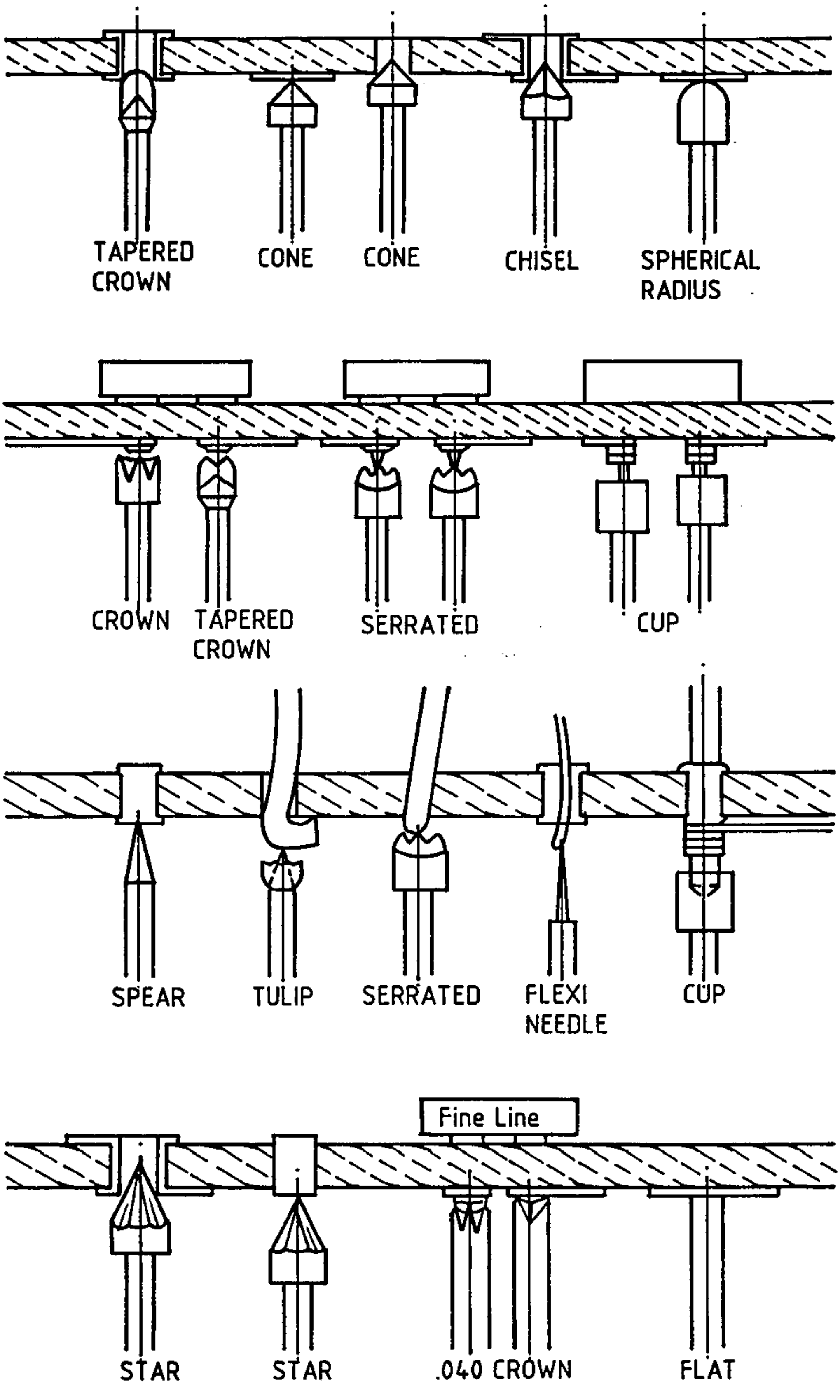


FIG 2.1(b) SOME TYPICAL PROBE TYPES SHOWN IN THEIR NORMAL TESTING ENVIRONMENTS

within the probe structure; (2). the ability of the probe/points to penetrate a test node sufficiently to produce a low impedance contact.

Testing the probes requires deflecting the probes through two thirds of their total travel for (on average) up to 2 million cycles, to determine their electrical and mechanical longevity, in order to permit the comparison of one set of probes with another. The survival rate is determined by the percentage of probes that will continue to function after life simulation.

To evaluate the electrical and mechanical parameters of the PCB test probes, it is necessary to simulate as close as possible the operating conditions within the test fixture, while at the same time speeding up the probe operation rate so that probes may be tested in a reasonable amount of time. The process may only be speeded up to a rate where the probe remains within its normal temperature operating range, due to the subsequent loss of lubrication from the probe assembly during testing.

The wide range of probe targets encountered on a PCB from flat pads to solder mounds or component leads, means the probes may be subjected to random variable side loads during their life-time in a test fixture. It is therefore necessary to include some side pressure on the probes during life simulation testing, which may require an angled plane as a target. Preliminary tests have already shown a considerable reduction in probe life, when tested to angled targets with their associated side pressure on the probe assembly (Fig.2.2).

The measurement of the total side to side movement of the plunger, in relation to the barrel, is made before and after life simulation and is used as an indication of wear, usually referred to as side play.

Previous probe evaluations have shown that some probes can have extremely long life cycles in order of 2 to 3 million operations, and may even perform satisfactory up to 4 million cycles, which means that considerable time is needed for testing.

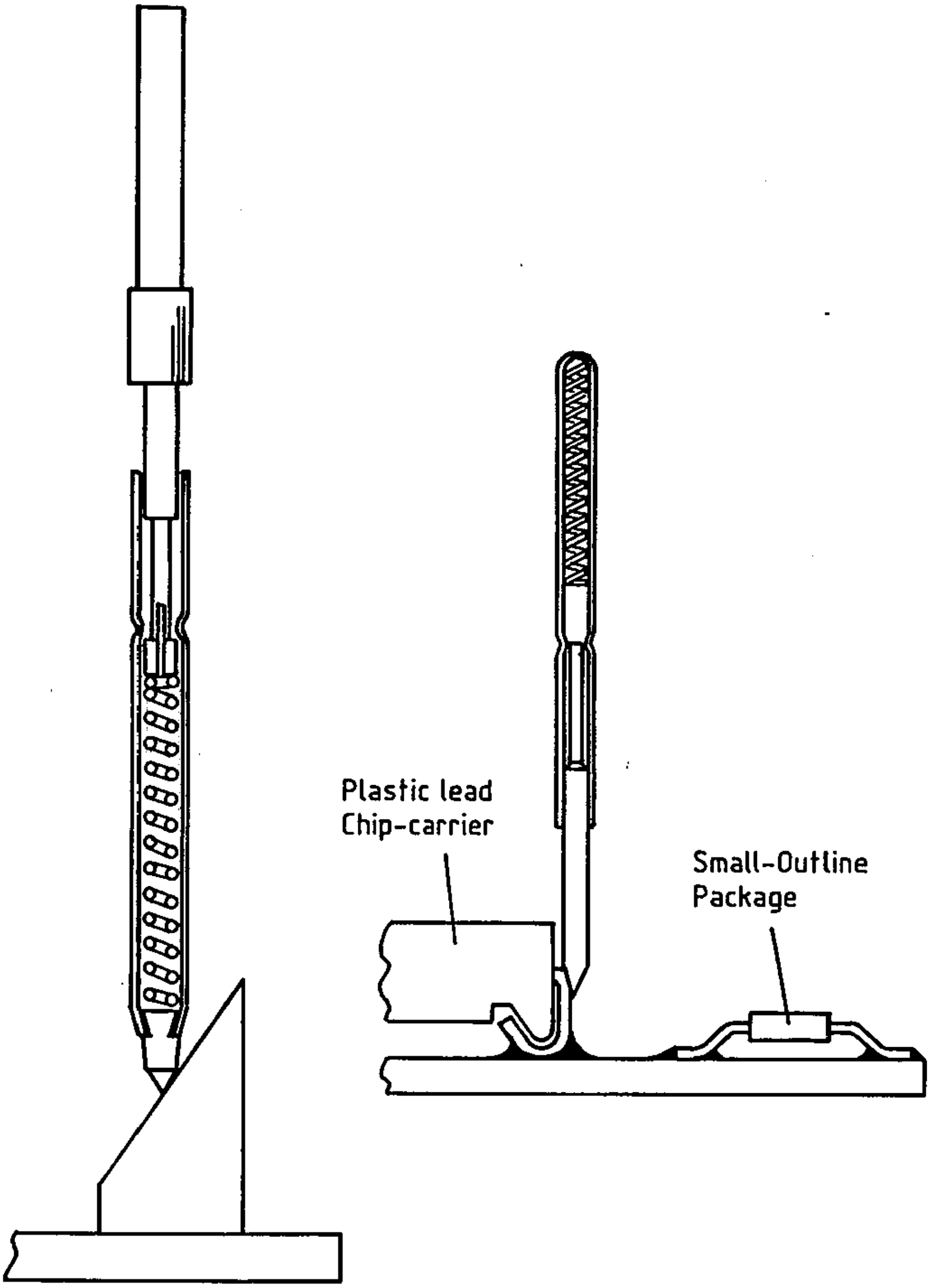


FIG. 2.2 ANGLED TARGET PROBE DIAGRAM

2.2 ELECTRICAL RESISTANCE MEASUREMENT

It is necessary to measure electrical resistance at frequent intervals in order to obtain a detailed picture of the probes resistive performance within the PCB test circuit. As the probe wears its electrical resistance slowly increases restricting the measuring ability of the ATE, particularly in cases where low ohmic value components are involved. Resistance measurements of the probe indicate significant changes in an upward or downward direction between readings taken over a short interval, with the average trend in an upward direction (Fig.2.3).

In service the probes produce a number of random high resistance, or less often, open circuit readings leading to good quality boards being rejected by the ATE. Due to the random variations in probe resistive values, it is not possible to compensate for them in the ATE software. Random opens may be explained where the probe jams over one cycle or a number of cycles, and then reverts to normal operation. It could also be caused when the probe does not penetrate the surface of the target, producing a high resistance or open reading (Fig.2.4). As the probe wears, its side play will gradually increase, leading to random opens where the probe misses its target due to wear and tolerance build up within the PCB and test fixture, producing a false open reading. These types of open readings can only be detected in tests where the probe is aligned to a designated pad or another target.

2.3 ENVIRONMENTAL CONTAMINATION OF PROBES

A considerable range of probe point styles are available, suited to various types of targets used for test evaluation, but in trying to decide on a pin style that is best for a given application, it becomes apparent that regardless which pin is chosen, the end result is a level of performance that is less than perfect. This fact is perhaps due to environmental conditions as well as being caused by the composition of the pin itself (See Fig.1.10). Contaminates can be deposited on the tip as well as penetrating the barrel during depression. For the most part these problems are sporadic, that is they only occur for a small percentage of the time, yet

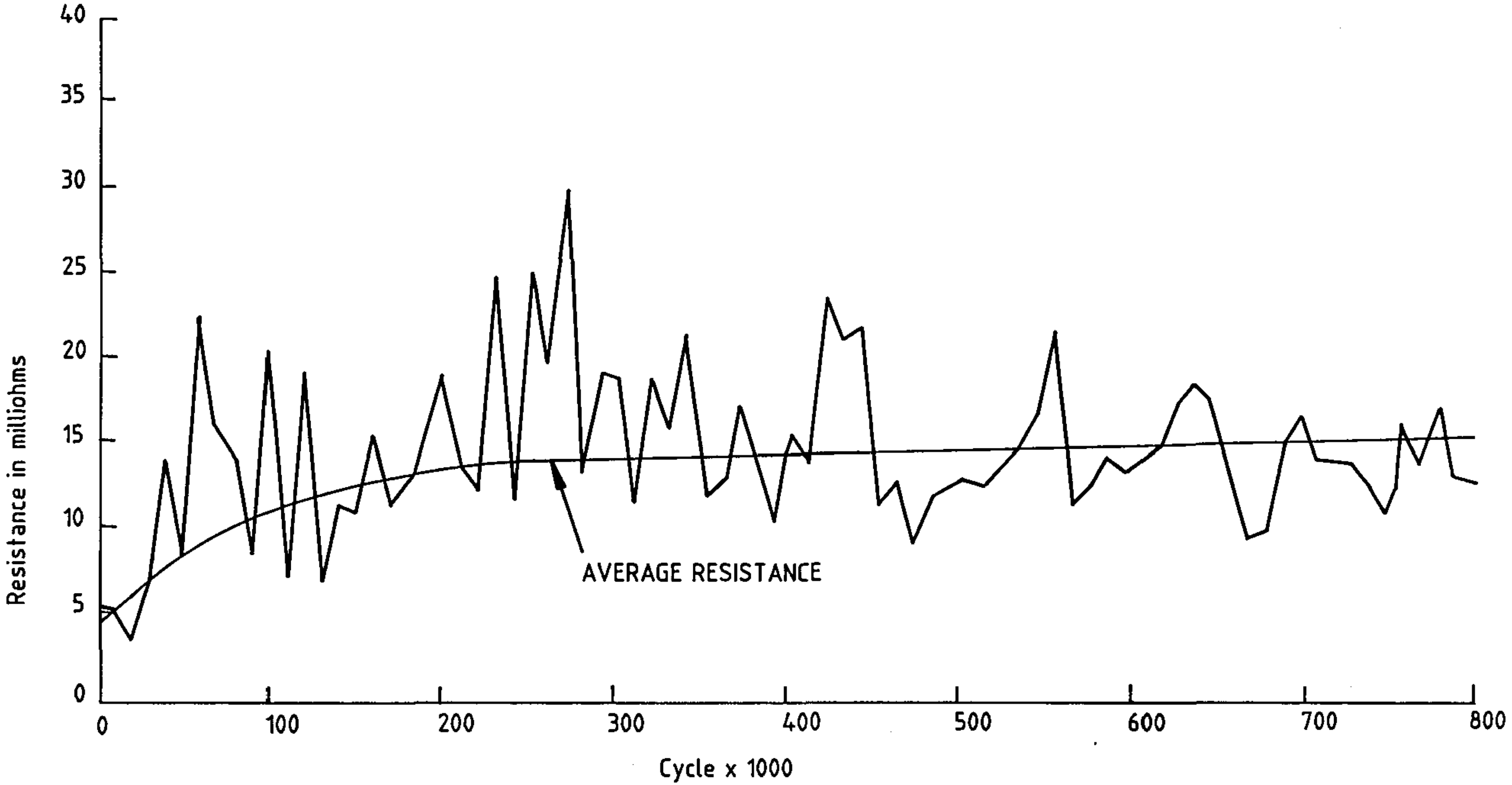


FIG. 2.3 PROBE MANUFACTURERS PROJECTED PERFORMANCE GRAPH

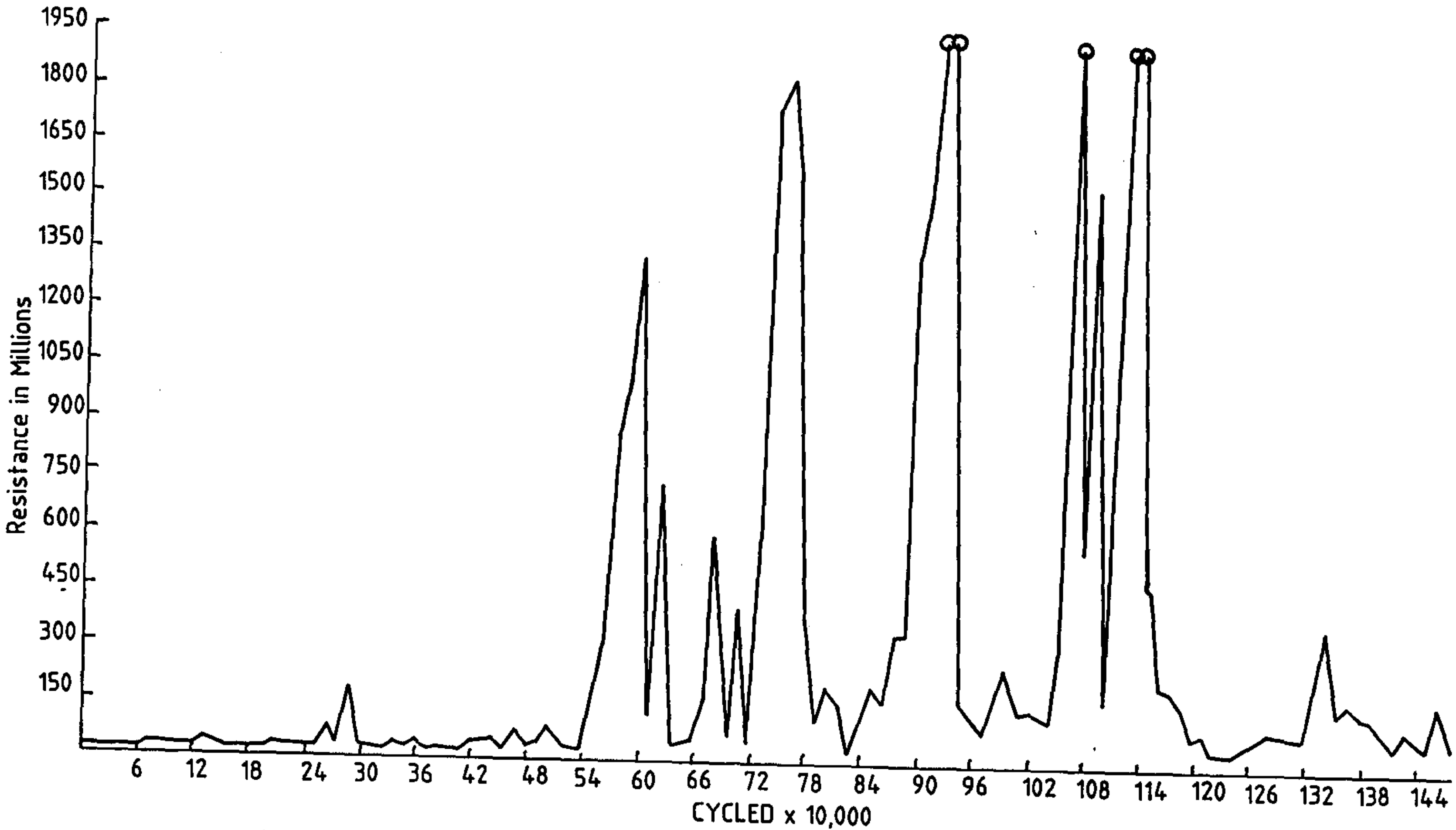


FIG. 2.4 RANDOM HIGH RES OR OPEN CIRCUIT RESISTANCE VALUES

when this failure rate is multiplied by a high pin usage then an undesirable level of failure can occur (23).

2.3.1 Testing in the Fixture

Life simulation testing is possible using a test fixture to simulate the exact conditions that the probe is normally subjected to in daily use, but this can lead to problems due to the probes long life. In some cases the fixtures may become worn out after testing only a few sets of probes with up to 50% failure. Due to the relatively slow operating cycle time of fixtures compared with testing machines, testing would be a very time consuming exercise using the test fixture. It also has to be considered that there are vacuum, mechanical and hand operated fixtures in general use with their own environmental conditions. One of the problems with vacuum actuation, is where environmental dust is drawn into the probe field, each test operation leading to external and internal contamination of the probes. If the vacuum fixtures were used under these circumstances, the test results would be more directly related to local atmospheric pollution conditions rather than normal wear. It is not possible to simulate average conditions without fixed standards being available, with respect to standard test dust which is freely available. Testing, therefore, in a clean environment would produce no more valid results than in an average laboratory.

2.3.2 Probe Life Simulation Testing Machine

It is desirable to observe probes subjected to life simulation testing to enable any abnormalities such as probes becoming jammed, which would not be possible using a test fixture. Test machines used by probe manufacturers are either motor and cam driven, or operated by pneumatic cylinders driven by compressed air. The probes are deflected through a percentage of their travel which is made adjustable in the machine design, usually 66.6%.

Both systems usually use a moving target plate which can accommodate a PCB as an alternative target which becomes part of the test circuit. Angled planes or other profiles may be attached to the target plate as required, to simulate any target profile.

2.4 MEASUREMENT OF LOW OHMIC RESISTANCE

Resistance measurements are made from the target to the probe receptacle using the four wire method to gain better accuracy over low ohmic ranges.

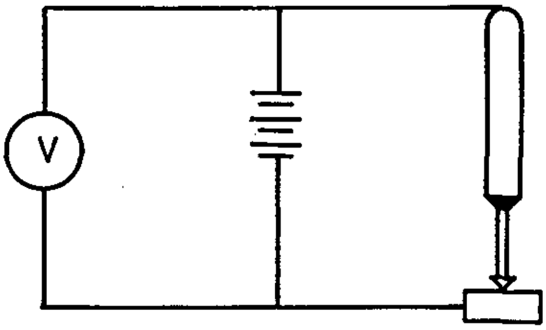
Methods of measurement which are suitable for medium resistances are in most cases unsuitable for low resistance measurements, chiefly because contact resistances cause serious errors. It is clear that contact resistances in the order of 0.001 ohm - negligible though they may be when a resistance of a 100 or more ohms is to be measured, are of great importance when the resistance to be measured is of the order of 0.01 ohm.

It is usually essential, with low resistance, that the two points between which the resistance is to be measured shall be very precisely defined. Thus the methods which are specially adapted to low resistance measurement employ potential connections. i.e.connecting leads which form no part of the circuit whose resistance is to be measured, but which connect two points in this circuit to the measuring circuit. These two points are spoken of as the potential terminals and serve to fix, definitely, the length of circuit under test (38), (Fig.2.5).

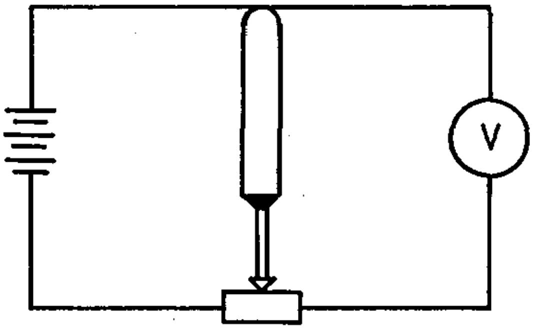
In low valued resistors, the use of four leads, rather than two leads, permits the measurement of the main resistance without the inclusion of the resistor leads. This can be seen in the application of a four terminal resistor measurement. The potential leads are attached as close as possible to the main body resistance. There is no current flow through the potential leads and this eliminates their resistance from the measurement. Resistance between the potential leads may then be determined without inclusion of the resistance of the current leads into the measurement (39), (Fig.2.6).

Test probes when new, depending on their type, have resistance values ranging from around 10 milliohms to 50 milliohms for the smaller closer spacing types, requiring precise measurement at frequent intervals within the low resistance range of measurement. Probe

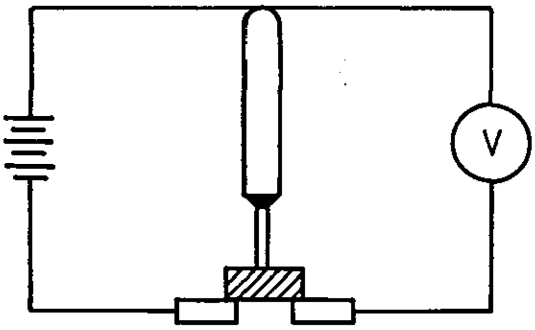
THE TWO AND THREE WIRE METHODS
ARE NOT RECOMMENDED



TWO WIRE



3 WIRE



THE FOUR WIRE TEST CIRCUIT PROVIDES THE
MOST ACCURATE RESISTANCE MEASUREMENT

FIGURE 2.5 FOUR WIRE OR KELVIN METHOD RESISTANCE MEASUREMENT

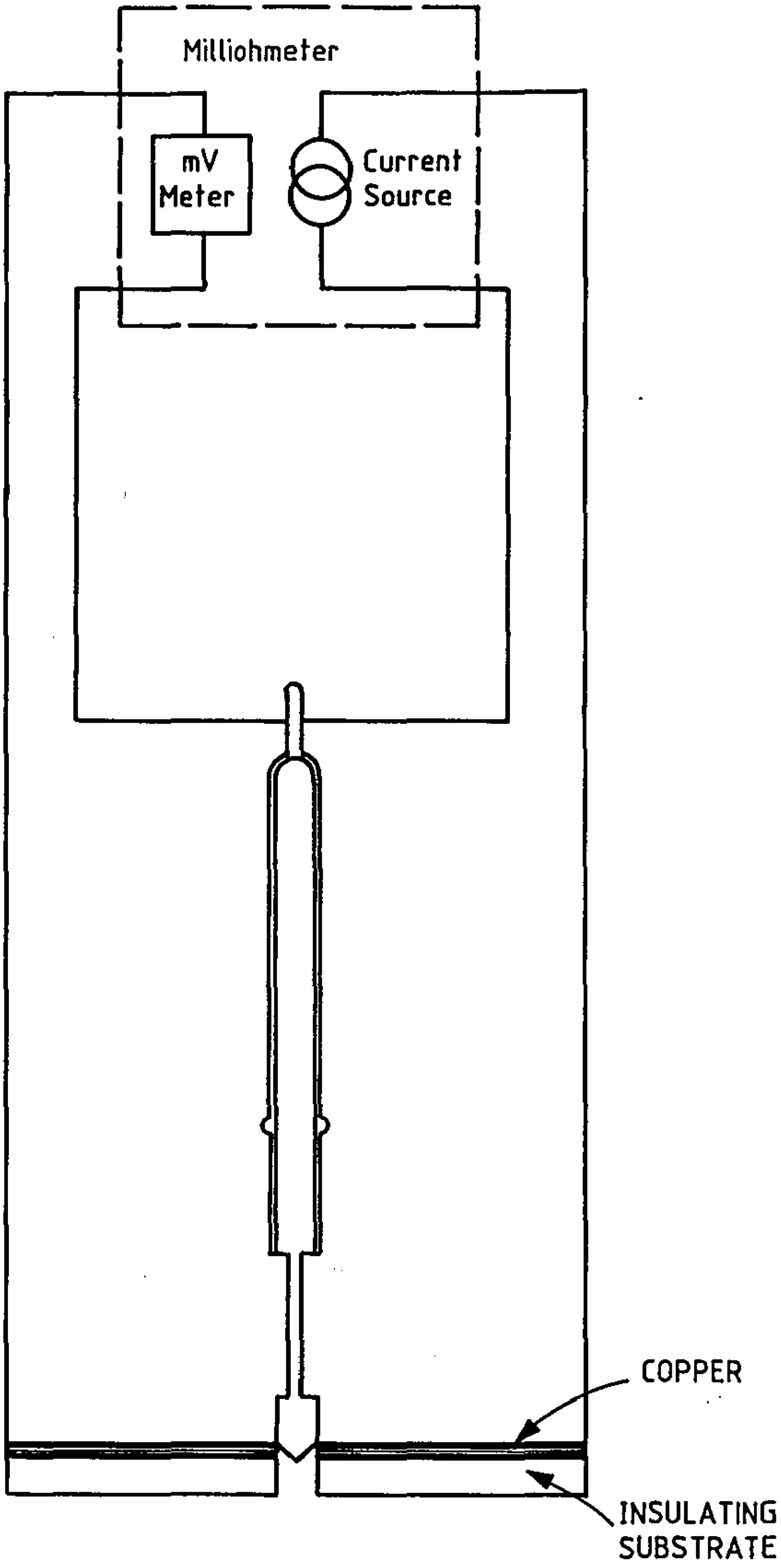


FIG. 2.6 RESISTANCE MEASUREMENT - FOUR WIRE METHOD

current ratings range from one amp to eight amps for the larger size probes in parallel for larger current requirements.

2.4.1 Test Current for Resistance Measurement

Measurement of the probes resistance is made when the probe is statically compressed at the rated stroke. Tests have also been made for comparison at the probes minimum compression, to verify changes in the internal resistance of the probe. A test current of 100 mA at 10v DC using the four wire method is used to measure the probes resistance. Each pin under test, in turn, has an accurate current source output routed by means of two wires, with a separate two wires to measure the voltage drop across the spring probe receptacle and the probe contact target.

The oscillatory frequency of the test machine is one hundred and twenty three strokes per minute. Other frequencies used by probe manufactures are, Augat using three hundred strokes per minute and I.D.I. using two hundred and twenty strokes per minute, higher rates would cause the probes to rise above their normal temperature range. Probe resistance measurements are made around every 10,000 operations but may be varied as dictated by the probes performance requirement (40).

2.5 DURABILITY OF LIFE SIMULATION MACHINE DESIGN

Life simulation testing may require the machine to run for long periods, running into days or even weeks in some cases. This being the case, the machine itself is subjected to the elements of sustained testing over a long period, therefore, the spring probe testing device must be designed to operate in a trouble free manner without attention for long periods of time . Its design must be robust, reliable and long lasting in order to repeatedly test sets of probes for over 3 million cycles.

In order to reduce testing time thus testing a larger sample of probes, it is an advantage from the time and statistical viewpoints, to be able to test a number of probes at the same time, because a larger sample will give a more accurate result. There have been cases where 20% of probes have failed within their first day of testing, so there are considerable advantages in using a machine able to test a number of probes simultaneously.

2.6 TEST MACHINE INSTRUMENTATION

Resistance testing, switching and measurement along with probe cycle counting instrumentation can be incorporated within the basic machine design, giving it a stand alone capability if required. Alternatively, all the electronic counting and measurement functions can be undertaken by a personal computer (PC), data logger or the ATE system itself. Another alternative is to have a basic stand alone system which can be plugged into a date logger or P.C. for more automated data acquisition. This arrangement will enable probes to be tested when data-logging or computer facilities are not available, due to a higher priority user or a breakdown situation. A test run on a set of probes may take up to six weeks or more in the worst circumstances, tying up equipment for long periods.

It is possible to test a single probe against a variety of targets with different profiles, unfortunately, this method is extremely slow as only one probe may be tested at a time. A stepper motor is used to drive a target plate round, changing the test profile as it moves. This method would not produce very statistically accurate results, due to the small sample of test results available.

CHAPTER 3

3 THE DEVELOPMENT AND MANUFACTURE OF THE EXPERIMENTAL TESTING MACHINE

3.1 GENERAL

The design criteria for the testing machine was for a quiet compact bench top design capable of continuous testing for periods of up to four to six weeks on average. A rigid mechanical design was essential with long life mechanical components because of the extended periods of continuous operation needed for probe testing. In achieving the criteria a rigid and reliable mechanical drive system was developed enabling extended variable probe deflection testing throughout the project. The choice of a motor drive rather than a pneumatic system resulted in a machine which was reasonably quiet in operation without the need for continuous running of the air compressor.

3.2 ELECTRO MECHANICAL DRIVE SYSTEM

The probe life simulation testing machine was developed and manufactured as follows:

Using a small Parvalux geared single phase motor of one eighth HP (93.25 WATTS). The rotational motion from the output of the motor gear box is converted by an eccentric mechanism, to produce a vertical downward force. This is exerted on the top of the target table by a cam and bearing assembly. Mounted on top of the target plate, is a variable inclined plane mechanism to allow adjustment of the probe displacement in the vertical plane.

Adjustment of the inclined plane enables probe deflection to be adjusted to any desired value. Probe manufacturers normally specify a maximum recommended probe deflection of two thirds of normal travel, by using this method any percentage deflection may be selected during probe testing.

Linear bearings are used to fix the target plate in position, biased by springs in an upward direction, causing the plate to return to its highest possible position after deflection has occurred due to the cam action. Two linear bearings with springs are used to secure and bias the target plate, resulting in a rigid structure. Screws are used to secure the linear bearing shafts to the target table, while the lower outer section relies on a tight push fit into the top GRP material of the upper section of the base unit.

The underside of the target plate has a dual rail recessed on the upper side, to enable any PCB desired target to be secured to the underside of the target plate. This allows the target to be slid in or out after tightening or untightening of the securing screws. As the target plate is pushed down by the cam's action it makes contact with the probe field directly beneath, deflecting the probes through a proportion of their travel. The distance by which the probes are compressed, can be selected by adjusting the angle of the variable inclined plane to achieve the desired value of probe deflection (Fig.3.1).

The drive motor chosen was a standard type single phase induction motor with a permanently connected phase shift capacitor. It was chosen because of its reliability, and availability as a stock item with a reasonably short delivery time.

3.3 CONSTRUCTION AND ASSEMBLY OF BASE STRUCTURE

It was decided to use steel of 1mm thickness and 12mm GRP laminate (G10) for the main base structure in order to produce a rigid construction, providing adequate damping against vibration caused by the motor and mechanical drive system.

The base plate is constructed from steel with the sides and top section made of GRP laminate which supports the motor and the reciprocating mechanism, resulting in a compact rigid assembly. The base design incorporates all the necessary space to house the electronic instrumentation (Fig.3.2).

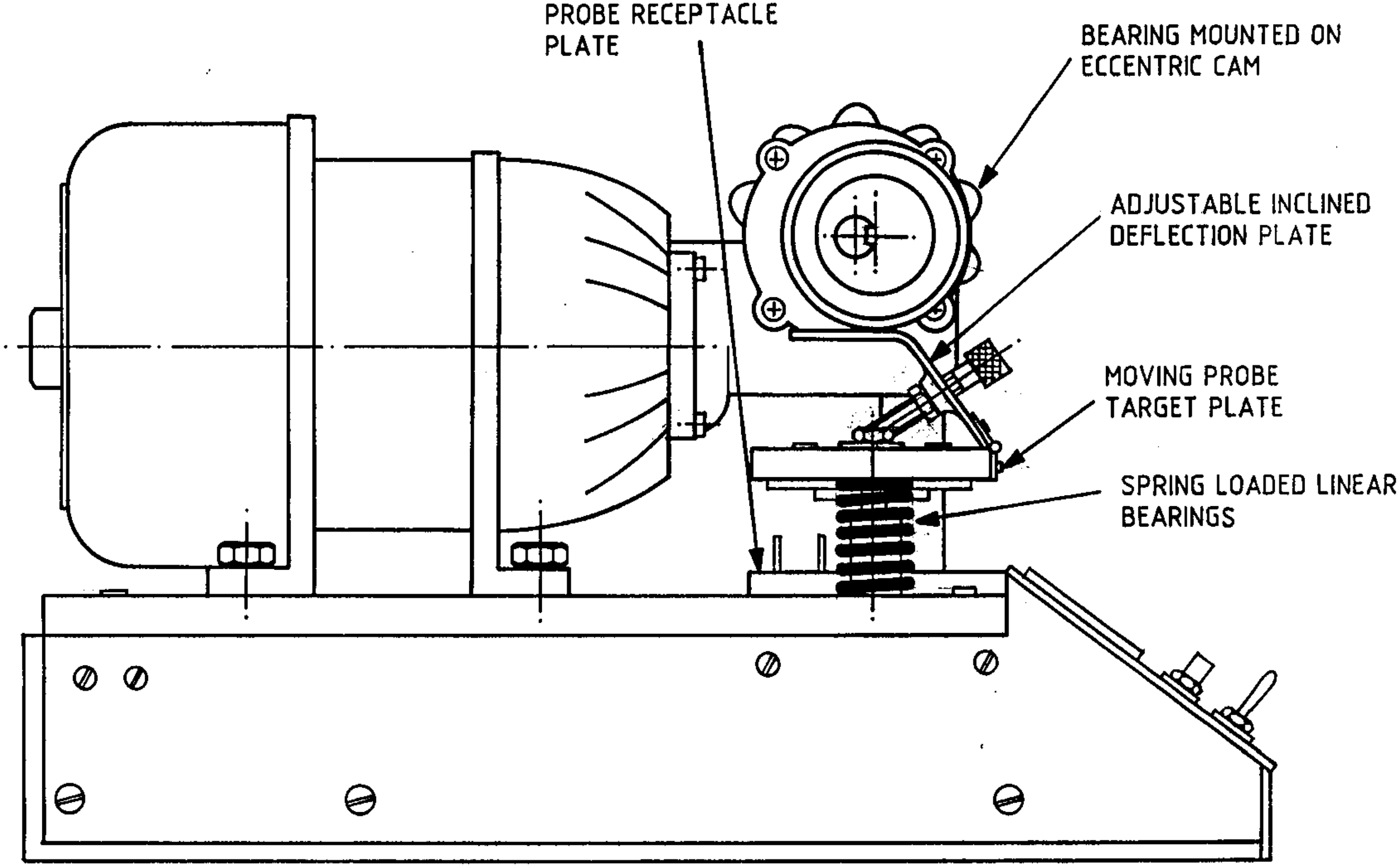
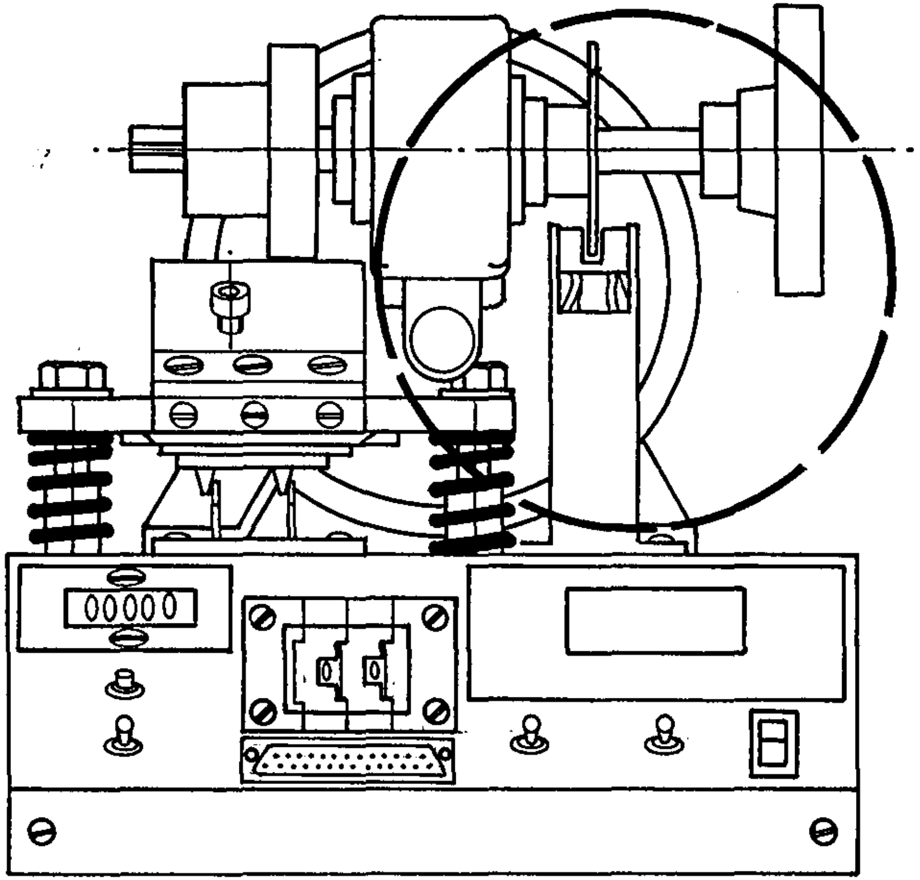


FIG. 3.1 CAM DEFLECTION AND SIDE ELEVATION

FIG. 3.2.a THE GENERAL ASSEMBLY FRONT ELEVATION



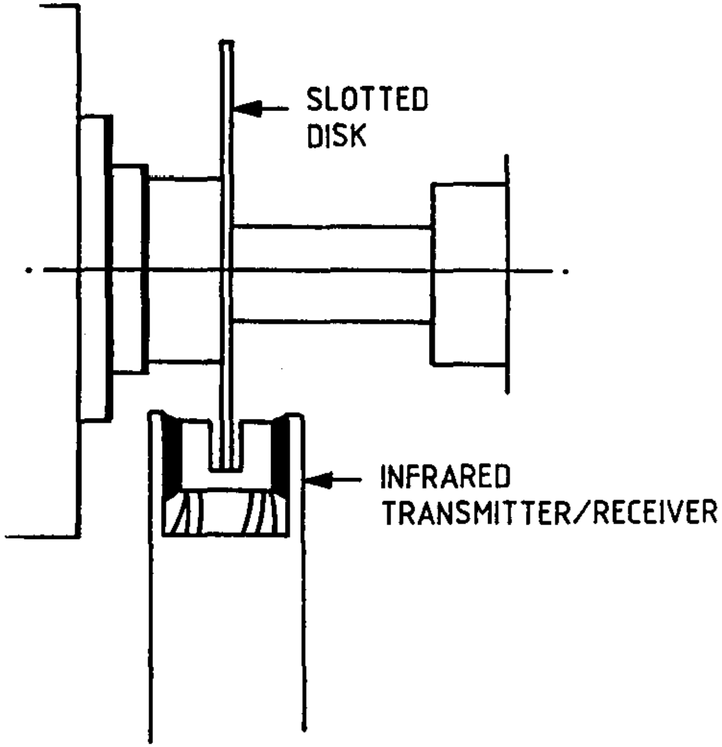


FIG. 3.2b INFRARED SOURCE/SENSOR COUNTING MECHANISM

The probe receptacle can take up to ten probe receptacles if required, probes are inserted and removed from the receptacles before and after testing. The plate is of epoxy glass material, 12mm in thickness giving a good dimensional stability as well as high electrical resistance characteristics.

Electrical connections for the resistance measurement circuitry to the probe receptacles are made by soldered joints. Screws are used to secure the plate to the upper section of the base unit, which is recessed to accommodate the receptacle plate.

The probe target plate makes use of nylon in the plates construction in order to insulate the resistance measurement circuit from the mains earth system with its burden of mains interference. The plate is of 10mm nylon in order to support the variable inclined plane mounted on its upper side. The plate angle is adjusted by a screw and locknut with the PCB target board fixture mounted underneath (Fig.3.3).

3.4 ELECTRICAL AND ELECTRONIC CONTROLS DEFLECTION COUNTER

All the controls are mounted on the front angled control panel (Fig.3.4). They include mains switches for power and motor control, the remainder being for instrumentation.

There are two L.C.D. panel meters, the left one to count the number of probe deflections which is driven by a slotted disk on the gearbox shaft.
An infra-red emitter and sensor is used to detect the interruptions introduced by the slotted rotatory disk, producing an electrical pulse to trigger the counter (Fig.3.5),(See Fig.3.2b).

3.4.1 Probe Resistance Measurement

The right hand L.C.D. Panel Meter is used to indicate probe resistance measurement, converted from a volt meter to measure milliohms, using the four wire method. By feeding a reference voltage, the meter is converted to an ohm meter giving a maximum reading of 2000 milliohms.

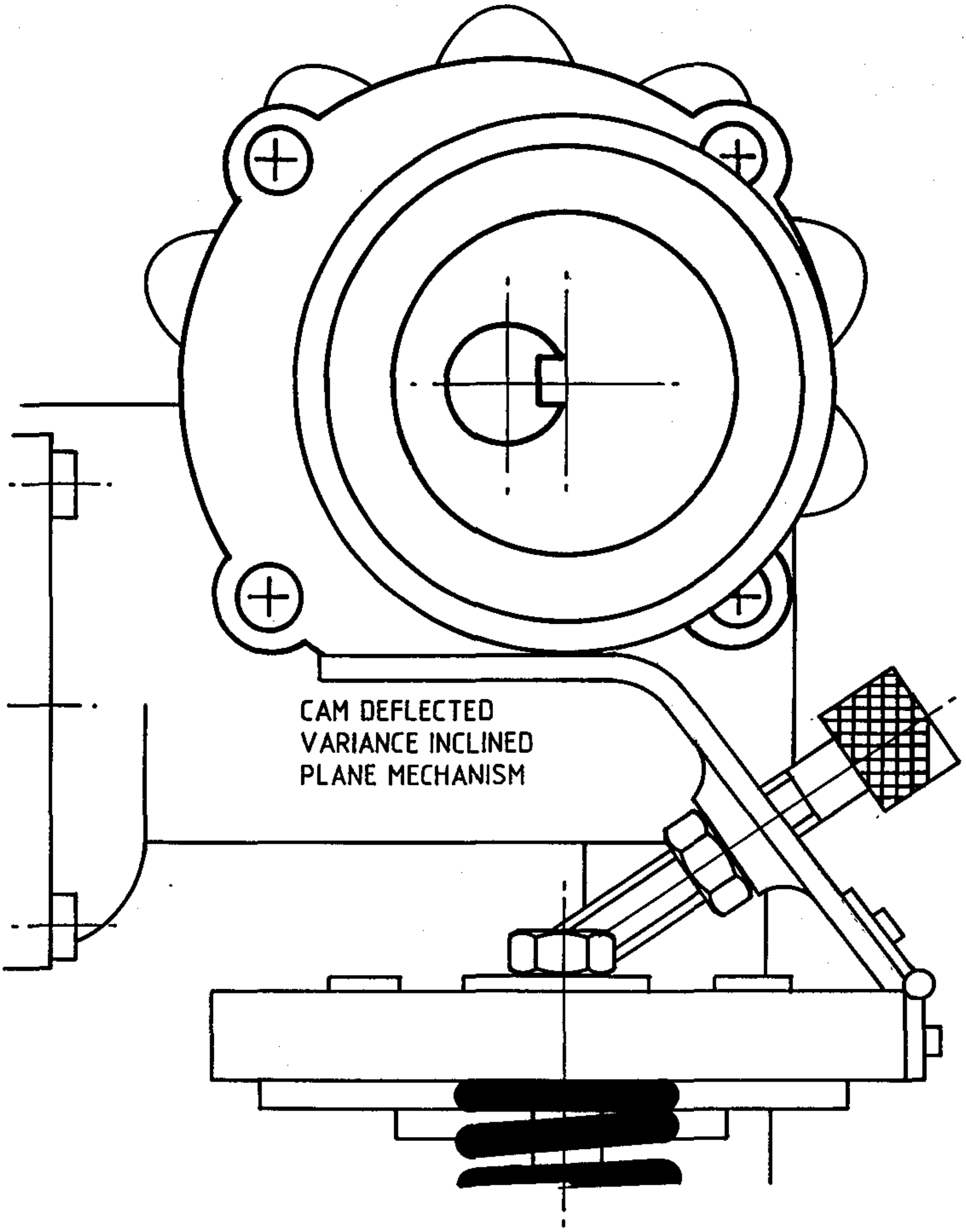


FIG. 3.3 PROBE DEFLECTION AJUSTMENT MECHANISM

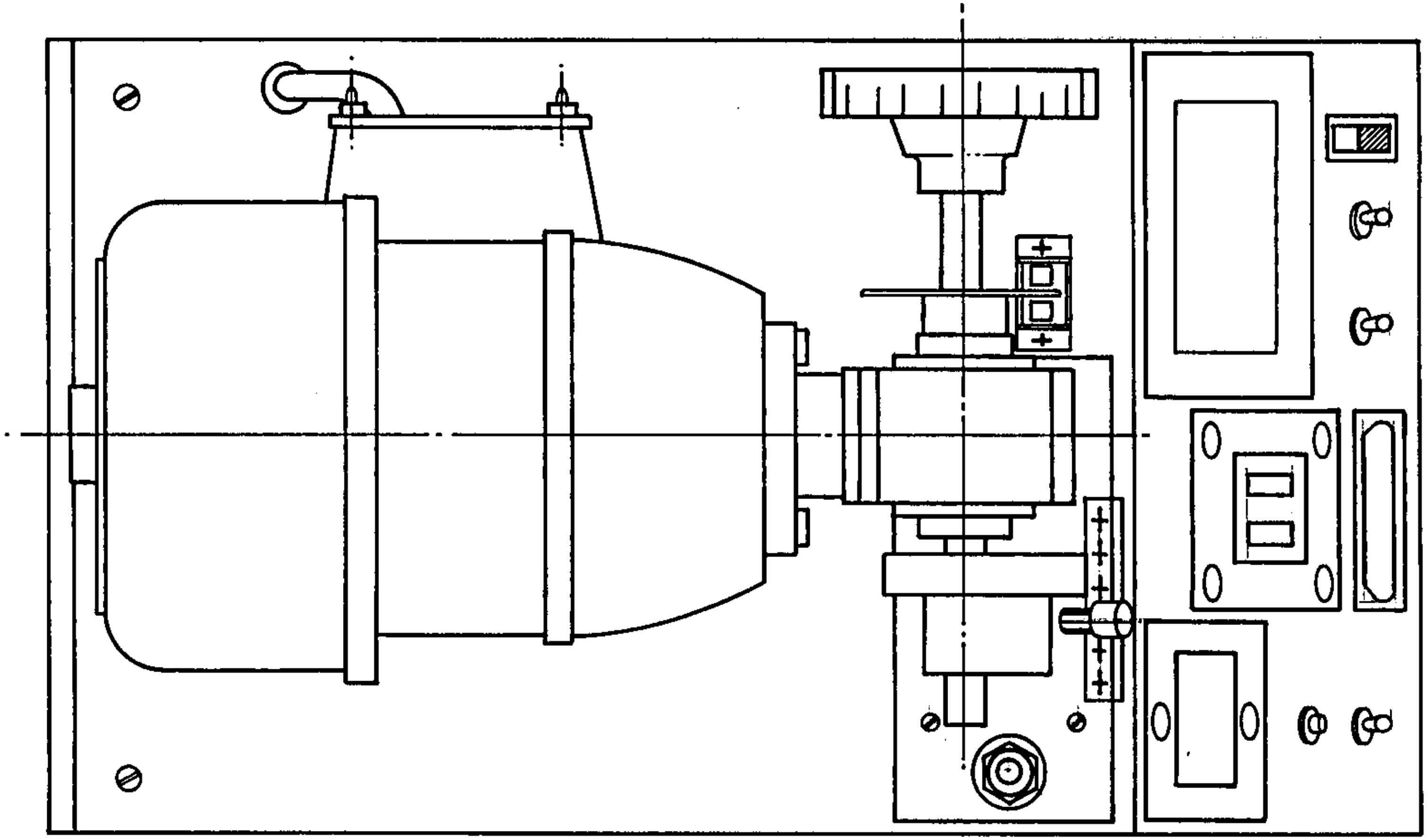


FIG. 3.4 THE GENERAL ASSEMBLY, PLAN ELEVATION INCLUDING FRONT ANGLED CONTROL PANEL LAYOUT

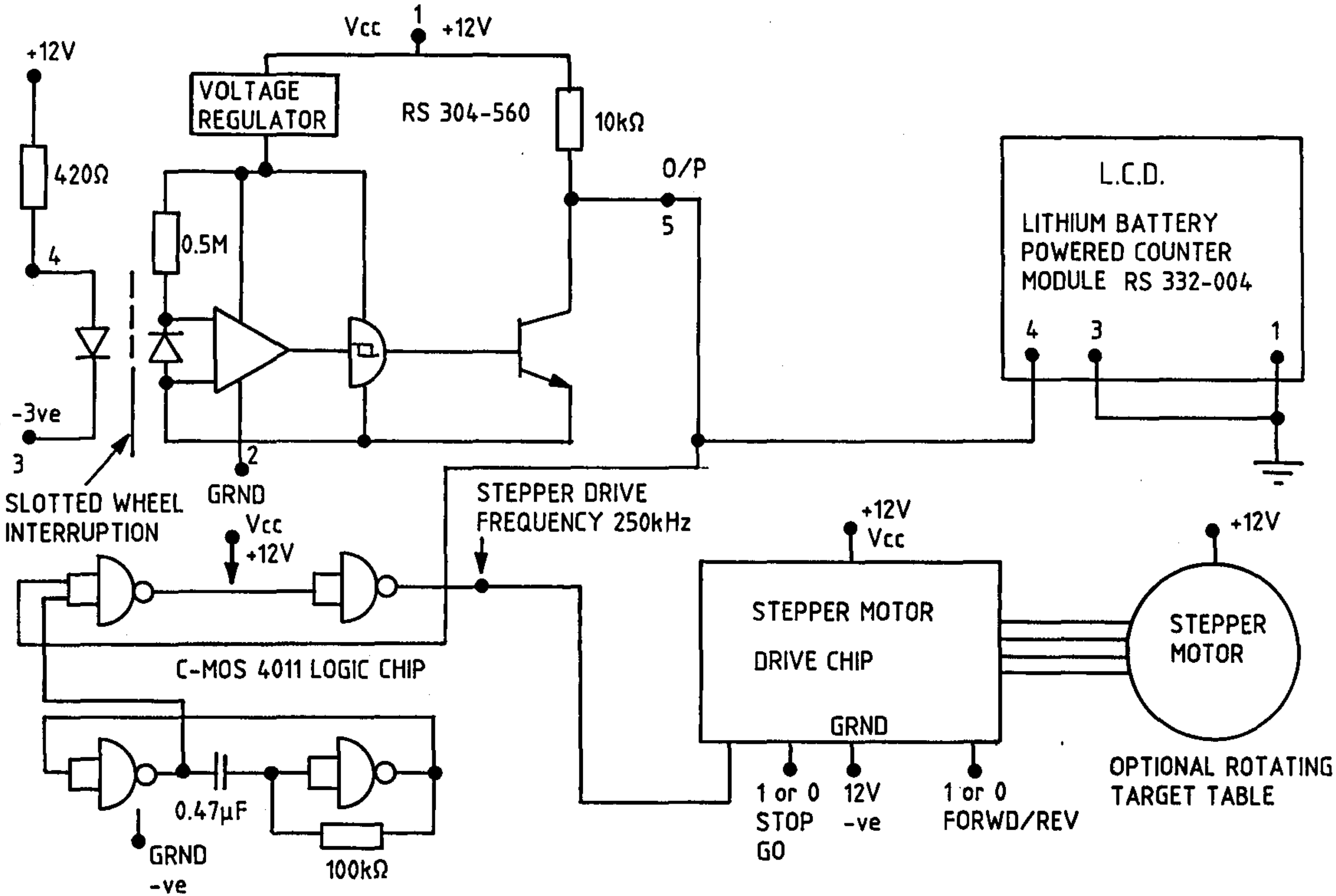


FIG. 3.5 PROBE DEFLECTION COUNTER AND STEPPER MOTOR DRIVE SYSTEMS

The dual ramp method of analogue digital conversion was devised in the 1960's, and was the subject of British Patents 852848 and 869262. The method allows high accuracy measurements to be achieved without the need for particularly close tolerance components. Consequently, it lends itself readily to lowcost and mass production methods. Several integrated circuit systems are available from various manufacturers.

The unit chosen for the measurement system is RS part no 332004 and includes not only the analogue to digital conversion circuitry, but also a liquid crystal display and attendant drivers. R.S data sheet no 3627 includes both mechanical and electrical specifications.

The dual ramp method is essentially a comparison method. In the chosen unit, the input voltage is compared with a reference voltage, in such a way that the display shows a number 2000 x V_{in}/V_{ref}. Generally the module is used as a voltmeter, and a source of reference voltage is provided which has a temperature coefficient of 200ppm/degrees C.

The most obvious method of measuring a resistance would be to pass a known current through the resistor, to measure the voltage developed across it, and then to use Ohm's Law to calculate resistance. However the result would be subject to variations not only from the errors in determining voltage, but also from uncertainty about the value of current.

The improved arrangement is a ratiometric method, in which the test current passes not only through the resistor under test, but also through a reference resistor. The voltage developed across the latter is used as the reference voltage for the panel meter.

Hence:- $V_{in} = I R_x$

$V_{ref} = I R_{ref}$

Displayed number = $2000 \times I R_x / I R_{ref} = 2000 \times R_x/R_{ref}$

Since this arrangement does not use the module's reference voltage source, the problems which its temperature coefficient would have caused are avoided. Notice also that the exact value of the current I is not important, as it does not appear in the ultimate equation. Some constraints should be placed upon the value of this current however to ensure satisfactory operation:-

(a) I x R_{ref} should be about 100mV. This is the value of V_{ref} the module is designed to work with. Smaller values will unduly increase the significance of any errors in the analogue input circuitry of the module. Overlarge values of V_{ref} may cause saturation and non-linearity.

(b) Should the current (I) vary with time, it should do so at low frequency. The two resistors R_x and R_{ref} are unlikely to have the same stray capacitance and inductance, so high frequency variations would not be properly cancelled out.

(c) The current (I) should be within the current carrying capacity of the resistors, and very much larger than the input bias current of the panel meter.

This was realised by choosing R_{ref} = 1 ohm, I = 100mA derived from the 50hz mains supply , rectified, smoothed and regulated to about 12V and fed via a 120 ohm resistor. Since R_{ref} is 1 ohm, the displayed number is a direct reading of R_x in milliohms (Fig.3.6).

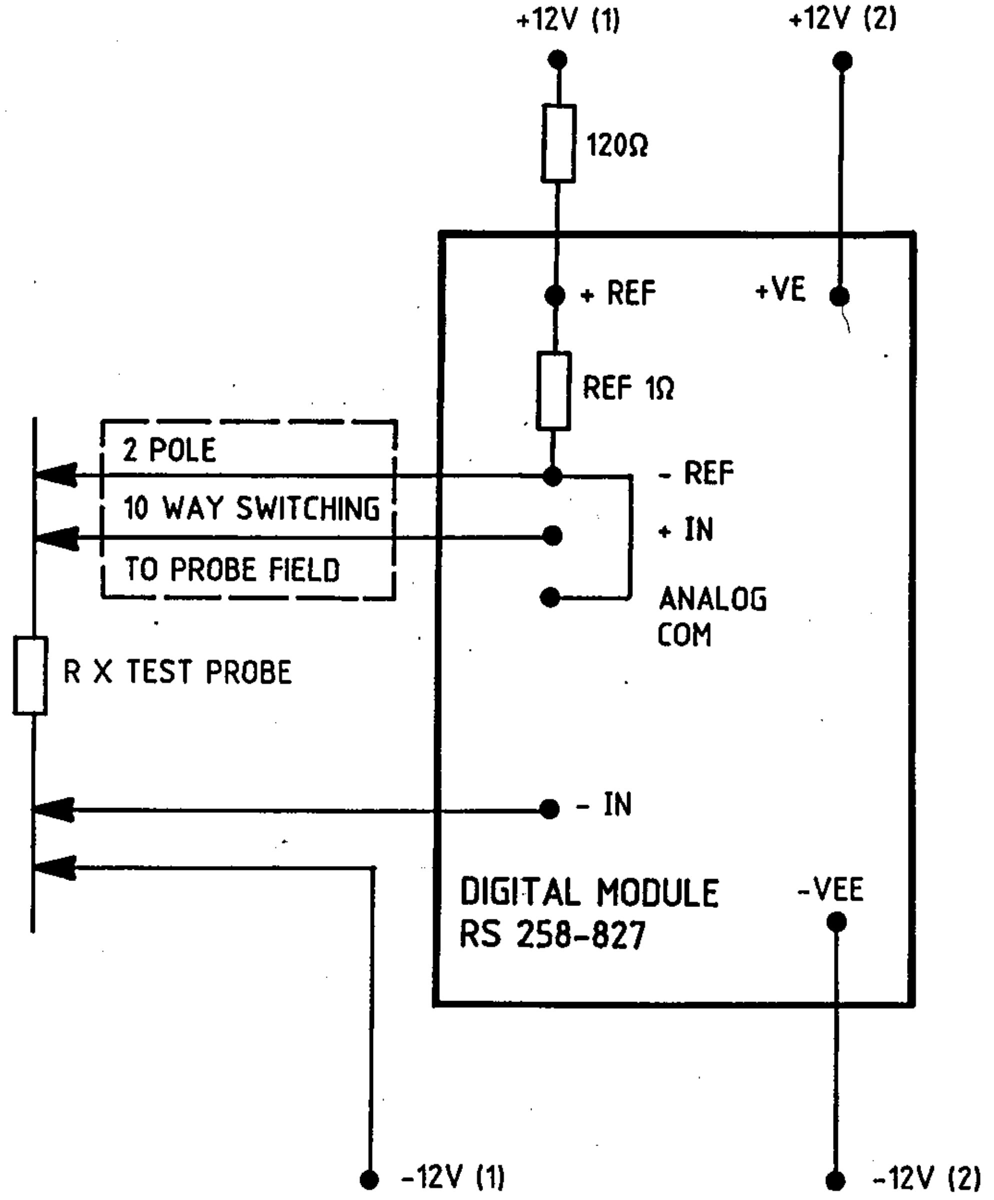
3.4.2 Control System

a). Probe Selection:

Using a dual thumb wheel switch, four wire resistance measurement can be switched to measure all ten probe resistance values accurately in turn.

b). Data logging Plug:

The termination is available for four wire resistance measurement by an external device, such as a ATE system, a Datalogger or a Personal Computer (PC), if required.



TEST CURRENT 100mA
RANGE 0 → 2000mΩ

FIG. 3.6 PROBE TESTING MACHINE RESISTANCE MEASURING CIRCUIT c). Stepper motor driven target plate:

A synchronised stepper motor drive is available to drive a multiprofile target plate, to enable testing a probe to a variety of typical targets. The drive uses an astable multivibrator to supply the correct frequency to the stepper motor drive circuit.

The motor will only run when there is an output from the counter transducer. The motor used is a Parvalux permanent capacitor induction type with a speed of 1400 RPM and a gear reduction to 123 RPM. The motor is mains powered at mains voltage.

d). Internal DC power supplies:

The DC supplies required to drive the electronic system are housed in the base unit, using a printed circuit card designed and manufactured for the purpose.

It is loaded mainly with voltage regulators, in order to supply the instrumentation with the appropriate voltage and current reference supplies. The transformer chosen has two windings, in order to achieve two isolated supplies required for the resistance measurement circuitry. A stepper motor drive system is also located on the PCB (Figs.3.7 & 3.8).

A set of both mechanical and electrical drawings were completed after the design stage, in order to construct and assemble the test machine efficiently (See Figs.3.1, 3.2, 3.4).

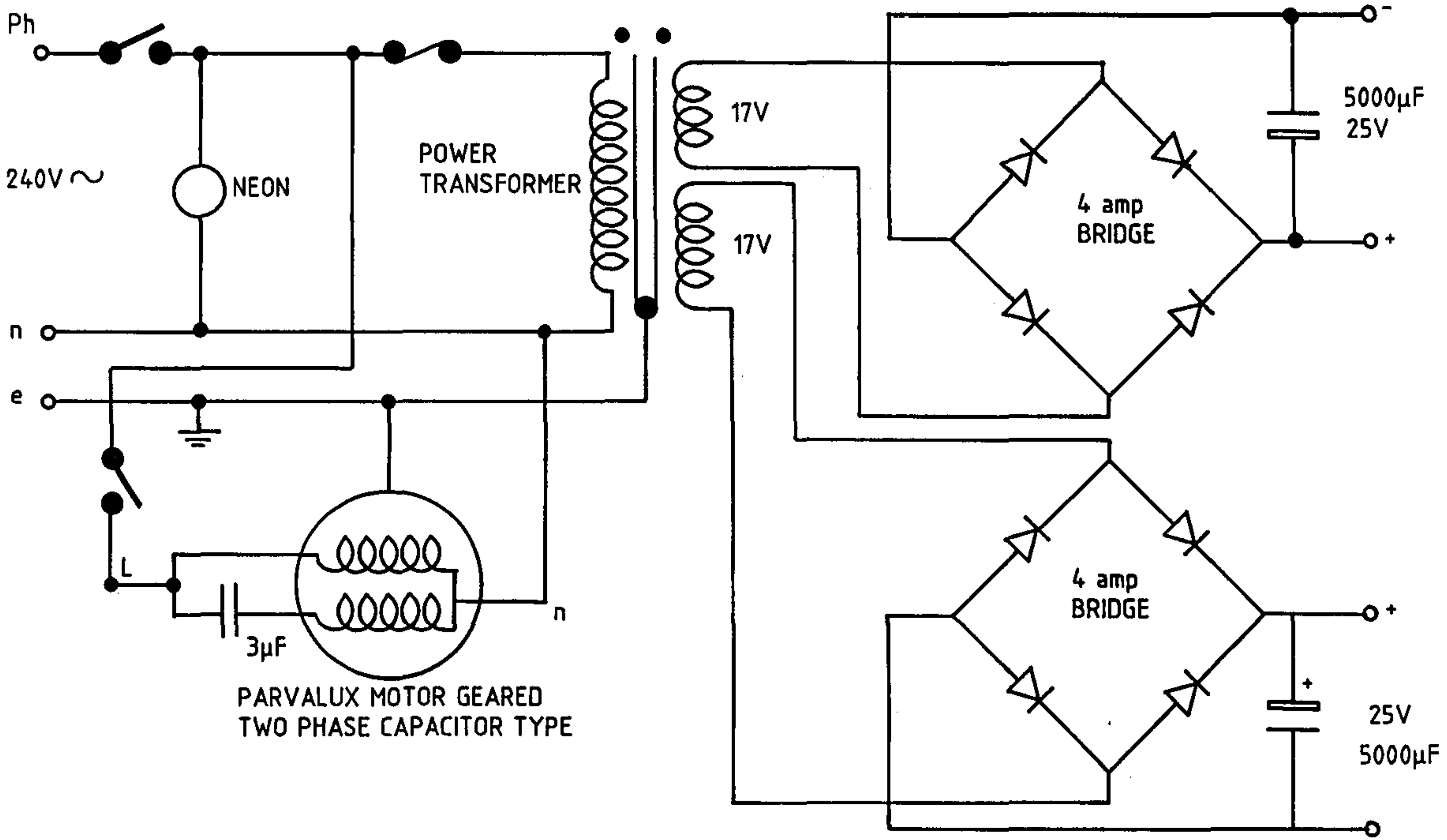


FIG.3.7 POWER AND RECTIFICATION WIRING DIAGRAM

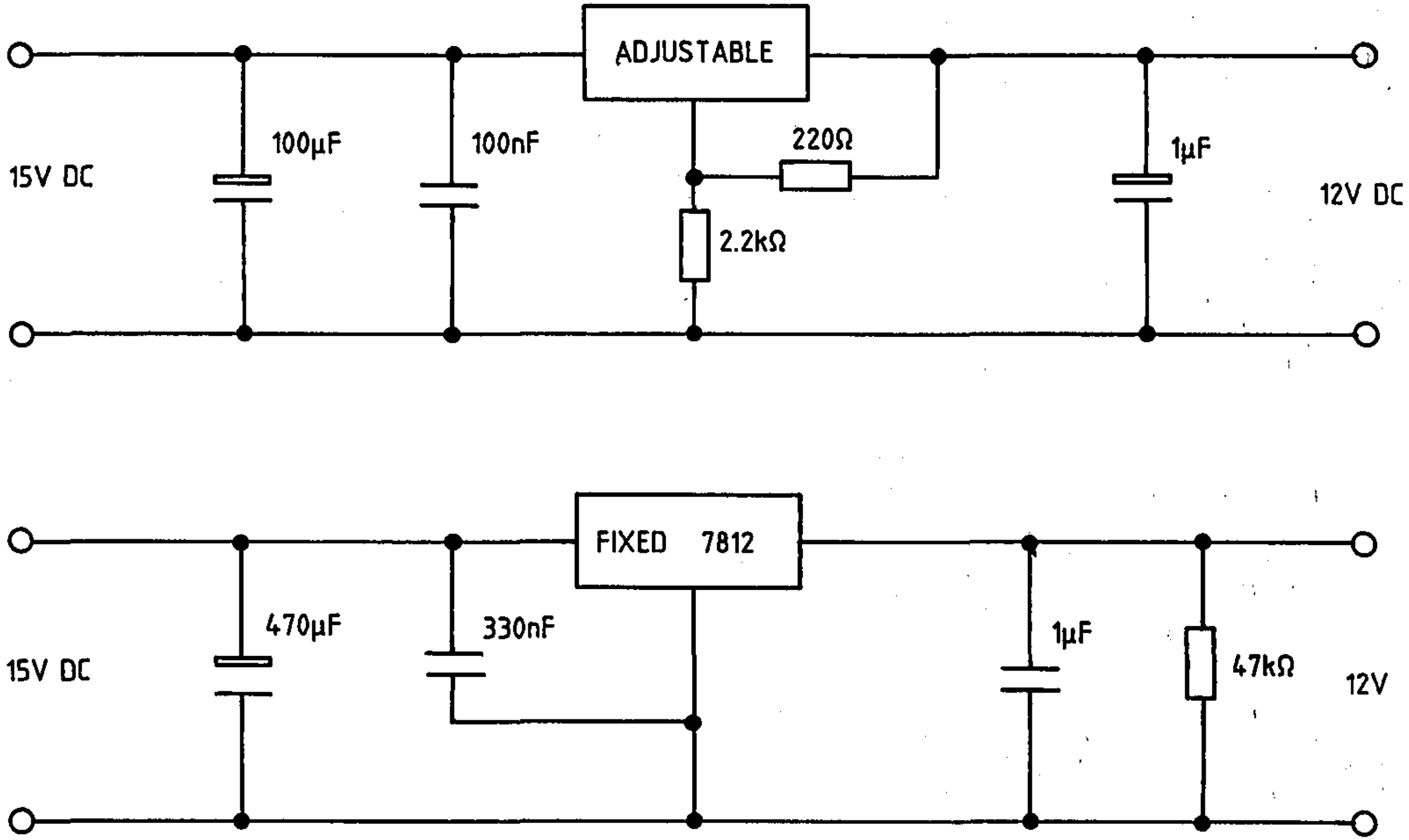


FIG.3.8 P.S.U. SMOOTHING AND REGULATION

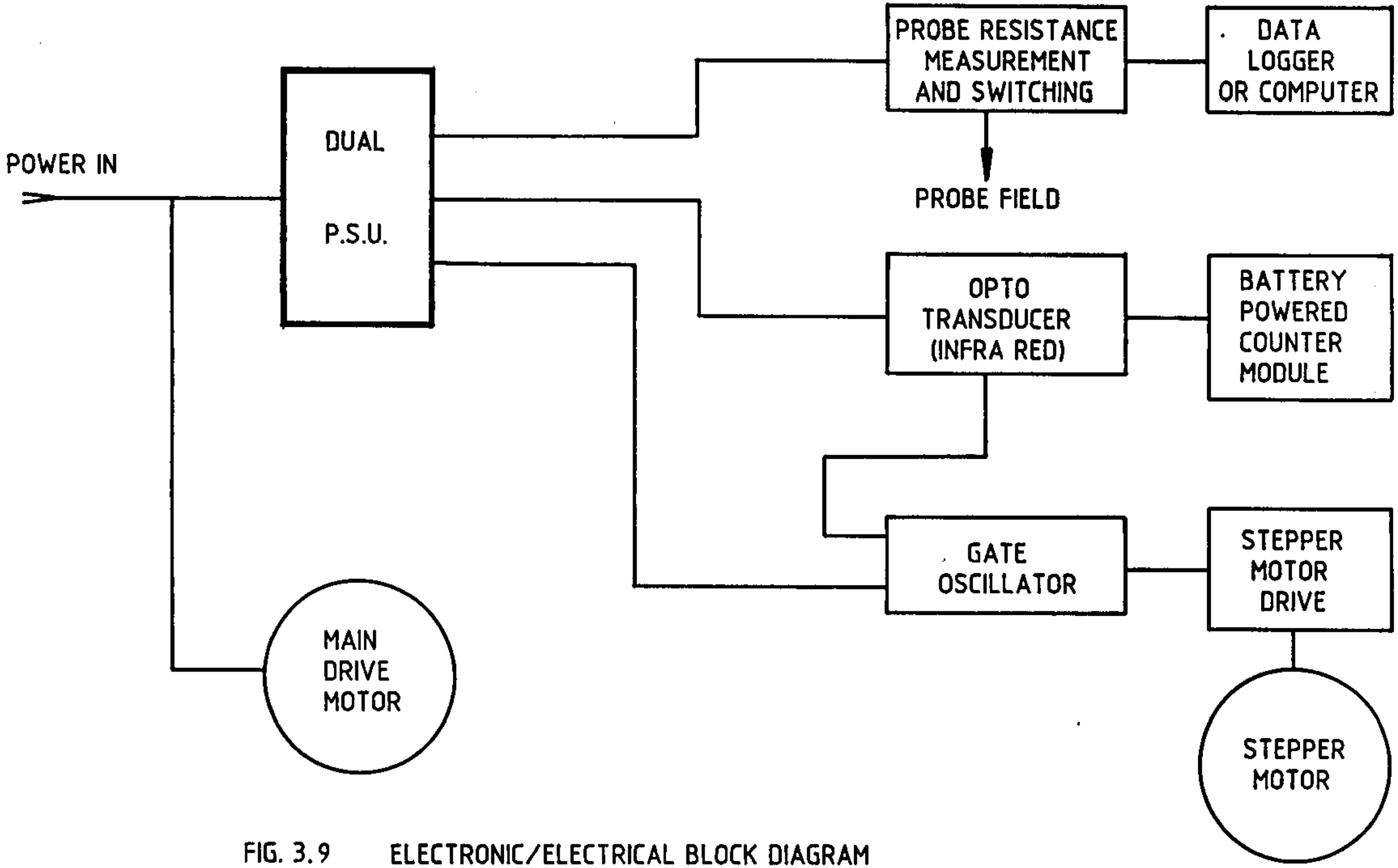


FIG. 3.9 ELECTRONIC/ELECTRICAL BLOCK DIAGRAM

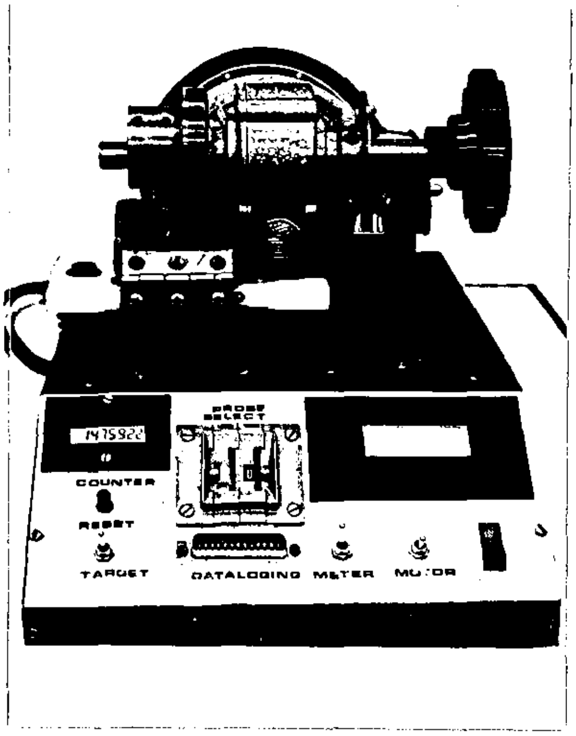


FIG 3.10a : FRONT VIEW OF PROBE TESTING MACHINE

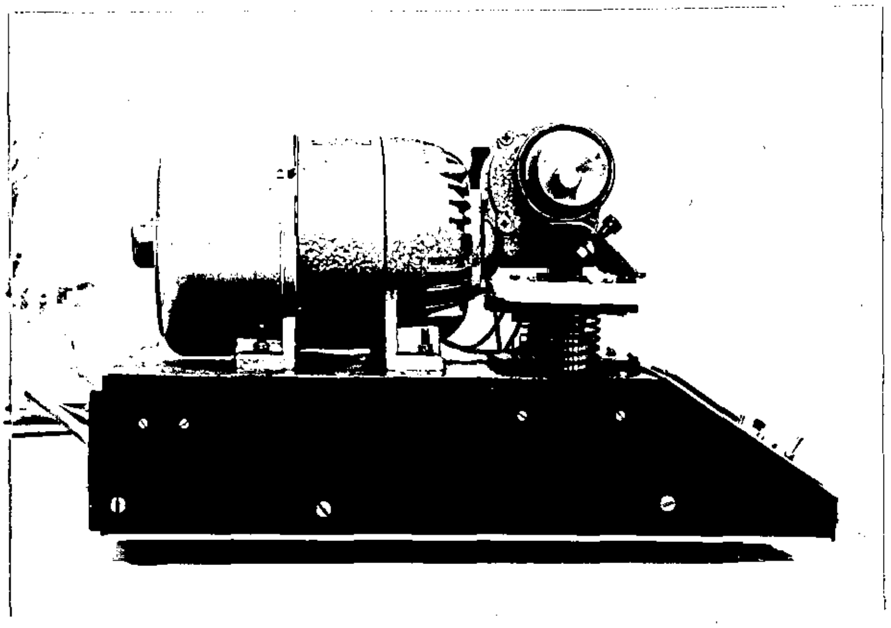


FIG 3.10b : SIDE VIEW OF PROBE TESTING MACHINE

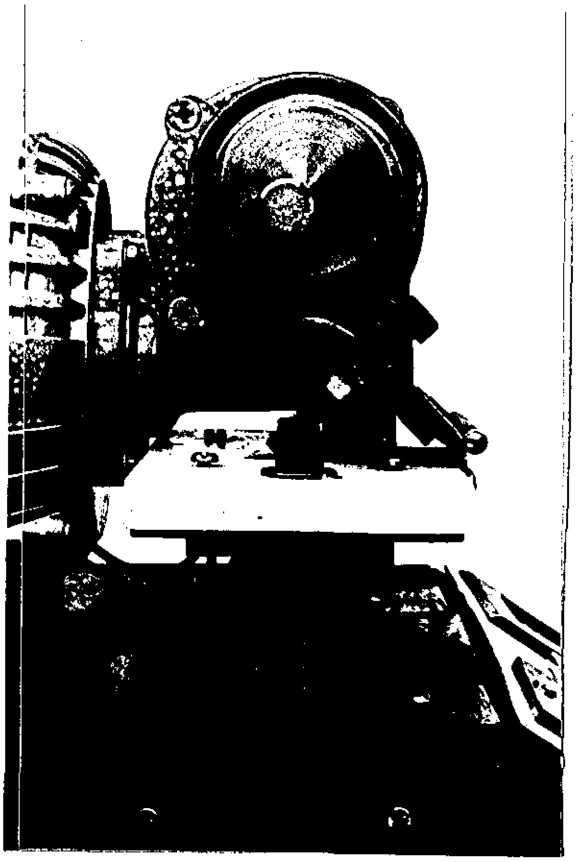


FIG 3.11 : SIDE VIEW OF PROBE TESTING MACHINE

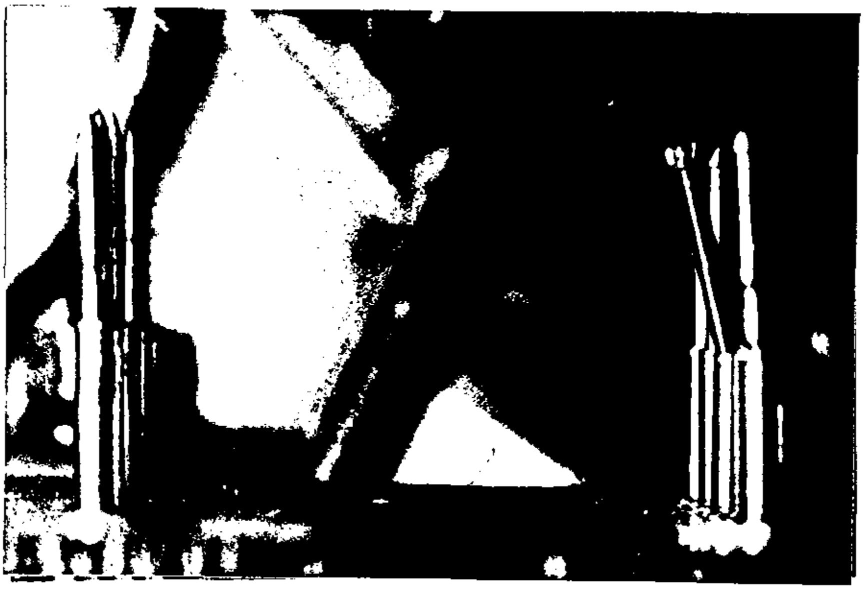


FIG 3.12a : PROBES & RECEPTICLES FITTED INTO EPOXY GLASS BASE PLATE

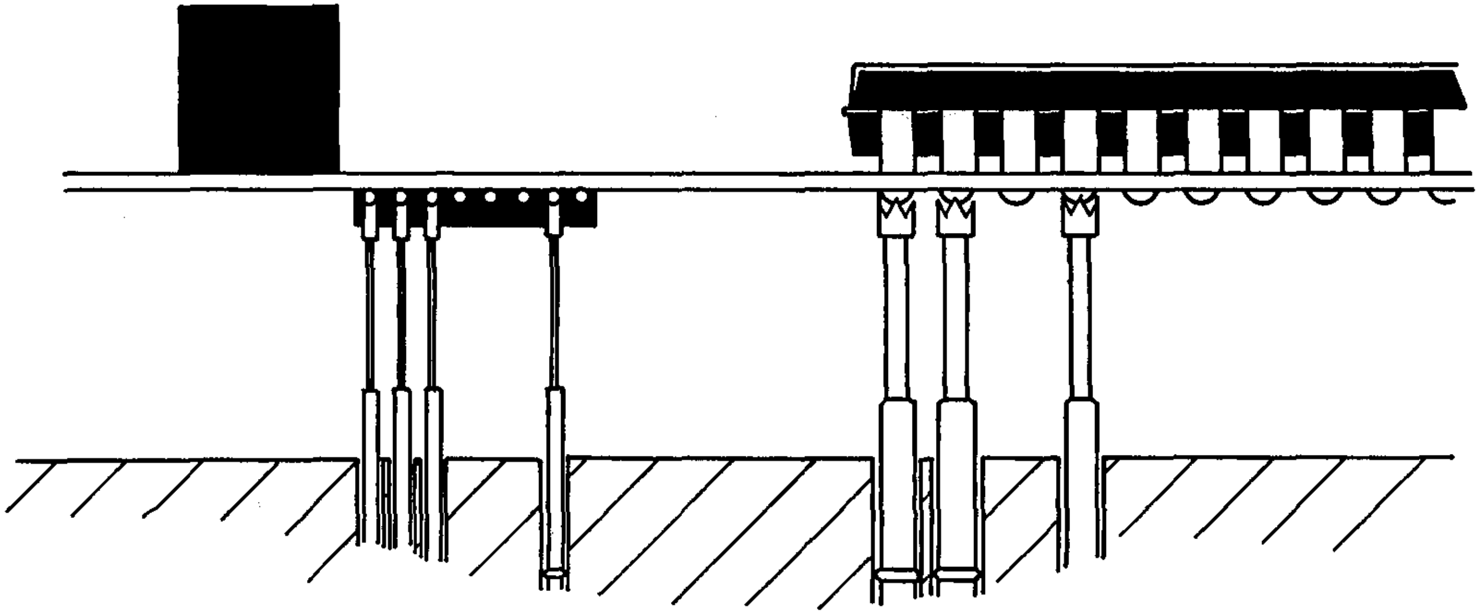


FIG. 3.12 P.C.B./ATE CONTACT INTERFACE

CHAPTER 4

4 EXPERIMENTAL PROCEDURE

4.1 GENERAL

The experimental programme was designed to evaluate probe characteristics during extended life testing. This resulted in the measurement of all appropriate electrical and mechanical parameters during the testing of ten sets of ten probes (100 probes in total) over a period of ten months.

It is possible to use the machines on-board measurement instrumentation, but a more affective way is to use a calibrated standard instrument in order to verify the calibration of the on-board system when the probes are in the machine. Measurements are taken of probes resistance before they are fitted in the life simulation machine, using the calibration standard instrument and afterwards in test machine. By using this method any difference in values may be compensated for in the resistance test measurements results.

The calibration standard instrument may also be used for verification when using an external computer or ATE logging of probe field resistance, before and after life simulation testing.

4.2 CALIBRATION OF RESISTANCE MEASURING SYSTEM

The calibration standard instrument uses the four wire method of measuring low resistance, the meter has four test leads two of each connected to a double contact test clip. On each test clip, one connection is used to inject the test current of 5 mA, while the other is used to measure the potential drop across the probe. By using a four terminal network, the inaccuracies caused by lead resistance are eliminated from the measurement circuit.

It is possible to measure resistance values over the range of 0.001 ohm to 200 ohms with an accuracy of plus/minus 0.1% of the range, using a test power of 5 MW maximum, with 0.1%/degree centigrade ambient temperature drift (RS No. 611953),(Fig.4.1). Most of the

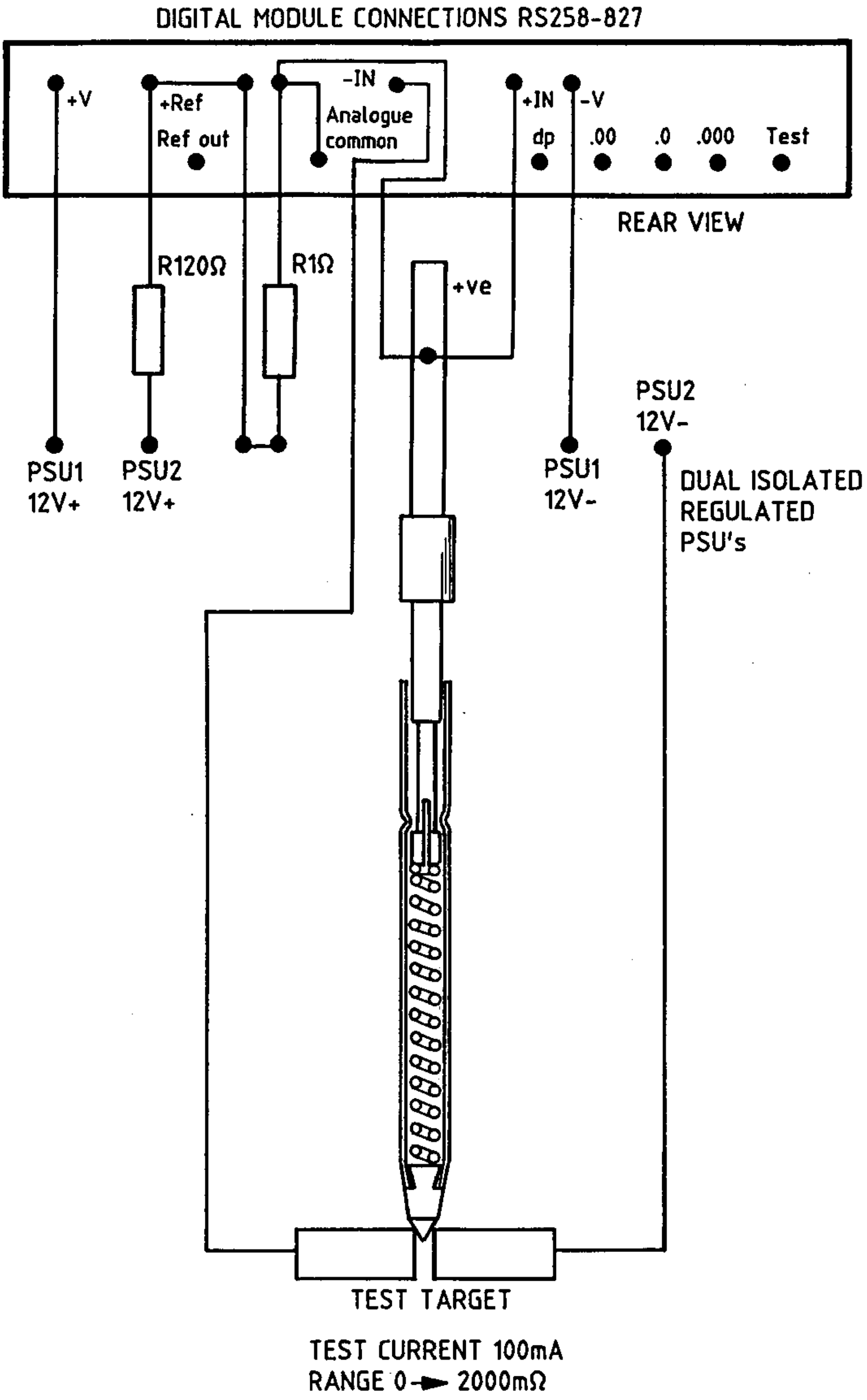


FIG.4.1 FOUR WIRE RATIOMETRIC METHOD USED TO MEASURE LOW RESISTANCE

measurements taken are in the range of 5 milliohms to 2000 milliohms, which is the range of the on-board measurement system used on the test machine.

It may be necessary to make occasional measurements using the calibration standard instrument, where high or open circuit values are encountered.

4.3 MEASUREMENT OF THE SPRING PROBES MECHANICAL PARAMETERS

The spring test probes mechanical parameters are checked before the probes are inserted into the receptacles of the test machine, to confirm whether they conform to their manufacturers published specifications. In the case of the probes used for testing in the machine, there were no great variations in the values measured prior to testing.

Test specifications for probe spring force are quite loose in that the spring force is quoted as plus or minus 20% of the probes stated value in the case of one manufacturer, which means the spring force before testing can differ by 40% compared with another probe from the same batch. In other words, one probe could have a spring value of plus 20% while another could have a value of minus 20%, both from the same batch installed in the same test fixture (41).

4.3.1 Measurement of Probe Spring Force

A.J.J. Lloyd M 5 K Tensile Testing Machine is used to measure the probes spring force before and after probes have been subjected to testing in the life simulation machine.

The machine is a versatile and compact bench mounting materials testing machine, used for evaluating the tensile, compressive, bending and stiffness properties of a wide range of ductile and rigid materials. There are two digital displays on the panel, the left hand display shows the load values, while the right hand display shows the extension or distance travelled. It is possible to display the resultant information in graph form on the machines XY recorder.

A quick and easily interchangeable range of stiff electronic load cells are available for any material or force range.

The probes for spring testing are fitted between the base anchor point and the load cell extension bar, which is supported by the motor driven cross head section. During testing, the cross head is driven downwards compressing the spring probe through the force transducer. The two parameters of force - Newtons and displacement in mm, are continuously being displayed during the test by the machines two digital indicators. It is possible to select the rate or time in which the probe is deflected, by adjusting the speed at which the cross head is driven.

4.4 INSERTING THE PROBES INTO THE MACHINE RECEPTACLES

To avoid probe damage occurring during insertion into the life simulation tester, it is advisable to remove the probe target plate which ensures that damage does not occur to the probes during insertion or withdrawal. Probes can however be inserted or withdrawn without this operation, but there is a risk of probe damage occurring. It is a relatively simple task to replace, secure and tighten after probe insertion or removal, as there are only two screws involved.

While the probe target plate is removed, the PCB target may be examined or replaced with one of a different profile or angle. Two of the four wires in the measuring circuit are connected to the PCB target, using soldered joints for a reliable low resistance connection. It is necessary to use extra flexible wire leads for this purpose as the probe target plate is continuously in motion, deflecting the probes during testing.

Once the probes have been inserted and the target plate positioned, initial measurements of probe resistance can be made to ensure sound connections exist throughout the measurement circuit. It is advisable to examine the machine for loose parts and lubrication in view of test duration, which may be several days or weeks.

4.4.1 Probe Deflection Adjustment

The distance the test probes are deflected through, can be set by adjusting the angle of the variable inclined plane, this enables adjustments to be made from 0 to 100 percent deflection for most types of probes.

Manufacturers recommendations are usually no more than two thirds in order to preserve spring life. However, testing has to be performed beyond this point in order to effectively evaluate probe performance. Adjustment is achieved by turning a screw with an allen key, and locking its position with a spanner and locknut (See Fig.3.1).

At this stage, the machine can be switched into operation, where the probe resistance values can be logged at regular intervals. It is possible to take resistance measurements from zero deflection up to the set value determined by the angle of the inclined plane, usually two thirds travel as specified by probe manufacturers.

Most measurements are taken at (a). zero and (b). two thirds, in order to compare relative changes during life testing, but it may be found necessary to take measurements at other deflection values, determined by test results.

A visual examination can be made when probe resistance measurements are taken to check whether probes have become jammed or bent, as most of those conditions would not be evident when taking probe resistance values into sole consideration. Preliminary testing has shown, that partly jammed probes produce comparable resistance values with a probe which has not become jammed, bent or deformed.

4.4.2 Probe Cycling Time

The probes resistance measurements are logged every ten thousand cycles (approximately every eighty minutes). Most probes will be tested to between two to three million cycles, depending on the type of target the probes are tested to.

Severe angled targets cause the probes to wear more quickly due to the side pressure applied to them, sometimes causing probes to fail in less than a million cycles. While others directed to a smooth flat target, may reach two to three million cycles before severe mechanical or electrical failure occurs. If however a probe becomes jammed when it is in the extended position, it will be buckled, bent or jammed solid into the probe receptacle, by the action of the target plate. In this case it is often difficult, or impossible to remove the test sample from the probe receptacle. Test probes in this condition cannot be fully evaluated due to damage caused in their removal from the receptacle, and in some cases it is not possible to measure spring pressure and side play in these probes. It is therefore desirable to test a reasonable size sample on each occasion.

In order to remove probes from the machine, it is necessary to first remove the target plate with its attached PCB target on the underside, which is the same operation as fitting the probes, except in reverse order. In most cases, 80% to 90% of the probes can be removed without difficulty, as they are designed to be a push fit in the receptacle and only need withdrawing using normal finger pressure. Some probes that cannot be removed by normal means may be removed by the use of normal electronic servicing tools. The odd probe that defies attempts of removal, is often destroyed with its receptacle defying all attempts before destruction. This is only the case where probe tests are extended towards total mechanical failure, requiring the replacement of receptacle and probe before testing can commence.

Once the probe samples have been removed, they can be identified by their switching position number which is used in their resistance testing sequence of measurement. The probes may be attached to an adhesive label or stored in a numbered container, for further evaluation for the effects of wear.

4.4.3 Post Testing Probe Evaluation

Evaluation of mechanical and electrical parameters (which is in addition to the log of resistance measurements taken over the test period) includes: (a). the measurement of side play movement; (b). the measurement of probe tip wear due to contact with the PCB; (c). the measurement of probe spring pressure; (d). the static measurement of probe resistance, compressed and relaxed as a calibration reference for the on-board resistance measuring instrumentation.

Photographic records are taken to demonstrate the effects of wear on various component parts of the probe assembly, using both light and X ray photography.

CHAPTER 5

5. EXPERIMENTAL RESULTS

5.1 GENERAL

The performance of automatic test equipment used in testing printed circuit boards depends on the type and quality of test probes fitted within the test fixture, and a large number of probes were tested to evaluate their performance. The probe is the critical link between the UUT and the test system, for without a reliable spring probe performance high speed automatic test equipment would not be very reliable. Yet the spring probes performance has often been overlooked, resulting in costly delays. High resistance values are the main problems during service, whilst mechanical factors due to flexibility or wear of probe components are responsible for the so called false errors during PCB testing. It is for this reason that the resistance monitoring experiments were conducted in order to assess the probes electrical and mechanical performance over various test periods.

The apparatus developed to perform life simulation testing can accommodate up to ten probes for a given test. To simulate actual conditions the probes were tested on a range of targets from flat through to angular; in increments up to 60 degrees. The probe targets used were copper clad PCB or stainless steel for flat targets the resist film was stripped off immediately before the test commenced to achieve an oxide/contamination free target. In the case of angled targets a copper angled section was soldered onto the printed circuit board target, with any flux or other contamination being removed by using a fine abrasive followed by trichloroethylene, thus leaving a bright clean uncontaminated copper surface. The resistance of each probe was taken using the external measurement system before each set of ten probes was inserted into their receptacles, located on the probe tester platform. Resistance measurements were then undertaken once again, in order to verify calibration of the on-board resistance measurement circuit.

Electrical resistance measurements were logged every ten thousand cycles of testing. This value was chosen to make direct comparisons with probe manufacturers published data. Using the four wire D.C. method of resistance measurement (42) (see figs.2.5 & 2.6), readings were taken over each set of ten probes (100 in total) at two thirds compression (which is the manufacturers recommended deflection), for one, two or three million cycles as deemed necessary for each experiment. The cyclic deflection rate of the testing machine was 123 revs per minute and for 10,000 operations this required the probe resistance measurements to be taken approximately every 80 minutes . Resistance values were fed into a computer to produce a graphical standard printout, see appendix 1. The graphs of electrical resistance were plotted for each probe tested, enabling comparisons to be made for each probe's performance within its test environment.

The probe chosen for life simulation was the tulip style head probe, recommended for 2.54mm (0.10inch) centres with a spring force of 189,9 GM (6.7 oz), current rating 3 amps. The new probe contact and internal resistance is specified by the manufacturers at a maximum value of 50 milliohms; the probe materials are contact barrel of nickel/silver and gold lined; the spring material is stainless steel; the plunger is of full hard beryllium copper, rhodium plated over nickel (or optional gold plated over nickel). A maximum probe deflection of 6.35mm (0.250inch) is available but only two thirds of this is recommended for test applications. There are approximately eight suppliers of test probes world wide, each producing a considerable range of similar types.

Probe performance depends on the materials from which the probe is manufactured, and its ability to maintain a consistently low interfacial contact resistance on every target (43). Probe life is measured in cycles, one cycle being the depression and release of the plunger. Alignment of the fixture, spring and barrel material and plunger travel, all affect probe life. Most spring probes are designed for a spring life exceeding a million cycles if used under approved conditions (no severe side loading and free of environmental contamination). Since the spring is the most important of the probe components it means that should it break the probe will fail. The spring provides the compliant force to the plunger which allows the probe tip to access non uniform PCB surfaces, enter holes in the PCB and adjust to variations in component lead lengths. The spring force should be high enough to provide a low electrical resistance contact, and it may vary from less than one ounce to sixteen ounces, depending on the surface material to be contacted. The cleanliness of the PCB target and probe tip are a key factor in ensuring a low resistance contact. A clean gold plated circuit or substrate requires low plunger force, sometimes as low as half an ounce, whilst a solder plated PCB may require three to five ounces and a plunger tip geometry suitable to penetrate surface and tin oxides. If flux or other contaminates are present forces of 5 to 8 ounces may be required.

5.1.1 The Experiments

The ten experiments performed were split into two categories, the first being a group of six tests with the primary objective of investigating contact resistance performance. Three of these tests were conducted at copper angled targets of 45 degrees and 60 degrees, whilst the remaining three were targeted at a flat copper PCB. Resistance values were measured every 10000 cycles for each of the ten probes. The 2.54mm centre tulip head probe had a noted spring force of 189.9 GMS, and was chosen for five of the six experiments because of its reputation amongst fixture manufacturers for long and robust reliable service. The first of the six tests (Test 101) used the same probe but with a lower spring force.

With these six experiments tested between 2 and 4 million cycles, there was only a small percentage of mechanical failures up to 1.2 million cycles (manufacturers guaranteed spring performance is up to 1 million). The only major mechanical failure was a probe plunger breaking off which was aligned to a 60 degrees target for the series of tests. Cycles after 1.2 million produced some mechanical failure associated with excessive wear. The resistance data was converted into graph form and categorised under ten performance headings, thus allowing comparisons to be made between various levels of performances. Experiments 101 to 106 produced a large amount of useful resistance test data with considerable differences in individual probe performance throughout the series of tests.

To identify all possible mechanical failure modes a second series of tests were conducted. These series of tests (107 to 109) used a similar probe type of comparable parameters with the previous six experiments but with a reputation amongst fixture manufacturers of producing a less durable performance. Tests were conducted using samples of ten probes to various stages of wear, and to almost destruction in a minority of cases. Their life ranged from half a million cycles to a maximum of two million in one experiment. Using data and information obtained from both series of experiments, a table of mechanical failure categories was produced. With the less durable B category test probes mechanical wear was evident at an earlier stage of the experiments, with wear debris visible around the probe receptacle mounting plate at an earlier stage. One of these mechanical tests was taken beyond the probes normal service life (as with some of the electrical parameters) in an effort to identify all possible mechanical failure categories.

Finally a much harder stainless steel flat target (test 110) was used to evaluate any different levels of performance between the normal copper target and this target. Early results were very interesting and showed that the initial high values of contact resistance slowly reduced as the points gradually penetrated deeper into the outer surface of the metal.

5.2 PROBE PERFORMANCE EVALUATION

The six tests were categorised according to their resistive performance from 0 to 1.2 million cycles, (the probe manufacturers guarantee performance up to 1 million cycles). Test continued after 1.2 million to identify any possible fault categories of a mechanical nature. One was extended up to 4 million cycles.

In order to evaluate and categorise a set of probes' performance during life simulation testing it is necessary to specify the probe's performance which is deemed acceptable. Values of more than 1000 milliohms between the UUT and ATE would, according to a major telecommunications test department, be unacceptable. To ensure detection of the majority of faults for all types of circuits preferred probe resistance values should be less than 100 milliohms.

Probe performance is divided into the ten categories listed below (in order that the resistive performance ranges could be assessed in detail):-

Category 1. Resistance values not exceeding: 50 milliohms (Fig.5.1)

Category 2. Resistance values not exceeding: 150 milliohms (Fig.5.2)

Category 3. Resistance values not exceeding: 250 milliohms (FIG.5.3)

Category 4. Resistance values not exceeding: 500 milliohms (FIG.5.4)

Category 5. Resistance values not exceeding: 750 milliohms (FIG.5.5)

Category 6. Resistance values not exceeding:1000 milliohms (FIG.5.6)

Category 7. Resistance values not exceeding:1250 milliohms (FIG.5.7)

Category 8. Resistance values not exceeding:1500 milliohms (FIG.5.8)

Category 9. Resistance values not exceeding:2000 milli ohms (FIG.5.9)

Category 10.Permanent open circuit value exceeding 2000 milliohms

Categories 1 to 6 would be acceptable commercially. Category 7 would be a borderline case and should be avoided if possible. Categories 8,9 and 10 would be unacceptable commercially.

Category suffix (a) - Stable

Category Suffix (b) - Unstable (Fig.5.10).

The test results for each experiment were all categorised according to the above table and further divided into low, medium and high category values (Figs.5.11 to 5.16).

5.2.1 Average Resistance Values

In most cases the average resistance performance of a test batch of ten probes shows performance values which may seem reasonably acceptable (Figs.5.17 to 5.20), but when compared with the minority of probes producing unacceptable repetitive connections to the target, multiplied by the number of probes in a typical fixture the average value seems to have less significance (44). This is because it only needs one ineffective probe out of possibly two, three hundred or perhaps thousands installed in a test fixture for the ATE to reject a succession of perfectly good circuit boards due to this one ineffective node connection. The average resistance of a probe may be of less significance when looked at from this viewpoint, because a minority of probes producing consistent or sporadic high

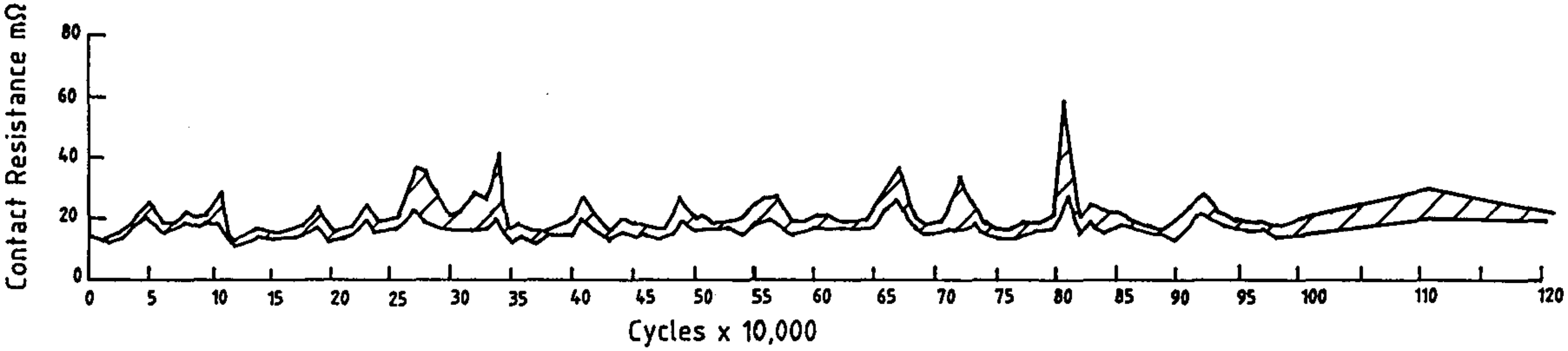


FIG. 5.1 PROBE7. TEST 105. CAT 1. 50mΩ TOLLERANCE ENVELOPE FOR 10 READINGS

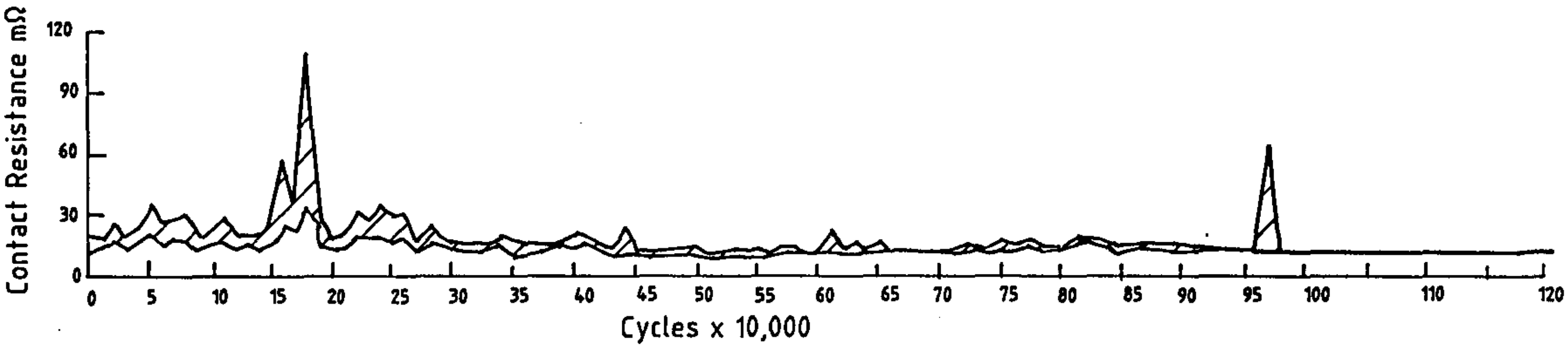


FIG. 5.2 PROBE 9. TEST 105. CAT 2. 100mΩ TOLLERANCE ENVELOPE FOR 10 READINGS

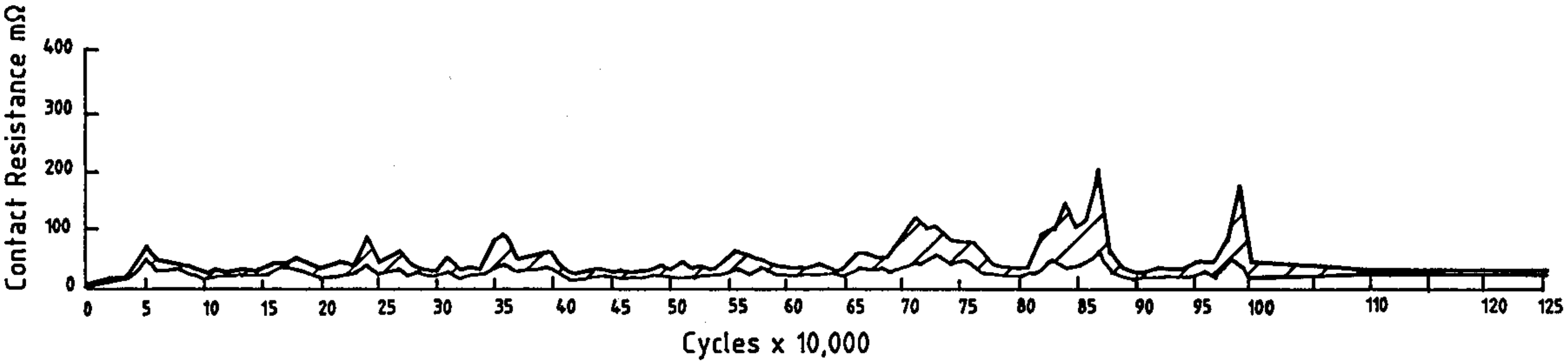


FIG. 5.3 PROBE 10.TEST 105.CAT 3.250 mΩ. TOLLERANCE ENVELOPE FOR 10 READINGS

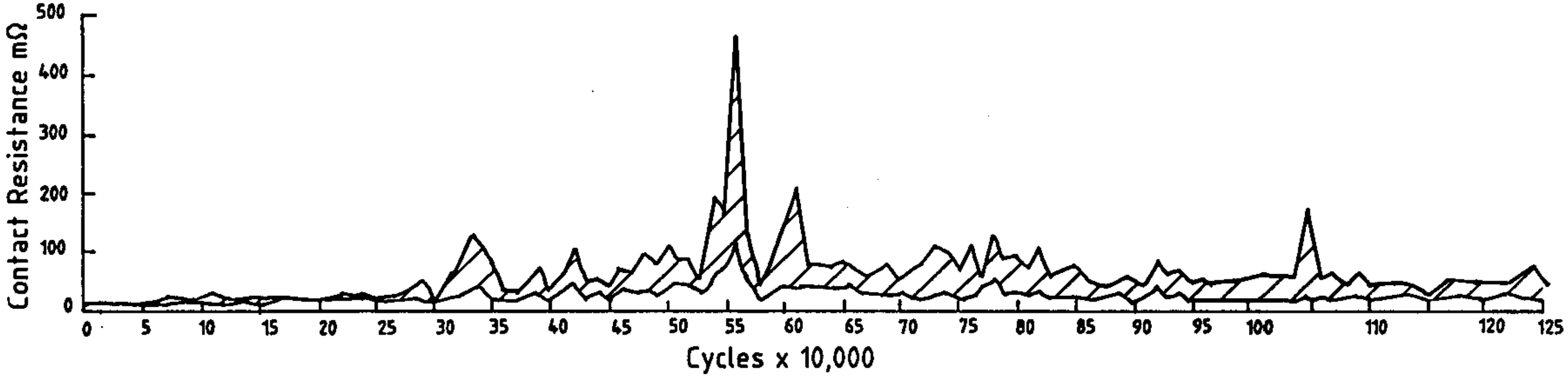


FIG. 5.4 PROBE 2.TEST 103.CAT 4.500mΩ. TOLLERANCE ENVELOPE FOR 10 READINGS

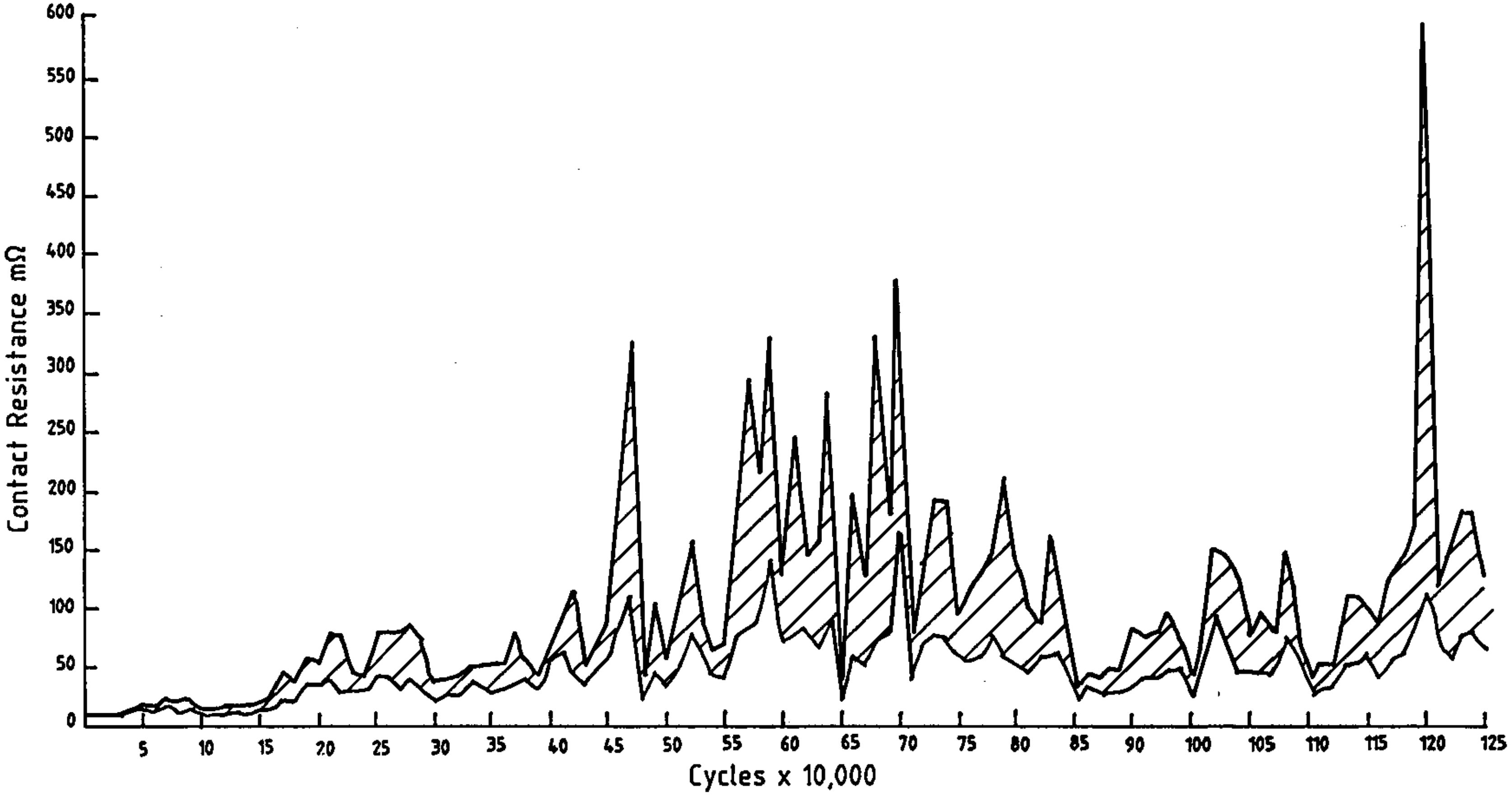


FIG. 5.5 PROBE 5. TEST 103. CAT 5. 750mΩ.

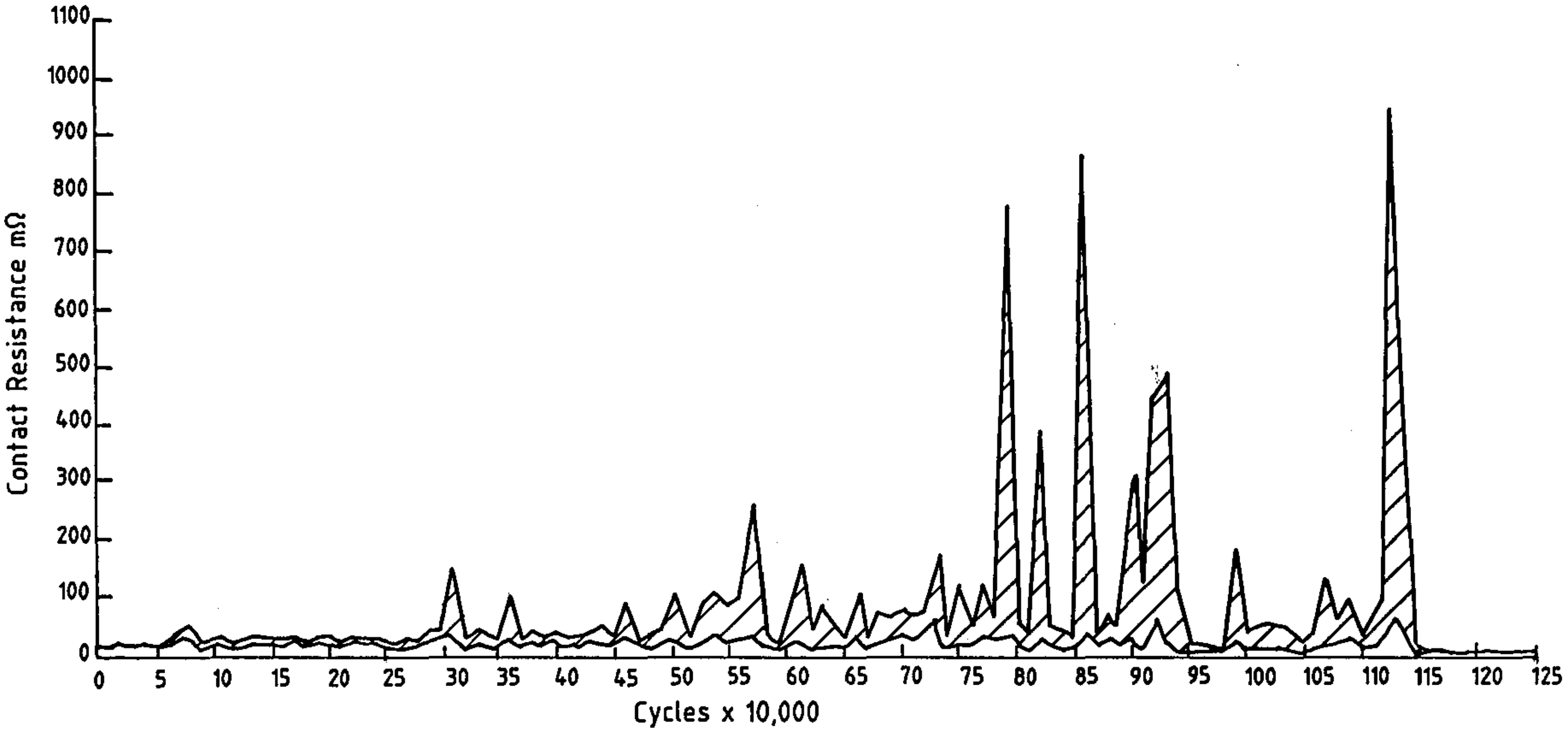


FIG. 5.6 PROBE 1.TEST 103.CAT 6.1000mΩ

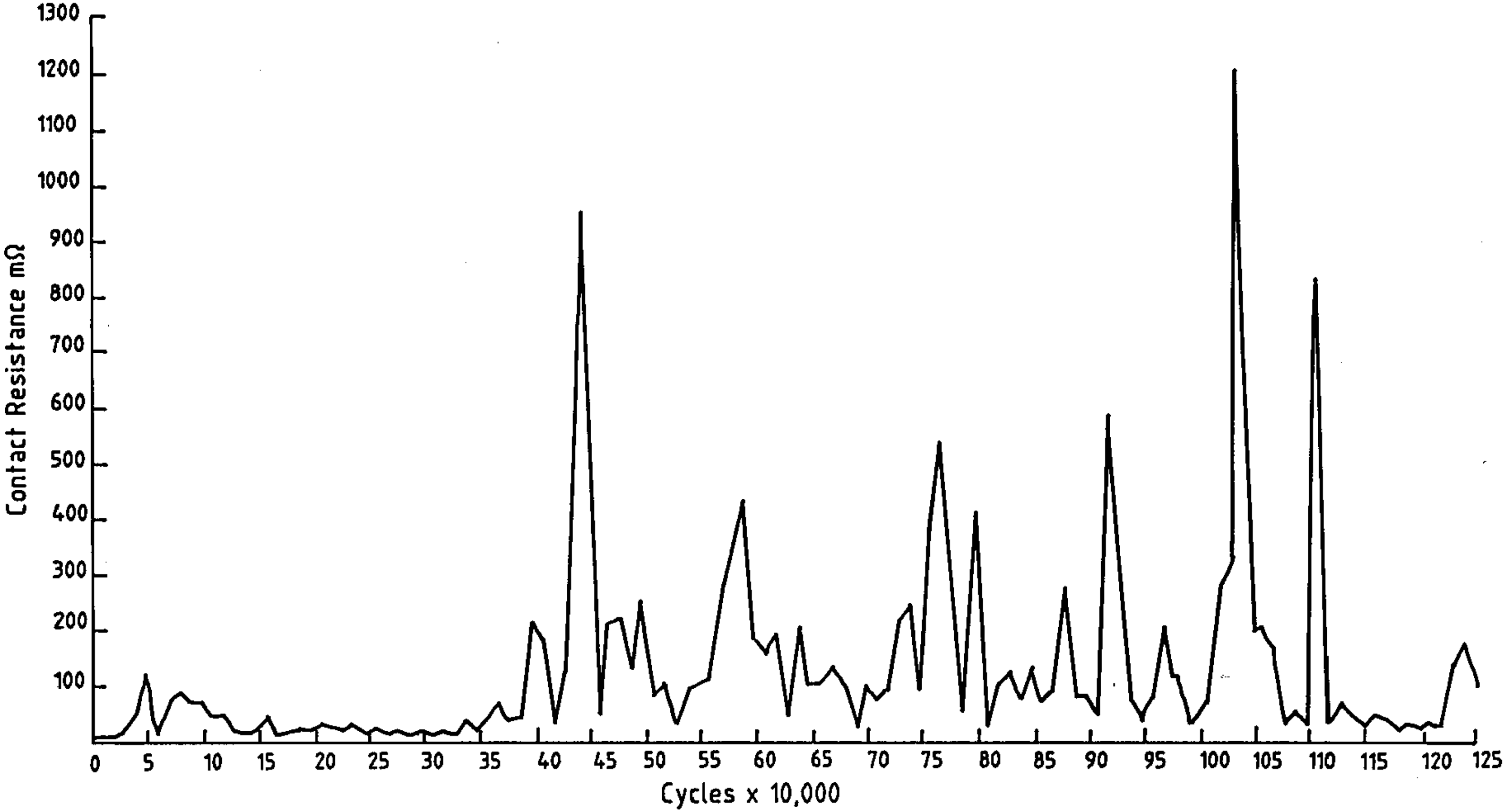


FIG 5.7 PERFORMANCE CAT. 7.1250Ω

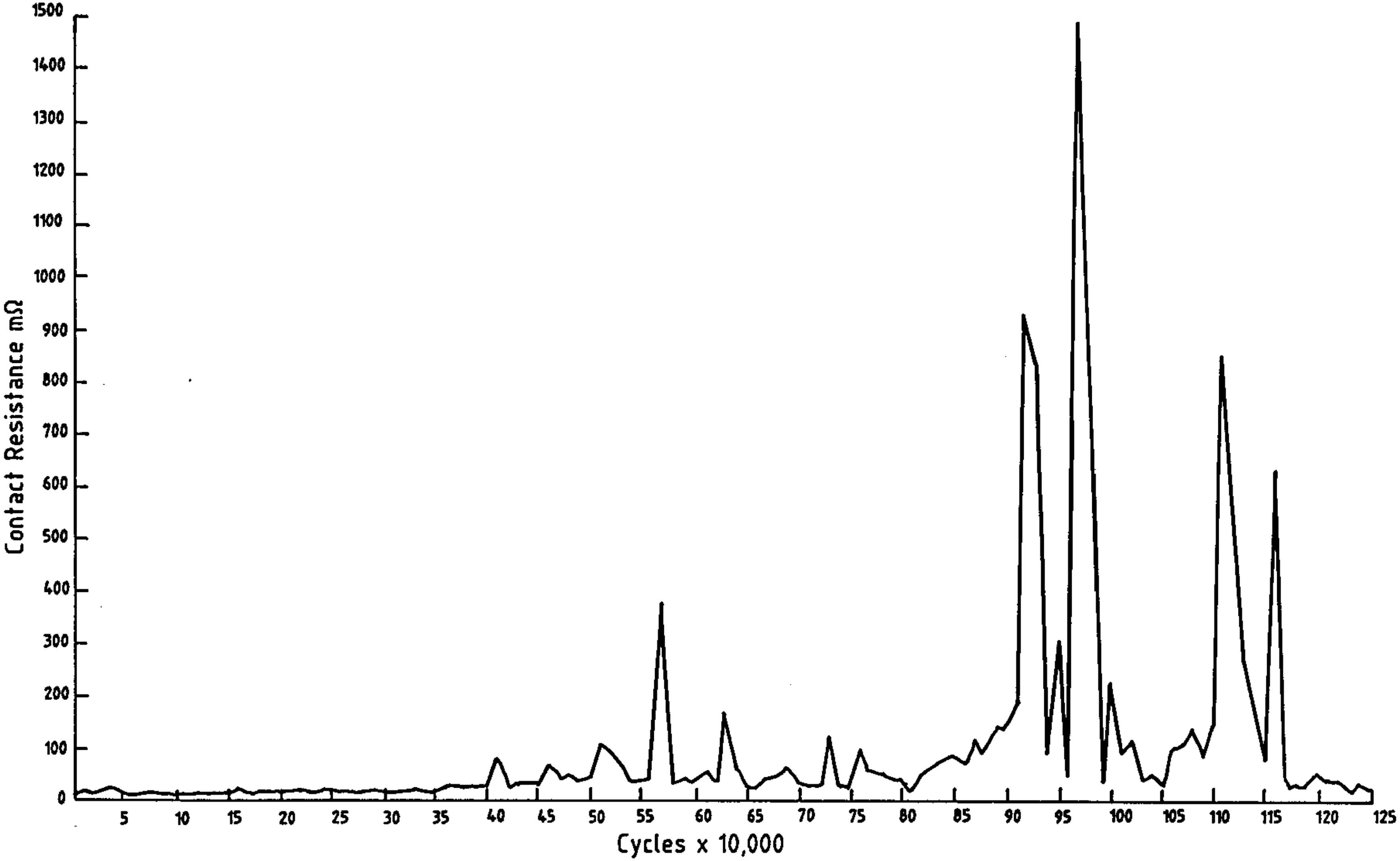


FIG. 5.8 TEST 106. PROBE 7. CAT 8. 1500mΩ

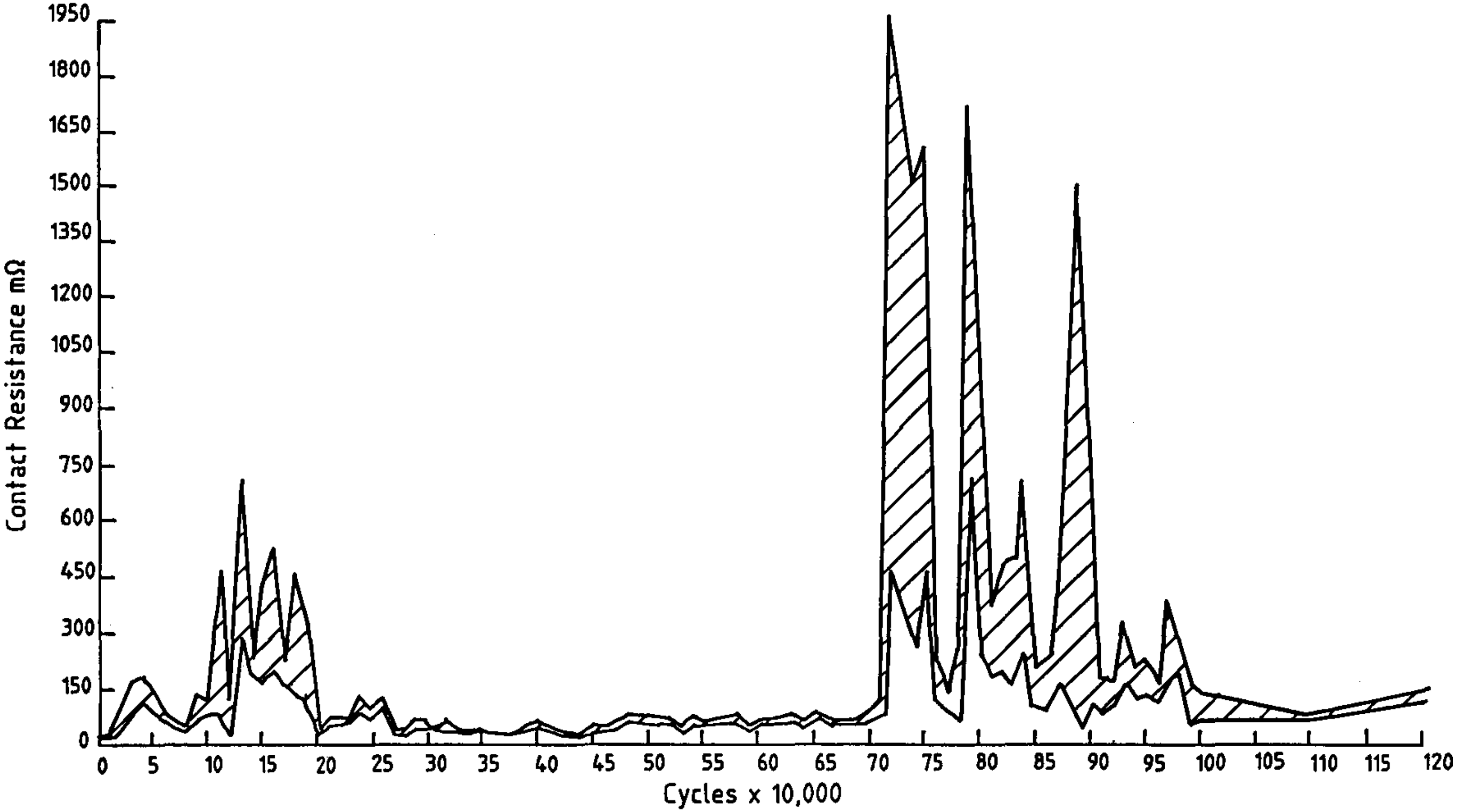


FIG. 5.9 PROBE 4.TEST 105.CAT 9.

PERFORMANCE CATEGORY.	RESISTANCE		RESISTANCE RANGE.
	STABLE A OR	UNSTABLE B	
1	*	*	50 mΩ
2	*	*	100mΩ
3	*	*	250mΩ
4	*	*	500mΩ
5	*	*	750mΩ
6	*	*	1000mΩ
7	*	*	1250mΩ
8	*	*	1500mΩ
9	*	*	2000mΩ
10	✓	*	PERMANENT OPEN CIRCUIT VALUE.

FIG. 5.10 PROBE PERFORMANCE CATEGORIES.

PROBE No.	PERFORMANCE CATEGORY SEE FIG. 5-X	RESISTANCE m Ω 2000 MAX.				
		LOW	MEDIAN	HIGH	STABLE (a)	UNSTABLE (b)
1	9b			✓		✓
2	4a	✓			✓	
3	4a	✓			✓	
4	9b			✓		✓
5	9b			✓		✓
6	9b			✓		✓
7	9b			✓		✓
8	9b			✓		✓
9	9b			✓		✓
10	5a		✓		✓	
AV	5 (mΩ)		✓			✓
RANGE MAX.	9b (mΩ)			✓		✓
RANGE MIN.	1a (mΩ)	✓			✓	
CATEGORY TOTALS	1 to 10	2	1	7	3a	7b

FIG. 5.11 TEST 101 FLAT CU TARGET

1.2 X10^6 CYCLES.

PROBE No.	PERFORMANCE CATEGORY SEE FIG. 5 - X	RESISTANCE mΩ (2000 MAX.)				
		LOW	MEDIAN	HIGH	STABLE (a)	UNSTABLE (b)
1	4a	✓			✓	
2	6a				✓	
3	9b	✓		✓		✓
4	9b			✓		✓
5	9b			✓		✓
6	9b			✓		✓
7	6b		✓			✓
8	9b			✓		✓
9	9b			✓		✓
10	9b			✓		✓
AV	5	✓				
RANGE MAX.	9b			✓		
RANGE MIN.	1a	✓				
CATEGORY TOTALS	1 to 10	2	1	7	2a	8b

FIG 5 - 12 TEST 102 RESULTS 45° ANGLED CU 2/3 COMPRESSION.

PROBE No.	PERFORMANCE CATEGORY SEE FIG. 5 -	RESISTANCE mΩ (2000 MAX.)				
		LOW	MEDIAN	HIGH	STABLE (a)	UNSTABLE (b)
1	6b		✓			✓
2	4a	✓			✓	
3	9b	JAMMED	AT	310 ✓	Kc/s	✓
4	9b			✓		✓
5	5a	✓			✓	
6	9b	JAMMED	AT	390 ✓	Kc/s	✓
7	6a	✓			✓	
8	1a	✓			✓	
9	1a	✓			✓	
10	3a	✓			✓	
AV	4a	✓			✓	
RANGE MAX.	9b			✓		✓
RANGE MIN.	1a	✓			✓	
CATEGORY TOTALS	1 to 10	6	1	3	6	4

FIG. 5 - 13

PROBE 5 25 Y 6.7 DG

TEST 103 RESULTS ANGLED TARGET

1.2 X 10^6 CYCLES.

PROBE No.	PERFORMANCE CATEGORY SEE FIG. 5-	RESISTANCE mΩ (2000 MAX.				
		LOW	MEDIAN	HIGH	STABLE (a)	UNSTABLE (b)
1	9			✓		✓
2	9			✓		✓
3	9			✓		✓
4	4	✓				✓
5	9			✓		✓
6	6	✓			✓	
7	8			✓		✓
8	9			✓		✓
9	9			✓		✓
10	9			✓		✓
AV	6			✓		
RANGE MAX.	9b			✓		✓
RANGE MIN.	4b		✓			✓
CATEGORY TOTALS.	1 to 10	2	0	8	1	9

FIG. 5.14 TEST 104 RESULTS FLAT TARGET

1.2 X10^6 CYCLES.

PROBE No.	PERFORMANCE CATEGORY SEE FIG. 5-	RESISTANCE mΩ (2000 MAX.)				
		LOW	MEDIAN	HIGH	STABLE (a)	UNSTABLE (b)
1	1	✓			✓	
2	9			✓		✓
3	1	✓			✓	
4	9			✓		✓
5	2	✓			✓	
6	9			✓		✓
7	3	✓			✓	
8	9			✓		✓
9	2	✓			✓	
10	3	✓			✓	
AV	4a	✓			✓	
RANGE MAX.	9b					✓
RANGE MIN.	1a				✓	
CATEGORY TOTAL	1 to 10	6	0	4	6	4

FIG. 5-15 TEST 105 RESULTS FLAT TARGET 1.2×10^6 CYCLES.

PROBE No.	PERFORMANCE CATEGORY SEE FIG. 5-	RESISTANCE mΩ (2000 MAX.)				
		LOW	MEDIAN	HIGH	STABLE (a)	UNSTABLE (b)
1	9			✓		✓
2	1	✓			✓	
3	1	✓			✓	
4	1	✓			✓	
5	1	✓			✓	
6	9			✓		✓
7	8			✓		✓
8	10			BROKEN OFF AT 230 Kc's		
9	9			✓		✓
10	9			✓		✓
AV	4a	✓			✓	
RANGE MAX.	9b			✓		✓
RANGE MIN.	1a	✓			✓	
CATEGORY TOTALS	1 to 10	4	0	5	4	5

FIG. 5 -16 TEST 106 RESULTS 60° TARGET
1.2×10^6 CYCLES

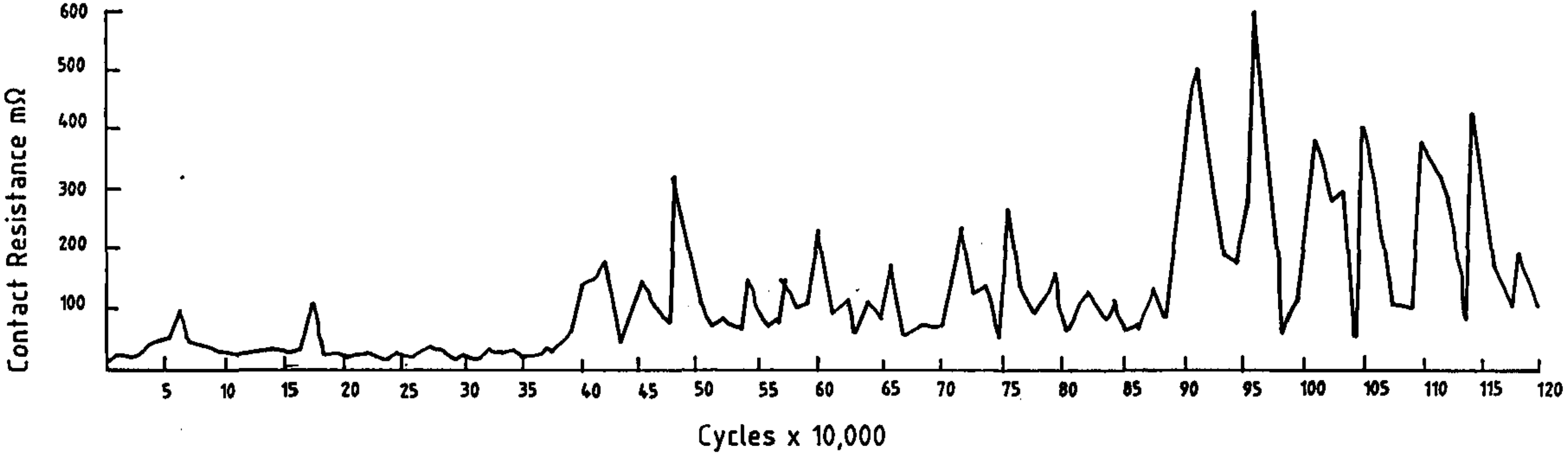


FIG. 5.17 TEST 102 AVERAGED OVER TEN PROBES

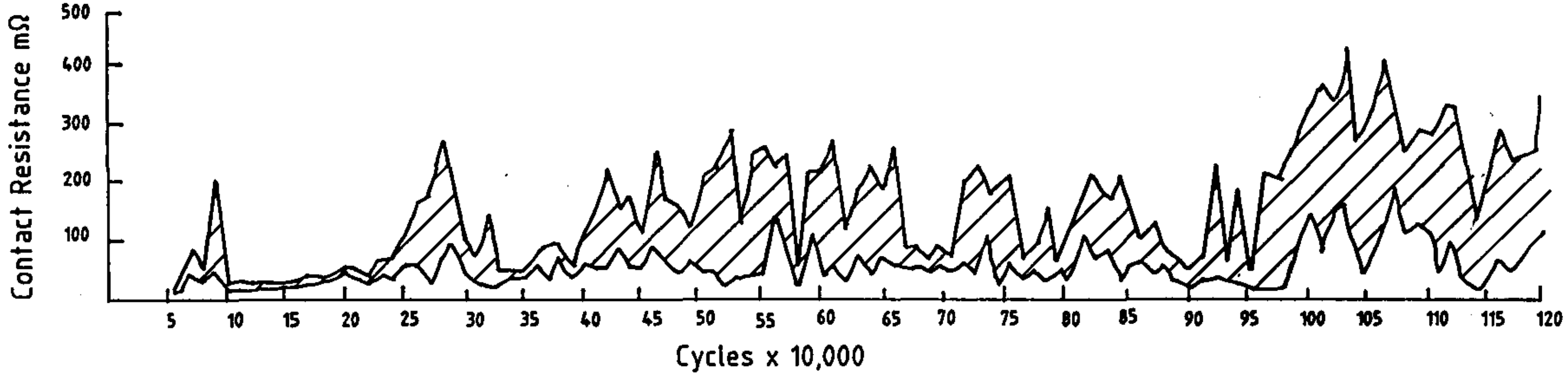


FIG. 5.18 TEST 103 AVERAGED OVER TEN PROBES

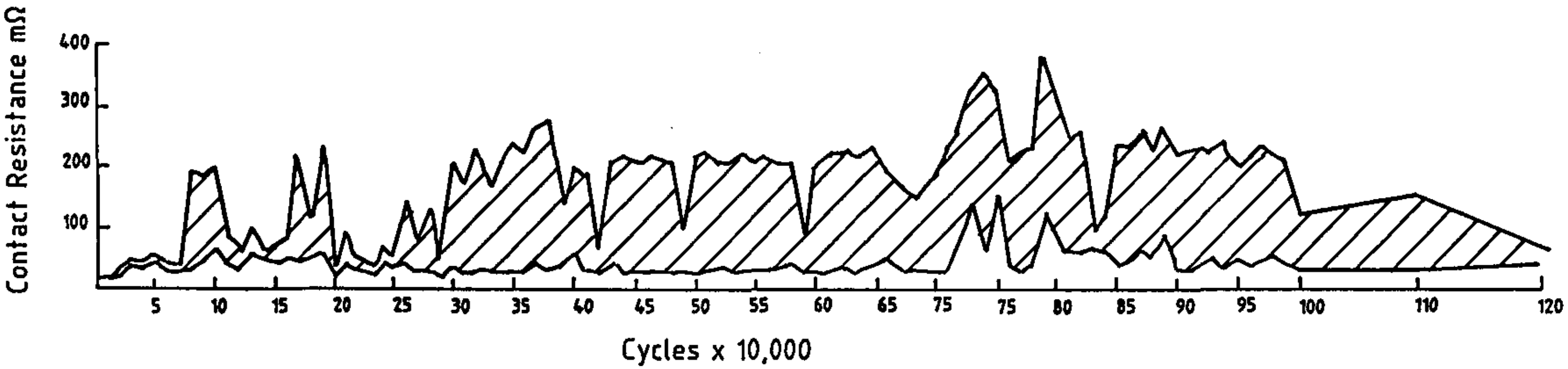


FIG. 5.19 TEST 105 AVERAGED OVER TEN PROBES

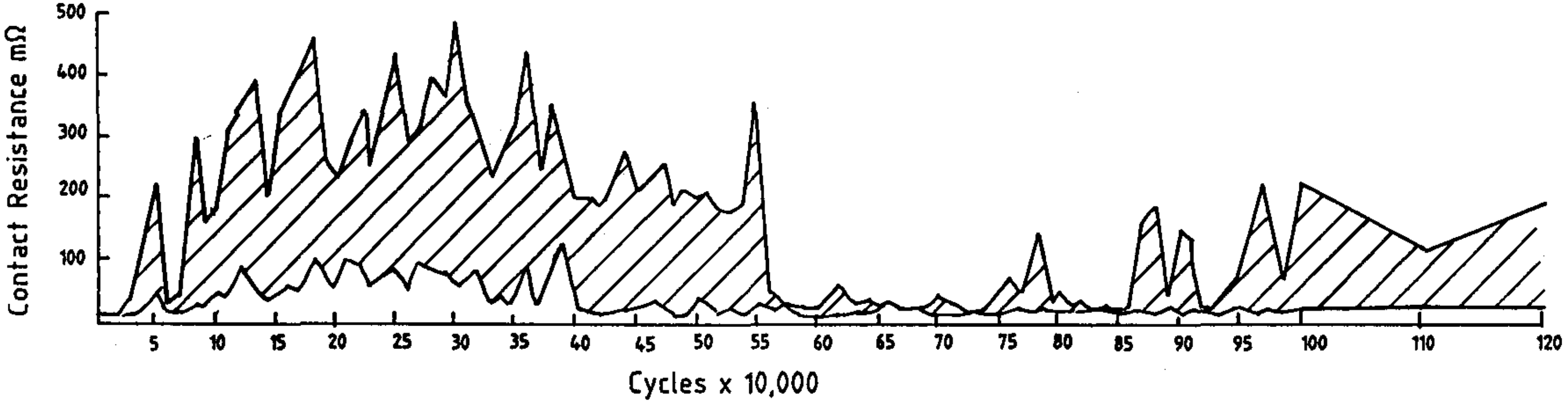


FIG. 5.20 TEST 106 AVERAGED OVER TEN PROBES

readings will be averaged by probes delivering consistent low resistance values. It is the probes that produce repetitive or sporadic high readings that will have the most undesirable effect upon the ATE with the rejection of perfectly good PCBs. Due to contact resistance phenomenon (as may be seen in a number of the graphs of contact resistance) ten successive readings taken on one probe may cover a resistance range from 25 milliohms to 4000 milliohms in one worse case set of readings (see Fig.5.9)

The range of resistance measurements taken during testing may go through cycles where the range of values widens and narrows throughout the testing period, or in other cases the values may remain narrow and consistent throughout testing to beyond 1.2 million.

5.3 PRELIMINARY TESTING

Initial preliminary testing was undertaken to develop a reliable method to validate the accuracy of data taken by the test machine, unfortunately variations in consecutive readings led to doubts regarding the accuracy of the resistance measurement, which was later attributed to contact asperity phenomenon. This is where the probe contact micro movement makes contact over variable areas of the surface, which means that different areas of potentially contaminated hill & valley profile make contact at different points every time the contacts are engaged. The result being a hit and miss situation with variable successive values recorded.

During these initial tests readings were taken at 10,000 cycle increments, but due to the problems of variable contact phenomenon, resistance values measured were of a random nature and not repeatable. A solution to the problem was found by taking ten readings per probe at the same interval of 10,000 cycles. Each reading taken (with two cycles operation between readings) produced results in the form of a tolerance envelope with its upper and lower limit. The ten readings per probe were used to calculate the average value for each reading with its upper and lower limit for the ten readings taken (see Fig.5.9).

Graphs illustrating the resistance tolerance envelope were produced for each of the ten probes in each of the six tests; 60 graphs in total. In some of the tests where probe performance was good and readings were reasonably constant, tolerance envelopes were narrow. In these cases contacts remained clean throughout with little or no contact fretting.

5.4 CONTACT RESISTANCE

New probes fitted into the testing machine initially exhibited a test resistance value between seven and twenty milliohms, whilst the testers resistance measurement ranges from zero to two thousand milliohms (readings above this value would be logged as open circuit). Values of resistance in excess of this value would severely inhibit the ATEs ability to make accurate confirmation of low impedance circuitry within the UUT.

Probe test data has shown that a number of probes subjected to life simulation testing developed sporadic high resistance characteristics during a testing sequence. This was found to be caused by insulating layers either on the probe tip or more likely on the surface of the copper target (Fig.5.21) (see Fig.5.9). Over a period of time these insulating layers on some probes were punctured or worn away thus allowing the contact to revert to its normal low value (Fig.5.22). On some of the probes this process was repeated, producing an intermittent contact connection (see Fig.5.6).

Over the range of resistance measurements taken from zero up to two thousand milliohms, a large percentage of the probes were classified in the high range category for the six tests. The overall average figure being 58.3% high, 5% median and 36.6% low. The 36.6% low probes produced low repetitive stable values up to 1.2 million cycles (Figs.5.23, 5.24). A small number of these probes (5%) went on producing low resistance values (of 30 to 70 milliohms) beyond the two million cycle, and in one case up to three million deflections. Probe samples from the same source often exhibited high value readings early into a test run with similar cleaning or test conditions. This was possibly caused by contamination at some stage during manufacturer, or thin or non existent noble plated layers over the probe tips.

FIG 5.21a : INSULATING CONTAMINATION ON PROBE CONTACT: MAG 75

FIG 5.21b : INSULATING CONTAMINATION ON CU TARGET: MAG 50

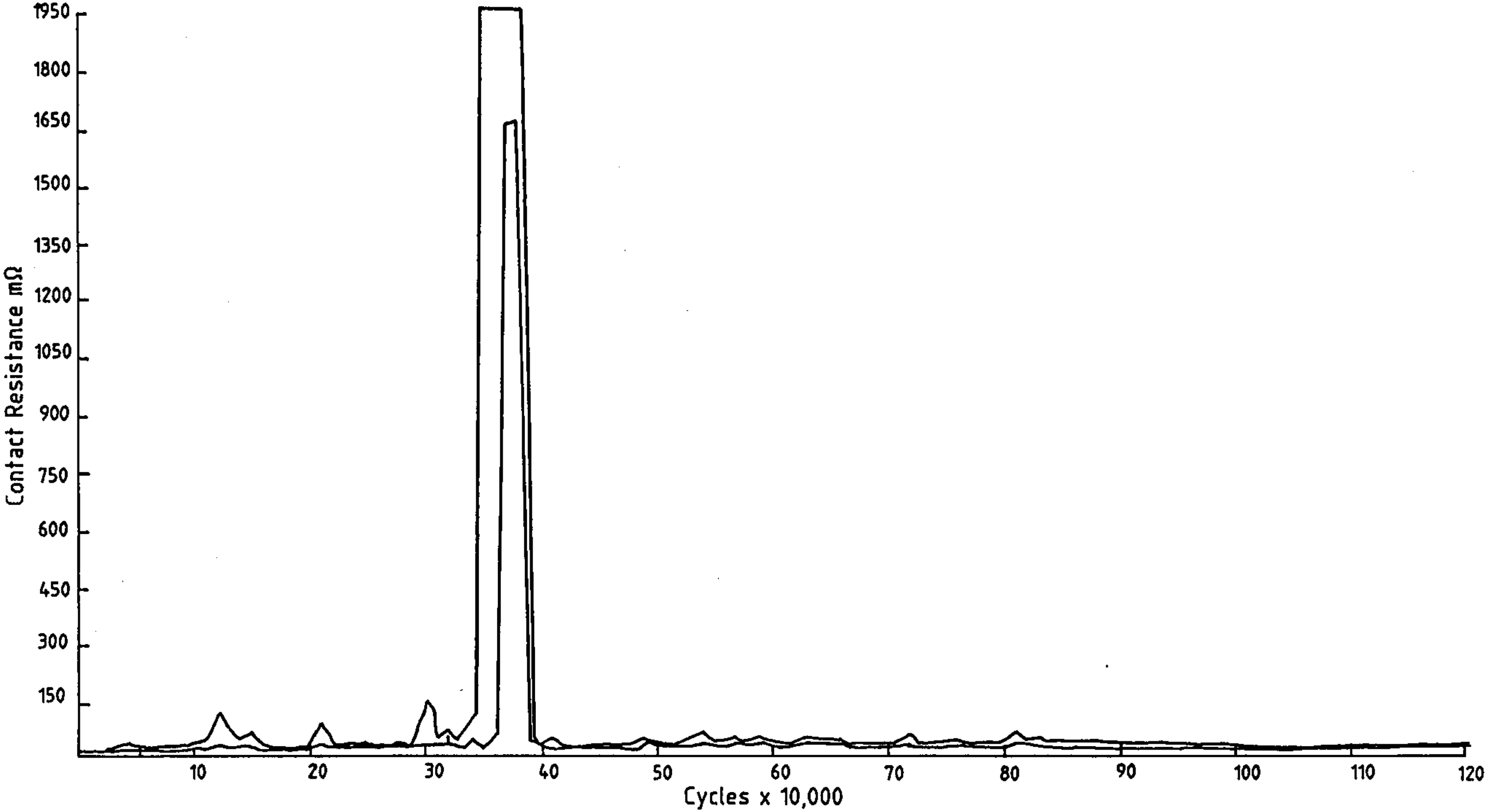


FIG.5.22 PROBE 8 TEST 105 HIGH VALUE EVENTS-REVERTING TO NORMAL PERFORMANCE

TEST	TARGET	RESISTANCE PERFORMANCE CATEGORY.			MECHANICAL EVENTS TO 1.3 MILLION.
		LOW	MEDIAN	HIGH	
101	CU FLAT	20%	10%	70%	P.6. JAMMED ONCE AT 948K.
102	CU 45°	20%	10%	70%	NONE
103	CU 45°	60%	10%	30%	P.3. JAMMED AT 320K INTERMITTENT. P.6. JAMMED AT 400K. INTERMITTENT.
104	CU FLAT	20%	0%	80%	NONE
105	CU FLAT	60%	0%	40%	NONE
106	CU 60°	40%	0%	50% 10% (BROKEN)	P.8. BROKEN PLUNGER AT 230K.
AVERAGE ANGLE TARGET.		40%	6.66%	53.33%	10%
AVERAGE FLAT TARGET.		33.3%	3.33%	63.33%	3.33%
OVERALL AVERAGE.		36,67%	5%	58.33%	6.66%

	MECHANICAL EVENTS AFTER 1.3 MILLION.
TEST 101	P.3.4.6. BROKEN SPRINGS.
TEST 103	P.4. WORN TULIP POINT.
TEST 104	P.1 & 4 WORN TULIP PTS: ROUGH. OF DEF: WORN PLUNGERS.
TEST 105	P.3.4.10. WEAR THROUGH PLATES.
TEST 106	BROKEN ON REMOVAL. P.2.3. ROUGH. OF DEF: WORN PTS. WORN THROUGH PLATES.

FIG. 5.23 SUMMARY OF TEST RESULTS FOR CONTACT RESISTANCE:
TEST 101 - 106 TO 1.2 MILLION CYCLES.

TEST (10 PROBES)	TARGET	RESISTANCE PERFORMANCE CATEGORY.			CONTACT RESISTANCE		MECHANICAL EVENTS
		LOW-R	MEDIAN	HIGH-R	STABLE	UNSTABLE	TO END OF TEST.
101	CU FLAT	2	1	7	3	7	3
102	CU 45°	2	1	7	2	8	0
103	CU 45°	6	1	3	6	4	3
104	CU FLAT	2	0	8	1	9	2
105	CU FLAT	6	0	4	6	4	3
106	CU 60°	4	9 PROBE 0	SAMPLE 5 (1 BROKEN)	4	5 1 BROKEN	4
TOTALS FOR ANGLED TARGETS.		12	2	15 1 BROKEN	12	17 1 BROKEN	7
TOTALS FOR FLAT TARGETS.		10	1	19	10	20	8
TOTALS FLAT & ANGLED CATS.		22	3	34 (1 BROKEN)	22	37 1 BROKEN	15
AVERAGE ANGLED TARGET.		4	0.66	5.33	4	6	2.3
AVERAGE FLAT TARGET.		3.33	0.33	6.33	3.33	6.66	2.6
OVERALL AVERAGE EACH TEST.		3.67	0.50	5.83	3.67	6.33	2.5

Fig. 5.24 PROBE CONTACT RESISTANCE PERFORMANCE SUMMARY OF EXPERIMENTAL RESULTS FOR CONTACT RESISTANCE. TESTS 101 TO 106. TO 1.2 MILLION CYCLES.

Where ever base metal becomes exposed there is always the possibility of the onset of contact fretting due to a combination of oxidation and vibration.

The probe manufacturers specified value of 50 milliohms contact resistance was accurate in most of the early phases of testing, but this value was often followed by random sometimes cyclic high values as the experiments progressed. A number of graphs were produced illustrating the various types of probe resistance performance over the range of the six tests (See Figs.5.1. to 5.6.).

The resistive performance of the sixty probes tested, have been divided into ten performance categories for both angled and flat targets. Thirty two of the probes (53.3%) were in the worst category nine - 2000 milliohms; followed by category one - 50 milliohms with 13.3%; category four and six - 500 & 1000 milliohms were equal with 8.3%; category three - 250 milliohms had 5%; and categories two, five and eight all equal at 3.3%. Category ten which is open circuit accounted for 1.7% due to mechanical failure, and finally category seven (1250 milliohms) was the only division with zero per cent (Fig.5.25).

5.4.1 The Increase of Contact Resistance

High resistance values indicate that contamination is present and on investigation has been shown to be caused by the following:

Contact fretting detected on the PCB copper target during testing was responsible for considerable increases in contact resistance. Contact fretting is caused by a small amplitude oscillatory motion between two solid surfaces, contact wear occurs and if the debris oxidises or corrodes, as normally occurs with base metals insulating particles building up and increasing contact resistance (45-46). This is particularly the case where contacts are subjected to vibrations which are present in the testing machine (Fig.5.26).

The resistance increase or variation of some of the probes may point to the development of insulating layers on the contact interfacial surfaces due to chemical reactions caused by

PERFORM ANC CAT mΩ	EXPERIMENTS						CATEGORY TOTALS.	
	101 F	102 A	103 A	104 F	105 F	106 A	NO	%
1 50mΩ			2		2	4	8	13.33
2 100mΩ					2		2	3.33
3 250mΩ			1		2		3	5
4 500mΩ	2	1	1	1			5	8.33
5 750mΩ	1		1				2	3.3
6 1000mΩ		2	2	1			5	8.33
7 1250mΩ							0	0
8 1500mΩ				1		1	2	3.33
9 2000mΩ	7	7	3	7	4	4	32	53.32
10 OPEN CIRCUIT						1 MECH. FAILURE	1	1.7

Fig. 5.25 SUMMARY OF TESTS FOR CONTACT RESISTANCE TESTS 101-106 TO 1.2 MILLION CYCLES (A. ANGLED TARGET F FLAT TARGET).

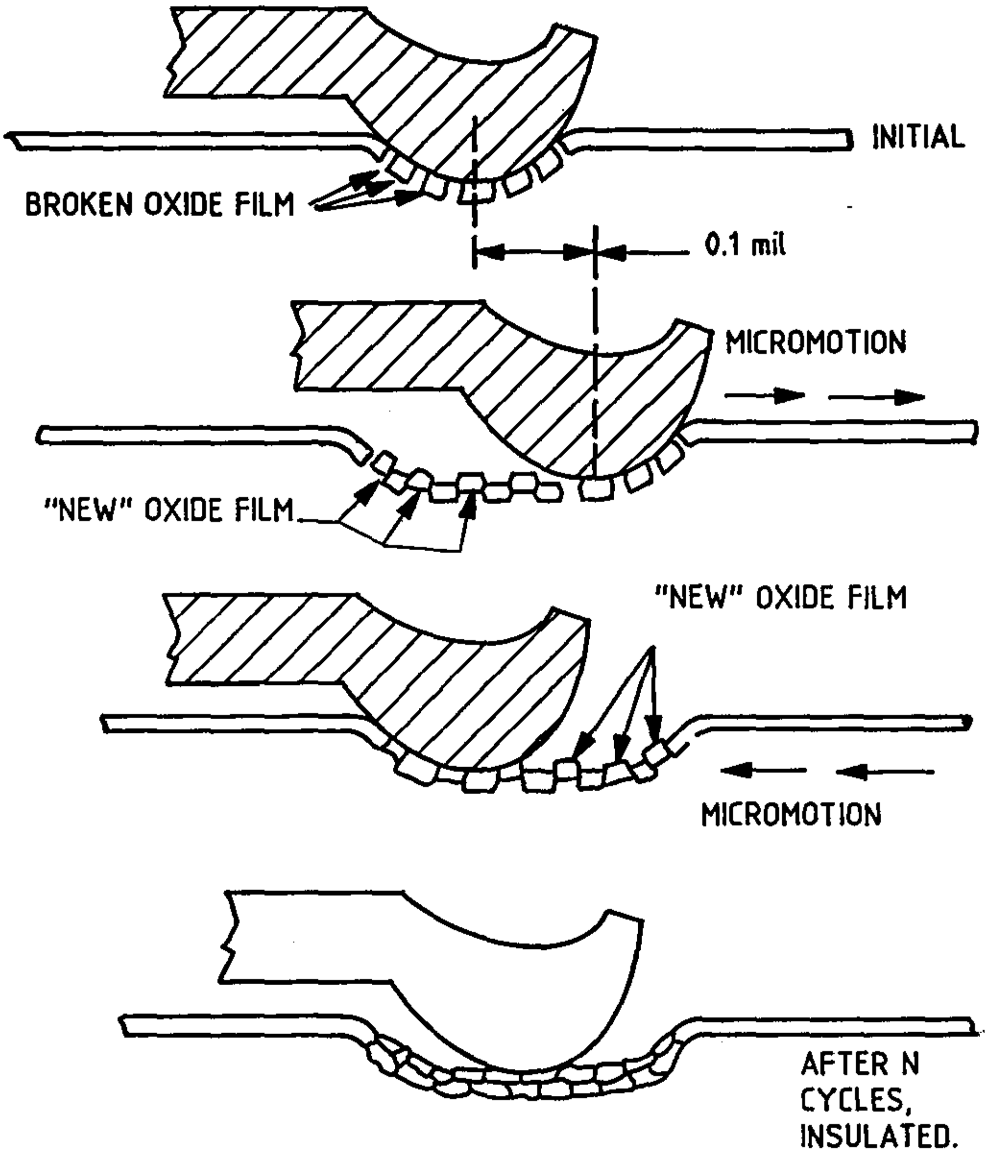


FIG. 5.26 GRAPHIC ILLUSTRATION OF CONTACT FRETTING COROSION PHENOMENA

outgassing of plastics, PCBs and components, thus producing the development of insulating layers on the contact surface.

Atmospheric pollution (which may be particulate contamination) affecting the contact surface or elements, may cause corrosion or the formation of insulating layers on the contact surfaces (Fig.5.27). Production contamination is due to such things as solder flux, lacquer or vapour out-gassing from different plastics.

Internal wear within the probe structure, followed by the accumulation of wear debris within the probe assembly becoming oxidised or polymerised also has the effect of causing increased contact resistance (Fig.5.28). The values recorded were always lower than the interfacial contact resistance component.

The noble plated layers wearing through to base metal on some probes caused the onset of contact fretting (Fig.5.29).

Friction polymers caused by sliding metal contacts such as spring probes, potentiometers relays and switch contacts may generate by-products due to wear, particularly after long cycling. In most cases, visible by-products are finely divided particulates of contact material and metallic oxides. They appear as black deposits near sliding surfaces and may cause intermittent or momentary spikes. The substance is formed in the presence of organic atmosphere cyclic action polymerising chemically organic vapours.

Due to the nonconformity of the insulating film thickness or asperities on contact surfaces, it is improbable that two successive readings on the same contact will be identical. What is important is that a high measurement means there is contamination on the surface (47).

5.4.2 New Probe Contamination

During testing it was noted that there were a small number of probes that exhibited high resistance characteristics at the beginning or early into the tests (Fig.5.30). To avoid these

FIG 5.27a : PROBE PARTICULATE CONTAMINATION: MAG 70

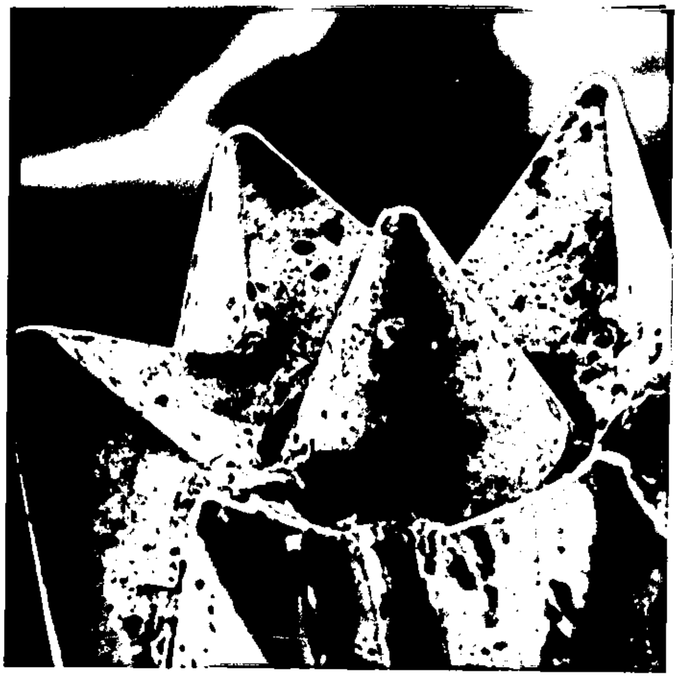


FIG 5.27b : PROBE PARTICULATE CONTAMINATION: MAG 70

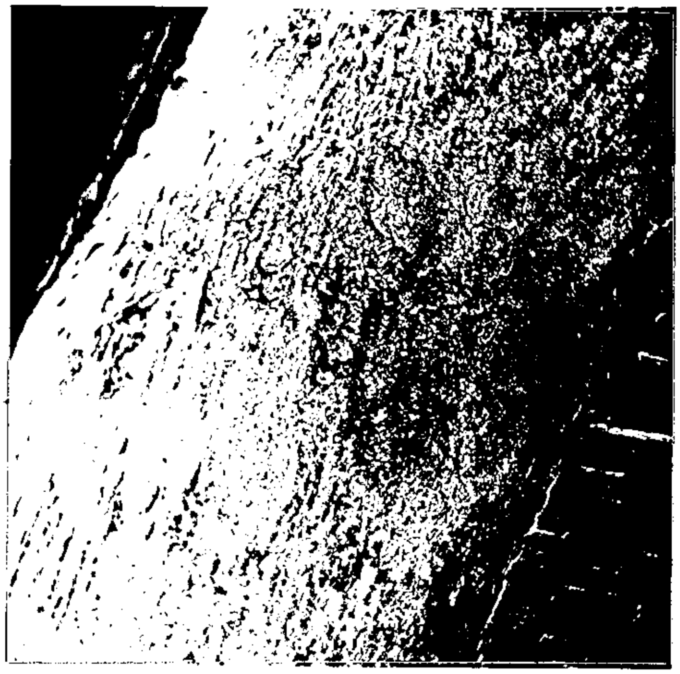


FIG 5.27c : CONTACT TARGET SURFACE CONTAMINATION : MAG 100

FIG 5.27d : CONTACT TARGET SURFACE CONTAMINATION: MAG 50

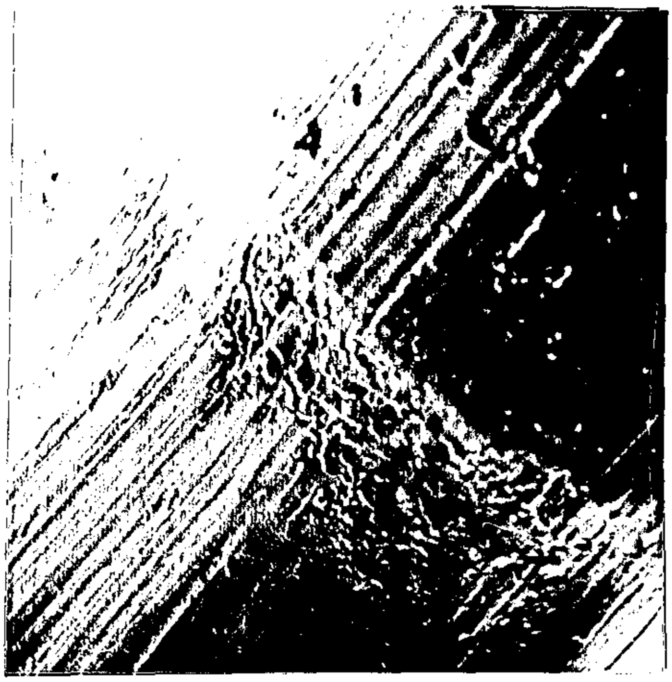


FIG 5.28a : WORN PROBE PLUNGER SHOWING WEAR DEBRIS: MAG 100

FIG 5.28b : EXCESSIVE PROBE WEAR RESTRICTED TO ONE SIDE ONLY: MAG 50

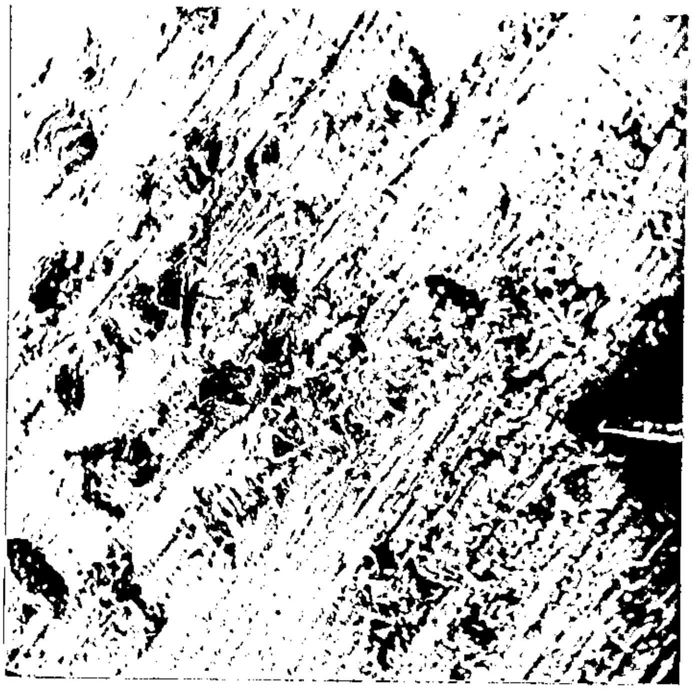


FIG 5.28c : PROBE PLUNGER SHOWING (LOOSE) WEAR DEBRIS: MAG 200

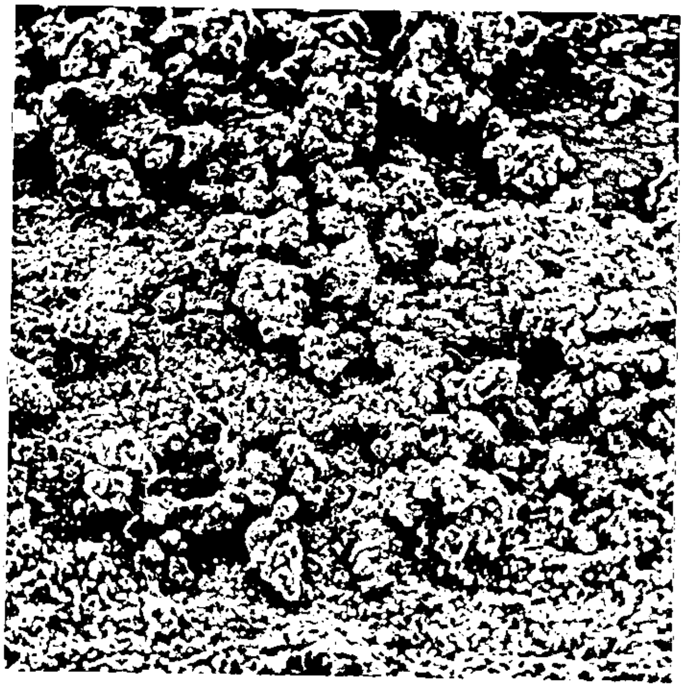


FIG 5.28d : LOOSE WEAR DEBRIS EJECTED FROM PROBE STRUCTURE: MAG 1K

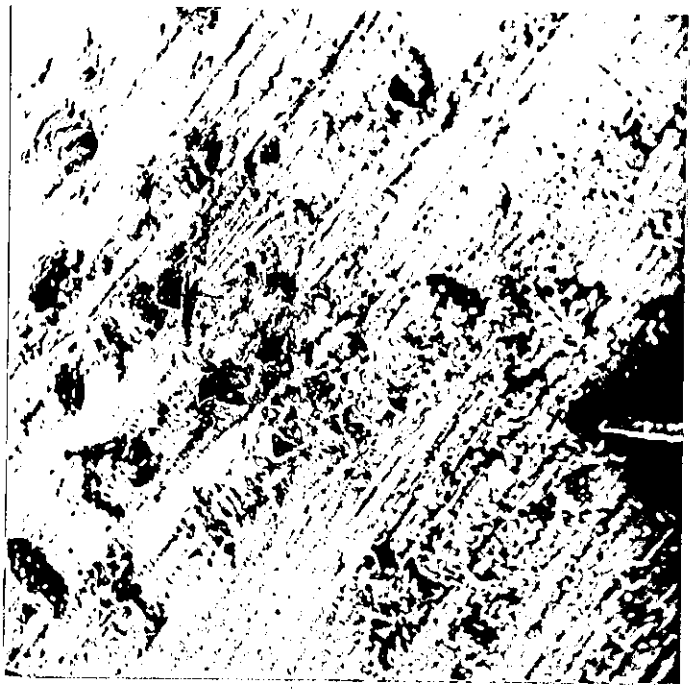


FIG 5.28c : PROBE PLUNGER SHOWING (LOOSE) WEAR DEBRIS: MAG 200

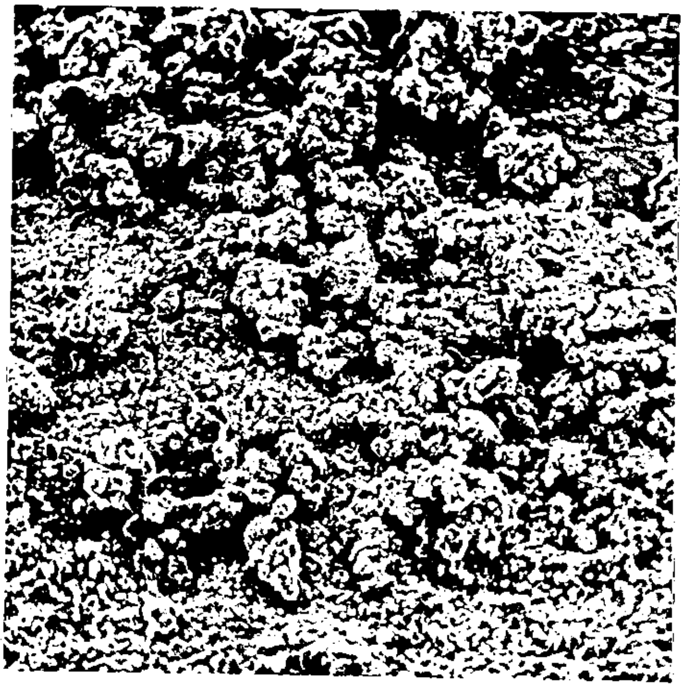


FIG 5.28d : LOOSE WEAR DEBRIS EJECTED FROM PROBE STRUCTURE: MAG 1K

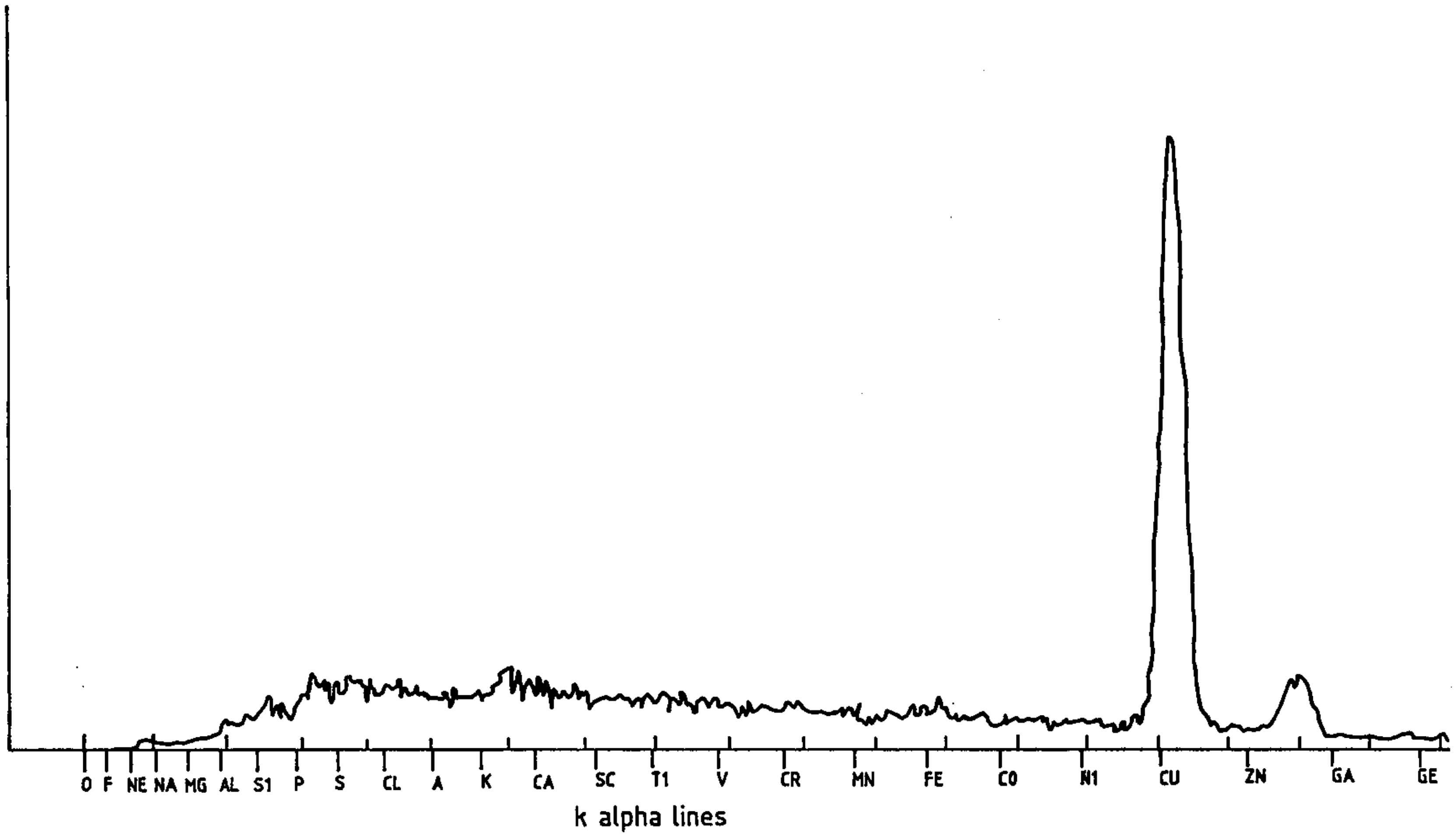


FIG 5.29 LINK SYSTEMS ELEMENTAL ANALYSIS SHOWING WEAR THROUGH TIP TO COPPER BASE METAL

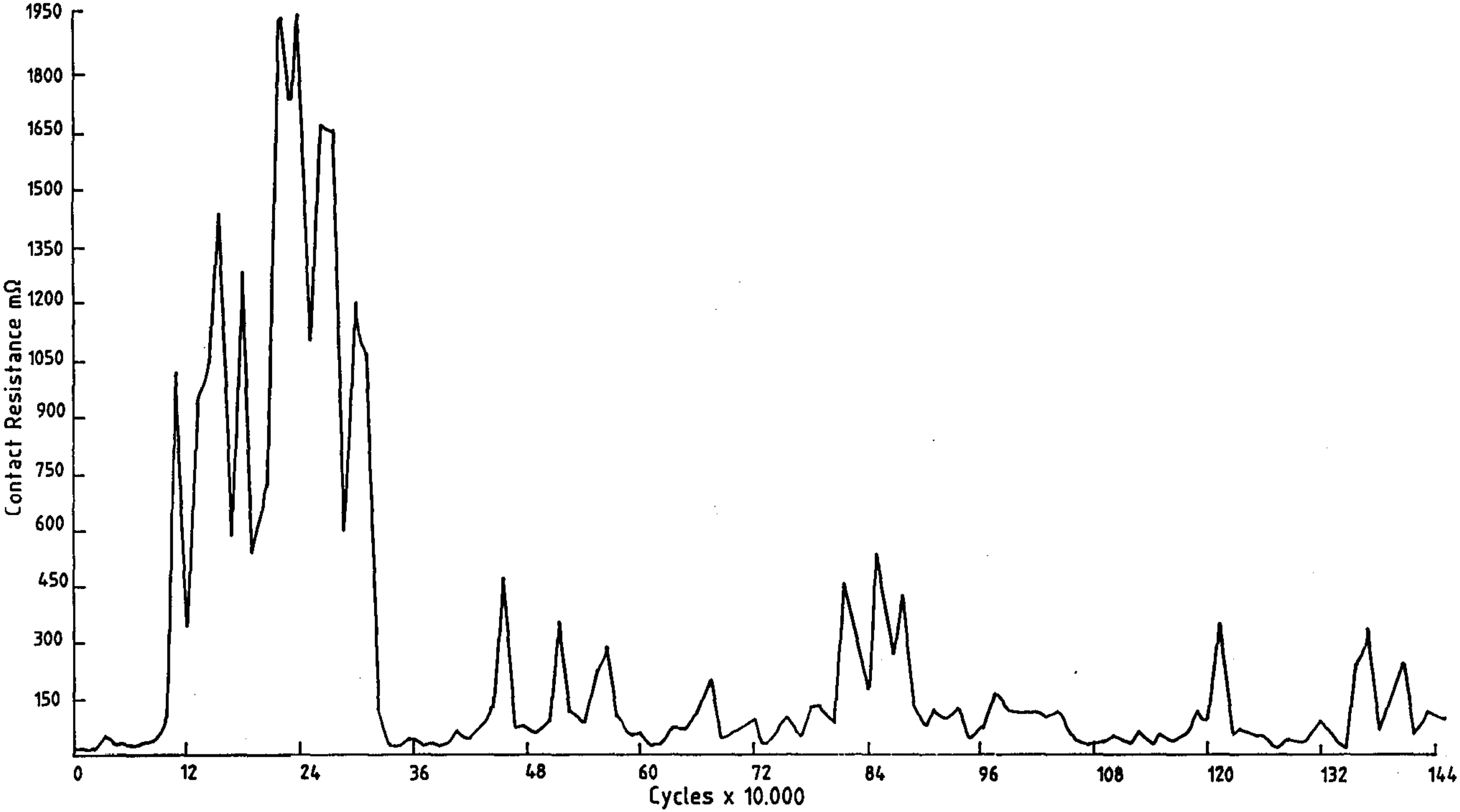


FIG. 5.30 PROBE 1, TEST 101, A SERIES OF EARLY HIGH VALUE CONTACT EVENTS.

occurrences considerable care was taken to ensure that the probe target was scrupulously clean. Another measure taken to verify the accuracy and calibration of the measuring system was to connect the probe body to the target plate to provide a low resistance circuit through to the probes tip. Any excessive value of resistance was likely to be interfacial contact resistance on the probe tip, as all the probes were new prior to being installed into the machine. The insulating layers therefore must have evolved during probe manufacture or during storage (48). The high values show the presence of an insulating layer between the tip and target. In certain cases these high values of resistance may persist well into or throughout the entire testing period, in other cases the insulation may become detached or worn over part of the testing cycle. The cause could be due to chemical residues (plating salts) left after the probe manufacturing processes, developing insulating layers on the gold plated surfaces. This phenomena has only occurred in a few cases, and therefore cannot be attributed to contact fretting which normally occurs later in test cycling.

5.4.3 The Development of Dark Marks on PCB Target Area

During the tests it was noticed that dark marks appeared at varying stages on the bright copper target, which were first thought to be wear marks where the probe tips had worn away the copper target. The appearance of the dark marks often coincided with increases in contact resistance which can be seen from some of the graphs (see Fig.5.9). The dark areas were located exactly at the points where the probes made contact with the copper PCB target. It would seem apparent that these marks were caused by fretting corrosion shown photographically as layers of oxide over the contact area in the micrographs (Fig.5.31). The symptoms were identical to work carried out by other researchers and a number of published papers have investigated the phenomena in considerable detail (49-50-51-52-53).

5.4.4 Contact Resistance Variation

Surface contamination is one of the most serious causes of failure of connectors, switches and other contact connecting devices. The most common types of contaminants are: oxide and corrosion products; particulates; films formed by thermal diffusion processes; debris

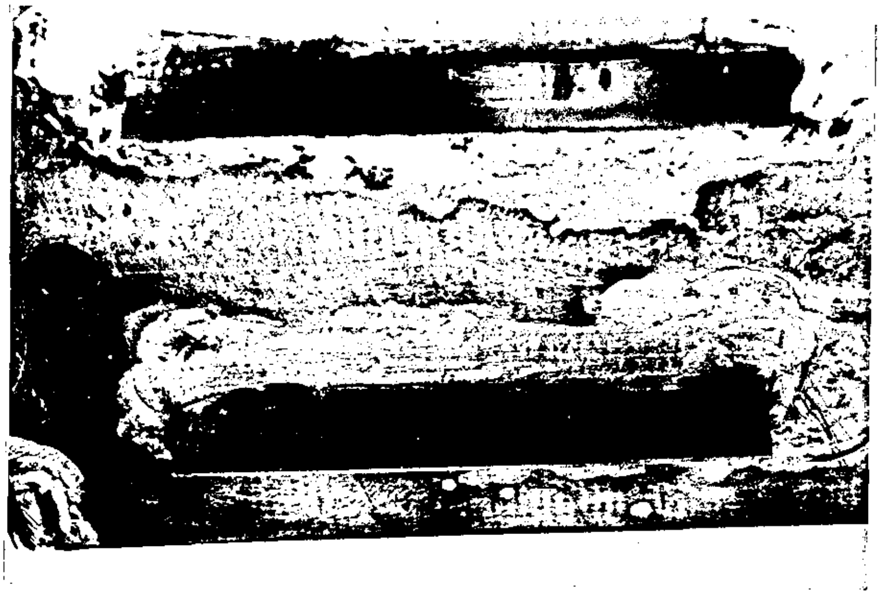


FIG 5.31a : DARK MARKS ON PCB TARGET AREA (CONTACT FRETTING)

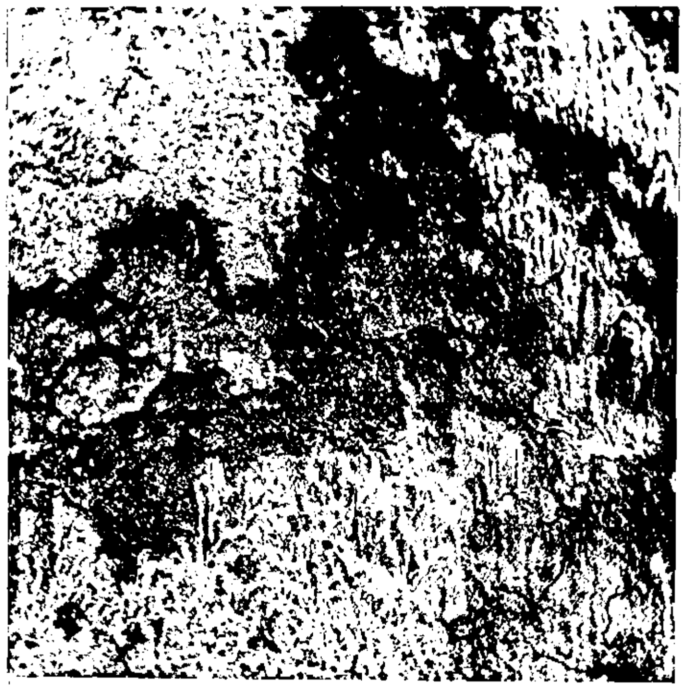


FIG 5.31b : ELECTRON MICROGRAPH SHOWING DARK MARKS ON PCB SURFACE: MAG 200

produced by mechanical wear and fretting; outgassing and condensation on contact surfaces of volatiles from non contact materials. Insulating layers produced in this way tend to be non uniform with irregular contact surfaces on a microscopic scale. Plane surfaces tend to a wave profile with a rough texture to the surface. Peak to valley dimensions can be from tenths to several micrometers. As contacts are bought together they touch at only a few of the high profile asperities. If more contact force is applied more asperities come into contact as the surfaces move together. If the surface is covered by a non conductive layer such as oxide film and this film remains unbroken, then the contact area will remain zero (45). On surfaces where the contaminating film is seen to be uniform, the effect of asperities on contact surfaces means there will be a wide variation of resistance measurements taken at the same contact point. It is therefore improbable that two successive readings on the same contact will be identical (54).

5.4.5 The Formation of Insulating Coatings During Testing

The time taken to test a set of ten probes up to 1.2 million cycles took on average four weeks, and a further one to three weeks depending on the number of cycles tested after 1.2 million. Samples were tested from 2 million to 4 million cycles, and during the test period the probes and target were exposed to the immediate atmospheric environment within the test laboratory which may have had an effect upon the probes and target.

Throughout the test period insulating layers formed upon the target and probes. As the probe targets for the six tests were copper they were more vulnerable to these effects than those of noble metal layers plated on the probes surface. Testing in a vacuum or inert gas atmosphere would help to prevent insulating layers developing on both contact surfaces, but would not represent the normal environmental conditions prevailing within a production test environment. Testing probes on a short time scale which is a feature of some probe manufacturers testing procedure, would not allow some types of insulating layers to develop which would normally occur during production testing in the fixture. The object of these tests however was to study the probes resistive behaviour, including the interfacial resistive connection to the probe target which is normally a PCB.

5.5 POSSIBLE ARC DAMAGE TO THE PROBE TIPS.

To avoid load or arc damage to probe tips, the resistance measuring test current was only applied to closed probe contacts on the test machine, even though the test currents were quiet small (10mA). It may be possible in a UUT - ATE connection interface arrangement, for probe damage to occur if the test fixture actuation is not synchronised correctly to the ATE system. Probe damage would occur if the probes had to break for example a power supply circuit into a UUT. This would only happen if the ATE system had energised the UUT at the time of loading or unloading the UUT. Where a probe may have to carry a large current, for example, power supply or short circuit UUTs, and contact resistance is higher than that associated with clean surfaces significant heat is generated at the interface. This promotes oxidation of the contact material, further reducing the area of metallic contact. Heat may destroy probe lubricants, reducing further the probes life or performance. Fluctuating contact resistance can be one intermediate stage in contact failure.

5.5.1 Probe Internal Resistance

Throughout the programme of probe testing, results have shown that the internal resistance of the probe structure remained relatively low when compared with the high values of contact interfacial resistance. Even when probes were tested almost to destruction with springs broken or plungers worn through the side of probe barrels, internal resistances have been remarkably low in comparison with interfacial contact resistance measurements. (Figs.5.32 to 5.37). As contact resistance is a function of contact pressure, measurements of the probes spring pressure were taken but were found to be of the same order as the rest of the ten probe test sample, indicating that the high resistance values were not due to weakening spring pressure within the probe structure. During a test period a sample probe exhibiting high value readings at 170,000 thousand cycles was removed, to examine the probe tip prior to cleaning. The internal resistance was measured at 15 milliohms whilst the measurement taken of the probe target averaged 190.2 milliohms. After intensive cleaning with the solvent Trichloroethylene the average value taken over ten readings was 44.8 milliohms, a

PROBE No.	RESISTANCE mΩ		
	READINGS (1) PER PROBE TAKEN AT 1.5 x 10^6 Hz	PROBE INTERNAL COMPONENT.	INTERFACIAL CONTACT RESISTANCE.
1	24	7	17
2	22	12	10
3	45	10	35
4	14	11	3
5	528	12	516
6	226	18	208
7	211	16	195
8	25	15	10
9	62	22	40
10	11	11	0
AVERAGE	116.8	13.4	103.4
RANGE UPPER	528	22	516
RANGE LOWER	11	7	0
RANGE	517	15	516

FIG. 5.32 COMPARISON OF INTERNAL AND INTERFACIAL VALUES. TEST 101 FLAT CU TARGET TAKEN AT 1.5 X 10^6 Hz

PROBE No.	RESISTANCE mΩ		
	TOTAL VALUE.	PROBE INTERNAL COMPONENT.	INTERFACIAL CONTACT COMPONENT.
1	37	21	16
2	12	11	1
3	36	20	16
4	33	24	9
5	344	27	317
6	193	15	178
7	253	17	236
8	1609	16	1593
9	851	22	829
10	118	18	100
AVERAGE	348.6	19.1	329.5
RANGE MAX.	1609	27	1593
RANGE MIN.	12	11	1
RANGE	1597	16	1592

FIG. 5.33 COMPARISON OF INTERNAL AND INTERFACIAL VALUES TEST 102 45° CU TARGET 2/3 DEFLECTION AT 2 X 10^6 Hz.

PROBE No.	RESISTANCE mΩ		
	AVERAGE FOR 10 READINGS TAKEN AT 1.4X10^6	PROBE INTERNAL COMPONENT.	INTERFACIAL CONTACT COMPONENT.
1	11	9	2
2	38	12	26
3	2.37	10	227
4	849	12	837
5	25.4	5	20.4
6	49.8	12	37.8
7	10	10	0
8	10	5	5
9	12	4	8
10	43.1	8	35.1
AVERAGE	128.5	8.7	119.8
RANGE MAX.	849	12	837
RANGE MIN.	10	4	0
RANGE	839	8	837

FIG. 5.34 COMPARISON OF INTERNAL AND INTERFACIAL VALUES . TEST 103 45° ANGLED CU TARGET TAKEN AT 1.5 X 10^6 Hz

PROBE No.	RESISTANCE mΩ		
	AVERAGE FOR 10 READINGS TAKEN AT 2.5x10^6 Hz.	PROBE INTERNAL COMPONENT TO TARGET	INTERFACIAL CONTACT COMPONENT.
1	2509	45	2464
2	1900	37	1863
3	1223	53	1170
4	47	45	2
5	9	9	0
6	OPEN CIRCUIT	82	INF.
7	24	23	1
8	11	11	0
9	1077	53	1024
10	3021	36	2985
AVERAGE	1091.2	39.4	1056.5
RANGE MAX.	3021	82	2985
RANGE MIN.	9	9	0
RANGE	3012	73	2985

FIG. 5.35 COMPARISON OF INTERNAL AND INTERFACIAL VALUES TEST 104 CU FLAT TARGET TAKEN AT 2.5 x 10^6 Hz

PROBE No.	RESISTANCE mΩ			
	AVERAGE OF LAST 10 READINGS AT 2 X 10^6 Hz	COMPRESSED INTERNAL.	RELAXED INTERNAL.	INTERFACIAL CONTACT RESISTANCE
1	19	10	12	9
2	1609	11	14	1598
3	14.6	8	9	6.6
4	38.5	11	14	27.5
5	32.1	4	7	28.1
6	19.4	9	8	10.4
7	30.2	8	7	22.2
8	27	14	9	13
9	15.8	4	6	11.8
10	211.8	7	8	204.8
AVERAGE	201.7	8.6	9.4	193.1
RANGE MAX.	1609	14	14	1598
RANGE MIN.	14.6	4	6	6.6
RANGE	1594.4	10	8	1591.4

FIG. 5.36 FINAL RESISTANCE TEST AT 2 X 10^6 Hz TEST 105
FOR INTERNAL AND INTERFACIAL VALUES
CU STRAIGHT TARGET.

PROBE	RESISTANCE IN MΩ				
	AVERAGE OF LAST 10 READINGS AT 3×10^6 Hz	COMPRESSED INTERNAL	RELAXED INTERNAL.	PROBE INTERNAL VALUES.	INTERFACIAL CONTACT RESISTANCE
1	407	110	29	28	379
2	673	15	12	30	643
3	212	27	21	8	204
4	49.1	51	19	8	41.1
5	24.8	21	17	6	18.8
6	6 4	30	18	3	61
7	470.2	15	16	DISINTEGRATED	455.2
8	BROKEN AT		230 Kc s		
9	105.3	21	9	18	87
10	65.5	12	9	4	61.5
AVERAGE	230	33	16.6	13.1	216.6
RANGE (MAX)	673	110	29	30	643
RANGE (MIN)	24.8	12	9	3	41
RANGE	648.2	98	20	27	602

FIG. 5.37 TEST 106 FINAL RESISTANCE TEST AT 3×10^6 Hz
0 FOR INTERNAL AND INTERFACIAL VALUES
TABLE ANGLED 60° TARGET.

reduction factor of 4.25 in total contact resistance. A visual examination of the probe head showed no visual defects to the probe points, it would therefore appear that the problem was caused by insulating layers present on the probe's contact surfaces, due to manufacturing or the effects of life simulation testing. This procedure was repeated with test 106 and test 110 producing similar results (Figs. 5.38, 5.39).

The average recorded values for six tests were 19.1, 39.4, 13.1, 7.9, 13.1, 9.4, milliohms. These values would not impose any limitations on an ATE system in performing its task. The problems arise when interfacial values were considered; where the average recorded values by comparison were 329.5, 1056.5, 103.4, 119.8, 216.6, 193, measured at the end of each experiment. It should be noted that these values are averages which do not reflect the worse individual probe performance. It may be observed from the test results that the major limiting factor in 99% of cases is interfacial resistance with internal resistance imposing little limitation during testing.

5.5.2 Relaxed and Compressed Probe Resistance

Measurements of the probe internal resistance were taken during Test 110 to establish any differences between relaxed and compressed readings. The measured probe internal values for a relaxed probe ranged from 2 to 12 milliohms, with an average reading of 7.9 milliohms for a set of ten probes. The compressed readings ranged from 3 to 10 milliohms with an average of 6.4 milliohms (See Fig.5.39). Similar results were observed during test 105 where in compression the average reading was 8.6 milliohms, and in the relaxed position reading was 9.4 milliohms (See Fig.5.36).

Measurements for test 101 and 102 were conducted for relaxed and compressed values, with the relaxed values being significantly larger. Test 101 showed a marked difference in recorded values for new probes and a new target. The measurement at two thirds deflection (compressed) averaged over the ten probe sample was 12.8 milliohms, whilst the average value recorded at minimum deflection (relaxed) was 25.9 milliohms. This demonstrates the effect of extra contact pressure which may be observed in the graphs showing spring performance

PROBE No.	RESISTANCE mΩ			
	AVERAGE OF LAST 10 READINGS AT 3 X 10^6 Hz	AVERAGE AFTER CONTACT CLEANING.	REDUCTION IN INTERFACIAL CONTACT RESISTANCE	PROBE INTERNAL RESISTANCE.
1	407	19.5	387.5	28
2	673	11.9	661.2	30
3	212	11.4	200.6	8
4	49.1	18.6	30.5	8
5	24.8	12.6	12.2	6
6	64	10.9	53.1	3
7	470.2	13.1	457.1	
8	BROKEN AT 230 KHz			
9	105.3	13.2	92.1	18
10	65.4	20.1	45.3	4
AVERAGE	230	14.5	215.5	13.1
RANGE MAX.	673	20.1	661	30
RANGE MIN.	24.8	10.9	12.2	3
RANGE	648.2	9.2	648.8	27

FIG. 5.38 FINAL RESISTANCE VARIATION DUE TO CONTACT CLEANING TEST 106 CU TARGET.

PROBE No.	RESISTANCE mΩ						
	CONTACT TARGET MOVED & CLEANED AVERAGED OVER 10 READINGS.		DIFFERENCE	INTERNAL COMPONENT		INTERFACIAL VALUE	
	BEFORE	AFTER		RELAXED	COMPRESSED	BEFORE CLEANING	AFTER CLEANING
1	579	887.2	+308.2	6	4	575	883.2
2	121.8	40.9	-80.9	11	6	115.8	34.9
3	906.8	38.2	-868.6	10	3	903.8	35.2
4	241.5	111.5	-130	6	8	233.5	103.5
5	241.5	240	-1.5	9	6	235.8	234
6	24.8	32.1	+7.3	5	8	16.8	24.1
7	53.3	131.9	+78.6	8	10	43.3	121.9
8	387.2	131.9	-255.3	2	6	381.2	125.9
9	70.9	58.4	-12.5	12	8	62.9	50.4
10	1282	99	-1183	10	5	1277	94
AVERAGE	390.8	177.1	213.7	7.9	6.4	384.5	170.7
RANGE UPPER	1282	887	+308	12	10	1277	883.2
RANGE LOWER	24.8	32.1	-1183	2	3	16.8	24.1
RANGE	1257.2	854.9	-875	10	7	1260.2	859.1

FIG. 5.39 COMPARISON OF INTERNAL AND INTERFACING VALUES
BY MOVING AND CLEANING CONTACT TARGET ONLY
TEST 110 STAINLESS STEEL FLAT TARGET TAKEN AT 420 kHz.

(Fig.5.40). Similar measurements taken at one million cycles showed 298.5 milliohms compressed, and 391 milliohms relaxed and at two million cycles 116.8 milliohms compressed compared to 1331 milliohms relaxed (see appendix 1).

5.6 HIGH VALUES IN FLAT AND ANGLED TARGETS

During the initial tests with various copper targets (flat to angled targets of up to 60 degrees inclination), there was no intervention to remedy or verify any probes which were displaying relatively high values of resistance, in order to obtain an indication of the probes performance as supplied from the manufacturers. It was only after probes had been tested on various targets and undesirable effects were encountered, that investigations were undertaken to identify the cause or find a remedy for the problem. In the cases of high interfacial contact resistance, contact cleaning obviously reduces contact resistance, but in general the resistances will increase gradually to higher undesirable values as insulating layers form or contact fretting becomes established in copper or similar targets. In cases where values of high resistance need to be categorised into their individual components, such as the internal resistance value plus the interfacial contact resistance values, they may be separated into three components:-

1) Interfacial resistance due to insulating layers formed on the target plate.

2) Interfacial resistance due to insulating layers formed on the probe tip contact area.

3) Internal resistance values, which may be measured directly by using the normal four wire ohm-meter in the usual manner.

Deducting the internal value from the total will give the interfacial value due to the tip and target plate combined. By moving the target plate to a cleaned untested area, the target plate portion of interfacial resistance will disappear from the total value and may easily be calculated by subtraction from the previous reading, thus separating the three individual

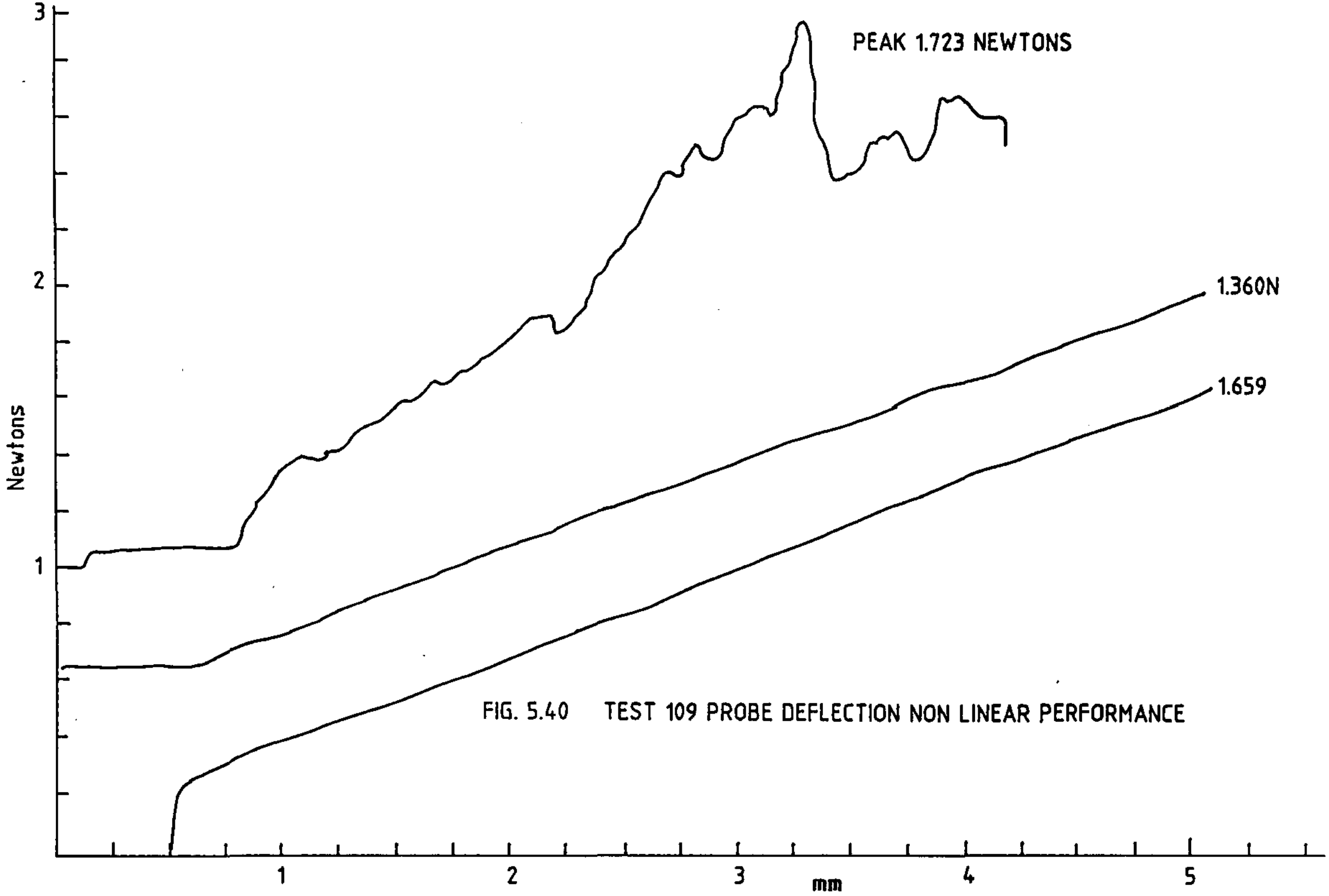


FIG. 5.40 TEST 109 PROBE DEFLECTION NON LINEAR PERFORMANCE

component values. Using this method it is possible to attribute interfacial resistance to the target plate or the probe tip (see Figs.5.38 & 5.39).

5.6.1 Probe Performance Comparisons Between Flat and Angled Targets

The average performance figures for angled targets show 40% of the probes producing low resistance values, 6.6% median and 53.3% high values. The figures for flat targets show only 33.3% producing low value readings, with 3.3% in the median range and 63.3% in the high range of measurement. This could be attributable to the absence of side pressure pushing the contact surfaces together (see Fig.5.23). The results show that angled targets are likely to produce a 10% better contact resistance performance compared with flat targets. Mechanical failure events however, indicate an overall incidence for angled targets of 10% compared with only 3.3% for flat targets. This shows as would be expected that side pressure is likely to cause a greater level of wear and probe breakages.

Some of the effects of side pressure resulted in uneven wear to the plunger and barrel components, sometimes with the exposure of the internal spring, or the plunger wearing partly through the side of the barrel where the probes were extended beyond their normal life (Fig.5.41). Probes subjected to side pressure displayed a lower overall resistance value, but in cases where there were no side loading, resistance measurements remained higher with greater fluctuations in values. Side loading keeps part of the coaxial interfacial sliding contact area pushed together, where contact pressure has the effect of lowering electrical resistance thus resulting in lower values measured across the probe assembly (See Fig.5.23). It is evident however that the increased wear on one side only reduces its overall useful life, due to increased side play and more variable resistance characteristics when the probe may also be targeted to a flat contact. Increased contact fretting to the target and wear debris oxidation, may also contribute to more variable resistance effects in the absence of side loading.

FIG 5.41a : SPRING WORN THROUGH PROBE BARREL

FIG 5.41b : PLUNGER BADLY WORN

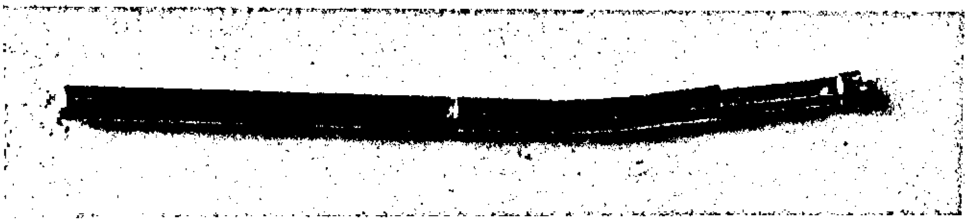


FIG 5.41c : PROBE BENT DUE TO JAMMED ASSEMBLY

5.7 MECHANICAL PERFORMANCE EVALUATION

Throughout the six experiments set up primarily to monitor electrical resistance performance, there occurred only a few mechanical failures, with tests running from 2 million to 4 million cycles. As a measure to identify the occurrence and range of mechanical probe malfunctions more rigorous extended testing was conducted over three further experiments (tests 107-109). The tests used copper and steel, flat and angled targets up to 75 degrees in order to induce any potential mechanical failure categories. The probes used for testing were of a similar type to those used in the other series of six tests. In one of the experiments the probes were tested to almost destruction. From the information gained the mechanical failure test categories were:-

1. Jammed assembly,
2. Broken springs,
3. Bent plunger jammed in barrel,
4. Plunger broken (angled targets),
5. Plunger worn through the barrel side (angled targets),
6. Excessive wear caused plunger and barrel to become separated,
7. Probe tip became worn - electroplate worn off the probe point leaving a blunt point, which was worn down to base metal where it was subjected to contact fretting,
8. Probe assembly became excessively worn to the point of disintegration,
9. Weakening spring force which could also be caused by wear debris lodged in probe assembly,
10. Probe became deformed and was compacted into its receptacle resulting in difficulty in removal.

Most of the categories listed above would not normally be experienced in practice due to rigorous testing beyond manufacturers projected life expectation, but were considered necessary in order to evaluate all of the possible failure modes (Fig.5.42).

TEST	TARGET	NEWTONS AVERAGE SPRING FORCE	NEWTONS NEW PROBE AVERAGE SPRING FORCE.	mm AVERAGE SIDE PLAY.	MECHANICAL EVENTS TO END OF TEST.
101	CU FLAT	0.5820	0.5942	0.25	P3 DAMAGED DURING REMOVAL P4 STOCK IN REC. BROKEN SPRING. P6 BRKN. SPRING.WORN POINTS.
102	CU 45°	0.8173	0.8097	0.35	NONE
103	CU 45°	1.048	0.7912	0.32	P3 JAMMED AT 320K INTERMITTENT P4 WORN TULIP POINTS. P6 JAMMED AT 390K INTERMITTENT
104	CU FLAT	0.9973	0.7882	0.41	P1 WORN POINTS.ROUGHNESS OF DEFLECTION. P4 GOLD PLATE WORN THROUGH ON PLUNGER.
105	CU FLAT	0.7777	0.8011	0.32	P3 WEAR THROUGH GOLD PLATE P4 & 10 WEAR THROUGH GOLD PLATE.
106	CU 60°	0.9869	0.7885	0.30	P2. WORN TULIP POINTS ROUGHNESS OF DEFLECTION. P3 WORN POINTS. ROUGHNESS OF DEFLECTION & WEAR THROUGH GOLD PLATE.
107	STEEL 60°	0.5818	0.5919	0.45	P3 & P5 WORN POINTS P4 PLUNGER WORN THROUGH BARREL P9 BENT P10 DAMAGED.
108	CU FLAT	0.5805	0.5931	0.24	P2,3,4 SPRING FAILURE. P7 & 8 JAMMED: WORN POINTS. P10 DAMAGED DURING REMOVAL.
109	STEEL 75°	1.589	1.453	0.21	P3 ROUGHNESS OF DEFLECTION WEAR DEBRIS: GOLD PLATE WORN THROUGH. P5 & 7 WORN TULIP POINT. ROUGHNESS OF DEFLECTION WEAR DEBRIS GOLD WORN THRO' P9&10 BROKEN.
110	S-STL. FLAT	0.9262	0.7959	0.33 0.318AV	SOME CENTRE POINTS FLATTENED DUE TO HARDER TARGET.

Fig. 5.42 SUMMARY OF MECHANICAL PERFORMANCE.

5.7.1 Mechanical Parameters

Preliminary measurements of all mechanical parameters were taken prior to probe insertion into the tester receptacles. Parameters measured were: side play, spring deflection force, probe tip profile, surface finish (Figs.5.43 to 5.45).

SIDE PLAY: The total side to side movement of the plunger was measured with the barrel clamped in a fixed position as this would normally be the position held in a probe receptacle. These measurements were made before and after life simulation and may be used as an indication of internal wear. Side play measurements were made by clamping the probe (up to the point where it normally emerges from the receptacle) into a shadow graph device, which is capable of projecting a magnified image upon a calibrated ground glass screen. Wire was attached to the probe plunger below the tip and was used to exert a side to side force upon the probe plunger. Side to side movement was then read from the calibrated ground glass screen. Side to side force is limited to a value below the elastic limit of the probe assembly. During normal production activities steep angled targets would subject the probes to a greater than normal side to side deflection, especially in the cases where the probes may have endured considerable wear at an earlier stage.

There are two factors which jointly contribute to side play movement. The first being the intrinsic flexibility of tubular and solid plunger components of the probe assembly, which is a fixed value and changes little due to wear. The second is the variation of tolerance margins of the individual probe components, which are effected by wear processes and the accumulation of wear debris within the probe structure. The individual probe components slowly wear away during service, increasing the probes side play and its chance of missing the centre of the test target on each successive actuation. Typical values measured for a new probe during testing were 0.3mm in total of which 0.2mm was due to tolerance margins, thus leaving 0.1mm due to the flexibility of the probes telescopic structure. However, where angled targets were concerned variation in the ratios were noticed throughout testing. These values were for new untested probes of 2.54mm (0.100inch) centres which were the same type used throughout testing. The average value for a sample of fifty new probes was

CONTACT SPRING FORCE N M		
PROBE	PRE-TEST N/M	POST TEST N/M
1	0.5988	0.5855
2	0.5970	0.5733
3	0.5827	0. —[1]
4	0.5967	0.5902
5	0.5978	0.5749
6	0.5923	0.5661
7	0.5982	0. JAMMED[2]
8	0.5939	0. JAMMED[3]
9	0.5982	0.5935
10	0.5759	0. —[4]
AV	0.5931	0.5805
RANGE MIN.	0.5759	0. 5661
MAX.	0.5988	0.5935

FIG. 5.43. PRE & POST TEST SPRING FORCE VALUES 2×10^6 TEST 108.

CONTACT SPRING FORCE NM		
PROBE	PRE-TEST NM	POST TEST NM
1	0.5969	0.5971
2	0.5978	0.5885
3	0.5939	BROKEN
4	0.5970	JAMMED AT 1464 KC
5	0.5989	0.5688
6	0.5850	948 KC JAMMED
7	0.5988	0.5817
8	0.5967	0.5954
9	0.5939	0.5701
10	0.5836	0.5725
AV	0.5942	0.5820
RANGE MIN.	0.5836	0.5688
MAX.	0.5989	0.5971 LC5N

7.4 m/m de MAX. VALUES OCCUR BETWEEN 1.7& 4.4 m/m

FIG. 5.44 TEST - 101 PRE- & POST TEST SPRING FORCE VALUES.

CONTACT SPRING FORCE IN N.

PROBE	TEST 107 500KHz	TEST 108 FLAT TARGET 2x10^6 Hz.
1	0.5862	0.5855
2	0.5473	0.5733
3	0.5845	DAMAGED
4	0.5849	0.5902
5	0.5837	0.5749
6	0.5797	0.5661
7	0.5916	JAMMED.
8	0.5856	JAMMED
9	0.5933 BENT	0.5935
10	DAMAGED	DAMAGED
RANGE UPPER	0.5933	0.5935
RANGE LOWER	0.5473	0.5661
RANGE	0.0460	0.0274
AVERAGE	0.5818	0.5805

REF-AVERAGE. VALUE FOR UNTESTED PROBE 0.5919 7.4 m/m de

TABLE 5.45 POST TESTING SPRING FORCE MEASUREMENTS.

0.203mm, however, where angled targets were accessed the side movement would be much greater due to flexing of the probe structure, thus raising values up to 1mm. In certain cases, tests using angled targets have shown uneven wear to probe components, thus having its effect on side play measurements taken at 90 degrees increments. In one worse case measurement, successive values of 1.00mm at 0 degrees and 0.5mm at 90 degrees were recorded due to the probe wearing in one position. Results show that in the majority of cases wear from flat targets (over 360 degrees) was even, but was confined to one area for angled targets thus leaving a worn striped area down the plungers side. Extensive use may result in values up to 1mm side play in some angled target applications (See Fig.5.42). In situations where longer thinner probe types are used flexing may be much more of a problem than side play, especially where test pad targets are small because combinations of side play and flexing will cause even more probes sliding off or missing the target. The average side play value for new probes was 0.2mm and after testing the average value for one hundred probes was 0.318mm. In test 104 which was a flat cu target,probe one exhibited side play values (measured after 2.5 million cycles) of 0.98mm at 0 degrees and 1.10mm at 90 degrees. This was the worst example for the one hundred probes tested, although probe six in the same test had measured at 0.29mm for 0 degrees and 0.27mm at 90 degrees. The average values for the group were 0.41 at 0 degrees and 0.43 at 90 degrees, thus showing the considerable variation in individual probe performance (Figs.5.46 to 5.55).

SPRING PERFORMANCE ASSESSMENT: As the probe spring is one of the more important components of a test probe, its failure will immediately cause a probe to cease to function, therefore all the probes were tested before and after the experiments. Using the tensile test machine all probes were deflected through their noted travel producing a graph of spring force delivered to the probe plunger (Fig.5.56).

Sample batches of new probes were tested in order to produce average values for the probe types for comparison with the ten batch sample of probes used in life simulation testing. Comparative results showed insignificant variation in spring force before and after testing, except where plungers were jammed solid inside the probe barrel or where the springs became broken. A considerable amount of wear debris was discharged from inside the probe

PROBE No.	PLUNGER FORCE		SIDE PLAY mm		MECHANICAL EVENTS	RESISTANCE PERFORMANCE CATEGORY 1.25 Mdl.
	NEWTON	GRAM OZ	0°	90°		
1	0.5971	60.89 2.14	0.30	0.31	NONE	9b
2	0.5885	60.01 2.11	0.29	0.28	NONE	4a
3	DAMAGED DURING REMOVAL FROM RECEPTACLE BROKEN SPRING SUSPECTED.					4a
4	STUCK IN RECEPTACLE. BROKEN SPRING. JAMMED ONCE AT 1464					9b
5	0.5688	58.0 2.04	0.25	0.27	NONE	9b
6	JAMMED		0.18	0.16	BROKEN SPRING WORN TULIP POINT.	9b
7	0.5817	59.32 2.09	0.28	0.31	NONE	9b
8	0.5954	60.71 2.14	0.23	0.25	NONE	9b
9	0.5701	58.13 2.05	0.25	0.26	NONE	9b
10	0.5725	58.3 2.05	0.24	0.25	NONE	5a
AVERAGE VALUE	0.5820	59.3 2.09	0.25	0.26	-	-
AVERAGE NEW	0.5942	60.59 2.13	0.20	0.20	-	-

Fig. 5.46 TEST 101. CU. FLAT. 2 MILLION CYCLES MECHANICAL PERFORMANCE.

PROBE No.	PLUNGER FORCE		SIDE PLAY mm		MECHANICAL EVENTS	RESISTANCE PERFORMANCE CATEGORIES.
	NEWTON	GRAM OZ	0°	90°		
1	0.8160	83.214 2.935	0.35	0.35	GENERAL THERE WERE NO MECHANICAL FAILURE CATEGORIES IN THIS EXPERIMENT	4a
2	0.8391	85.570 3.018	0.25	0.25		6a
3	0.8171	83.326 2.939	0.35	0.35		9b
4	0.8244	84.071 2.965	0.35	0.35		9b
5	0.8059	82.184 2.898	0.37	0.35		9b
6	0.8340	85.05 3.000	0.39	0.34		9b
7	0.8166	83.275 2.937	0.35	0.37		6b
8	0.8216	83.785 2.955	0.34	0.36		9b
9	0.7823	79.777 2.814	0.37	0.35		9b
10	0.8160	83.214 2.935	0.43	0.45		9b
AVERAGE	0.8173	83.346 2.939	0.35	0.35		
AVERAGE NEW VALUE	0.8097	82.56 2.912	0.195	0.20		

Fig. 5.47 TEST 102: CU. 45° : 2 MILLION CYCLES MECHANICAL PERFORMANCE.

PROBE No.	PLUNGER FORCE		SIDE PLAY		MECHANICAL EVENTS	RESISTANCE PERFORMANCE CATEGORY.
		GRAM.	mm			
	NEWTON	OZ	0°	90°		
1	0.8717	88.894 3.135	0.35	0.37		6b
2	0.7547	76.963 2.714	0.34	0.30		4a
3	BROKEN SPRING		0.32	0.31	JAMMED AT 320K INTERMITTENT.	9b
4	0.8267	84.305 2.973	0.33	0.35	WORN TULIP POINT.	9b
5	0.6501	66.296 2.338	0.31	0.33		5a
6	BROKEN SPRING.		0.28	0.30	JAMMED 320K INTERMITTENT	9b
7	1.909	194.676 6.866	0.25	0.27		6a
8	1.791	82.643 6.442	0.27	0.27		1a
9	0.8104	82.643 2.915	0.48	0.48		1a
10	0.7733	78.859 2.781	0.27	0.30		3a
AVERAGE	1.048	106.909 3.770	0.32	0.32		-
AVERAGE NEW VALUE	0.7912	80.68 2.84	0.21	0.21		-

Fig. 5.48 TEST 103: CU. 45°: 4 MILLION CYCLES.

PROBE NO.	PLUNGER FORCE		SIDE PLAY mm		MECHANICAL EVENTS.	RESISTANCE PERFORMANCE CATEGORY.
	NEWTON	GRAM OZ	0°	90°		
1	0.7665	78.166 2.757	0.98	1.10	WORN TULIP SECTION: ROUGHNESS OF DEFLECTION	9
2	0.7896	80.522 2.840	0.41	0.43		9
3	0.8188	83.499 2.945	0.34	0.37		9
4	1.537	156.740 5.528	0.36	0.36	GOLD WORN THROUGH ON PLUNGER.	4
5	0.9195	93.769 3.307	0.33	0.32		9
6	0.8891	90.669 3.198	0.29	0.27		6
7	0.7749	79.023 2.787	0.31	0.32		8
8	0.8222	83.846 2.957	0.33	0.33		9
9	0.8807	89.812 3.167	0.41	0.42		9
10	1.775	181.011 6.384	0.39	0.41		10
AVERAGE	0.9973	101.705 3.587	0.41	0.43		
AVERAGE NEW VALUE.	0.7882	80.37 2.835	0.22	0.22		

Fig. 5.49 TEST 104: CU: FLAT: 2.5 MILLION CYCLES MECHANICAL PERFORMANCE.

PROBE No.	PLUNGER FORCE		SIDE PLAY mm		MECHANICAL EVENTS	RESISTANCE PERFORMANCE CATEGORY.
	NEWTON	GRAM OZ	0°	90°		
1	0.7688	78.401 2.765	0.35	0.30		1
2	0.8188	83.499 2.945	0.30	0.30		9
3	0.8172	83.336 2.939	0.35	0.35	TIP & PLUNGER WEAR THROUGH GOLD PLATE.	1
4	0.8588	87.579 3.089	0.30	0.29	TIP & PLUNGER WEAR THROUGH GOLD PLATE.	9
5	0.7165	73.067 2.577	0.45	0.45		2
6	0.8216	83.785 2.955	0.35	0.34		9
7	0.7474	76.218 2.688	0.30	0.29		3
8	0.7384	75.30 2.656	0.30	0.30		9
9	0.7991	81.49 2.874	0.25	0.25		2
10	0.6912	70.487 2.486	0.29	0.30	TIP & PLUNGER WEAR THROUGH GOLD PLATE.	3
AVERAGE	0.7777	79.316 2.797	0.32	0.31		
AV NEW VALUE	0.8011	81.69 2.88	0.20	0.20		

Fig. 5.50 TEST 105: CU FLAT: 2 MILLION CYCLES MECHANICAL PERFORMANCE.

PROBE No.	PLUNGER FORCE		SIDE PLAY mm		MECHANICAL EVENTS.	RESISTANCE PERFORMANCE CATEGORY.
	NEWTON	GRAM OZ	0°	90°		
1	1.002	102.182 3.604	0.30	0.30		9b
2	1.309	133.489 4.708	0.30	0.32	WORN TULIP POINT: ROUGHNESS OF DEFLECTION.	1
3	0.9802	99.959 3.525	0.25	0.25	WORN TULIP POINT: ROUGHNESS OF DEFLECTION WEAR THROUGH PLATE.	1
4	0.8661	88.323 3.115	0.30	0.30		1
5	0.9302	94.860 3.346	0.20	0.22		1
6	0.9319	95.033 3.352	0.48	0.51		9
7	BROKEN DURING REMOVAL FROM RECEPTACLE.					8
8	BROKEN AT 230kHz					10
9	0.9602	97.919 3.453	0.35	0.37		9
10	0.9161	93.422 3.295	0.25	0.25		9
AVERAGE	0.9869	100.648 3.549	0.30	0.31		
AVERAGE NEW VALUE	0.7885	80.40 2.836	0.21	0.215		

Fig. 5.51 TEST 106; CU 60° ANGLED: 3 MILLION CYCLES. MECHANICAL PERFORMANCE.

PROBE No.	PLUNGER FORCE			SIDE PLAY mm		MECHANICAL EVENTS
	NEWTON	OZ	GRAMS	0°	90°	
1	0.5862	2.108	59.779	0.25	0.40	
2	0.5473	1.968	55.812	1.00	0.51	LOOSE ASSEMBLY
3	0.5845	2.102	59.606	0.40	0.30	WORN TULIP HEAD.
4	0.5849	2.103	59.647	0.60	0.58	PLUNGER WORN THROUGH BARREL.
5	0.5837	2.099	59.524	0.40	0.45	WORN TULIP POINT.
6	0.5797	2.085	59.116	0.35	0.36	
7	0.5916	2.128	60.330	0.36	0.34	
8	0.5856	2.106	59.718	0.40	0.60	
9	0.5933	2.134	60.503	0.35	0.32	BENT.
10	DAMAGED DURING REMOVAL FROM RECEPTACLE.					DAMAGED
AVERAGE	0.5818	2.092	59.337	0.45	0.42	
AVERAGE NEW VALUE.	0.5919	2.129	60.361	0.20	0.20	

Fig. 5.52 TEST 107: STEEL 60° ANGLE: ½ MILLION CYCLES. MECHANICAL PERFORMANCE.

PROBE No.	PLUNGER FORCE			SIDE PLAY mm		MECHANICAL EVENTS
	NEWTON	OZ	GRAMS	0°	90°	
1.	0.5855	2.106	59.708	0.30	0.35	
2	0.5733	2.062	58.464	0.30	0.28	SPRING FAILED.
3				0.30	0.35	SPRING FAILED :WORN THROUGH PLATE.
4	0.5902	2.123	60.187	0.19	0.21	SPRING FAILED.
5	0.5749	2.067	58.627	0.20	0.20	
6	0.5661	2.036	57.729	0.20	0.19	
7	PLUNGER JAMMED INTO BARREL.					JAMMED & WORN TULIP HEAD.
8	PLUNGER JAMMED INTO BARREL.					JAMMED
9	0.5935	2.134	60.524	0.201	0.18	
10	COMPACTED INTO RECEPTACLE DAMAGED DURING REMOVAL					DAMAGED DURING REMOVAL.
AVERAGE	0.5805	2.088	59.205	0.24	0.25	GENERAL. 6 BADLY WORN 1 BENT & JAMMED 1 BADLY WORN.
AVERAGE NEW VALUE.	0.5931	2.133	60.48	0.20	0.20	PLUNGER WORN THROUGH BARREL.

Fig. 5.53 TEST 108: CU FLAT: 2 MILLION CYCLES MECHANICAL PERFORMANCE.

PROBE No.	PLUNGER FORCE			SIDE PLAY mm		MECHANICAL EVENTS.
	NEWTON	02	GRAMS	0°	90°	
1	1.360	4.89	138.6	0.30	0.35	
2	1.641	5.90	167.3	0.20	0.20	
3	1.659	5.96	169.1	0.20	0.25	Roughness of deflection: wear debris: gold worn off.
4	1.480	5.32	150.9	0.20	0.20	
5	1.723	6.19	175.7	0.25	0.23	Worn tulip point: roughness of deflection: wear debris: gold worn off.
6	1.6	5.75	163.1	0.20	0.25	
7	1.723	6.19	175.7	0.15	0.20	Worn tulip point roughness of def: wear debris: gold worn off.
8	1.526	5.48	155.6	0.20	0.20	
9	COMPACTED INTO RECEPTACLE DAMAGED ON REMOVAL.					DAMAGED: JAMMED SOLID
10	ASSEMBLY PARTLY DISINTEGRATED.					Plunger and barrel detached due to excessive were.
AVERAGE	1.589	5.715	162.	0.212	0.235	
AVERAGE NEW VALUE.	1.453	5.22	148.1	0.15	0.15	

Fig. 5.54 TEST 109 STEEL 75°: $1/2$ MILLION CYCLES.

probe No.	PLUNGER FORCE			SIDE PLAY mm		MECHANICAL EVENTS GENERAL.
	NEWTON	02	GRAMS.	0°	90°	
1	0.8597	3.092	87.6	0.37	0.35	SOME CENTRE TULIP POINTS FLATTENED DUE TO HARDER TARGET.
2	0.9030	3.24	92.08	0.33	0.32	
3	0.7868	2.83	80.2	0.28	0.27	
4	0.8519	3.06	86.87	0.29	0.31	
5	0.8204	2.95	83.66	0.41	0.38	
6	0.7076	2.54	72.1	0.33	0.29	
7	0.8087	2.90	82.46	0.32	0.31	
8	1.095	3.93	111.66	0.30	0.32	
9	1.168	4.20	119.1	0.41	0.43	
10	1.261	4.53	128.5	0.28	0.29	
AVERAGE	0.9262	3.32	94.42	0.332	0.327	
AVERAGE NEW VALUE	0.7959	2.86	81.16	0.193	0.207	

Fig. 5.55 TEST 110: STAINLESS STEEL FLAT:
2 MILLION CYCLES
MECHANICAL PERFORMANCE.

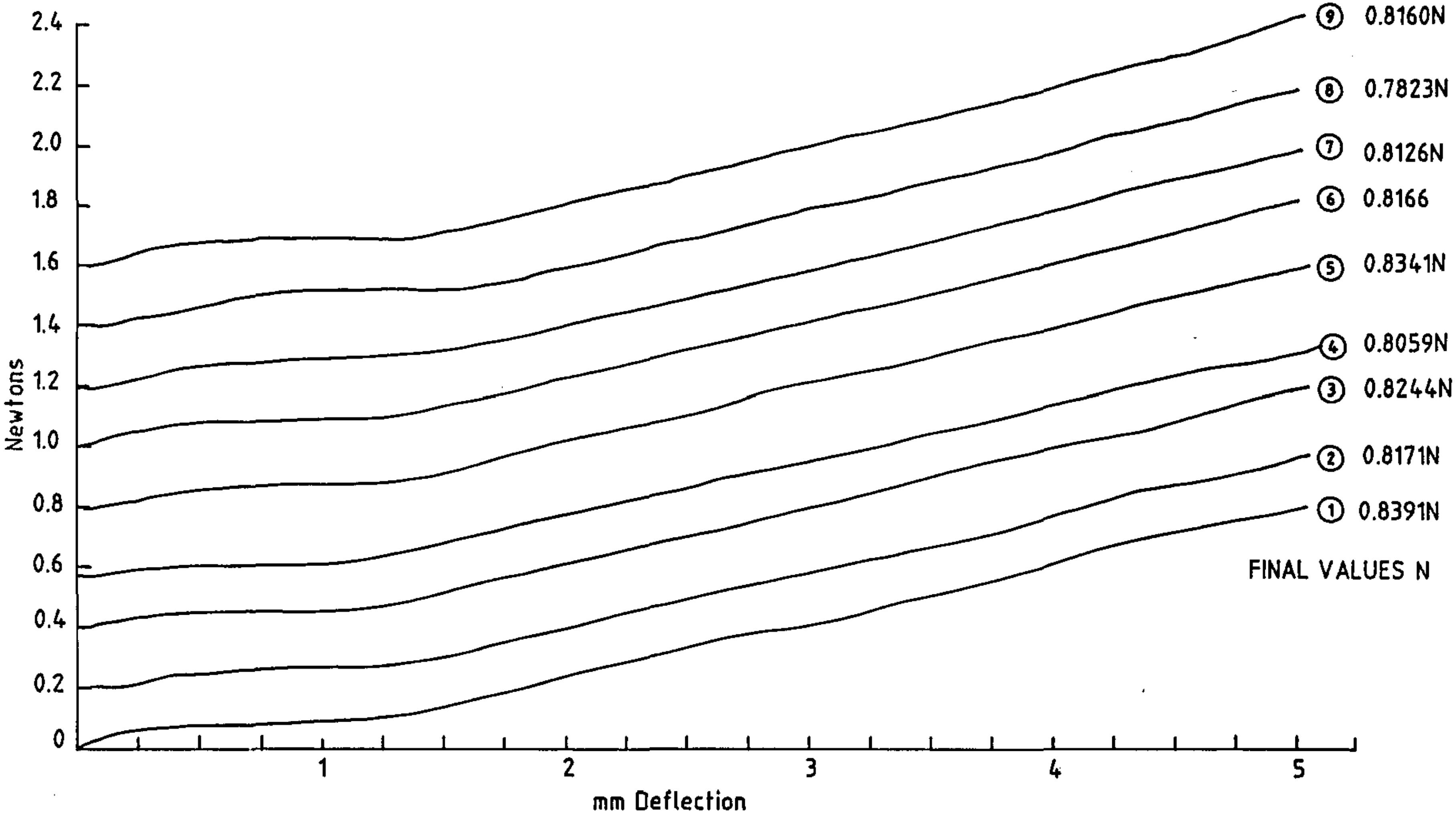


FIG. 5.56 TEST 102 SPRING FORCE MEASUREMENT OVER PROBES RANGE OF DEFLECTION.

structure during the probes transfer from the life simulation machine to the JJ tensile testing machine. The Probes sliding action improved after storage or further testing, probably due to debris falling out. Testing was conducted in a vertical position with the probe heads uppermost (as would be the case in most test fixtures), and so most of the debris remained trapped inside the barrel until a change of orientation was effected, which happened during transfer and further testing. Stiff probes or probes exhibiting symptoms of roughness of deflection often slid more easily after testing or evaluation. In the cases where broken springs were suspected radiographs were taken to investigate and verify the cause of the probes failure. Spring failure often occurred after extended testing beyond the guaranteed one million cycles.

In the first series of experiments (tests 101 to 106) the main purpose was to evaluate contact resistance, there was no incidences of broken springs up to 1.2 million cycles. The broken springs occurred during extended testing beyond 1.2 million cycles. The three broken springs in test 101 occurred during testing between 1.2 million and 2 million cycles. (see Fig.5.23). In the second series of experiments, test 108 also produced three spring failures beyond the 1.2 million figure. Apparent broken springs may be due to a number of different causes, e.g. a bent plunger which may have caused the probe to become locked solid, or wear debris and the slight deformation of the plunger may cause a similar effect. By releasing or freeing a jammed probe, it was then possible to ascertain whether the problem was caused by the spring or a combination of other factors. Using X ray photography indisputable evidence was produced showing probe samples with broken springs. Test results confirm satisfactory performance up to 1.2 million deflections for the majority of 100 probes tested.

ELECTRON MICROSCOPY: Photographs show in considerable detail the effects of probe wear to the plunger and probe head. It can be seen in several cases where the tulip angled points are severely worn away, or chips of the base metal substrate are missing from the crown points leaving a rough rocklike appearance to a number of the probe crown points (Fig.5.57). Analysis of the probe contact point surfaces were performed visually during initial testing using an optical microscope. When the probes had completed their test cycle

FIG 5.57a : CHIPPED PROBE POINT SHOWING ROCKLIKE COPPER SUBSTRATE: MAG. 47.

FIG 5.57b : PROBE HEAD CONTAMINATION & WEAR: MAG 75.

programme they were again investigated on a scanning electron microscope (SEM). Elemental analysis of the probe contact area was achieved using the LINK facility of the SEM and AUGER electron spectroscopy, which showed conclusive evidence where the plated contact surface had become worn away to copper base metal (See Fig.5.29). Visual observations using the optical microscope indicated that fretting corrosion had taken place on the copper probe target. Black regions were visible at the probe target contact area both for angled and flat targets tested (See Fig.5.31).

Wear debris was collected from the probe assembly and subjected to analysis using the SEM which showed that the wear debris particles were predominately copper (Fig.5.58). In all the cases SEM investigations were conducted at the completion of the tests and not after an equal number of cycles. SEM investigations showed a considerable amount of particulate contamination to a number of the probe heads, most of the debris being airborne in origin, and of a non metallic or non mineral appearance. It is possible that it could have been deposited in the probe field area of the test machine by the action, for example, of the motor cooling fan. This event is similar in vacuum operated test fixtures due to the large amounts of air transferred over the probe field during test activity. The investigation into probe plunger outer bearing surfaces showed variable amounts of scoring into the cylindrical surface, either confined to mainly one area for angled targets or spread all around for flat targets. On some of the test samples variable amounts of metallic wear debris had been compacted into the worn cylindrical surfaces of the probe plungers. The wear debris often contributes to probe roughness of action or probes becoming completely jammed into the barrel.

X RAY PHOTOGRAPHY: The probes suspected of having broken springs were X rayed and were found to have broken springs. Once a spring breaks,the two halves of the spring start to screw the two broken spring sections together (usually due to the deflecting action of the test machine), which gradually reduces the spring force available to the plunger (Fig.5.59). In some cases a probe spring may break in more than one place as shown in one example where two broken sections became combined, but the third section remained separate thus leaving a visible gap. In another test sample the two broken sections of a

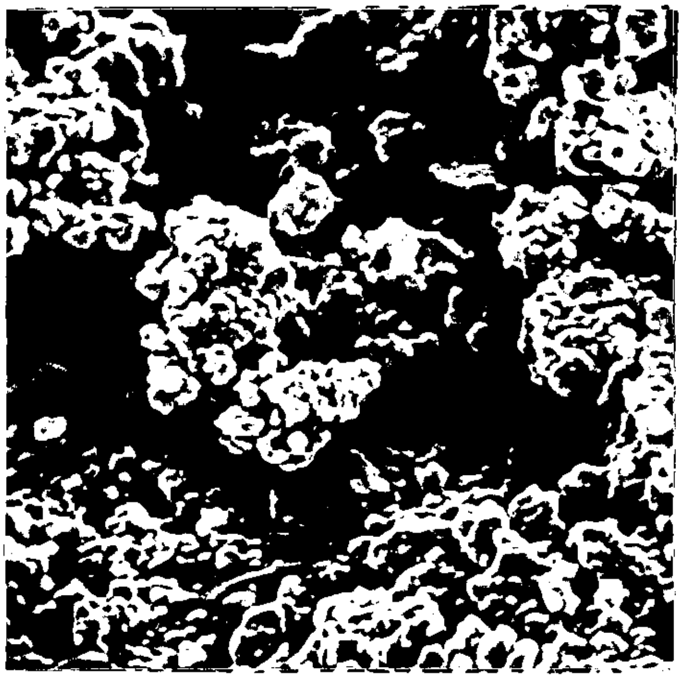


FIG 5.58a : PROBE INTERNAL WEAR DEBRIS PREDOMINATELY COPPER: MAG 5K

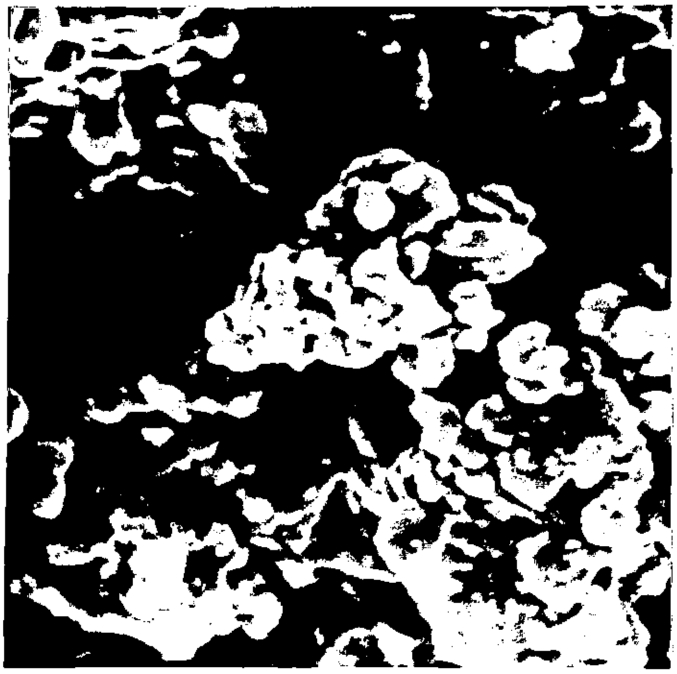


FIG 5.58b : PROBE INTERNAL WEAR DEBRIS PREDOMINATELY COPPER: MAG 10K

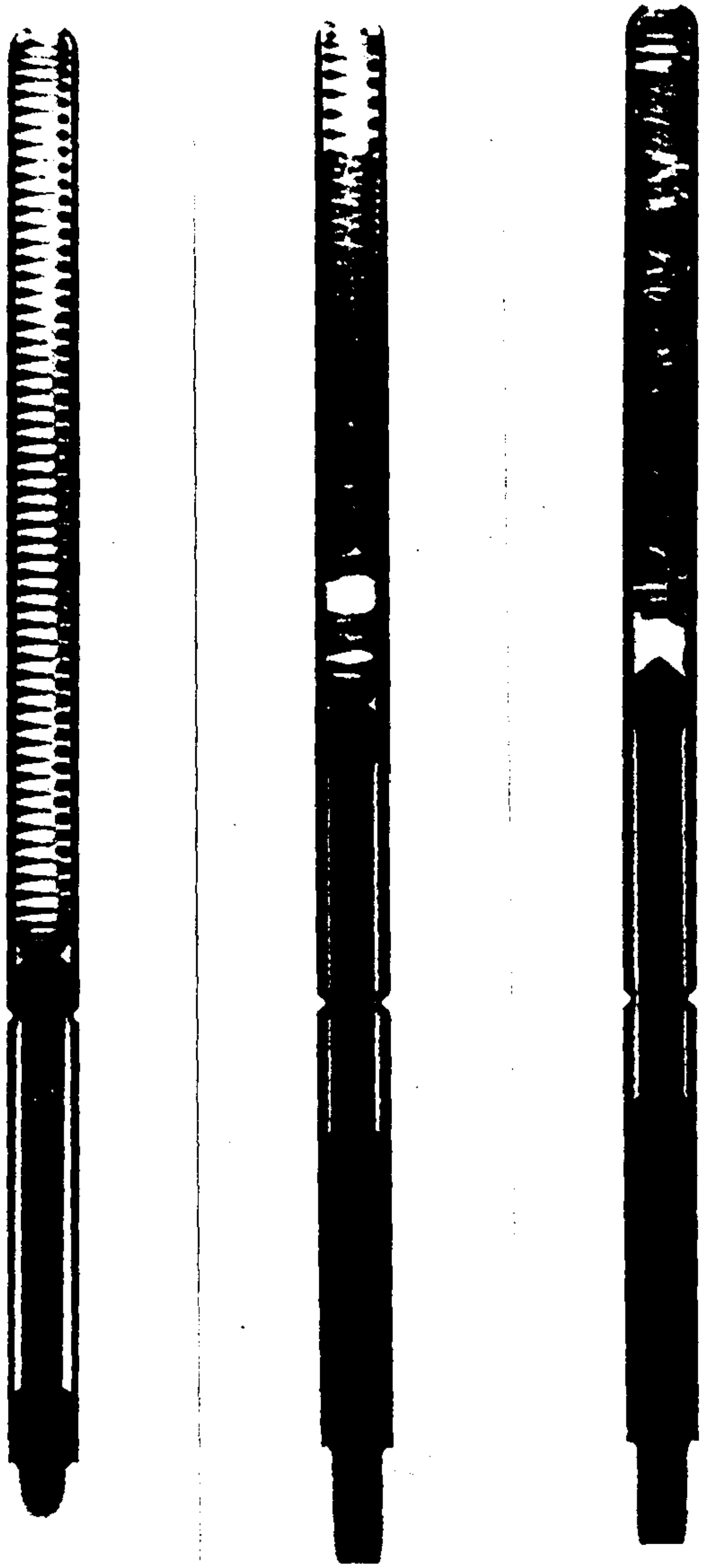


FIG 5.59a,b,c : XRAY PHOTOGRAPHS SHOWING 1 NORMAL & 2 BROKEN SPRINGS

spring also became combined with no deflecting force available at the plunger. The photograph of a new probe highlights the difference between good and failed test samples. Due to the grainy nature and the magnification of the X ray photographs, it is not possible to be certain whether the photographs show any wear debris trapped inside the probe assembly. There is no doubt however, that a considerable amount of debris did become trapped inside the probe assembly during simulated testing since the majority escaped during mechanical evaluation for spring pressure and side play.

5.7.2 Probe Resistive Performance after 1.2 Million Cycles

In the majority of samples tested, the probe performance after 1.2 million cycles continued in a similar pattern as before. The average probe resistance values continued to rise slowly with an often widening spread of recorded values. However, resistance values measured often decreases during prolonged testing as was the case in experiment test 103 (45 degree target), where average resistance values peaked in the three million cycle and then reduced to earlier performance measurements, continuing low readings up to 4 million cycles. This could be attributed to lack of contamination and mechanical problems. The values recorded during test 105 (flat target) show on average a consistent performance throughout the test up to the final 2 million cycle reading.

The mechanical problems that developed on certain probes during testing before 1.2 million cycles were related to erratic resistive performance. These events were test 101/probe 6 jammed at 948 KHZ; test 103/probe 3 jammed at 320 KHZ (both probes performed erratically throughout the test); and finally test 103/probe 6 that developed sporadic resistive behaviour at 250 KHZ, eventually becoming permanently jammed for the remainder of the test. It would seem apparent from the mechanical/electrical relationship that in relatively major contact resistance variations the minor mechanical occurrences will have their effects on contact resistance, for in such cases maximum contact pressure is required to penetrate resistive layers which are present on the contact surfaces. Rough probe action may cause variable contact pressure when it occurs in repetitive PCB testing, as may be seen in the spring test graph (See Fig.5.40). Rough probe deflection may precede jamming in the minority of cases with probes displaying erratic variable resistance behaviour at an earlier stage during the test.

5.8 STAINLESS STEEL TARGET

One of the later tests used a stainless steel target plate to try and eliminate the effect of contact fretting on the probe target. Initial test values were high when compared with a softer copper or solder target. Indeed some readings were logged as open circuit which is beyond the 2000 milliohms range of the on-board measuring system (Fig.5.60).

Test reading resistance values settled down to acceptable values for eight out of the ten probes undergoing life testing, thus leaving the remaining two exhibiting high values at 1000 milliohms. As an extra test to check the resistance measurement system, all probe bodies below the tip were, in turn, connected to the contact plate to further verify the internal resistance of each probe, and as a further verification of the measurement circuitry. In all ten cases, values were below 90 milliohms. It was deemed necessary to eliminate the contact plate as an element of suspect high surface resistance over some of its area, so the plate was moved four millimetres, effectively producing a new uncontaminated target area for each probe head. The measurement process was then repeated, showing no significant change in the overall readings, two of which were still showing the high readings displayed earlier, thus indicating interfacial contact resistance (see Fig.5.39).

The initial high values of resistance which decreased on testing are attributed to the inability of the probe points to penetrate the surfaces of the harder stainless contact plate with the associated reduced contact surface area. The reducing resistance values due to increased contact surface area, as the testing progresses, allows the probe points to penetrate further into the probe target surface. Probe tip wear may have the effect of wearing through any insulating layers present on the probe tips, as the testing progresses. Initial test results show on average, reducing resistance values in the early part of the experiment as the testing progresses, where normally in testing one would expect values on average to increase (55).

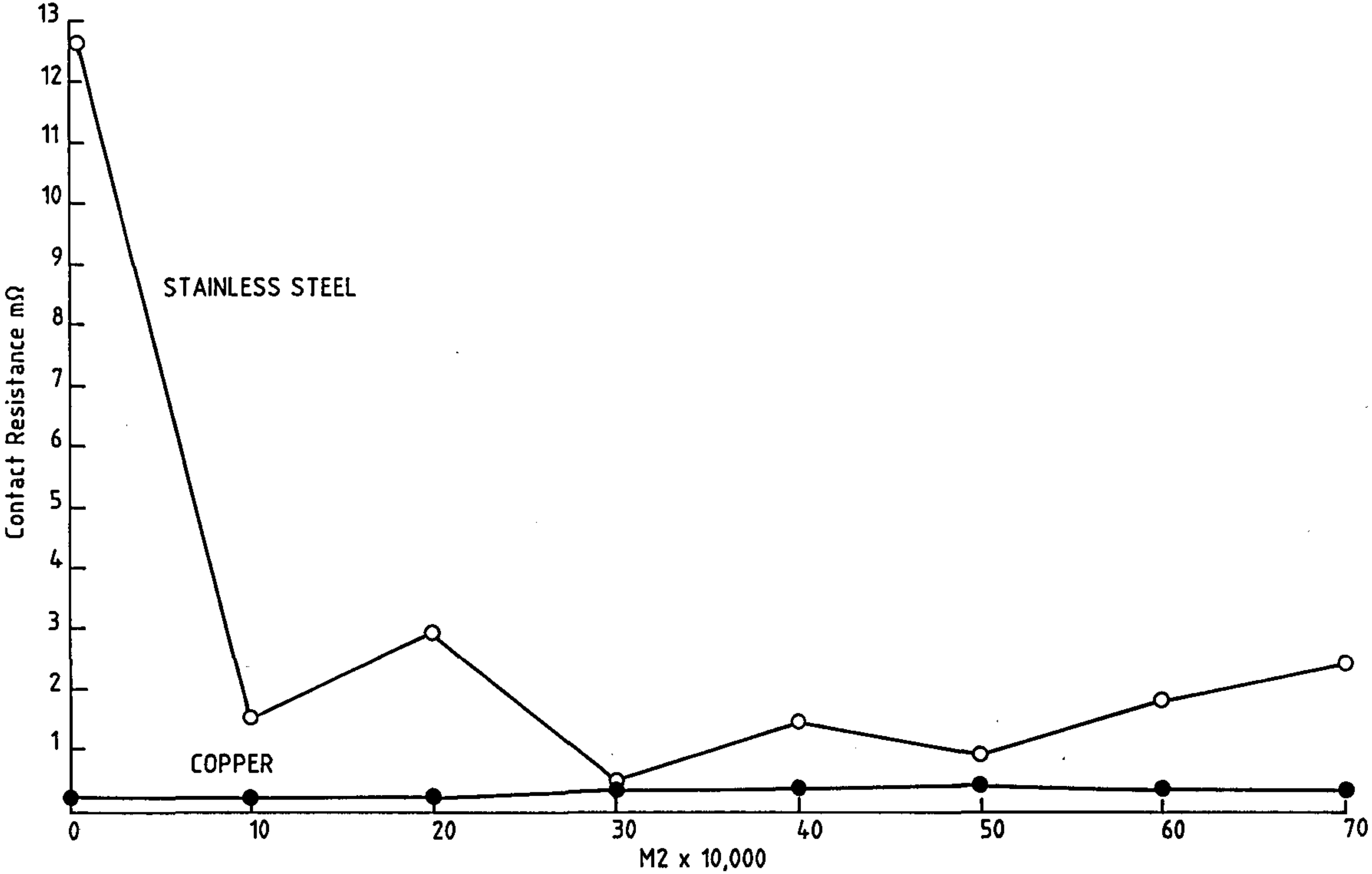


FIG. 5.60 COMPARISON OF INITIAL TEST RESISTANCE BETWEEN A SOFT COPPER TARGET AND A HARDER TARGET OF STAINLESS STEEL FROM TABLES

During lengthy testing the probe points often became domed or rounded with no sharp contact points to penetrate any possible insulating layers that were present which caused contact resistance often to increase.

5.9 GENERAL OBSERVATIONS

The test results showed that high and variable contact resistance was the most likely factor to cause serious problems during PCB testing. In the tests conducted the probe & receptacle internal resistance values before, during and after testing generally stayed within low levels. There were only a small number of mechanical failures (when compared with the electrical failure events due to high contact resistance), and these occurred after extended testing. In the majority of cases mechanical events tended to be permanent compared with the often temporary nature of electrical contact resistance events that often reverted back to normal service. It was noted that large variations in spring pressure may effect contact resistance, where the contact may have become contaminated as the probe starts to wear due to clogging or jamming. Side play gradually increased due to wear, but there was no evidence of probe wear during the normal life of a probe (1 million cycle tests). The high contact readings for the 32 probes in category nine (during the normal life span of a probe), were due to interfacial resistance layers on one or both of the contact surfaces, except in a minority of cases when mechanical problems developed.

CHAPTER 6

6 DISCUSSION

6.1 DISCUSSION OF TEST RESULTS

The range of experiments conducted are discussed with suggestions for overcoming some of the problems encountered during the test period. The mechanical performance of the probes during testing generally produced results indicating considerable reliability to beyond 1.2 million cycles, unfortunately the electrical performance over the same period produced less desirable results. The more undesirable effects were periods of cyclic or spasmodic high interfacial contact resistance predominating in most of the probe samples tested. This phenomena has been observed in all the experiments undertaken to verify the probes performance as one of a pair of electrical contacts. Contact resistance is a function of contact pressure, and so results indicating variations in the probe spring pressure and the effects of excessive side play during testing are included in the chapter. Possible future alternatives to multiple spring probe contacts particularly when considering miniaturisation of electronic circuitry are investigated.

6.1.1 Repetitive Simulated Machine Testing

The conditions which exist in a normal test fixture compared to that of the simulated test machine show that in most cases, a probe in a normal test fixture will only make contact once with each PCB target pad as the UUT will be replaced by another after it has been tested. This means that in most cases the fixture probes have a new target during each testing operation, so in reality the targets may all be clean, or contaminated, or a combination of both, reflecting the conditions of the production line on a daily basis. As targets are accessed once or twice by the test probes it should not be possible for contact fretting corrosion to develop on probe target pads, but it would be possible for it to develop on probe tips after considerable use. In situations where high values of resistance were encountered the problem may be due to the interfacial insulating layers which may be on the target pads, or on the probe point tips, but the blame would probably be attributed to the probes.

To simulate test fixture conditions it would be necessary to change the probe target every cycle the probes were deflected during a test. To operate in an inert gas environment due to the effect of the oxygen atmosphere would also be desirable since this would prevent contact corrosion fretting, but this would also eliminate the effect on the probe contact tips which is an equally unrealistic situation. This problem is overcome in some contact applications by using read relays, where the contact operates within an enclosed glass envelope with an inert gas or vacuum environment, a magnetic field is used to actuate the contact through the glass envelope. Other alternatives are to surround the contact area with a suitable inert jelly or grease, so preventing the development of insulating layers forming upon the interfacial surfaces, however this would not be possible when applied to PCB testing due to a new PCB target at every test.

6.1.2 The Correct Probe for a Particular Target

Various factors have to be considered when selecting the correct probe for a particular application. Consideration must be given to a number of parameters for optimisation of probe performance e.g. the type of test system, continuity, in circuit or functional all affect the choice of spring probes. Other factors such as centre spacing have to be considered because of its limiting effect on the receptacle and plunger tip (probe sockets mounted to close together may cause a short circuit). Plunger travel refers to the distance the plunger may be depressed. Variations in target surface height and the fixture design can affect the amount the plunger needs to be depressed. Manufacturers recommend values for each product, however, deviation from the recommended value does not mean poor performances in all cases. Recommended travel is usually two thirds of the maximum value, which should provide variation for slightly over or under travel without loosing electrical integrity, whilst over deflection may lead to early spring failures.

Contact targets cover a range of materials which include copper, solder and gold. The gold because it is soft requires a smooth probe tip to prevent damage to the surface. The geometry of the tip in relation to the target is important because of its surface area, material and spring force, which are all contributing factors to the probes electrical characteristics and contact reliability.

6.2 PROBE INTERNAL RESISTANCE MONITORING

Probe internal resistance may be monitored during testing by attaching a pair of measurement connections to the probe head, which may be achieved by the use of a double contact bull dog clip, necessary when using the four wire resistance measuring method. However, there are problems due to the action of the testing machine causing the contact clip to become detached. This effect may be overcome by soldering the two test wires into position, but unfortunately the heat produced has a degenerative effect upon the probes subsequent performance, thus leaving the one option of clipping the measurement wires onto the probe head whilst making the measurement. This method eliminates any interfacial contact resistance due to insulating layers on either the target or the probe tip. Verification of accuracy may be achieved by using the external system of resistance measurement, connected between the probe receptacle and the probe head. Using this method it is necessary to transfer the double contact clip through all ten probe heads, whilst making internal resistance measurements. Wires that have been soldered onto probe heads during the experiments have eventually work hardened, subsequently breaking off due to the test machine action.

The internal probe resistance measured from the probe receptacle to a point on the probe head below it points, shows from information derived from the experiments, that probe internal resistance values remain of a low order compared with comparative interfacial values for the same tests. The resistance reading for most of the tests are in the range of 10 to 50 milliohms. There are however one or two readings that go as high as 82 milliohms out of 60 samples tested but generally compared with interfacial values, internal values are comparatively low (See Fig.5.35). The internal measured values will normally remain consistent for up to one or two million test cycles, which may be due to the sliding internal contact action which seems to keep the internal contact surfaces reasonably free from the development of insulating materials.

Where the debris becomes free to move around within the probes telescopic structure the oxide formed is likely to be of a smaller particle size compared with most of the wear debris present, and will be ejected more easily by the probes repetitive telescopic pump action due to its smaller particle size. The wear debris is being continuously subjected to abrasive action from other wear particles, whilst the probes telescopic structure makes a reasonably low contact resistance through the probes internal components due to scraping and grinding actions. The effects which may be seen from some of the electron micrographs, show wear debris particles attached to the probe telescopic structure (Fig.6.1). The electron micrographs also show a relatively large particle size when compared with the probe components, there is also an absence of small particles present on the probe plunger. Other electron micrographs show wear debris taken from probes subjected to extended testing, the probes were shaken around, compressed and relaxed releasing the debris from the internal structure (Fig.6.2).

6.2.1 Probe Spring Pressure

In the mechanical tests, probe spring pressure was measured before and after simulated machine testing, revealing little significant difference (See Fig.5.43), but in order to measure spring force the probes had to be removed from the test machine receptacles before being tested in the JJ Tensile Testing Machine. In all cases probes were stored in numbered bags prior to testing, and during removal for testing, wear debris was visible which was caused by changes in orientation of the probes during removal and storage. Once a probe is removed after testing, examined and further tested in other machines for spring pressure, some or all of the debris within the probe structure will escape during the process. The mechanical tests conducted on the JJ Tensile Testing Machine before and after simulated machine testing shows very little variation in spring pressure, yet during the simulated testing variations occurred due to the accumulation and movement of wear debris, worn probe components or a combination of both. In test 101, Probe 4 jammed due to the accumulation of wear debris trapped inside the probes structure but became free after removal from the test machine. This was also noticed in subsequent tests where probes became jammed and afterwards became free after further testing. Six probe springs failed, three in test 101 and three in test

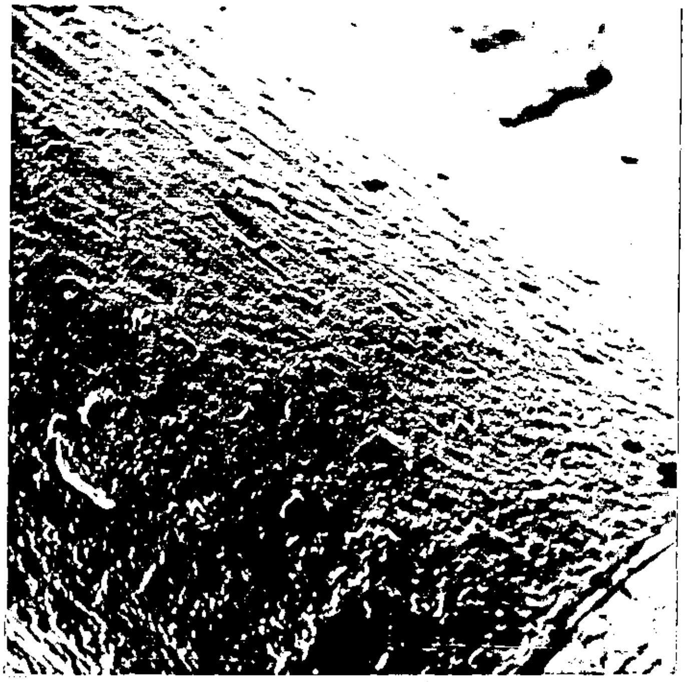


FIG 6.1 : WEAR DEBRIS ATTACHED TO THE PROBE PLUNGER: MAG 100

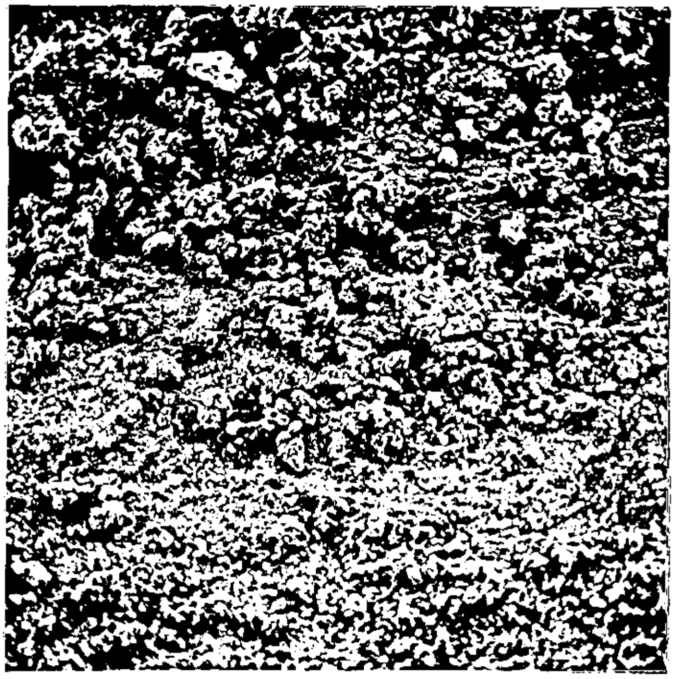


FIG 6.2 : WEAR DEBRIS EXPELLED FROM THE PROBE ASSEMBLY: MAG 500

108 both tested to 2 million cycles (See Fig.5.59). During PCB testing in a fixture and in the evaluation testing machine, it is evident that variations will occur in the spring force delivered to the probe plunger as wear debris is produced and it circulates within the structure causing variation in spring force. In other cases probes may become jammed (See Fig.5.40). The fact that probes become jammed during circuit board testing operations proves that they must exhibit variable contact force which are apparent in the resistance graphs. Considerable variations in contact force may occur and may be responsible for variations in contact resistance. The life evaluation testing machine has no facility for logging spring probe contact force which, if possible, would permit the continuous monitoring of probe contact force in relation to contact resistance. Contact resistance is always measured by making connections on non-contact wearing surfaces below the probe head, thus avoiding any worn or contaminated area of the probe plunger head.

6.2.2 Side Play

Side play becomes a problem when probes increasingly slide off or short to adjacent circuit board targets. This is often caused by tooling and fixture tolerances, component placement variation and side play movement in the test probe resulting from the wear or flexibility within the assembly. Side play measurements taken before and after testing show some variation between experiments and targets accessed, often non linear where the probes are targeted to angled contact points with the probe components wearing in only one plane. In test 107 (See Fig.5.52) side movement was measured at 1mm with a value of 0.51mm measured at 90 degrees to the original value, however, wear debris tends to escape during probe transfer and testing for side play, causing larger variation in measured values. The average side play for most new probes was 0.2mm whilst worn probes measured values were sometimes in excess of 1mm. The side movement measurements ranged from 0.25mm in test 101 at 2 million cycles, and 0.45mm in test 107 at 0.5 million cycles (See Fig.5.42). There were marked differences in the wear rate between probes supplied by several manufacturers, for the probes were supplied over a period of 12 months with newer models being introduced over that period.

6.3 INCREASING RESISTANCE RANGE AS TESTING PROGRESSES

As probe testing progresses, resistance values in general increase whilst at the same time the range or spread of recorded values widens. This phenomena may be seen in some of the graphs produced from the test results (See Fig.5.19).

It is evident from the test results that as insulating layers form on contact surfaces they form the major resistive component of ATE/UUT interconnecting circuitry, and can be of a variable nature for a number of reasons. Most electrical contacts are degraded by contamination. Contact surfaces are irregular on a microscopic scale, for plane surfaces have a waviness on which a rough surface is superimposed with peak and valley profile surface, and when brought together they touch at only a few of the surface asperities. As the load is increased due to the effect of spring pressure, more peaks and valleys make contact reducing overall contact resistance as the contact surfaces move closer together, increasing the contact surface area which depends on the spring load and the hardness of the two contact metals.

As the probe surfaces become covered by insulating layers which may be oxide film, production line contamination or atmospheric contamination, the metallic contact area will be zero if the insulating layer is unbroken by the contact spring load. Should the voltage across the contact area be large then the insulating film may be electrically punctured, therefore the probe performance will be dependant on the voltages present during testing. Generally the softer and more conductive the metal used for the test targets the lower the contact resistance will be at a given probe force.

Contact contamination is caused by a foreign substance on a contact surface, preventing or reducing metallic contact and thereby degrading contact resistance. Some apparently innocent substances e.g. fluxes may corrode or degrade contact surfaces which eventually result in contact failure.Thin films developing on contact surfaces may prevent contact being made if the spring contact force is low, but may have no effect in conditions where the spring probe contact force is higher. The interaction of organic vapours evolving from connector housings, PCBs and wire insulations etc.. with the connector contact materials, may cause the formation of surface films and an increasing contact resistance. Various investigators (56-57-58) have examined these interactions previously, and have concluded that organic vapours may leave a carbonaceous film on the contact surface. Frictional polymer formation on Pd based materials has also been investigated in detail by several investigators (59-60-61-62). It is believed (57) that the absorption of organic vapours on these materials is the first step in the process of frictional polymer formation. The interest in using Pd and R 156 (60Pd, 40Ag) based contacts necessitates an understanding of the actions of various organic vapours on these materials. An additional concern has been that some of the material employed in connector housings, printed wiring boards and discrete interconnect wiring etc.., may emit chlorine containing compounds (63). The interaction of these compounds with Pd based materials may leave a surface film of Pd Ci which is resistive (64-65-66). The materials containing silver may form a silver chloride film (67). These interactions usually are of little consequence at room temperature with low RH (68), but the interactions may become significant at higher temperatures employed in manufacture and testing (69).

In most cases test results show interfacial contact resistance between probe heads and targets as the predominant factor in ATE - UUT interconnection resistance. Test results have shown that in the worst case, test 104, the average interfacial contact resistance was 26.8 times the relatively low average internal value measured after 2.5 million cycles (See Fig.5.35). Relative contact movement indicates significant variation in contact resistance, but it should be noted that contaminated contact resistance can be affected by the number of asperities coming into contact by contact pressure, and the amount of contact contamination of various forms which are:

A). Oxidation and Corrosion:

Base metals develop insulating coatings of oxide and corrosion products due to exposure to the atmosphere. In most cases these layers will thicken with time accelerated by air pollution.

B). Particulates:

In contact applications particles are of two main types: airborne, and those generated by contact wear debris which are produced by closure or opening contact activation. Cooling fans in electronic equipment or vacuum activation of test fixtures, may concentrate airborne particles onto PCB test pads or the probes within the test fixture.

C). Thermal Diffusion:

As probes and test pads use mainly thin layers of noble metal or fingers in the case of PCB test contacts, thermal diffusion of substrate metal through the contact material can occur on its surface (70). The base metal is transformed into oxides at the surface sufficient to degrade contact resistance.

D). Contact Fretting:

Contact fretting may occur to the target, the probe tip or both, due to the repetitive frictional action of the testing machine. Contact wear occurs and the debris formed oxidises or corrodes the base metals, the resultant insulating layers build up increasing contact resistance. Further contact wear may remove insulating layers causing cyclic variation in contact resistance (See Fig.5.26).

E). Friction Polymer:

Friction polymers are also responsible for increased contact resistance. When probes are contaminated with organic chemicals or gases, repetitive contact friction action causes the organic materials to polymerise creating an insulating layer over the effected contact surface. Organic chemicals may be present in PCB substrate materials, component encapsulations or may be caused by cleaning fluids used in manufacture.

F). Manufacturing processes:

Probe or PCB pad contacts are subjected to various manufacturing processes which may cause contamination on the probe contact or pad area. Amongst the most common are: Contact plating salts which are not completely removed during the manufacturing process; the incomplete removal of flux residues during cleaning procedures and fingerprint contamination during manufacture caused by handling (this may cause serious problems with mated contacts using low contact force).

6.3.1 Probe Performance During Testing

A problem that exists when testing probes is that the repetitive contact of a probe with a contaminated surface, may cause materials to transfer from one contact surface to another. If a probe tip becomes contaminated, it can usually be cleaned by wiping with lens tissue moistened with trichloroethylene or other volatile solvents. However stubborn forms of contamination may only be removed by immersing the probe tips in an ultra sonic cleaning bath. It is desirable to make many contact resistance measurements on a given test sample because of variability in the distribution and the properties of surface contaminants. In a production assembly line environment, a single contaminated test pad would transfer material to its test probe tips which in turn would be transferred to subsequent test pads. The effects of contamination may take time to develop (depending on the type of contamination), before it has any detrimental affect upon the test results.

Test results show in the majority of cases (where contact resistance is measured on a repetitive basis with respect to the performance of PCB test probes) that the probes performance over a period of testing is unpredictable. In some cases they will develop repetitive or sporadic high resistance performance characteristics after a short period, whilst in other cases within the same test batch, they will give acceptable performance throughout their life expectancy of 1 million cycles. This may be explained where micro movement or further contact movement during probe deflection causes varying parts of the contact surface, with its asperities and contaminated areas, to repeatedly access the same area of contact which may or may not be contaminated on both or one contact surface. Contamination on some areas of contact surfaces could exist from the start due to manufacturing or storage problems. If the area or areas of contamination are small and there is some contact movement, various parts of the contact surface may be aligned to each other on a microscopic scale resulting in a contact resistance performance of a random nature. In other cases if there is little or no relative movement between the two surfaces, resistance measurements will be of a more constant nature and may persist throughout the testing exercise.

As both interfacial contact surfaces align to various multi contact asperity areas with their potentially random contact resistance values, there may also be occurring at the same time, the slow degradation of contact surfaces due to contact wear or fretting where probes may have varying thickness of plated noble layers on their surfaces. This may explain the varying levels of performance between the same batch of ten probes in some of the tests, where high values would or would not develop within a test.

Where noble layers are thin or non existent, contact fretting will eventually occur, whilst at the same time on other probes interfacial resistive layers may be at their development stage with progressively increasing resistance values. Particulate or environmental contamination is responsible for some of the increasing interfacial test values. Airborne dust particles were observed in the electron micrographs and appeared to have been caused by the machine motor's cooling fan, but would normally be caused by the test vacuum actuation system of the test fixture (Fig.6.3).

6.3.2 Contact Resistance Concerning High and Low Energy

Probes within a test fixture will be subjected to different conditions whilst performing their task of making contact with the UUT. Some of the probes will be loaded to near their full current carrying capacity, with voltages sometimes approaching and even up to 240V mains voltages; or even above in a minority of test applications. Other probes, perhaps in the same fixture, will be used to make minute measurements of current voltage and resistance, and so contact resistance will have a much more significant role in measurement. In situations where voltage and energy levels are high a different contact phenomena may exist, e.g. in a switching circuit where energy levels and voltages are high any resistance may be broken down and the subsequent flow of current will cause a physical change in the contacts micro geometry, thus producing a cold low resistance weld as in the case of mains voltage power switches. This type of contact is often referred to as a wet circuit, as the contact molecules move around the contact interface. In circuits where the voltage and/or current in a circuit are too low to cause any physical change in a contact, the circuit is said to be a dry circuit.

FIG 6.3a : PARTICULATE AIRBORNE CONTAMINATION: MAG 70

FIG 6.3b : PARTICULATE AIRBORNE CONTAMINATION: MAG 70

The development of various forms of insulating layers on contact surfaces will have an effect similar to a zener diode, behaving like a voltage triggered switch depending on the type of contamination present. This has been illustrated by J.H. Whitley's work of the AMP Corporation in the USA which has shown the various breakdown voltages of contaminant films (71), (Fig.6.4).

It is evident where voltages and/or currents fall into this category and where probe tips may have extremely thin insulating layers on their surfaces, that the applied voltage may be too low to electrically puncture the film, regardless of how thin and electrically weak the film may be. Contacts tested under dry circuit conditions and shown to be conductive would also be conductive at any arbitrarily lower value of voltage or current. Probes within the test fixture would either be subjected to voltages or currents high enough to puncture or vaporise insulating films which may be already present or have formed over a period upon the contact surface, or in other cases subjected to lower voltages or currents unable to penetrate insulating layers present on the contact surfaces. Probes in the lower voltage/current category would be responsible for most of the problems encountered during normal testing activity.

Wherever an attempt is made to bring two contact surfaces together, but the voltage energy levels are too low to produce a wet contact, there is never certainty of a reproducible low resistance connection between both of the contact surfaces. Looking at the micro geometry level, the surfaces will consist of a hill & valley profile where there may be micro movement between each contact operation, causing different asperities to connect on each closure. Contacts that are contaminated with oxide, friction polymers, fretted, or any other contaminate coatings are likely to be of a non linear nature, with peaks of the contact microstructure appearing through the insulating layer, and therefore repetitive contact resistance due to micro movement is likely to be of a more random nature as various parts of the contact surface either fail or make contact with each other. In cases of wear debris present on contact surfaces, contact operation or movement may cause the debris to move around the surface sometimes causing variable or open resistance effects (See Fig.5.58).

SOME CHARACTERISTICS OF FILMS GROWN ON COPPER SUBSTRATES AND GOLD PLATED NICKEL SUBSTRATES

BASE METAL	FILM	VOLTAGE AT BREAKDOWN (VOLTS)	BREAKDOWN FIELD (VOLT/CM)
GOLD	IRON OXIDE	0.95	8.0×10^5
GOLD	**	1.4	1.1×10^6
GOLD	IRON OXIDE & COBALT OXIDE	2.6	1.0×10^6
GOLD	IRON OXIDE**	1.2	9.2×10^5
GOLD	IRON OXIDE**	2.6	1.2×10^6
COPPER	COPPER OXIDE	1.4	3.9×10^5
COPPER	COPPER OXIDE	1.0	5.5×10^5
COPPER	COPPER OXIDE	1.6	5.7×10^5
COPPER	COPPER OXIDE	1.1	3.4×10^5
COPPER	COPPER OXIDE	1.5	5.1×10^5
COPPER	COPPER OXIDE	2.6	6.9×10^5
COPPER	COPPER OXIDE	4.0	5.3×10^5
COPPER	COPPER OXIDE	3.5	5.1×10^5
GOLD	COBALT OXIDE	5.7	1.0×10^6
GOLD	COBALT OXIDE	10.0	1.4×10^6

**MAY CONTAIN NICKEL OXIDE

FIG. 6.4 (71)

6.3.3 Performance Variations for Test Probes

Electronic circuits can often tolerate resistance increases of hundreds of milliohms and still function, particularly since typical insulating films present on surfaces can be destroyed by signal strengths of a few volts. Contacts exhibiting random infrequent events or discontinuities may only exhibit very small contact resistance increases. These apparent anomalous observations can be considered consistent with modern contact theory, where relative motion at microscopic levels causes surface films surrounding metallic asperities to produce resistance changes for very short durations.

Other explanations, involving two metal surfaces separated by a thin non homogenous film (comprising oxide, contaminates and particular matter) and through which the electrical signal is conducted, have been verified and are considered to fit the experimental observations better (72). The link between static contact resistance increases and the tendency to increased contact intermittency has been reproduced experimentally by mating tin on tin surfaces (73). Low amplitude relative motion, up to 0.2mm, degraded the tin surface by fretting (a mechanism whereby metal freshly exposed is then oxidised and the cycle repeated regularly; Tin-on-tin or tin on gold contact systems are particularly prone to fretting. The extent of metal weight loss this causes depends on chemical parameters (such as absorption rates) as well as mechanical factors, contact pressure, number of cycles and degree of relative motion (74). In preference to individual contacts, a series of tin contacts were monitored to produce a regular predictable trend towards increasing contact intermittency. On individual contact after a particular elapsed test time, mating asperities may either be clean or oxidised (providing the random, temporary poor or rogue contact), but the general trend over a group of contacts is one of increasing variable behaviour. This is matched by increasing, albeit small, contact resistance measurement and once the degradation mechanism is initiated, both relatively long and short duration events begin to occur. The tendency is towards a burst or string of short resistance variations. A few very short events rapidly increase in number, giving the appearance of long pulses of resistance variation. As a result true long pulses develops.

The use of base metal contacts is more likely to cause variable resistance problems examined in experimental work, and can be employed for test work in a more predictable and controlled manner, by employing high contact forces and restricting micro movement between mating surfaces. These experimental studies have tended to produce contact failures more rapidly than they occur in practice. The aim remains, however, to establish predictable real life acceleration factors.

Whilst discussion has been confined to base metal contacts, gold plated contacts can also degrade and produce intermittent problems. Under vibrations, gold plating can be worn through to the nickel or copper substrate-particularly in certain localised regions, and fretting causes the wear debris to build up and produce surface contamination associated with variation in resistance values (75).

6.4 MECHANICAL FAILURE

In nearly all the tests conducted the mechanical failure rate was low when compared to defects due to high resistance. The main failure reasons during the testing period to 1.2 million (N.B. probes guaranteed performance is up to 1 million) was a broken plunger to an angled target and three jammed probes (See Fig.5.23). In the situation where probes became jammed variable contact resistance preceded the event, because the probe plunger force varied due to jamming during testing deflection. Before a probe becomes completely jammed in one fixed position it goes through a number of cycles delivering variable contact force to its target, with the increased likelihood of variation in contact resistance to the target (See Fig.5.40).

Probe testing evaluation indicates that mechanically the majority of probes perform well, up to and often well beyond their recommended life cycles. Excessively worn probes can give satisfactory results (if side play is ignored) where they are directed to large targets, as long as noble plated layers stay intact. Mechanical effects due to wear on the probe points often cause contact resistance problems. Where wear occurs to the probes telescopic structure the trend is for contact resistance to remain low even though noble plated layers may have worn through. However this does cause dramatic increases in contact resistance when it happens to probe tip contact points, for it is less likely for contact action to remove insulating layers which may have formed on contact tip surfaces due to the absence of any form of wiping action, this also seems to keep coaxial interfacial surfaces of the probe structure free of insulating oxide layers. The repetitive action of the probe with possible wear debris trapped within the structure may help to keep sliding surfaces clean, due to contact wiping action over the probes coaxial surfaces. When probes are not used for a period of time oxidation within the probe structure including wear debris may cause internal resistance values to rise. This effect was detected after probe testing and storage for a period of time. As the probes become worn the probe plunger becomes less rigid within the coaxial structure allowing a greater range of side movement. This side movement may be restricted to some degree if the probe structure becomes clogged with metallic wear particles.

6.4.1 Contact Cleaning

Cleaning contact surfaces in most cases leads to a considerable reduction in contact resistance when probes have been in prolonged service or tested towards their full life expectancy (See Fig.5.38). However in cases where noble plated layers have worn away or tip points have broken down to base metal, contact resistances will rise back to their values over variable periods of time. In the cases where noble plated layers remain in tact and there is no further contact contamination, resistance values may remain low for considerable periods of contact operation. There is therefore no long term purpose in cleaning contact points with damage to noble plated contact surfaces as the only solution is probe replacement.

Items selected to clean probe head points must therefore not be capable of scratches or scraping away gold plated surfaces, tools such as wire brushes made from hard materials may do more harm than good. It is also possible for wear debris from probe contact tips or cleaning tools to be left behind on contact surfaces leading to the development of insulating layers in later use. Cleaning liquids used must not leave surface residues after evaporation for the same reason. Ultrasonic cleaning may be one solution for the removal of probe tip insulating layers present, but would require the probes removal from their test fixture. In some cases it may not be possible to remove all contact contamination without the use of some form of abrasive tool, which could lead to damage or removal of the noble plated layers. In some circumstances therefore, wholesale probe replacement may be the only answer proving to be the cheapest solution in the long term.

6.5 TEST PROBES THE POTENTIAL WEAK LINK IN MOST ATE SYSTEMS

The test probe is considered by most people involved in PCB testing as the weak link, or perhaps one of a number of weak links in a test system. It is the only part of the interconnecting system between the ATE computer and the UUT which may be responsible in adverse circumstances for variable or open interconnecting resistance. The spring loaded test probe may be considered as perhaps the most important component in the ATE system since without it contact is impossible (76-77), (Figs.6.5 to 6.7).

During the test phase, if the probes should measure a point and obtain an incorrect reading, the system is often programmed to tap the point again to be sure that the probe has not made a bad connection (78). Test fixtures are available with built in ultrasonic vibrators as another way to ensure the probe tips make contact through any form of contamination which may be present on the test targets or probe tips. Ultrasonic vibration guarantees contact reliability and keeps probes clean. (US PAT NO 3996516 DBP No 2344239).

Increasing miniaturisation is gradually making the manufacture of probes, test fixtures, PCBs, components more difficult and testing an even harder task. Closer spacing of components means smaller diameter probes with less spring pressure available to achieve a lower contact resistance through any insulating layers which may be present on the probe tip or target. As long as designers compete to increase packaging density up to and often beyond practical limits, test probes and the fixtures that support them will have to shrink to meet the space available. Probe manufacturers have been working to reduce diameters without making unacceptable sacrifices in rated life, stiffness conductivity, spring force at the tip and uniform lifetime performance (79).

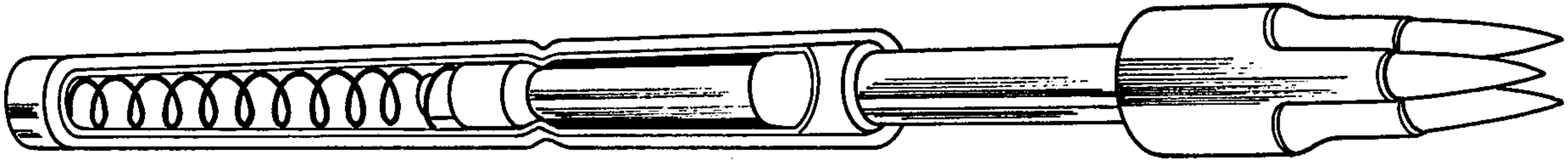


FIG. 6.5 NEW TIP STYLE TO DEAL WITH DIRTY PADS

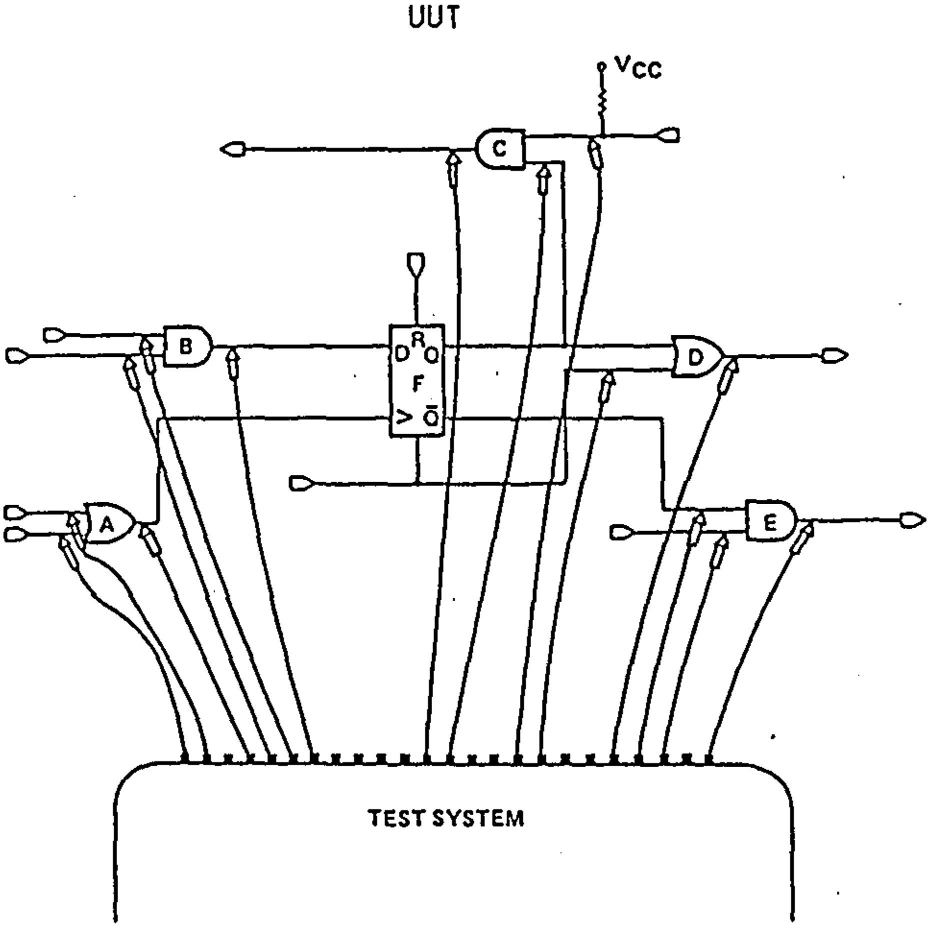


FIG. 6.6 ATE - UUT INTERFACE CONNECTING WIRING

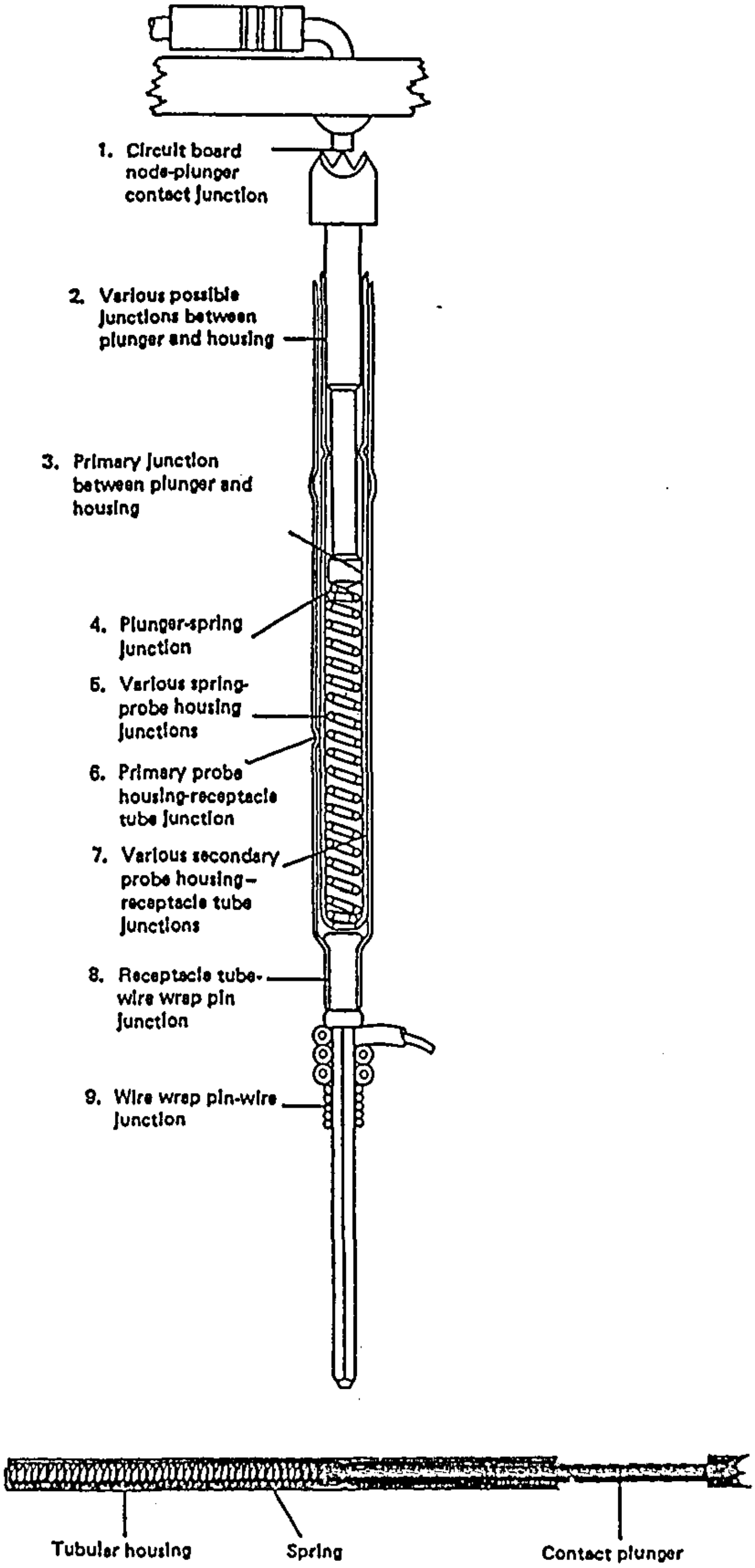


Fig. 6.7 PROBE COMPONENT CONTACT JUNCTIONS.

6.6 POSSIBLE ALTERNATIVES FOR RESOLVING TEST PROBLEMS IN THE FUTURE

One way to eliminate the unpredictable contact performance of spring probes is to eliminate them from the test system and replace them with an alternative; unfortunately at present there seems to be no reliable proven alternative method to make hundreds or thousands of reliable repetitive connections to PCB pins and pads. However there are some potential alternatives that may be developed. One method presently used but still needing a test fixture and probes, is to look at a PCBs electronic signature, making comparisons with a known perfect PCB, however this cannot solve the problem of eliminating test probes and fixtures. Another alternative which has been looked at by Bartlett and Merrill in the USA in 1975 is to look at the infrared emission from a PCB under test. They claim there are two types of response that can be obtained when a printed circuit board is electrically energised. There is the expected electronic response and there is also a thermal response, but conventional ATE methods have been concerned with evaluating only the electronic response. The thermal response can be determined by measurement of the emitted infrared radiation, and can supply additional information about the electrical performance of a PCB, which is based on the fact that the infrared radiation is proportional to the electrical power dissipated as heat by the board. An infrared scanner can measure the temperature of components and thermal nodes on a board without the need to physically contact the board. All circuitry and components that could cause functional failure can be measured with one infrared scan, thus all the data necessary to perform fault isolation can be obtained in one test, instead of conventional electronic test methods. There are three general classes of printed circuit boards, which ATE systems must test. Fault isolation of the different classes is necessarily done in different ways. IR test techniques are more effective for fault isolation of analog and hybrid boards than for digital boards (80).

6.6.1 Contactless Probing

Using electron beams and lasers to measure internal signals in ICs and boards, may offer an alternative to probing in the fixture. Using contactless probing, either e-beams or lasers may be used in much the same way as traditional mechanical probes to measure the logic scales of specific locations on a IC or PCB. Where mechanical probing is limited to bond pads or large geometries, however, contactless probing can measure the scale of virtually any node within an IC or PCB; even through a passivation layer and with no capacitive loading. In addition to detecting logic scales, extremely accurate information can be obtained regarding the voltages and timing of internal IC signals, including rise and fall times, amplitudes and propergation delays. This allows failure analysis and design debuggers, who have traditionally been limited to analyzing data obtained at the devices outputs, to actually go "inside" the device and take measurements, in much the same way as oscilloscopes and logic analyzers are used to probe printed circuit boards. "E-beam testing offers a unique opportunity for designers and product engineers to look at the ICs internal signals" according to John Large, director of Motorolx's Advanced Product Analysis Centre in Austin Tex.

E-beam Probing:

There are, of course, significant differences in the fundamental mechanisms behind e-beam and laser probing techniques, resulting in some major differences in the cost of instrumentation, the ease of operation and most important, the type and quality of information generated. A total of five companies at present produce commercial e-beam probing systems: Applied Beam Technology (a subsidiary of International Scientific Instruments) Fremont, Calif; Cambridge Instruments, Cambridge England; Integrate Circuit Testing (ICT) Munich, West Germany; Lintech Instruments, Cambridge England; and the most recent Sentry /Schlumbergers VHSIC Test Systems Div. San Jose, Calif. In comparison, there are only two commercial suppliers of laser probing systems: Dataprobe Corp., Santa Clara, Calif., (marketed by Mitsui Comtech Corps Calif); and ICT. Although laser probing systems have not enjoyed the commercial success of e-beam probes to date, recent developments in electro- optic and other advanced laser probing techniques show incredible potential.

The well known scanning electron microscope (SEM) serves as a foundation for all e-beam probing systems, where the electron beam of the microscope acts as the probing beam. In fact one reason for the popularity of e-beam probing is that it is possible to convert a standard SEM into a e-beam prober, adding a secondary electron analyzer and appropriate beam control/image analysis electronics. The secondary electron analyzer is critical, because it traps these electrons that are collected and analyzed to determine the voltage and logic state of the target area (81).

Information can be generated by an e-beam prober in several ways, the most useful of which are waveform measurements, dynamic voltage contrast and logic state mapping. Waveform measurements which provide the most quantitative information are taken by focusing the beam on a specific node in the IC, and measuring the voltage over a time using a stroboscopic technique.

Laser Probing:

The two commercially available laser probing systems from Mitsui/Dataprobe and ICT are dramatically different in operation. The Dataprobe model produces logic state maps by focusing the laser beam on the drawn region of a transistor, inducing photocurrents (indicative of the logic state) which can be detected on the power pin of the device. The laser is moved to the point of interest by positioning the XY stage. In comparison the ICT laser probe system uses a scanning laser beam to image the device. The system is capable of optical beam induced current (OBIC) imaging, which is especially useful for detecting hot spots or batch ups, and can also be used for detecting logic states (82).

The scanning electron microscope has evolved from being an inspection tool into a testing method for quantitative measurement of voltage within one integrated circuit. Sophisticated interfaces to CAD and ATE systems have also been developed.

The e-beam probe is a SEM (Scanning Electron Microscope) which is able to display differences in voltage within a chip in real time. The SEM image has areas of high or low contrast, dependent on the surface electrical potential present on conducting paths. Quantitative information can also be extracted by the electron beam acting as a non-contacting oscilloscope probe.

The voltage contrast phenomenon was first observed in the mid 1950s about 20 years after the SEM was developed, and important research work was carried out through the 1960s. The primary electron source sends electrons towards the surface with an energy around 1 KeV, which will neither load nor damage the circuit under test. Secondary electrons with an energy distribution between O and 15 eV are emitted from the surface, but their net energy is affected by the electric field surrounding the conductor. If it has a positive potential it will obviously tend to retard secondary electrons, and this loss in energy, forms the basis for the measurements using the e-beam probe because there is a simple relationship between the secondary electron energy and the surface potential. One of the keys to the usefulness of the technique is that circuits can be run at their appropriate clock speed, and yet observed at a slowed down rate by stroboscopic techniques i.e. scanning the device at a rate with a specific relationship to its clock speed. Picture quality is unfortunately not as good with strobe techniques due to the reduced signal to noise ratio, although a frame store will improve the quality of the voltage contrast picture greatly.

Another big advantage of the e-beam is that it can measure the surface potential of conductors buried in dielectric or passivation. The conductor is capacitively coupled to the dielectric surface, and the capacitance is generally greater than the substrate and the surface. Thus a change in potential on the conductor is approximately equal to the change in the dielectric surface potential, and secondary electron emission from the dielectric can be used as a measure for this charge. The familiar problem of inaccessibility is still apparent with multilayer devices, where some points of interest might be situated beneath a metal connection path and so additional vias have to be created. The beam testers have a potential to operate up to the G HZ region, using a 10 to 20 PS pulse on the beam (83).

6.6.2 The 3D XRay PCB Inspection System

The 3-D X-Ray PCB inspection system announced at Nepcon West (Ansheim California in March 89), is another potential alternative to the use of probes for fault identification in the future. The x-ray inspection system is said to be capable of reconstructing the structure of a solder joint from the boards surface to the top of the joint. The product is based on a technique dubbed "Scanned Beam Laminography" by the company which developed it -

(Four Pi Systems). The company was set up in 1986 with the aim of solving solder inspection and providing critical process control for PCB production. The company developed a technique called "Automated digital radiography" for PCBs. The scanned beam laminography technique is a further development of this X-ray inspection technology, enabling users to 'slice' through a PCB and successively build up a three dimensional picture of the boards solder joints. It uses a scanned beam X-ray source above the board, and a rotating X-ray detector below it. Images in the centre of the focal plane will be clearly detected by the detector system, while images not in focal plane will appear around the fringe of the detector as it rotates. Images processing will subtract these "fringe" images, leaving a strong image of the facial plane. Claims of the technique enables it to see under blind connectors, plccs, ceramic chips, heat sinks and overhanging material. The system can find defects like lifted leads, solder voids and bridges, and solder balls (84).

6.6.3 Automatic Visual Testing

Visual methods of testing PCBs are now well established where a stored video image of a perfect circuit board is systematically compared with each circuit board delivered by the production line. Human inspection of to days densely packed PCBs is not feasible or economical. This is because product rejects (as many as 40%) can be traced to PCB loading errors and so machine vision systems have been developed to meet the challenge. Early systems using TV - camera signals converted to binary values, were affected by ambient light variations and could not distinguish between touching or overlapping objects. Grey scale image processing which converts each camera image pixel into a six or eight bit format, can differentiate between 256 shades of grey, greatly improving object edge definition and clear separation of overlapping objects with minimal influence from ambient lighting. Finding PCB errors early in the assembly process has traditionally been handled by human visual testing, followed by in circuit testers. Advances in computerised pattern recognition have given muscle to automatic visual testing (AVT) techniques, which use machine vision technology to capture images of the board under test and generate electrical signals representative of the visual area. This data is then applied to a computer using pattern recognition software, which compares the boards visible elements with the position, sizes and orientation of components on a known good PCB . Defects such as components that are incorrect, missing, miss orientated, or damaged can quickly be detected. However, AVT will not flag electrical shorts, faulty components, or improper functional performance.

According to engineers at Cognel Corps, Needham, Mass. USA., equipment can detect more than 99% of the loaded PCB defects, with false rejects below 3%. Up to two minutes are required to test a loaded PCB with all covered faults detected in only one pass. Programming an AVT system involves showing it the board to be inspected and new or revised board test plans can be implemented by down loading computer aided design and manufacturing co-ordinated information to its component lay out. According to Cogned engineers an AVT system takes about a day to learn a typical board lay out, whilst the retraining for board revisions takes about half this time. Automatic data logging and detailed statistical reports provide immediate inputs on the production operation, and so process - control correction steps can be rapidly implemented to improve the yield of boards coming off the production line.

Since AVT does not involve board contact, fixturing costs and delays are nonexistent and the possibility of board damage is low. AVT manufacturers claim that combining AVT with incoming parts inspection eliminates the need for an in-circuit tester. It is claimed that AVT will locate assembly errors (which account for most faults on PCBs), shorts testing will detect shorts errors, and incoming inspection will screen out defective components. The tester system accepts a loaded PCB from an automated materials handling system and uses a scanning system to locate any board positioned within 12mm of expected location, eliminating the need for precise fixturing or probes. The boards identification code is then used and the appropriate test routine is called up (85).

6.7 PROBLEMS OF PROBE TESTING

Although the trend must be towards the use of more sophisticated techniques in the future, there is still a long way to go before practical problems relating to the mass testing of circuits within a manufacturing environment may be over come. While it is still possible to go on testing ICs and boards using the existing mechanical spring probes, the incentive will not be great enough for manufacturers to look at other possible alternatives, for a solution to the slowly increasing problems due to increasing miniaturisation and circuit density. Using electron beam techniques every circuit would have to be tested in a vacuum chamber with the air removed before testing could commence. There may be problems associated with testing in a vacuum environment for certain types of components, but with time as in most situations the problems are eventually resolved. In the future with progressive decreases in terminal and track spacings, there will come a time when it is no longer possible to continue using spring probes to gain access to nodes within the circuit. This is already the case with multi layer boards unless special provision is made using extra vias.

It is generally accepted today that most problems associated with the reliability and performance of electronic circuits are caused by mechanical devices rather than electrical problems. The comparative unreliability of electrical connectors and contacts being one of them. While contacts are exposed to atmospheric corrosion and the effects of the various production processes, with the mechanical contact action causing possible fretting corrosion, the spring probe will always be the weak link in the test chain.

Most of the problems encountered will be with probes used in test circuits where voltage/energy levels are not great enough to break down any insulating layers that may exist on contact surfaces. These are likely to be fet inputs to instrument amplifiers or devices with high input impedances and low voltage levels. In the majority of other cases voltage energy levels will be more than adequate to break down and destroy any contact contamination (71). One analogy that serves to demonstrate this effect is the action required to initiate a welding arc. It is necessary to keep tapping or stroking the welding electrode onto the target requiring welding. Only when a part of the surface to be welded has been cleared of contamination by the tapping or stroking action is a low resistance circuit initiated, resulting in the striking of the arc which once initiated vaporises any form of contamination. If however voltage/energy levels were low it would be impossible to initiate a low impedance circuit through the oxide or contamination coated surface.

It is not possible to guarantee how a set of probes engaged in PCB testing will perform due to the number of variable factors that adversely effect the probes ability to achieve repetitive low impedance contacts over a period of time. Whitley states that as much as we hate to admit it, and as much as many of us have worked to improve the situation, there is still no generally applicable and technical accepted relationship between contact resistance, its magnitude and variation, and the practical performance, life and reliability of the associated contact. Neither theoretically nor empirically have we been able to demonstrate such a generally valid relationship (86). The most important general factor has to be cleanliness associated with everything from the manufacturing processes, through the various stages of testing, to the environment and storage conditions for the various components used for manufacturing and testing. Some of these will obviously be more important than others e.g. components or areas of the product which are involved in the ATE - PCB interface.

The main problem area has to be the probe tip/target interface as confirmed by the test results, showing the probes internal resistance values to be relatively insignificant compared with the values of interfacial resistance that may develop during testing. Another problem with cause for concern, is contact contamination attributable to airborne particles deposited and concentrated into the probe field by the vacuum actuation used in most test fixtures. Air pollutant gases released during manufacturing into a building or industrial suburb of a city, may be the cause of insulating layers developing on so called clean contact surfaces with the loaded PCBs themselves. Once interfacial contact resistance develops it may be sporadic or cyclic in nature (See Fig.5.9), and in applications where high numbers of probes are required in fixturing an unacceptable failure rate may occur.

CHAPTER 7

7 CONCLUSIONS AND FURTHER WORK

7.1 GENERAL

The study has shown that during the repetitive testing of spring contact probes to a fixed target, the major problem encountered has been the development of interfacial contact resistance layers between the probe contact points and the PCB or copper target. Some of the insulating layers are caused by mechanical or chemical contact phenomena established over a period of time, and related to mechanical or chemical contact degradation. The interfacial insulating layers developed on the two contact surfaces were the major factor responsible for the relatively high and variable contact resistance values monitored over the testing period. This considerable variation in contact performance over ten identical samples corroborates Whitley's work on contact resistance (86) that there is no generally accepted relationship between contact resistance, its variation and contact performance. Some of the test batch samples show excellent performance well beyond life expectancy displaying consistent low value readings, whilst other samples become sporadic or cyclic. The possible cause being the absence of contamination, or better quality or thicker noble plated layers on some of the probe tips thus preventing the development of contact fretting. Sporadic performance may be due to relative movement of the two interfacial contact surfaces contacting on various asperities, and contamination due to relative movement.

7.1.1 Mechanical Performance

Probe mechanical performance to just beyond the guaranteed life is effective with 6.6% of mechanical failures observed. Variations in spring pressure at the plunger tip have their effects on contact resistance if surfaces become contaminated, thus requiring greater contact pressure to produce a low resistive connection. In the few cases where probes became jammed (with the possible associated effect on contact resistance), the probes would go through stages of variation in contact force before becoming jammed. During the early testing within the guarantee period, side play would not give any cause for concern for most of the probe types tested, although the smaller centre spacing probes with greater flexibility would be more prone to the effects of side play. It is only after 2 to 4 million cycles during testing to some angled targets that the effect of side play becomes more significant. Mechanical factors such as the wearing through of noble plated layers with its subsequent effect on contact resistance is not initially detectable as a mechanical failure, but will lead to rapid deterioration in contact resistance over a period of time.

The probes internal components unlike contact performance relies on a number of contact faces which are connected in a series parallel configuration with a number of parallel paths available for the current to take. These internal resistance values through the probe components stay very low when compared with interfacial values, mainly due to alternative parallel paths and the contact wiping action. Base metal surfaces exposed after plate layers have worn through are kept relatively free of oxides or other insulants, by contact wiping action and wear abrasion due to debris particles within the probes telescopic structure. The predominance of low internal resistance measured during testing of probes in a relaxed or deflected position, demonstrates that the probe internal resistance values are of little relevance in comparison with possible probe head interfacial resistance. The overall spring performance is satisfactory even up to 3-4 million cycles with only 6% of failures during testing.

7.2 THE PROBE AND MANUFACTURING

The progressive miniaturisation of components with reducing termination spacing, creates the necessity for greater accuracy of test fixtures, probes and circuit boards. The reduction of probe size and target pads relates to a comparable reduction in spring pressure with increasing contact resistance, because of the probes in-ability to penetrate oxide films or other contamination that may be present. It is probable that probe performance will be reduced if other measures such as contamination free products, test probes and a cleaner overall environment are not given more precedence. Smaller diameter probes mean a more flexible structure (stiffness normally decreases in proportion to the cube of the diameter, with less current carrying capacity), thus increasing the likelihood of probes missing or slipping off their designated targets. Higher thermal emissions mean more board movement and stacking up tolerance margins making a miss or slide off on angled target more likely. The increasingly popular surface mount chip components which may be automatically placed using epoxy resin as an adhesive, may be liable to movement during curing and could adversely effect the probes ability to hit a target accurately.

Reduced probe and pad target area with reducing spring pressure will increase contact resistance during testing with its limitation on testing in some circumstances. Smaller probes with their smaller contact area and spring pressure will mean higher ATE - UUT interface ohmic resistance, even before contact degradation can develop after routine testing. It will often be possible to compensate for this effect, but not if it is of a variable nature as is often the case with contact contamination of most types.

Probe wear will compound the effects of tolerance build up by causing progressively increasing side play with a greater chance of a probe missing or slipping off its target, resulting in a poor contact, no contact or a short circuit to the next node. In addition, the performance and life of probes are reduced if they receive significant lateral pressure in operation.

7.2.1 Poor Contact Resistance Development

The selection of an ideal probe will serve to reduce the number of times a probe produces a less than desirable contact with the UUT, but will not completely eliminate the problem often defined as false errors. At times, probe performance may appear to be good, but if multiplied by the number of probes used in large fixtures, there are situations where the total number of false errors may exceed actual errors on the units under test. Some of the problems are due to mechanical factors, where due to side play and tolerance build up in PCBs and UUTs probes may miss or slide off their target. However the problem is more likely to be the development of insulating layers on the UUT and test probe contact area, due to contamination in manufacturing or during testing activity, with greater incidence in dry contact situations where voltage and energy levels are low. Contamination may be in the form of a finger print, gaseous, particulate, chemical, or could be due to mechanical effects of contact action, taking variable periods of time before becoming active. Contact resistance is caused by either the effects of the contacts mechanical action or the chemical/environmental induced insulation upon the contact surfaces. Absolute cleanliness during manufacture, storage and testing may reduce contact resistance problems, but will not alleviate the effects of mechanical action where contact fretting corrosion causes the development of oxide insulating layers over the contact surface. There is also the mechanical/chemical combination effect, where combined chemical contamination with mechanical contact action causes insulating friction polymers to develop over contact surface areas. A contact action in the form of a wiping motion (as in the case of the probes internal assembly), would help to keep the conducting surfaces reasonably free from insulating layers, but the normal make and break probe action at present is not capable of preventing insulating layers from developing on probe points or tips.

7.3 SUGGESTIONS FOR FUTURE WORK

There are three methods all with possibilities for future work:-

Spring Performance Monitoring Test Machine:

Further information may be derived during testing, if a test machine could be developed that was capable of monitoring spring performance, thus showing the relationship between contact pressure and contact resistance effected by spring performance, wear and wear debris. Variations in contact force caused by the accumulation of wear debris within the structure or probe components becoming jammed or deformed, could be identified in real time rather than visual inspection, and testing at a later stage. It would require the use of measurement transducers fitted underneath the probe target interfaces, with appropriate electronics for recording in a digital or analog format. This would involve logging 10 values of resistances and ten values of spring contact force at every cyclic increment chosen for data logging or recording.

Testing to a Guaranteed Clean Target Area:

Useful data could be acquired on contact resistance if the probes were tested to a guaranteed clean target area, which in the present testing circumstances is gradually being degraded by the growth of insulating layers during testing over extended periods of time. A system might be developed using a moving self cleaning target which would ensure target cleanliness over the variable duration of tests. An abrasive or buffing device could be used to ensure target cleanliness over the testing period, allowing continual assessment of probe head only, thus trying to eliminate interfacial contact resistance and target interfacial values. Continuous or automated cleaning of the target area could be achieved using a rotating disk or a moving strip target, which as an alternative could be made in the form of a continuously cleaned loop or band which may be cleaned mechanically or chemically.

Using an Inert Gas Environment Around the Probe Area:

The use of an oxygen/contamination free environment could possibly produce some useful data in respect to contact fretting and the growth of oxide upon contact surfaces. By allowing comparisons between probes tested in a contaminated atmosphere of various forms and an inert gas, would enable the exact causes of the development of insulating layers to be more accurately identified. Environmental testing, however, would require a considerable investment in apparatus/equipment making the test machine complex and expensive, thus requiring the use of gas cylinders and/or filtration devices to control the test environment over long periods of time. The probe batch tested would be completely enclosed by a gas tight housing with a gas sealed mechanical drive system. Using the enclosed test environment it would be possible to test probe batches over a range of temperature and humidity, with the addition of an appropriate heater/humidifier unit delivering filtered/unfiltered air of the desired quality for life simulation testing.

REFERENCES

REFERENCES

1 DRAPER.C, "Printed Circuits & Electronic Assemblies". p.V11.

2 DUKES, "Printed Circuits". Macdonald. pp.V-4.

3 LEONIDA.G, "Handbook of Printed Circuit Design & Manufacture". Electrochem Pub. Ltd, 1981. p.123.

4 EISLER.P, "The Technology of Printed Circuits". Heywood & Co. p.5.

5 WOLFENDALE.E, "The Junction Transistor & Its Applications". Heywood & Co. p.5.

6 SIMPSON.J, "Physical Principles & Applications of Junction Transistors". Oxford. p.1.

7 BARDEEN.J. & BRATTAIN, (1948). "Physical Review 74230".

8 SHOCKLEY.W, "Bell System Technical Journal 28".

9 BUCK.T.J, "4-Mil Wiring Technology: a Necessity not an Option". CK Div. Kollmorgen Corp USA. pp.1-11.

10 DRAPER.C, "Printed Circuits & Electronic Assemblies". p.7.

11 DUKES. "Printed Circuits". Macdonald. pp.33-42

12 LUND.P, "The Generation of Precision Artwork for PCBs". Wiley. pp.18-22.

13 EISLER.P, "The Technology of Printed Circuits". Heywood & Co. p.34.

14 DRAPER.C, "Printed Circuits and Electronic Assemblies". p.40.

15 SMITH. "Photo Engraving in Relief". Pitman & Co. 3rd edition.

16 TILL.W.C. & LUXON.J.T, "Integrated Circuits". Prentice Hall. pp.356-365.

17 WARNER.R.N, "Integrated Circuits Design Principles & Fabrication". McCraw Hill. p.127.

18 TILL.W.C, "Integrated Circuits Materials Devices and Fabrication". Prentice Hall. p.11.

19 PYNN.C, "Low Cost Board Test Handbook". Zehntel. p.3.

20 DWYER.P, "Performance Testing Options". Electronic Manufacture & Test Journal. pp.19-20.

21 BATESON. "In-Circuit Testing". Van Nostrand Reinhald. p.24.

22 BROWN. "Lifting the Defect Detection Burden". Electronic Manufacture and Test Journal, April 85. pp.41-43.

23 BEAUCHESNE. R, "Continuity Testing of PCBs". ATE East Conference Brighton MA USA, 1983. p.111-10.

24 BSS 5750. British Standard Institute.

25 SCHADWILL, "The Impact of Future Factory Manufacturing". Conference Paper Electronic Production Show & Con Electronic Production Efficiency Conference EXP84, USA. Everett & Charles. p.21

26 PAGE-WALTON. J, "Inspecting Bare Boards Automatically". Electronic Production Journal, March 87. p.11.

27 ELLIOTT. D, "Troubleshooting Solder Defects". Electronic Manufacturing & Test Journal, November 86. p.15.

28 BATESON. "In-Circuit Testing". Van Nostrand Reinhald. P.XI.

29 JOSELYN. L, Test Journal, March 87. p.11.

30 BSS 6001. British Standards Institute.

31 RUGGERO. M.B, "Weston Metal Tools Conference". USA, 1970.

32 NICHOLSON. B, "Quality Starts with Bare Board Test". Electronics Manufacture & Test Journal, Jan 87.

33 BATESON, "In-Circuit Testing". Van Nostrand Reinhald. p.155.

34 BENNETTS. B, "Designing & Manufacturing for Test". Electronics Manufacture & Test Journal, April 88. pp.23-26.

35 DAVIS. C, "Probing for the Perfect Contact". Electronic Manufacture & Test Journal, April 84.

36 Electrical Engineers Ref Book (1961). Newnes. pp.7/2-7/4.

37 KEMPSTER. M.H.A, "Materials for Engineers". pp.146-147.

38 BELL. D.A, "Electronic Instrumentation & Measurements". Reston, USA. p.139.

39 Standard Practice for construction & use of a Probe for Measuring Electrical Contact Resistance. American Society for Testing & Materials. B667-80. Philidelphia PA.

40 BUCKLEY. P, "Developing a way to beat the Pack". Electronic Manufacture & Test Journal, Feb 86. P.61.

41 BURNS. J.E, "Bed of Nails Testing Part 11". Electri Onics Journal, USA, Nov 84. p.43.

42 Measuring Contact Resistance of Electrical Connections (Static Contacts). B539-80 American Society for Testing Materials, Philadelphia PA.

43 ROBINSON. R, "The Importance of the Spring Contact Probe in ATE". Test & Measurement World, June 84. p.158.

44 GORRDANI. J.A, "Test Fixturing for PCB". Electronic Packaging & Production Journal. USA. Dec80. P.74.

45 MORTON ANTLER, "Effects of Surface Contamination on Electric Contact Performance ". IEEE Circuits & Devices Journal, 1987. pp.8-19.

46 MORTON ANTLER, "Fretting of Electrical Contacts Materials Evaluation under Fretting Conditions". Special Technical Publication STP780 American Society for Testing & Materials, Philadelphia PA, 1982. pp.68-85.

47 TOMPSET. D.E, "Development of a Contact Resistance Probe for Detecting Contamination on Connector Contacts". IEEE CH 1457. 1979.

48 EAGAN. T.F, "Contamination During Manufacture of Low Energy Elect. Contacts". Proc. Holm Conf. on Elect. Contacts, 1968. p.267.

49 WHITLEY. J.H, "Reflection on Contact and Connector Engineering". 33rd IEEE Holm Conference, Chicago, IL, USA.

50 BOCK. E.M, & WHITLEY J.H, "Fretting Corrosion of Electrical Contacts". 20th Holm Seminar on Electrical Contacts, 1974.

51 WHITLEY. J.H, "Investigations of Fretting Corrosion Phenomena in Electric Contacts". Proc. Eighth International Conference on Electric Contact Phenomena, 1976. P.659.

52 ABBOTT. W.H, & WHITLEY J.H, "The Lubrication and Environmental Protection of Alternatives to Gold for Electronic Connectors". IEEE Transactions on Parts, Hybrids & Packaging, March76. P.51.

53 IRELAND.T.P, STENNETT. N.A, & CAMPBELL.D.S, "Fretting Corrosion in Tin contacts". Inst. of Metal Finishing, E.M.Branch, Coventry. UK. (LUT), March 89.

54 HOLM.R, "Electric Contacts Handbook 4th Ed". New York, Springer-Verlag, 1967.

55 ANTLER. M, "Contact Resistance of Oxidised Metals Dependence on Mating Material". IEEE. Trans. on Components, Hybrids & Manufacturing Technology. Vol CHMT-10. No.3. Sept87.

56 HORN.G.L, "The influence of Organic Vapours from Insulating Materials on Contact Resistance". Proc. 20th Holm Seminar on Electrical Contacts, Chicago, 1974. 275.

57 SHARMA S.P, "Contact Contamination Formation of Carbonaceous Deposits on Electrical Contacts". Proc. of 17th Holm Seminar on Electrical Contacts, Chicago, 1971. 178.

58 HORN.G.L, and MERL.W.A, "The Influence of Vapours of Organic Insulants on Contact Resistance of Gold & Silver Alloys". Proc. 7th International Conference on Elect. Contact Phenomena, Paris, 1974.

59 HERMANCE.H.W, and EGAN.T.F, "Organic Deposits on Precious Metal Contacts". Bell System Technical Journal 37, 739, 1958.

60 SPROLES.JR.E.S, "The Effect of Frictional Polymer on Performance of PD Connector Contacts". Proc. 30th Electronic Comp. Conf. IEEE 317, 1980.

61 CROSSLAND.W.A. and MURPHY.P.M.K, "The Formation of Insulating Organic Films on PD - AG Contact Alloys". IEEE Trans PHPIO, 64, 1974.

62 ABBOT.W.H, "Frictional Polymer Formation on Precious Metal Alloys". Proc. 25th Holm Seminar on Elect. Contacts, IIT, Chicago, 11, 1979.

63 SCHUBERT.R, Bell Telephone Laboratories, Columbus; Ohio, Private Communications.

64 SHARMA.S.P, "Atmospheric Corrosion of Pd and Pd-AG Alloys, Part 11 - Film Chemistry". 27 Holm Seminar on Electrical Contacts, Chicago, Sept 21-23, 1981.

65 HAGUE.C.A, and ANTLER M, "Atmospheric Corrosion of Pd-AG Alloys, Part 1 - Film Growth and Contamination Effects". 27th Holm Seminar on Electrical Contacts, Chicago, Sept 21-23, 1981.

66 ANTLER.M, DROZDOWICZ.M.H, and HAGUE.C.A, "Connector Contact Materials:Effect of Environment on Clad Palladium, Pd-AG Alloys and Gold Electrodeposits". Proc 31st Elect Comp. Conf. Atlanta, 1981.

67 SHARMA.S.P, "Atmospheric Corrosion of Cu, Ni and AG". J.Elect. Chem. Soc., 125, 2005, 1978.

68 SHARMA.S.P, and SPROULES.E.S, "Reaction of Palladium with Chlorine and Hydrogen Chloride". 27 Holm Seminar on Electrical Contacts, Chicago, Sept 21.23, 1981.

69 SHARMA.S.P, and DASGUPTA S, "Reaction of Contact Materials & Vapours Emanating from Connector Products". IEEE CHMT Soc. 1983.

70 ANTLER.M, "Gold Plated Contacts Effect of Heating on Reliability". Plating Vol 57. 1970. 615-618.

71 WHITLEY.J.H, "Table of Breakdown Voltage". Amp. Corp. USA.

72 CURENCE.R, & RHOADES.W, "Predicting & Modelling & Measuring Transient Resistance Changes of Degraded Electrical Contacts". Xerox.

73 ABBOTT.W.H, "Time Distribution of Intermittencies Versus Contact Resistance for Tin-Tin Connector Interfaces During Low Amplitude Motion". Battelle Columbus Laboratories.

74 UHLIG.H.M, "Corrosion & Corrosion Control Chapter 7: Effects of Stress". Wiley.

75 HODDER F, & SOLLARS P, "Testing Connectors". Electronic Manufacture & Test, September 1988. P.41-44.

76 UDALL.G.F, "How to Select Probes". Electri Onic, April 83. P.30.

77 BREWER.J, "A Better Spring Probe Tip". Circuits Manufacturing, Dec84. P62-64.

78 ADRIEV.N, "Bare Board Testing". Electronic Packaging & Production, June 85. p.94.

79 QUINN.G.C, "SMT Puts the Squeeze on". Circuits Manufacturing, June 85. p.40-44.

80 MERRILL.R.D, & BARTLETT D.R, "Infra Red Testing ATE System". RCA Engineer, May 75. P.49-50

81 ISCOFF.R, "E-Beam Probing Systems:Filling the Sub Micron Gap". Semi Conductor International, Sept 1985. p.62.

82 SINGER.P.H, "Contactless Probing". Semi Conductor International, May 87. p.188.

83 HICKLENTON.A, "E-Beam Testing". Test Journal, May 88. p.26.

84 3 D XRay Inspection Systems. Electronic Manufacture & Test, April 89.

85 BIERMAN.H, "CAE Data Bases Can Streamline Chip & Board Test Systems". Electronics Week, Nov 1984.

86 WHITLEY.J, "Ragnor Holm Scientific Achievement Award Paper". Chicago, I.L. USA.

APPENDICES

Test 101 - FLAT TARGET; 2/3 COMPRESSION; I.D.I.

	Probe Deflection		Probe Deflection		Probe Deflection	
Probe No	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ
	0 cycles		12000 cycles		24000 cycles	
1	014	025	009	021	012	027
2	010	021	033	033	013	1400
3	007	010	009	097	011	032
4	014	030	023	046	175	051
5	021	031	063	129	105	198
6	011	016	013	033	058	120
7	011	032	009	022	010	026
8	012	027	009	033	010	018
9	012	037	013	024	014	022
10	016	030	014	044	030	066
av.	012	025	019	048	043	196
max	021	037	063	129	175	1400
min	007	010	009	021	010	018
	36000 cycles		48000 cycles		60000 cycles	
1	043	080	019	069	016	041
2	036	062	031	046	022	099
3	007	027	010	021	013	020
4	1196	085	0/C	123	893	212
5	038	060	032	051	040	084
6	051	227	036	105	041	105
7	011	050	009	058	012	041
8	011	046	012	043	013	027
9	016	027	018	041	019	050
10	061	194	682	048	092	056
av.	147	085	094	060	116	073
max	1196	227	682	123	893	212
min	007	027	009	021	012	020
	72000 cycles		84000 cycles		96000 cycles	
1	025	048	025	072	086	073
2	016	1981	033	576	018	263
3	016	021	013	023	014	024
4	463	068	1090	1462	1528	143
5	056	143	082	397	214	866
6	029	109	031	372	079	310
7	015	195	020	041	014	043
8	029	077	026	093	026	063
9	020	059	040	064	028	059
10	141	262	451	1380	020	681
av.	081	296	181	448	202	252
max	463	1981	1090	1462	1528	866
min	015	021	013	023	014	024

	Probe Deflection		Probe Deflection		Probe Deflection	
Probe No	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ
	108000 cycles		120000 cycles		132000 cycles	
1	1023	138	330	042	917	244
2	017	147	016	136	026	614
3	013	018	014	015	012	015
4	971	388	338	814	058	1552
5	352	616	343	1117	216	1333
6	064	229	074	196	051	165
7	020	1789	013	068	027	078
8	020	128	020	135	043	244
9	041	072	032	098	114	320
10	031	1649	045	664	056	074
av.	255	517	122	328	152	463
max	1023	1789	343	1117	917	1552
min	013	018	013	015	012	015
	144000 cycles		156000 cycles		168000 cycles	
1	1037	1016	1429	685	573	1440
2	021	1808	013	083	012	060
3	011	133	023	032	014	020
4	0/C	612	395	196	181	461
5	289	322	229	1991	152	963
6	071	101	066	209	072	101
7	033	684	037	024	013	045
8	030	1790	016	083	022	813
9	157	916	188	329	246	182
10	034	1105	019	218	027	243
av.	187	848	241	385	131	432
max	1037	1808	1429	1991	573	1440
min	011	101	013	024	012	020
	180000 cycles		192000 cycles		204000 cycles	
1	1266	540	531	730	715	836
2	013	204	014	520	015	140
3	023	019	027	026	025	026
4	470	1285	335	121	840	856
5	142	835	196	874	184	341
6	101	124	061	041	118	048
7	018	069	025	151	052	121
8	016	112	018	150	026	125
9	206	218	531	296	226	296
10	096	308	024	196	028	1380
av.	235	371	176	310	222	416
max	1266	1285	531	874	840	1380
min	013	019	014	026	015	026

	Probe Deflection		Probe Deflection		Probe Deflection	
Probe No	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ
	216000 cycles		228000 cycles		240000 cycles	
1	0/C	1016	1726	1393	0/C	1818
2	025	251	016	281	017	471
3	036	032	059	025	032	044
4	299	843	0/C	427	529	0/C
5	346	1650	1079	1699	264	951
6	082	044	070	038	084	196
7	033	038	090	027	018	101
8	021	106	019	284	018	999
9	388	140	189	423	119	206
10	035	063	075	580	040	0/C
av.	140	418	369	517	124	598
max	388	1650	1726	1699	529	1818
min	021	032	016	025	017	044
	252000 cycles		264000 cycles		276000 cycles	
1	1096	1409	1674	1141	1665	0/C
2	019	287	021	290	040	610
3	012	099	018	025	018	069
4	618	0/C	313	0/C	221	392
5	1972	1960	0/C	1622	1278	1495
6	082	249	073	034	085	224
7	017	216	058	036	056	133
8	016	251	079	490	039	1498
9	322	213	178	170	115	211
10	121	401	028	092	024	068
av.	427	565	271	433	354	522
max	1972	1960	1674	1622	1665	1498
min	012	099	018	025	018	068
	288000 cycles		300000 cycles		312000 cycles	
1	588	815	1190	0/C	1067	0/C
2	036	317	020	129	020	1163
3	050	050	011	021	022	028
4	691	214	268	0/C	278	397
5	646	969	017	016	015	026
6	074	106	008	013	016	015
7	126	058	031	029	010	0/C
8	184	1270	036	073	024	488
9	163	343	308	495	092	143
10	043	090	014	092	010	071
av.	260	423	190	108	155	291
max	691	1270	1190	495	1067	1163
min	036	050	008	013	010	015

Probe No	Probe Deflection compressed mΩ	Probe Deflection relaxed mΩ	Probe Deflection compressed mΩ	Probe Deflection relaxed mΩ	Probe Deflection compressed mΩ	Probe Deflection relaxed mΩ
	324000 cycles		336000 cycles		348000 cycles	
1	117	1102	021	518	023	1527
2	014	154	012	071	014	109
3	020	023	020	044	018	045
4	649	0/C	286	643	101	840
5	062	076	076	186	129	254
6	023	017	036	021	070	041
7	014	014	015	038	018	058
8	024	486	032	146	028	253
9	163	234	193	104	410	504
10	012	015	012	226	011	070
av.	109	235	070	199	082	370
max	649	1102	286	643	410	1527
min	012	014	012	021	011	041
	360000 cycles		372000 cycles		384000 cycles	
1	035	1480	016	1141	018	963
2	015	071	015	214	019	242
3	328	056	030	1490	329	115
4	1769	0/C	197	1030	354	525
5	058	078	059	126	071	103
6	025	024	048	020	046	026
7	021	028	039	091	041	061
8	037	1774	022	0/C	025	075
9	475	451	293	1560	728	086
10	016	019	014	030	020	035
av.	277	442	073	633	165	223
max	1769	1774	293	1560	728	963
min	015	019	014	020	018	026
	396000 cycles		408000 cycles		420000 cycles	
1	020	1670	058	699	036	1855
2	030	312	027	173	055	400
3	328	116	011	065	008	046
4	475	0/C	1209	1566	0/C	1146
5	123	106	109	099	087	133
6	040	063	130	043	074	056
7	046	072	022	254	043	041
8	022	277	018	104	037	691
9	388	913	322	368	303	497
10	017	026	016	018	014	022
av.	148	395	192	338	073	488
max	475	1670	1209	1566	303	1855
min	017	026	011	018	008	022

	Probe Deflection		Probe Deflection		Probe Deflection	
Probe No	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ
	432000 cycles		444000 cycles		456000 cycles	
1	065	695	121	1535	477	1438
2	054	1191	099	553	025	130
3	008	046	008	045	006	044
4	1090	153	1928	575	850	O/C
5	094	083	331	193	120	180
6	061	040	076	071	064	103
7	063	031	083	039	014	051
8	051	143	054	242	019	236
9	469	621	372	1020	110	1190
10	012	015	016	024	015	039
av.	196	301	308	429	170	379
max	1090	1191	1928	1535	850	1438
min	008	015	008	024	006	039
	468000 cycles		480000 cycles		492000 cycles	
1	071	1516	069	1485	049	960
2	037	272	112	352	073	513
3	007	079	008	419	009	079
4	869	1682	400	624	261	1849
5	148	142	233	336	196	171
6	066	111	026	085	079	087
7	027	048	036	081	072	190
8	080	253	029	654	040	636
9	068	265	119	368	291	780
10	016	028	026	034	015	032
av.	138	439	105	443	108	529
max	869	1682	400	1485	291	1849
min	007	028	008	034	009	032
	504000 cycles		516000 cycles		528000 cycles	
1	087	1146	343	548	116	1860
2	052	796	064	985	378	165
3	008	060	010	047	008	029
4	1578	1303	998	1282	1162	1542
5	141	116	237	086	177	172
6	079	049	074	036	061	039
7	075	060	017	078	044	069
8	100	1386	032	716	026	481
9	260	1391	187	643	157	320
10	017	025	024	026	022	115
av.	239	633	198	444	215	479
max	1578	1391	998	1282	1162	1860
min	008	025	010	026	008	029

	Probe Deflection		Probe Deflection		Probe Deflection	
Probe No.	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ
	540000 cycles		552000 cycles		564000 cycles	
1	077	955	217	1070	290	1990
2	021	116	019	433	019	1260
3	008	050	009	209	008	092
4	960	1347	1025	O/C	932	O/C
5	134	102	142	235	136	220
6	088	045	062	040	053	034
7	047	078	045	113	044	145
8	025	178	187	1145	329	1760
9	199	1082	021	171	029	200
10	014	042	014	030	014	028
av.	157	399	174	382	185	636
max	960	1347	1025	1145	932	1990
min	008	042	009	030	008	028
	576000 cycles		588000 cycles		600000 cycles	
1	096	1072	050	1651	046	457
2	023	1125	027	1305	307	1964
3	010	050	013	1461	017	175
4	1782	835	688	O/C	O/C	458
5	193	053	1123	1856	317	210
6	083	040	095	057	088	029
7	137	082	095	1280	097	054
8	878	1783	1023	324	1336	1074
9	035	083	148	110	666	1033
10	016	023	015	016	019	017
av.	325	514	327	895	321	547
max	1782	1783	1123	1856	1336	1964
min	010	023	013	016	017	017
	612000 cycles		624000 cycles		636000 cycles	
1	015	1432	018	1739	071	1088
2	017	1226	072	812	050	1687
3	009	054	012	357	014	150
4	O/C	O/C	1248	108	482	1380
5	145	284	387	133	451	338
6	051	043	092	043	058	060
7	052	073	089	175	066	082
8	126	204	741	401	044	665
9	050	255	301	701	210	1043
10	019	044	043	025	019	041
av.	053	401	300	449	146	653
max	145	1432	1248	1739	482	1687
min	009	043	012	025	014	041

	Probe Deflection		Probe Deflection		Probe Deflection	
Probe No.	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ
	648000 cycles		660000 cycles		672000 cycles	
1	067	1050	114	1493	211	541
2	035	1871	035	0/C	051	1275
3	011	543	012	183	008	052
4	0/C	0/C	0/C	0/C	1812	1760
5	672	813	580	374	063	074
6	073	039	053	049	062	033
7	157	026	130	138	020	117
8	047	113	067	472	191	147
9	1303	1620	1863	1451	777	1645
10	020	021	020	050	018	122
av.	265	677	319	526	321	576
max	1303	1871	1863	1493	1812	1760
min	011	021	012	049	008	033
	684000 cycles		696000 cycles		708000 cycles	
1	040	697	056	1058	068	274
2	031	1445	104	731	028	0/C
3	010	060	017	178	010	157
4	0/C	961	534	961	0/C	0/C
5	060	110	126	225	217	184
6	054	086	051	073	068	075
7	027	296	037	137	045	099
8	592	426	064	533	393	374
9	1712	0/C	1322	0/C	1062	1438
10	014	096	015	063	014	014
av.	282	464	232	439	211	326
max	1712	1445	1322	1058	1062	1438
min	010	060	015	063	010	014
	720000 cycles		732000 cycles		744000 cycles	
1	096	1994	022	077	060	182
2	139	969	041	583	022	862
3	013	038	010	030	009	035
4	074	042	1274	0/C	178	260
5	515	1419	073	086	155	140
6	044	070	085	042	103	054
7	028	164	031	068	053	075
8	048	1678	618	250	1754	706
9	775	973	136	407	1070	0/C
10	032	068	016	028	015	028
av.	176	741	230	174	341	260
max	775	1994	1274	583	1754	862
min	013	038	010	028	009	028

	Probe Deflection		Probe Deflection		Probe Deflection	
Probe No.	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ
	756000 cycles		768000 cycles		780000 cycles	
1	096	223	045	106	129	316
2	031	1695	032	1560	060	093
3	009	043	010	035	010	070
4	131	708	976	565	484	615
5	500	295	342	174	446	254
6	064	041	072	064	092	038
7	058	084	066	091	037	132
8	1850	1890	1574	0/C	397	702
9	254	452	172	1420	025	177
10	016	021	018	025	019	045
av.	300	545	330	448	169	244
max	1850	1890	1574	1560	484	702
min	009	021	010	025	010	038
	792000 cycles		804000 cycles		816000 cycles	
1	131	295	082	161	447	515
2	026	073	034	156	039	450
3	011	047	019	091	008	072
4	1183	1290	0/C	0/C	1416	0/C
5	167	791	163	140	130	097
6	088	029	275	038	132	036
7	075	071	1485	070	096	077
8	112	344	214	176	172	173
9	176	1760	430	0/C	475	1541
10	017	079	030	030	019	027
av.	198	477	303	107	293	332
max	1183	1760	1485	176	1416	1541
min	011	029	019	030	008	027
	828000 cycles		840000 cycles		852000 cycles	
1	305	1620	168	207	508	331
2	057	158	024	168	028	043
3	011	080	011	084	028	118
4	1070	143	0/C	1736	0/C	685
5	136	102	118	086	124	074
6	157	036	272	076	438	079
7	072	092	058	069	310	070
8	033	209	116	145	211	081
9	654	0/C	717	0/C	0/C	0/C
10	015	036	018	038	042	038
av.	251	275	166	289	211	168
max	1070	1620	717	1736	508	685
min	011	036	011	038	028	038

	Probe Deflection		Probe Deflection		Probe Deflection	
Probe No.	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ
	864000 cycles		876000 cycles		888000 cycles	
1	263	757	414	999	124	1320
2	022	082	032	050	040	405
3	010	217	013	124	011	128
4	1999	O/C	1390	O/C	O/C	O/C
5	116	091	117	081	067	054
6	195	077	171	064	118	174
7	160	141	1035	170	358	077
8	174	1233	354	1135	354	1546
9	1803	1972	911	O/C	753	O/C
10	025	154	022	063	013	029
av.	476	524	445	335	204	466
max	1999	1972	1390	1135	753	1546
min	010	077	013	050	011	029
	900000 cycles		912000 cycles		924000 cycles	
1	072	228	114	378	092	079
2	040	075	029	101	037	063
3	011	155	010	799	010	125
4	O/C	668	1225	O/C	O/C	O/C
5	057	062	074	116	221	461
6	089	061	105	197	071	105
7	420	073	128	170	352	142
8	1401	O/C	1533	936	O/C	1521
9	518	273	480	400	367	1572
10	014	027	018	053	022	042
av.	291	180	371	350	146	456
max	1401	668	1533	936	367	1572
min	011	027	010	053	010	042
	936000 cycles		948000 cycles		960000 cycles	
1	124	116	032	083	065	105
2	034	055	021	082	030	044
3	009	128	023	067	013	079
4	O/C	773	O/C	808	O/C	452
5	235	303	052	045	053	061
6	037	123	035	jammed	099	O/C
7	371	089	317	130	144	059
8	O/C	780	164	272	138	193
9	311	1091	451	1608	504	841
10	020	037	026	029	031	050
av.	142	349	124	347	119	209
max	371	1091	451	1608	504	841
min	009	037	021	029	013	044

	Probe Deflection		Probe Deflection		Probe Deflection	
Probe No.	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ
	972000 cycles		984000 cycles		996000 cycles	
1	166	235	125	153	107	082
2	029	103	025	195	041	050
3	013	381	010	1165	013	083
4	1165	133	563	945	0/C	542
5	059	148	063	147	092	093
6	013	0/C	032	0/C	158	0/C
7	034	662	086	081	616	087
8	087	136	154	254	276	093
9	1290	1956	895	1003	664	1246
10	015	040	018	040	012	020
av.	287	421	197	442	219	255
max	1290	1956	895	1165	664	1246
min	013	040	010	040	012	020
	1008000 cycles		1020000 cycles		1032000 cycles	
1	109	126	113	166	098	086
2	028	070	023	065	031	086
3	011	150	011	665	009	219
4	1552	0/C	1740	1077	0/C	0/C
5	067	141	070	1241	235	1386
6	182	0/C	191	0/C	613	0/C
7	493	082	121	105	047	057
8	155	080	159	415	142	202
9	261	1783	384	0/C	670	559
10	011	018	012	022	012	026
av.	286	306	282	469	206	327
max	1552	1783	1740	1241	670	1386
min	011	018	011	022	009	026
	1044000 cycles		1056000 cycles		1068000 cycles	
1	105	195	036	190	024	045
2	032	538	024	116	027	875
3	009	138	011	103	036	963
4	1329	0/C	0/C	0/C	0/C	0/C
5	318	424	202	164	170	1332
6	0/C	0/C	0/C	0/C	058	0/C
7	172	195	307	102	1803	153
8	128	156	311	764	0/C	0/C
9	658	1390	1308	1632	876	0/C
10	013	020	014	021	018	024
av.	307	382	276	386	376	565
max	1329	1390	1308	1632	1803	1332
min	009	020	011	021	018	024

	Probe Deflection		Probe Deflection		Probe Deflection	
Probe No.	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ	compressed mΩ	relaxed mΩ
	1080000 cycles		1092000 cycles		1104000 cycles	
1	019	036	033	038	046	035
2	026	110	032	104	030	382
3	010	152	012	926	048	062
4	0/C	0/C	0/C	0/C	1312	1220
5	1048	673	409	307	231	182
6	1226	0/C	1140	0/C	098	0/C
7	417	192	1703	432	192	064
8	587	0/C	1562	0/C	176	943
9	963	172	1024	1038	1562	1469
10	017	022	018	116	014	023
av.	479	193	659	423	370	486
max	1226	673	1703	1038	1562	1469
min	010	022	012	038	014	023
	1116000 cycles		1128000 cycles		1140000 cycles	
1	022	034	061	039	022	035
2	021	123	020	785	025	090
3	053	076	065	923	014	169
4	0/C	1906	402	0/C	1486	0/C
5	215	176	308	442	732	160
6	0/C	0/C	387	0/C	278	0/C
7	1465	275	520	080	786	057
8	986	1883	0/C	0/C	0/C	1486
9	782	1981	1482	1530	1373	0/C
10	015	023	017	026	016	024
av.	444	719	362	546	525	288
max	1465	1981	1482	1530	1486	1486
min	015	023	017	026	014	024
	1152000 cycles		1164000 cycles		1176000 cycles	
1	044	037	032	037	059	070
2	028	060	028	085	026	336
3	038	114	019	109	012	826
4	0/C	1207	0/C	1254	0/C	0/C
5	354	334	403	204	376	903
6	042	0/C	235	0/C	194	0/C
7	750	041	373	270	846	065
8	494	224	232	142	221	334
9	1860	0/C	696	0/C	1403	1526
10	023	025	017	023	022	028
av.	403	255	226	265	351	511
max	1860	1207	696	1254	1403	1526
min	023	025	017	023	012	028

TEST 104 - FLAT TARGET; 2/3 COMPRESSION; I.D.I.

Probe Deflection - Compressed

10 readings. (mΩ)

0 cycles

Probe No.										
1	009	009	009	009	009	009	009	009	009	009
2	010	012	011	012	013	012	012	011	012	011
3	009	010	011	010	010	010	010	011	011	011
4	013	013	014	014	014	016	015	015	016	015
5	010	011	010	012	011	011	010	011	012	011
6	011	012	012	011	012	013	013	013	012	012
7	010	012	013	013	012	015	015	014	015	014
8	016	022	033	035	016	019	019	030	027	026
9	011	011	011	011	012	011	012	012	012	012
10	013	014	014	015	016	015	012	013	013	013
av.	011	012	013	014	012	013	012	013	013	013
max	016	022	033	035	016	019	019	030	027	026
min	009	009	009	009	009	009	009	009	009	009

10000 cycles

1	010	010	010	011	010	010	010	010	011	011
2	022	018	020	022	021	021	020	021	023	023
3	010	011	011	011	011	010	010	010	011	011
4	018	018	018	018	019	019	018	019	019	019
5	055	044	045	044	039	040	046	053	042	042
6	088	131	139	193	197	202	417	293	338	394
7	011	011	010	010	010	010	010	010	011	010
8	010	011	010	011	011	011	011	012	012	012
9	110	148	347	153	221	226	221	299	114	159
10	012	013	013	013	013	012	013	012	013	013
av.	034	041	062	048	055	056	077	073	059	069
max	110	148	347	193	221	226	417	299	338	394
min	010	010	010	010	010	010	010	010	011	010

20000 cycles

1	011	011	011	011	011	011	011	012	012	012
2	016	021	041	020	044	044	041	051	040	027
3	013	014	013	015	014	017	015	017	017	016
4	012	011	013	012	012	012	012	013	013	012
5	011	011	013	013	012	012	012	012	012	012
6	023	024	025	025	025	025	026	026	027	040
7	010	009	011	011	011	010	011	010	011	010
8	017	017	020	018	017	017	016	018	020	016
9	040	089	080	106	073	078	143	052	026	208
10	051	053	082	067	068	069	070	097	112	068
av.	020	026	030	029	028	029	035	030	029	042
max	051	089	082	106	073	078	143	097	112	208
min	010	009	011	011	011	010	011	010	011	010

Probe Deflection - Compressed

Probe No.

10 readings. (mΩ)

30000 cycles

1	012	012	011	013	012	012	012	012	012	012
2	019	020	031	031	032	026	026	031	023	023
3	018	020	022	025	021	024	024	022	023	025
4	021	023	023	022	024	023	023	024	024	020
5	012	012	013	012	013	012	013	012	013	013
6	054	056	057	065	079	075	071	087	092	101
7	012	013	012	013	013	013	013	013	013	012
8	017	018	018	025	020	020	026	018	019	020
9	O/C	O/C	1673	O/C	O/C	O/C	O/C	O/C	O/C	O/C
10	083	094	074	081	093	107	108	098	086	084
av.	027	029	193	031	034	034	035	035	033	034
max	083	094	1673	081	093	107	108	098	092	101
min	012	012	011	012	012	012	012	012	012	012

40000 cycles

1	012	013	014	012	012	013	012	013	014	014
2	021	024	064	030	066	059	044	042	032	026
3	026	025	033	026	031	037	028	040	034	031
4	017	018	019	018	019	020	020	019	020	020
5	011	012	013	012	013	013	013	012	013	013
6	036	039	038	038	035	039	036	038	040	051
7	012	013	013	014	015	015	013	015	017	016
8	023	020	028	025	031	026	025	026	031	029
9	292	1822	O/C	O/C	617	O/C	O/C	1262	O/C	O/C
10	063	078	066	072	060	050	065	069	109	060
av.	051	206	032	027	089	030	028	153	034	028
max	292	1822	066	072	617	059	065	1262	109	060
min	011	012	013	012	012	013	012	012	013	013

50000 cycles

1	012	012	012	012	012	013	013	012	013	012
2	020	020	021	026	048	067	039	042	037	041
3	026	031	033	028	036	034	038	035	036	035
4	017	017	019	019	019	021	019	020	020	021
5	012	012	013	013	014	014	012	014	013	015
6	056	062	063	081	077	124	082	090	099	160
7	011	011	011	012	012	012	012	012	014	012
8	018	017	021	019	023	030	028	023	025	022
9	402	162	1236	653	1003	084	1042	862	112	1392
10	048	040	053	042	062	076	062	046	058	053
av.	062	038	148	090	130	047	134	115	042	176
max	402	162	1236	653	1003	124	1042	862	112	1392
min	011	011	011	012	012	012	012	012	013	012

Probe Deflection - Compressed

Probe No. 10 readings. (mΩ)

60000 cycles

1	012	012	012	013	014	013	013	014	014	014
2	019	026	023	026	033	034	036	035	041	035
3	018	020	021	023	023	025	028	030	035	059
4	021	020	020	021	021	023	021	023	022	025
5	022	021	023	022	022	025	022	024	024	024
6	069	063	072	081	096	091	088	095	093	087
7	013	013	014	014	017	013	014	014	017	017
8	015	017	017	022	022	029	027	030	034	022
9	1935	0/C	0/C	1552	1845	0/C	1722	1643	0/C	0/C
10	126	214	258	213	251	176	120	238	248	153
av.	225	045	051	198	234	047	209	214	058	048
max	1935	214	258	1552	1845	176	1722	1643	248	153
min	012	012	012	013	014	013	013	014	014	014

70000 cycles

1	015	012	013	014	015	013	015	014	015	013
2	032	031	033	028	031	034	035	048	054	050
3	016	013	014	014	018	014	016	016	017	016
4	041	043	046	062	047	061	054	058	052	053
5	016	012	013	013	013	013	012	013	013	013
6	037	036	054	041	048	043	054	050	068	059
7	014	013	014	013	014	013	013	013	015	014
8	018	018	022	025	029	023	029	028	031	030
9	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
10	147	139	180	445	391	374	320	254	249	428
av.	037	035	043	072	067	065	060	054	057	075
max	147	139	180	445	391	374	320	254	249	428
min	014	012	013	013	013	013	012	013	013	013

80000 cycles

1	014	018	013	015	010	014	015	015	015	015
2	017	025	020	024	029	027	030	030	030	031
3	012	015	012	013	018	016	017	017	014	017
4	033	033	036	037	043	041	044	041	044	042
5	013	015	013	012	013	013	016	013	014	013
6	119	086	132	133	169	123	188	192	185	163
7	013	023	013	013	018	016	015	014	015	025
8	017	023	025	029	028	033	038	027	028	043
9	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
10	158	281	439	472	508	752	486	227	277	307
av.	044	057	078	083	092	115	094	064	069	072
max	158	281	439	472	508	752	486	227	277	307
min	012	015	012	012	010	013	015	013	014	013

Probe Deflection - Compressed

Probe No.	10 readings. (mΩ)									

90000 cycles

1	012	012	013	013	013	013	013	014	016	013
2	018	031	023	024	023	026	046	052	052	040
3	034	041	077	062	061	068	065	059	043	063
4	013	013	013	013	013	013	014	013	014	013
5	018	017	018	018	018	018	020	020	020	019
6	064	063	066	074	086	069	070	067	081	093
7	015	015	016	016	016	016	017	016	051	016
8	019	023	037	036	040	045	029	029	045	041
9	1549	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C
10	533	998	1536	1686	O/C	380	1582	942	1362	O/C
av.	227	134	199	215	033	072	206	134	187	037
max	1549	998	1536	1686	086	380	1582	942	1362	093
min	012	012	013	013	013	013	013	013	014	013

100000 cycles

1	012	013	014	014	014	013	014	012	013	014
2	031	039	027	024	030	022	035	031	032	038
3	027	030	054	056	052	055	060	072	049	067
4	018	019	019	018	020	020	019	019	019	019
5	013	014	013	013	013	013	013	014	014	015
6	280	294	334	248	336	257	222	248	235	245
7	014	014	016	014	014	013	015	013	013	013
8	020	024	024	026	029	037	033	022	029	025
9	1568	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C
10	188	173	278	196	908	1113	903	771	892	1628
av.	217	068	086	067	157	171	146	133	144	229
max	1568	294	334	248	908	1113	903	771	892	1628
min	012	013	013	013	013	013	013	012	013	013

110000 cycles

1	012	013	014	013	012	012	012	012	012	011
2	033	063	074	055	042	054	118	105	086	075
3	021	036	027	040	032	036	041	033	030	035
4	053	079	106	118	045	050	062	057	046	050
5	037	046	047	050	053	056	063	073	062	069
6	079	090	107	099	102	068	101	137	167	174
7	016	018	015	016	016	017	020	018	020	019
8	016	019	024	022	021	018	019	020	024	020
9	O/C	O/C	O/C	O/C	O/C	O/C	O/C	1955	O/C	O/C
10	964	1253	1758	032	034	033	047	041	052	062
av.	136	179	241	049	039	038	053	245	055	057
max	964	1253	1758	118	102	068	118	1955	167	174
min	012	013	014	013	012	012	012	012	012	011

Probe Deflection – Compressed

Probe No.

10 readings. (mΩ)

120000 cycles

Probe No.										
1	012	014	012	013	014	012	013	013	014	013
2	026	039	030	037	046	043	045	081	085	088
3	025	052	029	030	046	035	025	035	036	026
4	061	058	042	081	064	082	043	063	089	042
5	816	576	703	1030	795	946	668	605	1068	771
6	057	055	047	064	065	075	071	055	068	067
7	017	019	015	019	019	018	018	016	020	020
8	016	018	022	019	032	024	021	028	037	023
9	O/C	O/C	O/C	O/C	O/C	O/C	1948	O/C	O/C	O/C
10	541	277	105	193	823	1009	682	072	080	135
av.	174	123	111	165	211	249	353	107	166	131
max	816	576	703	1030	823	1009	1948	605	1068	771
min	012	014	012	013	014	012	013	013	014	013

130000 cycles

Probe No.										
1	012	012	013	012	013	031	012	016	012	013
2	036	041	035	039	041	090	055	047	034	055
3	020	022	029	024	031	047	027	037	029	036
4	054	046	060	045	087	048	037	091	074	075
5	110	112	095	098	101	119	101	097	098	102
6	046	046	041	095	050	036	056	044	050	059
7	021	020	021	022	023	062	027	037	028	024
8	016	021	038	021	034	066	038	060	062	047
9	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C
10	1900	1979	O/C	1823	O/C	O/C	O/C	1991	663	576
av.	246	255	041	242	047	062	044	268	116	109
max	1900	1979	095	1823	101	119	101	1991	663	576
min	012	012	013	012	013	031	012	016	012	013

140000 cycles

Probe No.										
1	016	016	014	013	015	015	013	013	016	019
2	022	029	031	037	043	042	055	057	098	065
3	018	016	021	017	029	020	018	019	024	028
4	073	051	034	045	096	042	042	041	122	121
5	019	020	020	020	020	021	020	020	022	023
6	078	049	091	081	070	137	099	086	133	070
7	029	032	029	036	031	036	036	031	027	152
8	016	051	038	043	071	043	035	049	057	076
9	O/C	O/C	1315	1986	O/C	1402	1894	1952	1847	O/C
10	1971	1852	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C
av.	249	235	177	253	046	195	245	252	260	069
max	1971	1852	1315	1986	096	1402	1894	1952	1847	121
min	016	016	014	013	015	015	013	013	016	019

Probe Deflection - Compressed

Probe No.

10 readings. (mΩ)

150000 cycles

1	028	022	032	034	040	047	031	044	048	047
2	044	034	030	035	031	030	029	028	027	029
3	026	020	027	025	027	040	025	028	028	030
4	067	035	034	034	031	032	030	030	029	029
5	034	025	027	025	026	024	025	024	024	025
6	775	352	414	434	392	190	373	271	276	234
7	077	040	069	076	047	086	068	068	038	069
8	035	021	032	027	035	055	040	062	085	077
9	934	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C
10	1426	O/C	1030	1871	O/C	O/C	O/C	O/C	O/C	O/C
av.	344	068	188	284	078	063	077	069	069	067
max	1426	352	1030	1871	392	190	373	271	276	234
min	026	020	027	025	026	024	025	024	024	025

160000 cycles

1	106	030	028	029	060	028	029	033	030	030
2	116	087	119	111	131	173	144	355	258	417
3	041	031	039	032	063	047	051	035	040	039
4	021	021	022	028	042	022	023	022	022	026
5	022	022	023	022	023	022	024	022	023	028
6	053	102	094	076	123	074	077	081	080	099
7	017	015	016	016	016	016	016	016	017	015
8	018	022	022	019	054	034	044	013	028	026
9	1740	O/C	O/C	O/C	O/C	O/C	O/C	317	942	O/C
10	O/C	O/C	O/C	O/C	O/C	O/C	O/C	1852	O/C	O/C
av.	237	041	045	041	064	052	051	274	160	085
max	1740	102	119	111	131	173	144	1852	942	417
min	017	015	016	016	016	016	016	013	017	015

170000 cycles

1	034	030	031	033	030	046	051	049	033	042
2	117	186	240	216	410	272	333	280	313	379
3	028	027	033	031	028	038	040	046	034	032
4	032	026	037	035	032	038	039	039	032	035
5	024	024	024	025	024	024	024	025	024	025
6	147	104	188	223	150	183	164	186	184	197
7	017	017	017	017	018	016	017	018	017	018
8	013	016	018	018	022	029	040	028	019	022
9	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C
10	1206	1326	O/C	1375	O/C	O/C	O/C	O/C	1781	O/C
av.	179	195	073	219	089	080	088	083	270	093
max	1206	1326	240	1375	410	272	333	280	1781	379
min	013	016	017	017	018	016	017	018	017	018

Probe Deflection - Compressed

Probe No.

10 readings. (mΩ)

180000 cycles

1	049	058	053	030	019	051	054	047	035	048
2	256	220	254	305	345	360	486	255	426	028
3	036	041	044	045	060	056	058	063	062	054
4	028	030	045	037	032	039	038	035	034	032
5	024	025	024	026	028	025	026	026	025	025
6	081	104	188	155	080	140	153	193	153	139
7	015	016	016	019	027	017	018	019	018	020
8	015	027	026	020	032	046	046	028	023	025
9	O/C	O/C	1379	O/C	1664	1212	1621	O/C	O/C	O/C
10	O/C	1931	1918	1569	O/C	1769	O/C	O/C	O/C	1812
av.	063	272	394	245	254	371	277	083	097	242
max	256	1931	1918	1569	1664	1769	1621	255	426	1812
min	015	016	016	019	019	017	018	019	018	020

190000 cycles

1	107	108	080	171	167	182	126	084	193	108
2	1462	982	746	1162	1137	1202	1302	O/C	1723	1037
3	026	029	029	031	029	031	030	032	033	029
4	173	186	187	223	208	223	222	139	205	204
5	229	261	268	292	278	313	262	350	319	299
6	085	118	145	136	114	103	135	177	131	125
7	026	017	023	027	022	028	026	025	029	027
8	018	025	037	032	036	034	024	035	045	042
9	1673	O/C	O/C	O/C	O/C	O/C	O/C	O/C	1762	O/C
10	1023	1663	O/C	O/C	O/C	1982	O/C	O/C	1671	1971
av.	482	376	189	259	248	455	265	120	611	426
max	1673	1663	746	1162	1137	1982	1302	350	1762	1971
min	018	017	023	027	022	028	024	025	033	027

200000 cycles

1	115	040	092	286	230	083	233	062	121	248
2	535	745	777	803	892	1151	1161	O/C	O/C	1056
3	033	033	038	048	042	043	051	044	059	059
4	132	112	110	156	143	157	172	151	171	191
5	540	445	417	325	423	444	522	487	518	430
6	065	080	067	077	094	097	072	120	110	085
7	024	026	024	027	025	018	017	026	022	022
8	017	016	026	073	032	041	062	028	032	083
9	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	1047	O/C
10	O/C	1191	1791	1958	1291	1771	O/C	O/C	O/C	O/C
av.	182	298	371	417	352	422	286	131	260	271
max	540	1191	1791	1958	1291	1771	1161	487	1047	1056
min	017	016	024	027	025	018	017	026	022	022

Probe Deflection - Compressed

Probe No.

10 readings. (mΩ)

210000 cycles

1	094	192	185	173	089	045	051	046	278	047
2	256	304	432	317	604	1161	637	1082	1436	1591
3	036	041	043	057	050	047	050	049	078	048
4	147	153	162	160	150	107	158	143	201	122
5	035	032	036	034	035	037	038	038	036	034
6	044	052	090	068	079	081	075	133	076	073
7	020	021	034	027	021	021	020	020	030	019
8	021	085	101	105	038	035	039	033	048	025
9	O/C	O/C	O/C	O/C	1543	O/C	O/C	O/C	O/C	O/C
10	O/C	O/C	1921	O/C	O/C	O/C	O/C	1451	O/C	1321
av.	081	110	333	117	289	191	133	332	272	364
max	256	304	1921	317	1543	1161	637	1451	1436	1591
min	020	021	034	027	021	021	020	020	030	019

220000 cycles

1	068	039	105	041	058	055	108	058	078	107
2	675	513	678	802	1062	1123	834	O/C	1672	1582
3	352	376	992	805	1508	1921	O/C	1860	1682	1774
4	037	034	037	030	041	035	036	035	037	036
5	119	141	138	125	139	133	128	139	133	169
6	035	057	045	060	067	055	052	073	054	055
7	015	028	032	049	037	023	055	024	032	033
8	023	036	069	042	056	046	172	051	057	047
9	O/C	O/C	O/C	O/C	O/C	O/C	1831	1562	O/C	O/C
10	1502	1591	O/C	1092	O/C	1221	O/C	O/C	O/C	O/C
av.	314	312	262	338	371	512	402	475	468	475
max	1502	1591	992	1092	1508	1921	1831	1860	1682	1774
min	015	028	032	030	037	023	036	024	032	033

230000 cycles

1	060	051	053	077	089	085	076	079	148	080
2	150	272	161	190	171	212	295	171	292	360
3	394	594	656	1282	1363	O/C	O/C	O/C	O/C	O/C
4	026	029	033	030	047	044	034	043	101	057
5	057	055	058	047	049	050	050	056	057	061
6	063	062	055	086	085	089	070	099	075	092
7	020	022	022	023	019	024	025	022	018	023
8	019	029	033	035	031	026	036	038	083	027
9	1723	1042	O/C	1723	O/C	1992	O/C	O/C	O/C	O/C
10	O/C	O/C	O/C	1431	1676	1381	1682	O/C	1499	1052
av.	279	239	133	492	392	433	283	072	284	219
max	1723	1042	656	1723	1676	1992	1682	171	1499	1052
min	019	022	022	023	019	024	025	022	018	023

Probe Deflection - Compressed

Probe No.	10 readings. (mΩ)									
					240000 cycles					
1	048	039	113	078	075	064	102	067	089	087
2	047	037	035	050	034	037	048	037	038	050
3	401	772	942	1861	1821	1861	1964	0/C	0/C	1861
4	040	028	034	040	040	032	078	048	065	059
5	096	097	092	089	101	100	095	100	110	115
6	040	051	083	070	082	079	061	079	081	075
7	021	018	020	018	020	019	024	020	020	018
8	018	019	028	024	030	025	026	019	019	018
9	1262	1382	0/C	1981	1091	0/C	0/C	0/C	0/C	0/C
10	0/C	1612	1162	0/C	0/C	0/C	0/C	1421	1491	0/C
av.	219	405	278	467	366	277	299	223	239	285
max	1262	1612	1162	1981	1821	1861	1964	1421	1491	1861
min	018	018	020	018	020	019	024	019	019	018
					250000 cycles					
1	062	150	079	128	109	125	264	309	097	315
2	301	317	344	393	299	514	436	368	471	481
3	297	489	652	1346	979	1562	0/C	1903	1468	1523
4	029	048	037	049	034	063	221	188	029	361
5	351	283	294	272	226	303	306	287	314	384
6	127	140	118	120	105	132	146	216	117	180
7	020	030	024	027	031	031	032	030	021	026
8	018	030	029	026	031	032	104	091	025	030
9	0/C	1719	1882	0/C	0/C	0/C	0/C	0/C	0/C	0/C
10	1663	1842	0/C	1882	0/C	0/C	0/C	0/C	1805	0/C
av.	318	504	384	471	226	345	215	424	483	412
max	1663	1842	1882	1882	979	1562	436	1903	1805	1523
min	018	030	024	026	031	031	032	030	021	026
					260000 cycles					
1	079	387	141	256	124	220	405	239	106	325
2	454	418	724	691	392	627	963	1053	457	706
3	336	339	272	582	465	026	016	864	765	785
4	033	132	058	159	036	087	246	077	027	153
5	391	505	443	612	579	633	503	686	563	504
6	097	117	126	217	223	174	120	228	161	201
7	025	019	026	023	029	033	032	021	022	024
8	017	018	020	027	024	049	048	028	035	050
9	0/C	1598	0/C	0/C	0/C	843	1025	1882	1546	1802
10	1991	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
av.	380	392	226	320	234	299	373	564	409	505
max	1991	1598	724	691	579	843	1025	1882	1546	1802
min	017	018	020	023	024	026	016	021	022	024

Probe Deflection - Compressed

Probe No.	10 readings. (mΩ)									
	270000 cycles									
1	160	157	093	177	105	087	233	164	095	152
2	313	502	332	487	828	367	448	512	520	567
3	109	178	250	307	418	428	604	258	606	511
4	045	051	033	056	034	048	262	068	052	065
5	243	332	338	463	460	418	502	764	585	517
6	131	131	124	134	116	139	224	245	113	177
7	036	037	038	037	044	043	049	030	043	040
8	020	023	028	026	024	035	052	031	021	020
9	0/C	0/C	1635	1787	0/C	0/C	1682	1881	0/C	0/C
10	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
av.	132	176	319	386	253	195	450	439	254	256
max	313	502	1635	1787	828	428	1682	1881	606	567
min	020	023	028	026	024	035	049	030	021	020
	280000 cycles									
1	594	381	357	636	566	352	435	368	751	296
2	059	087	111	081	084	124	099	100	116	110
3	053	118	162	180	102	144	165	330	310	301
4	176	098	082	144	084	080	136	117	130	069
5	0/C	0/C	1788	1492	1454	1708	0/C	1872	1564	1791
6	043	040	037	032	030	039	040	036	035	049
7	046	029	043	112	027	044	042	052	037	038
8	081	108	071	204	080	115	129	106	199	132
9	1582	1695	0/C	0/C	0/C	0/C	0/C	0/C	0/C	1226
10	0/C	0/C	1836	0/C	0/C	0/C	0/C	0/C	0/C	0/C
av.	329	319	498	360	303	325	149	372	392	445
max	1582	1695	1836	1492	1454	1708	435	1872	1564	1791
min	043	029	037	032	027	039	040	036	035	038
	290000 cycles									
1	223	232	204	257	332	298	253	360	432	205
2	137	250	327	512	476	505	458	448	548	478
3	026	036	043	061	055	044	047	056	047	059
4	056	055	037	069	098	103	138	120	096	074
5	1421	1890	1645	0/C	1903	1791	1232	0/C	1214	1652
6	046	053	053	056	054	054	062	066	050	086
7	029	059	030	019	023	050	054	036	044	026
8	046	054	052	091	095	076	077	083	083	077
9	0/C	0/C	0/C	0/C	0/C	0/C	1743	1282	0/C	0/C
10	0/C	1681	1571	1819	0/C	0/C	0/C	0/C	0/C	0/C
av.	248	478	440	360	379	365	451	306	314	332
max	1421	1890	1645	1819	1903	1791	1743	1282	1214	1652
min	026	036	030	019	023	044	047	036	044	026

Probe Deflection - Compressed

Probe No.	10 readings. (mΩ)									
					300000 cycles					
1	160	397	237	287	343	365	375	340	276	352
2	264	408	476	482	664	498	487	415	010	432
3	024	049	042	037	038	051	051	052	057	052
4	082	091	120	092	084	142	087	247	227	235
5	0/C	0/C	0/C	0/C	1262	0/C	1521	0/C	1020	0/C
6	140	305	198	213	210	154	175	232	187	243
7	052	061	027	052	041	034	036	049	063	047
8	044	145	054	080	111	071	123	122	108	117
9	0/C	1302	0/C	0/C	0/C	0/C	1982	0/C	0/C	1972
10	1643	0/C	0/C	1261	0/C	1732	0/C	1964	0/C	0/C
av.	301	344	164	313	344	380	537	427	243	431
max	1643	1302	476	1261	1262	1732	1982	1964	1020	1972
min	024	049	027	037	038	034	036	049	010	047
					310000 cycles					
1	267	219	308	443	425	696	275	247	505	246
2	1858	0/C	1692	0/C	1113	0/C	0/C	1991	0/C	1882
3	039	051	063	079	116	127	142	105	100	116
4	016	017	017	019	022	022	021	017	020	019
5	0/C	0/C	0/C	0/C	0/C	0/C	1838	1982	1860	1832
6	038	046	033	074	055	043	050	029	036	036
7	030	034	032	114	037	029	024	044	031	031
8	066	131	249	962	246	522	143	369	175	155
9	0/C	0/C	1843	0/C	1494	0/C	1962	0/C	0/C	1862
10	1900	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
av.	526	083	529	281	438	239	556	598	389	686
max	1900	219	1843	962	1494	696	1962	1991	1860	1882
min	016	017	017	019	022	022	021	017	020	019
					320000 cycles					
1	705	371	375	320	645	317	341	516	537	906
2	0/C	1609	1332	1413	0/C	0/C	0/C	0/C	1304	0/C
3	052	054	063	071	088	104	113	093	125	110
4	019	020	018	020	028	024	025	028	021	018
5	1774	1421	1451	1918	1882	1736	1771	1732	1928	1593
6	053	065	047	068	075	069	046	070	061	069
7	102	044	038	034	040	047	037	042	034	094
8	271	091	149	188	181	193	149	139	177	634
9	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
10	0/C	1591	0/C	0/C	0/C	1882	0/C	1591	1790	1272
av.	425	585	434	504	419	546	354	526	664	587
max	1774	1609	1451	1918	1882	1882	1771	1732	1928	1593
min	019	020	018	020	028	024	025	028	021	018

Probe Deflection - Compressed

Probe No.

10 readings. (mΩ)

330000 cycles

Probe No.										
1	581	1092	586	587	284	632	507	324	612	320
2	0/C	0/C	0/C	0/C	1749	0/C	1698	0/C	1831	1331
3	031	037	034	036	043	048	038	048	047	046
4	023	019	025	030	020	032	022	024	019	023
5	893	1527	1526	1656	1397	1601	1975	0/C	1957	1684
6	030	045	038	036	032	038	049	045	063	044
7	042	134	048	047	051	082	089	089	038	049
8	096	925	312	298	316	428	328	287	557	256
9	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
10	0/C	0/C	0/C	1862	0/C	1841	1381	1431	0/C	1482
av.	242	539	367	569	486	587	676	321	640	581
max	893	1527	1526	1862	1749	1841	1975	1431	1957	1684
min	023	019	025	030	020	032	022	024	019	023

340000 cycles

Probe No.										
1	523	762	1033	952	1065	996	1061	492	696	721
2	1437	0/C	0/C	0/C	0/C	1270	1578	0/C	0/C	1199
3	034	041	053	056	066	064	071	087	084	065
4	019	023	018	020	025	025	022	024	026	029
5	0/C	1818	1785	0/C	0/C	1975	0/C	1371	0/C	0/C
6	037	039	054	045	062	066	045	064	048	065
7	053	042	182	062	039	087	160	047	072	039
8	074	109	1482	349	427	1769	1437	137	231	330
9	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
10	1301	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
av.	434	404	658	247	280	781	624	317	192	349
max	1437	1818	1785	952	1065	1975	1578	1371	696	1199
min	019	023	018	020	025	025	022	024	026	029

350000 cycles

Probe No.										
1	718	941	953	386	993	1205	1333	606	823	800
2	463	486	903	923	754	867	872	527	520	505
3	646	964	1035	1123	1136	1352	1484	1091	1187	950
4	018	019	020	020	023	020	022	019	025	020
5	645	575	1223	1392	1035	035	1783	1196	0/C	1010
6	022	026	020	024	029	023	035	024	039	020
7	024	056	025	023	020	056	024	046	027	020
8	154	1138	573	488	754	805	1462	776	1764	804
9	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
10	1120	0/C	1471	0/C	0/C	0/C	0/C	0/C	0/C	0/C
av.	424	525	691	547	593	545	876	535	626	516
max	1120	1138	1471	1392	1136	1352	1783	1196	1764	1010
min	018	019	020	020	020	020	022	019	025	020

Probe Deflection - Compressed

10 readings. (mΩ)

360000 cycles

Probe No.										
1	488	1136	951	1036	1017	883	1093	516	523	1184
2	521	635	747	723	626	692	607	694	902	894
3	986	1174	1303	1341	1681	1591	1703	1823	1541	1928
4	017	020	018	017	020	017	023	021	018	020
5	845	462	478	382	867	1502	1583	1191	992	1872
6	026	031	028	024	033	029	036	035	031	034
7	018	030	051	023	030	023	025	027	022	032
8	169	523	428	1591	658	266	687	571	053	1425
9	1694	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	1163
10	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C
av.	529	501	500	642	616	625	719	609	510	950
max	1694	1174	1303	1591	1681	1591	1703	1823	1541	1928
min	017	020	018	017	020	017	023	021	018	020

370000 cycles

Probe No.										
1	991	992	991	972	854	1212	1224	1321	1058	983
2	568	707	684	605	606	742	664	545	604	516
3	1609	1562	1662	1286	1602	1467	1723	1502	1502	O/C
4	018	020	023	017	020	018	818	018	022	020
5	726	1386	1815	1204	O/C	1973	1464	O/C	1946	1875
6	026	030	037	032	032	034	033	038	038	037
7	048	026	029	032	025	020	026	027	021	081
8	475	1920	1502	891	814	1082	437	1662	782	1732
9	O/C	O/C	1624	O/C	O/C	O/C	O/C	O/C	O/C	O/C
10	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C
av.	557	830	929	629	564	818	798	730	746	749
max	1609	1920	1815	1286	1602	1973	1723	1662	1946	1875
min	018	020	023	017	020	018	026	018	021	020

380000 cycles

Probe No.										
1	1153	728	1123	496	563	984	1025	787	1061	1032
2	386	402	270	407	430	383	376	280	350	395
3	1382	1543	O/C	1663	1896	O/C	1661	O/C	1871	1762
4	010	018	018	018	016	017	017	017	017	017
5	1273	1736	1352	1570	954	1365	818	1392	O/C	1395
6	036	034	038	035	028	034	033	050	048	027
7	111	023	024	020	020	030	019	020	018	162
8	367	1082	1762	393	803	695	1421	O/C	1671	1042
9	O/C	1643	O/C	1623	1763	O/C	O/C	O/C	1736	O/C
10	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	1011
av.	589	801	655	691	719	501	671	424	846	760
max	1382	1736	1762	1663	1896	1365	1661	1392	1871	1762
min	010	018	018	018	016	017	017	017	017	017

Probe Deflection - Compressed

Probe No.

10 readings. (mΩ)

390000 cycles

1	663	1035	1015	1082	882	1063	972	978	823	1002
2	404	563	567	510	395	454	537	467	448	552
3	626	1442	1333	1251	0/C	0/C	1747	1571	762	1382
4	015	016	017	016	018	016	018	016	017	016
5	1692	1782	1864	0/C	1623	1682	1482	1693	0/C	1684
6	032	031	041	039	030	027	044	044	040	041
7	021	022	028	023	021	208	079	018	029	030
8	323	1368	1703	1658	1532	528	1443	925	1861	1673
9	907	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
10	0/C	0/C	0/C	0/C	0/C	1498	0/C	0/C	1051	1782
av.	520	782	821	654	643	684	790	714	628	906
max	1692	1782	1864	1658	1623	1682	1747	1693	1861	1684
min	015	016	017	016	018	016	018	016	017	016

400000 cycles

1	903	906	827	824	768	792	1067	1037	1046	864
2	440	593	389	545	528	654	786	727	716	793
3	626	1478	1092	1571	1348	1242	1372	0/C	0/C	1703
4	015	017	016	016	016	016	015	017	017	016
5	1597	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
6	040	030	040	040	043	037	039	036	041	040
7	020	019	025	019	026	024	025	026	019	021
8	305	481	991	600	1292	1125	1242	805	764	1372
9	634	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
10	0/C	0/C	0/C	0/C	1171	0/C	0/C	0/C	0/C	0/C
av.	508	503	482	516	649	555	649	441	433	687
max	1597	1478	1092	1571	1348	1242	1372	1037	1046	1703
min	015	017	016	016	016	016	015	017	017	016

410000 cycles

1	748	1225	593	1027	593	1206	664	1003	1227	1295
2	270	427	563	411	534	447	482	378	536	595
3	156	305	218	388	371	607	342	487	621	574
4	016	019	018	019	021	019	020	020	023	021
5	478	953	936	1110	1905	1844	1842	0/C	0/C	0/C
6	022	026	030	030	044	026	026	033	036	032
7	029	088	024	025	028	530	023	025	028	026
8	114	430	562	904	863	1441	310	284	856	992
9	189	0/C	0/C	0/C	0/C	0/C	1968	1662	0/C	1621
10	0/C	992	1363	1238	0/C	0/C	0/C	0/C	0/C	0/C
av.	224	496	478	572	544	765	630	486	475	644
max	748	1225	1363	1238	1905	1844	1968	1662	1227	1621
min	016	019	018	019	021	019	020	020	023	021

Probe Deflection - Compressed

10 readings. (mΩ)

420000 cycles

Probe No.										
1	778	563	1361	1381	1519	723	925	1763	815	1065
2	368	336	345	443	374	362	328	314	311	352
3	169	307	422	426	484	436	778	473	615	726
4	017	018	018	017	020	018	015	020	021	020
5	1781	0/C	1909	0/C	0/C	0/C	1561	0/C	1761	0/C
6	023	020	029	026	028	033	020	030	036	036
7	030	042	071	164	059	040	237	059	057	050
8	136	592	1032	815	1354	1183	1121	651	1381	1328
9	1461	0/C	0/C	1851	0/C	1864	1398	0/C	0/C	0/C
10	0/C	1868	1321	0/C	0/C	0/C	0/C	1983	1531	0/C
av.	529	468	723	640	548	582	709	661	725	511
max	1781	1868	1909	1851	1519	1864	1561	1983	1761	1328
min	017	018	018	017	020	018	015	020	021	020

430000 cycles

Probe No.										
1	1123	754	1317	1442	1134	993	726	832	1002	1272
2	179	180	212	233	223	246	192	257	192	190
3	413	651	547	604	962	653	963	1172	461	575
4	016	016	016	017	016	016	016	017	015	016
5	1518	0/C	0/C	0/C	0/C	0/C	0/C	0/C	1860	0/C
6	025	025	025	029	030	024	029	033	026	024
7	030	029	090	050	046	039	036	050	028	101
8	142	225	207	184	256	165	189	1017	160	308
9	753	584	1763	0/C	0/C	987	0/C	0/C	247	1863
10	0/C	0/C	0/C	0/C	1726	0/C	1019	0/C	1493	0/C
av.	466	308	522	365	549	390	396	482	548	543
max	1518	754	1763	1442	1726	993	1019	1172	1860	1863
min	016	016	016	017	016	016	016	017	015	016

440000 cycles

Probe No.										
1	685	975	854	982	1371	1102	521	1226	847	1207
2	164	204	209	251	220	195	182	188	203	173
3	336	764	775	518	982	970	1021	727	562	923
4	015	017	016	017	017	016	015	017	016	017
5	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
6	022	021	026	037	030	035	030	828	023	036
7	025	320	025	043	124	043	035	035	044	037
8	176	556	352	363	687	361	1242	374	604	456
9	1854	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
10	0/C	0/C	1930	1982	0/C	1451	0/C	0/C	0/C	1958
av.	409	408	523	524	490	521	435	485	328	600
max	1854	975	1930	1982	1371	1451	1242	1226	847	1958
min	015	017	016	017	017	016	015	017	016	017

Probe Deflection - Compressed

Probe No.	10 readings. (mΩ)									
	450000 cycles									
1	327	396	1091	1485	1023	1022	1225	1184	1061	1075
2	177	161	213	176	206	212	209	201	189	146
3	283	297	537	561	714	640	745	630	030	614
4	015	015	016	016	017	017	016	016	016	017
5	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
6	025	024	025	025	026	034	027	036	032	044
7	033	035	027	102	031	058	035	186	041	043
8	112	318	1078	1083	841	605	1682	1447	894	0/C
9	1068	0/C	1901	0/C	0/C	1876	1282	1571	1541	0/C
10	0/C	1331	0/C	0/C	1211	0/C	0/C	0/C	0/C	1831
av.	255	322	611	492	508	558	652	658	475	538
max	1068	1331	1901	1485	1211	1876	1682	1571	1541	1831
min	015	015	016	016	017	017	016	016	016	017
	460000 cycles									
1	983	798	1203	0/C	1351	706	1642	1681	1498	1091
2	165	142	165	189	185	165	157	144	131	139
3	504	474	517	641	0/C	982	1014	998	1163	994
4	016	016	017	016	016	016	017	019	018	018
5	1993	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
6	031	027	033	029	023	029	027	033	031	031
7	031	036	029	079	415	022	028	029	036	035
8	142	316	1241	272	523	350	238	1082	1441	648
9	1184	1534	1261	0/C	0/C	0/C	0/C	0/C	0/C	0/C
10	1965	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
av.	701	417	558	204	418	324	446	569	616	422
max	1993	1534	1261	641	1351	982	1642	1681	1498	1091
min	016	016	017	016	016	016	017	019	018	018
	470000 cycles									
1	357	1081	1376	1341	1297	1887	1092	993	1002	1253
2	138	161	137	168	148	148	176	146	169	181
3	470	830	963	1142	1621	1375	815	1203	1313	1028
4	015	016	017	017	016	018	016	017	016	017
5	1572	1763	1702	1621	1927	1592	0/C	1832	1691	0/C
6	021	022	041	032	036	028	030	032	029	028
7	027	023	047	055	030	055	043	036	030	034
8	084	113	128	683	753	338	321	1582	438	776
9	028	1141	0/C	0/C	0/C	0/C	0/C	0/C	1563	1061
10	0/C	0/C	0/C	0/C	1771	0/C	0/C	0/C	0/C	0/C
av.	301	572	551	632	844	680	356	730	694	547
max	1572	1763	1702	1621	1927	1887	1092	1832	1691	1253
min	015	016	017	017	016	018	016	017	016	017

Probe Deflection - Compressed

10 readings. (mΩ)

480000 cycles

Probe No.										
1	505	462	441	370	568	402	1086	637	472	530
2	132	222	246	205	237	216	196	216	188	150
3	647	1685	1814	1618	1843	1782	0/C	0/C	1742	1668
4	015	015	016	015	016	016	016	016	016	016
5	1034	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
6	021	024	030	029	030	029	026	031	029	031
7	030	821	182	062	215	054	431	119	053	051
8	130	665	266	1206	932	380	671	1467	1287	1062
9	527	681	0/C	1674	0/C	0/C	0/C	0/C	0/C	0/C
10	0/C	0/C	0/C	0/C	1421	0/C	0/C	0/C	1782	0/C
av.	337	571	427	647	657	411	404	414	696	501
max	1034	1685	1814	1674	1843	1782	1086	1467	1782	1668
min	015	015	016	015	016	016	016	016	016	016

490000 cycles

Probe No.										
1	187	268	497	348	325	387	357	385	402	348
2	164	183	186	155	168	166	176	151	134	137
3	478	530	623	045	574	664	802	898	1083	995
4	018	016	015	017	016	018	019	019	020	018
5	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
6	022	022	027	027	023	038	028	035	032	036
7	103	138	112	092	085	134	169	275	290	183
8	173	386	353	1074	735	1376	715	432	921	874
9	1531	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
10	0/C	0/C	1981	0/C	0/C	1944	1260	0/C	0/C	0/C
av.	334	220	474	251	275	590	440	313	411	370
max	1531	530	1981	1074	735	1944	1260	898	1083	995
min	018	016	015	017	016	018	019	019	020	018

500000 cycles

Probe No.										
1	192	231	632	438	288	337	535	783	389	227
2	114	124	126	118	115	102	111	120	115	110
3	0/C	0/C	0/C	0/C	1712	0/C	0/C	0/C	0/C	0/C
4	016	017	017	019	020	023	021	019	024	021
5	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
6	020	027	027	024	030	035	036	031	039	039
7	120	087	046	051	056	102	093	836	075	090
8	138	552	192	678	587	363	244	536	873	723
9	568	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
10	0/C	0/C	0/C	0/C	0/C	1662	0/C	0/C	1379	0/C
av.	166	173	173	221	401	374	173	387	413	201
max	568	552	632	678	1712	1662	535	836	1379	723
min	016	017	017	019	020	023	021	019	024	021

Probe Deflection - Compressed

510000 cycles

Probe No.	10 readings. (mΩ)									
1	981	1157	O/C	O/C	O/C	1243	O/C	O/C	O/C	1905
2	162	171	194	179	163	146	146	162	158	143
3	129	443	636	755	1545	775	1022	428	572	951
4	014	016	021	017	021	019	018	018	020	019
5	245	300	317	299	293	435	463	413	653	557
6	026	031	037	039	042	045	041	042	048	040
7	784	184	155	1057	233	174	180	442	215	246
8	089	144	230	142	405	445	516	305	429	270
9	1195	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C
10	O/C	O/C	O/C	O/C	O/C	1188	O/C	O/C	O/C	O/C
av.	402	305	227	355	386	496	340	258	299	516
max	1195	1157	636	1057	1545	1243	1022	442	653	1905
min	014	016	021	017	021	019	018	018	020	019

610000 cycles

Probe No.	10 readings. (mΩ)									
1	398	468	343	408	189	326	437	234	343	457
2	029	028	025	030	026	032	032	028	033	031
3	O/C	1171	1127	1629	1691	1651	1704	1621	1973	O/C
4	014	016	018	020	020	020	019	021	022	019
5	070	077	093	099	096	115	094	105	137	120
6	017	019	020	020	019	020	018	020	020	017
7	164	185	056	038	053	066	163	086	079	070
8	1123	O/C	1424	1629	1491	1664	1571	512	O/C	308
9	1449	O/C	O/C	O/C	O/C	1483	1952	1428	1416	662
10	1413	1328	O/C	O/C	O/C	O/C	O/C	O/C	O/C	O/C
av.	519	411	388	484	448	597	665	450	502	210
max	1449	1328	1424	1629	1691	1664	1952	1621	1973	662
min	014	016	018	020	019	020	018	020	020	017

Probe Deflection - Compressed

Probe No. 10 readings. (mΩ)

710000 cycles

Probe No.										
1	137	146	146	053	062	212	268	303	265	080
2	037	046	045	052	048	048	050	053	052	043
3	0/C	0/C	1703	0/C	0/C	0/C	0/C	0/C	0/C	0/C
4	017	019	019	018	021	021	017	021	019	019
5	031	033	033	033	036	034	031	036	035	034
6	016	020	019	020	020	019	017	020	018	017
7	036	047	040	048	051	066	1619	324	1491	045
8	1862	1867	0/C	0/C	1366	1948	0/C	0/C	0/C	0/C
9	1137	1212	1768	1176	0/C	0/C	1491	1121	1725	1622
10	1778	992	1862	0/C	0/C	0/C	0/C	0/C	0/C	0/C
av.	561	486	626	200	229	335	499	268	515	265
max	1862	1867	1862	1176	1366	1948	1619	1121	1725	1622
min	016	019	019	018	020	019	017	020	018	017

810000 cycles

Probe No.										
1	1041	663	691	1092	1173	1033	1221	1106	1112	1092
2	036	040	040	040	036	036	038	034	035	035
3	0/C	0/C	0/C	1892	0/C	1779	1223	1833	1632	0/C
4	018	017	022	026	022	025	025	024	022	022
5	087	090	087	086	097	092	096	093	101	105
6	020	026	025	030	026	031	027	026	025	027
7	043	093	066	033	048	089	058	045	064	093
8	831	0/C	1575	0/C	1762	1810	0/C	0/C	1435	0/C
9	1342	1338	1962	0/C	1701	1886	0/C	1245	1438	1227
10	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
av.	427	323	558	457	608	753	384	550	651	371
max	1342	1338	1962	1892	1762	1886	1223	1833	1632	1227
min	018	017	022	026	022	025	025	024	022	022

910000 cycles

Probe No.										
1	978	1132	1287	1472	1652	0/C	1962	0/C	1826	586
2	043	040	037	044	042	036	037	036	034	032
3	1972	0/C	1819	1291	1321	0/C	1383	1874	0/C	0/C
4	027	037	030	030	034	034	033	036	033	030
5	091	096	125	116	119	120	139	122	123	108
6	048	054	043	058	057	044	068	042	046	039
7	080	098	036	045	034	033	124	122	048	054
8	1919	624	1761	0/C	0/C	0/C	0/C	0/C	0/C	1923
9	1582	977	434	680	1231	1761	1291	1282	1628	1482
10	1474	0/C	1801	0/C	0/C	0/C	0/C	0/C	0/C	0/C
av.	821	382	737	467	561	338	629	502	534	531
max	1972	1132	1819	1472	1652	1761	1962	1874	1826	1923
min	027	037	030	030	034	033	033	036	033	030

Probe Deflection - Compressed

1010000 cycles

Probe No.	10 readings. (mΩ)									
1	1163	0/C	0/C	1194	1177	1196	1154	0/C	1795	1716
2	026	030	029	023	028	027	030	042	026	036
3	0/C	0/C	0/C	1899	1888	1783	0/C	0/C	1905	0/C
4	015	015	017	017	018	020	021	019	016	022
5	295	339	553	466	527	715	688	601	703	473
6	051	060	057	050	050	065	073	087	053	063
7	089	140	116	146	135	222	387	457	231	287
8	503	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	1271
9	1476	0/C	1683	1691	1961	0/C	1572	0/C	0/C	1843
10	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	1990	1906
av.	452	116	409	685	723	575	560	241	839	846
max	1476	339	1683	1899	1961	1783	1572	601	1990	1906
min	015	015	017	017	018	020	021	019	016	022

1110000 cycles

Probe No.	10 readings. (mΩ)									
1	0/C	1485	1871	0/C	0/C	0/C	0/C	0/C	0/C	1450
2	037	037	044	040	043	056	051	052	048	042
3	0/C	1821	0/C	0/C	0/C	0/C	1641	1886	0/C	0/C
4	020	018	024	024	022	023	021	023	023	024
5	1063	913	1783	1723	1363	1537	1973	0/C	1687	1921
6	030	031	046	044	048	055	059	037	065	062
7	066	064	108	113	092	080	085	056	097	079
8	0/C	0/C	0/C	0/C	0/C	1551	0/C	1296	1535	0/C
9	221	198	1071	556	1445	1682	1258	1809	1689	1671
10	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C	0/C
av.	239	570	706	416	502	712	726	737	734	749
max	1063	1821	1871	1723	1445	1682	1973	1886	1687	1921
min	020	018	024	024	022	023	021	023	023	024

1210000 cycles

Probe No.	10 readings. (mΩ)									
1	355	968	592	465	735	647	350	296	453	685
2	030	040	054	048	046	058	040	048	046	045
3	0/C	0/C	862	0/C	0/C	1383	1925	1932	1695	0/C
4	015	018	018	018	020	020	020	018	019	019
5	443	1463	1248	1782	1832	1682	0/C	1532	1568	1592
6	040	075	072	057	070	064	061	062	090	057
7	027	030	030	036	031	032	016	026	029	026
8	1252	1501	1495	1271	438	0/C	1196	0/C	512	1572
9	320	1328	212	178	136	333	707	288	258	932
10	0/C	1884	1051	0/C	0/C	1869	1366	0/C	1229	0/C
av.	310	811	563	481	413	676	631	525	589	616
max	1252	1884	1495	1782	1832	1869	1925	1932	1695	1592
min	015	018	018	018	020	020	016	018	019	019