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Evaluation of conformal coatings for future spacecraft applications

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Abstract

Leadless surface mount components offer a great opportunity for higher density spacecraft electronics with improved electrical performance. This study has evaluated a primary unknown factor which can reduce the reliability of both leaded and leadless components solder-assembled to printed circuit boards. The unknown influence of conformal coatings on the long-term integrity of assemblies exposed to thermal fatigue has been assessed. Printed-circuit-board (pcb) materials have been tailored to match the coefficient-of-expansion characteristics of leadless components and packages without compromising the reliability of plated-through holes (for mixed-technology spacecraft assemblies). Such pcbs were populated with typical electronic devices to standard ESA process procedures by trained and certified operators. One set of assembled reference boards was maintained in the clean, uncoated state. The remaining boards were coated with either polyurethane, silicone or epoxy coatings. All assembled boards were submitted to the ESA 'verification of process' thermal cycling tests (−55°C to +100°C). All conventionally mounted (plated-through-hole technology) components passed the 200-cycle requirements. One SMD (surface-mount-technology) board failed the 500-cycle test requirement owing to thermal fatigue promoted by the epoxy conformal coating. Electrical open circuits occurred when cracks developed in soldered joints made to the castellations on leadless ceramic chip carriers. All non-coated conventional and SMD assembled circuits survived 1000 thermal cycles. For the coated boards, some leaded components failed electrically before 1000 cycles and these were readily identifiable as failures by optical means. However, the failed surface mount devices (open circuit) appeared to possess defect-free solder fillets. Only by electrical testing and metallography was it possible to identify microcracks within these defective SMD solder interconnections.

The report establishes the effect of seven potential spacecraft conformal coatings on the reliability of soldered connections. The repairability of these coatings has been evaluated. Many physical and mechanical properties of the coatings have also been determined with a particular relevance to ESA manned and unmanned spacecraft requirements. No one coating is best suited for all spacecraft applications. The report describes both the advantageous and the unfavourable features of the coatings under test.

Contents

Evaluation of conformal coatings for future spacecraft applications

1. Introduction

Electronic components possessing leads or leaded packages that have been solder-assembled on to printed circuit boards and then thoroughly cleaned are generally conformally coated. The conditions of coated spacecraft electrical circuits have been observed to vary from one ESA contractor to another. For instance, several types of polymer coatings are utilised and they may be applied to assembled boards in such a way that the components are either (a) thinly coated (i.e. no bridging of coating within the stress-relief bend of a component lead); (b) moderately coated to encapsulate the leads and form a fillet of coating around the edges of each component body; or (c) heavily coated to cause complete encapsulation of the lead and almost complete potting of the component body. Sometimes the circuits are completely potted in foam. Conformal coatings may be applied by spraying, brushing, dipping and, for polyxylene coatings, by using a special vacuum-deposition chamber. The main purposes of applying coatings are to provide protection against airborne contaminants and humidity during ground handling operations and, with the exception of polyxylene, to ensure that the components are mechanically stable during exposure to shock and vibration under launch conditions.

The relative differences in the expansion and contraction of the printed circuit boards (pcb), the components parts and the conformal coatings have been seen to produce cracks in the soldered interconnections during thermal cycling. Laboratory testing has shown that component-assembled pcbs covered with a thick conformal coating suffered from severe solder-joint cracking when subjected to 1000 cycles between -55 and +100°C. A typical solder joint failure caused by thermal fatigue is shown in Figure 1.a. Only limited cracking was observed on similar but uncoated boards, or on boards having a thinly applied coating. Solder-joint cracking is attributed primarily to the difference in coefficient of thermal expansion (CTE) between the conformal coating and the component packages, and secondarily to CTE mismatch between component and pcb.

It is envisaged that future spacecraft circuits will utilise large numbers of leadless surface-mounted components, as these offer a greater opportunity for higher-density electronics with improved electrical performance. However, when both leaded and leadless components (so-called dual-technology) are selected for assembly on to the same pcb, it is an ESA requirement that the pcb material selected shall have a compensated CTE, i.e. that the pcb shall be fabricated from a substrate having a CTE similar to that of the component package material [Ref.1].

Moreover, the leadless component, or surface-mounted device (SMD), must incorporate a certain defined stand-off height, as this is intended to allow the soldered interconnection some limited amount of stress-relief when the component is subjected to environmentally imposed thermal-cycling conditions or when the component dissipates thermal energy under spacecraft operational conditions. There is concern that the presence of a coating material in the stand-off volume beneath each component might induce additional stresses on the solder interconnections during thermal cycling.

An analysis of numerous results of thermal cycling programmes involving component assembled pcbs has been made by J.P. Halpin [Ref.2]. He found it possible to generate a fatigue-life curve relating the magnitude of the thermal cycle (equivalent to the stress range) to the number of cycles necessary to produce the first failure as illustrated in Figure 1.b. New spacecraft technology, or changes to materials and processes involving electronic circuits are submitted to verification tests; these results can be placed on the Halpin chart [Ref.3], and test circuits that survive are assumed to have fatigue curves no worse than the dashed curve shown in Figure 1.c.

The objectives of the present study are to evaluate the effect that conformal coatings have on dual-technology-assembled pcbs. It was also proposed to attempt to examine the Halpin chart by means of the continuous electrical monitoring of sample interconnections during thermal cycling in order to obtain an accurate record of the life until the first solder-joint failure.

Seven commercially available spacecraft conformal coatings have been selected (three polyurethane, three silicone and one epoxy). These were applied as thick coatings to three types of circuit boards in order to study their effect on:
- leaded conventional components solder-assembled to double-sided glass-polyimide pcb's;
- surface-mounted devices soldered to quartz-polyimide multilayer boards with central internal layers of copper-molybdenum;
- and the surface insulation resistance of both glass-polyimide and glass-epoxy pcb's.

Additional samples were made up to assess the effect of these coatings on the reliability of microwire wedge boards. Specific physical, mechanical, flammability and outgassing properties of the coatings were also established. An assessment of the ease of repair (maintainability) was also made for each coating. Wherever possible the relevant ESA specification was followed.

2. Experimental work

2.1 Selection of products

The first task in the conformal coating evaluation was a supplier/literature survey of commercially available coating products that were expected to fulfill the general ESA requirements for spacecraft materials. This survey covered a wide range of products, including urethanes, silicones, epoxies and polyxylene, but excluded acrylic coatings owing to their low mechanical-abrasion resistance and poor resistance to chemical solvents. The list was then reduced to seven products either having an extensive usage in the fabrication of current spacecraft or, for the more recent products, those expected to pass the ESA requirements for outgassing under vacuum [Ref.4]; offgassing, toxicity and flammability [Ref.5]; and having a suitable repairability [Ref.6]. The selected products were:

Silicones:
CV 1144-0 (Nusil Technology, USA/Dunlop Adhesives, UK)
MAPSIL 213 (MAP, France)
Sylgard 184 (Dow Corning, Belgium)

Polyurethanes:
Conathane EN 11 (Conap Inc., USA)
Solithane 113 (Uniroyal Chemical Co. Inc., USA/Thiokol, UK)
Uralane 5750 LV (Ciba-Geigy Corp., USA)

Epoxy:
Scotchcast 280 (3M Company, USA/3M Nederland BV)

2.2 Sequence of specimen manufacture and testing

The selected conformal coatings were procured during the same time period. The various double-sided and multilayer pcbs (lay-outs and electrical-continuity circuits described below) were fabricated by an ESA-approved manufacturer [Ref.7]. The boards were then assembled with components by trained and certified operators using ESA standard soldering materials, processes and cleaning methods [Ref.1,8]. The finished solder joints satisfied all ESA workmanship requirements (except where mentioned in Para. 2.3).

Removal of flux residues was ensured by making repeated cleaning operations; this is important to note, since such residues were seen, in a parallel study [Ref.9], to influence the surface insulation resistance in air, although they had little effect under spacecraft vacuum conditions. Quality controls on each coating product determined that the manufacturers' recommended shelf lives had not been exceeded and that basic rheology checks complied with data sheets.

The flow diagram and identification of specimens for the test programme are given in Tables I and II. Each test specimen type will be described in further detail. The coatings were, where necessary, mixed, then applied to the pcb surfaces by dipping in combination with brushing to yield complete coverage. The specimen boards had been inserted into specially made Delrin jigs which acted as a barrier or dam around the pcb edges. Coatings were then added in such a way that they ran into a 0.3 mm stand-off zone that had been deliberately designed beneath each component. Brush coating enabled the undersides of components and all lead wires to be suitably covered by a standard coating thickness of 1.0 mm from the pcb surface. It is important to note that the coatings were deliberately brushed to bridge the stress-relief loops and bends of the leaded components. On curing, the Delrin jigs were removed. The pcb specimens could then be individually mounted into specially constructed aluminium stiffener frames; this facilitated handling and reproduced the mechanical design of spacecraft electronic box assemblies.

Parts of the manufacturer's data sheets have been summarised in Table III, together with costs and the actual conformal coating application method. The main observations made by operators during the preparation of specimens have also been recorded.

2.3 Description of test specimens

Specimen 1 (Leaded Devices)
Double-sided pcbs made of 1.6 mm glass polyimide laminate with plated-through holes and a fused tin-lead finish. Resistors, diodes and transistors were mounted to ESA specification [Ref.8], except that no stress-relief bends were formed in the TO-transistor leads so that maximum stressing of the leads by the different coatings could be studied. Figure 2 illustrates the physical and electrical lay-out of these continually monitored circuits. The coefficient of thermal expansion was measured between $-60°C$ and $+150°C$ and was found to increase from 14 to 15 ppm in the planar (x) direction, and from 37 to 41 ppm per degree C in the thickness (z) direction.

Specimen 2 (Surface Mounted Devices)
Three-layer pcb made of quartz-polyimide containing a central layer of copper-molybdenum-copper (25, 50, 25%) 0.6 mm thick. This controlled-expansion multilayer board (mlb) has a low CTE, which was measured between $-60°C$ and $+150°C$ and was found to decrease from 9 to 6 ppm in the x direction and increase from 28 to 65 ppm per degree C in the z direction (ESTEC Metallurgy Report No. 2051). The mlb has a CTE similar to that of the selected SMDs (leadless chip carriers and chip capacitors) shown in Figure 3.a. The electrical monitoring circuit is given in Figure 3.b. Stand-off heights of 0.3 mm were achieved by using removable thin enamel-covered copper wires between mlb and SMDs during vapour phase soldering [Ref.1]. Solder pads were of copper, screen-printed with tin-lead paste and fused. The method of component assembly is illustrated in Figure 4.

Specimen 3 (Surface-insulation resistance)
The comb patterns selected for performing surface electrical-insulation tests conform to French standards and are shown in Figure 5. The insulation distance between tracks is 0.3 mm and represents the minimum track spacing at present permitted for SMD assemblies. Both epoxy and polyimide substrates were selected.

Specimen C (Ultrasonic bonds)
Ultrasonic bonding is the most widely used method of making interconnection on spacecraft high-density multichip modules. This miniature joining method was selected for the assessment of compatibility between conformal coatings and these delicate aluminium microwire wedge bonds. Leadless chip-carrier packages were used in the open state, i.e. without lids. Fine 38 μm diameter wires were ultrasonically welded to adjacent internal package aluminium bonding pads such that their weld lengths, loop heights and bond lengths were essentially equal for each package and coating under evaluation. These specimens are shown in Figures 3.a. and 4. They form the 'daisy chain' circuits which could be electrically monitored during thermal cycling (devices Z1 and Z2 in Figure 3.b.). Although it is doubtful whether coatings would ever intentionally encapsulate spacecraft microwire bonds, the Specimen C design was introduced into the programme because it incorporated materials and joints considered to be the most sensitive to changes in the physical properties of conformal

coatings during thermal cycling.

Specimen D (Flat sheet)
A specially constructed Teflon mould was manufactured in such a way that each of the coatings could be made into thin flat sheets measuring 300 mm × 200 mm and 2 mm thick.

Specimen E (Shear strength)
Rectangular aluminium plates measuring 60 mm × 25 mm and 3 mm thick were etch-cleaned and used for lap shear testing. Pairs of plates were placed in a jig, one above the other, so that they overlapped with a gap of 1mm and to a distance of 12.5 mm. Each conformal coating was flowed into samples containing this standard overlap volume and then cured.

Specimen F (Hardness test blocks)
Coatings were cast in Teflon moulds measuring 50 mm × 30 mm × 25 mm and then cured. Once released, the flat-sided blocks were submitted for hardness testing.

2.4 Repair procedures

Where possible, the ESA repair specification [Ref.6] was followed. Every component variant on Specimen type 1 and 2 pcbs was subjected to 'repair'. This consisted of the local removal of conformal coating and then component by a trained operator using techniques detailed in Paragraph 3.1. The leadless chip-carrier packages on Specimen 2 were replaced by new packages, whereas all other removed components were dressed and re-installed on the pcbs. After cleaning, additional conformal coating was made up and applied to each area of repair activity. In total, 35 repair operations were made: comments regarding the ease of achieving a satisfactory repair were recorded by both operator and inspector. As shown in Table I, the boards were then passed to the thermal cycling phase of the study.

2.5 Environmental tests

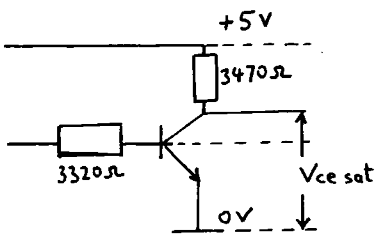
2.5.1 Thermal cycling
All the conformally coated component-assembled printed-circuit boards representing Specimen types 1 and 2 were subjected to 1000 thermal cycles in air. The parameters were as specified by ESA for solder-joint-verification testing [Ref.1, 8], i.e. −55°C to +100°C with temperature changes of 10°C per minute and 15-minute dwell times at each temperature extreme. The necessary cooling was achieved by forced gas circulation from a liquid-nitrogen supply. Heating at the required rates was achieved with the aid of controlled elements. Temperature control was achieved by means of thermocouples sandwiched between printed-circuit boards.

The soldered joints, metallisations and coatings were **visually examined** by two inspectors with a low-power binocular microscope. Records of appearances were maintained for all Specimen type 1 and 2 boards from the 'as-received' condition, and at each 100 cycle period up to the 1000 cycle completion of test. Electronic components and soldered joints displaying particularly interesting features were recorded by photography as the thermal-cycling sequence progressed. Certain aspects were finally observed by scanning electron microscopy (SEM) and this facilitated the cross-sectioning operations and subsequent metallographic preparation.

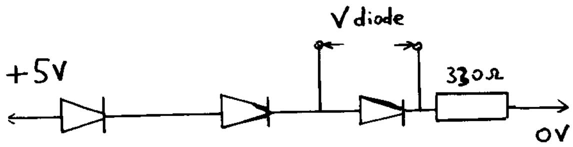
Metallographic Examination was made of selected joints; these were carefully sawn from the pcbs with a jeweller's saw blade and then mounted in a room-temperature-curing resin. The mounts were ground and polished to a 0.5 μm finish so as to dissect each interesting surface feature. Photomicroscopy took place at both low (optical) and high (SEM) magnifications.

Electrical tests were made to monitor the reliability of soldered connections during the thermal cycling operation. Every pcb was tested at commencement and at each of the 100-thermal-cycle inspection periods. The circuit diagrams are seen in Figures 2 and 3 for the leaded and leadless components respectively. A Behltman Invar Q5 10 power source and a Keithley 192 (DMM) voltmeter enabled measurements to be made on pcbs of **Specimen Type 1**:

TRANSISTOR



DIODE



Measurements were performed on each transistor under 5 V and through resistor R of 3470 Ω (R1 for Q1, R2 for Q2 and R3 for Q3 being the resistor limit intensity in each transistor). Voltage Vce measurements were recorded as T1 for Vce Q1, T2 for Vce Q2 and T3 for Vce Q3.

Voltage records were taken for the diodes CR1 (D1), CR2 (D2) and CR3 (D3) through a resistor of 330 Ω at a circuit voltage of 5 V.

The circuits were so designed that any discontinuity or breakdown of a soldered connection during thermal cycling would have no impact on other measurements.

Specimen Type 2 (see Figs. 3.b. and 4.)
Here the leadless chip carriers (LCC) contain interconnecting bonding pads, made by wedge-wedge bonds with microfine aluminium wire. The resistance of each LCC was measured (i.e. each wedge bond, conductor, soldered joint etc. in series) for carriers Z1, Z2, Z3, Z4 and Z5. If one joint becomes open circuit, the measurement will record infinite resistance.

Carriers Z3, Z4 and Z5 were designed to monitor the electrical continuity of the solder joint castellations; they were air-filled and lidded. Each LCC has 28 metallised castellations soldered to the controlled-expansion quartz-polyimide mlb.

The capacitance of the multilayer chip capacitors C1, C2 and C3 were also monitored on Specimen type 2 using Pontrec Genrad 1689 M equipment (f = 1000 kHz, $V = 0.1\ V_{eff}$). Insulation measurements were made with a Radiometer 1M6 megohmeter at 500 V for 1 minute.

Specimen C (see Figs. 3.b. and 4.)
The leadless chip carriers Z1 and Z2 that had been solder-assembled to Specimen Type 2 were designed to enable the effect to be assessed of coating materials on the sensitive daisy chain of interconnected bonding pads. These coating-filled packages (without lids) would record an infinite resistance when at least one bond had fractured (this was also monitored by visual inspection).

2.5.2 Humidity tests
Comb patterns (Specimen 3) supported on both glass-fibre/epoxy FR4 pcb substrates and polyimide pcb substrates (see Fig. 5) were covered with an even, 1 mm thick layer of each of the seven conformal coatings. Three uncoated control samples for each substrate material were also included. Once fully polymerised, the comb patterns (14 in total) were tested for surface insulation resistance (SIR) and capacitance. They were next transferred to a cabinet held at 90-95% RH and 40°C. Further SIR and capacitance measurements were made (under ambient conditions) immediately after 8 hours, 9 hours, 160 hours and 161 hours of exposure to these warm, humid conditions.

The insulation gap, or conductor track spacing, on the comb patterns was selected to be 0.3 mm as this is the present minimum spacing permitted by ESA for printed-circuit boards when the DC or AC peak voltage between conductors is less than 30 V [Ref.7].

2.5.3 Life tests
A further set of epoxy and polyimide comb patterns was coated and submitted to life tests at 125°C for 500 hours in order to determine the changes to SIR produced by exposure of these coatings to elevated temperatures in air.

2.5.4 Resistance of coatings to cleaning solvents
Three final sets of coated epoxy and polyimide comb patterns, together with uncoated control patterns, were immersed for 5 minutes in each of the following industrial cleaning solvents (maintained at 23°C):
— Isopropyl alcohol;
— Arklone P (Freon) (trichloro 1.2.2-trifluoro 1.2.2-ethane);
— Proparklone (trichloroethane 1.1.1 plus 7% isopropyl alcohol).

SIR measurements were made to establish whether these cleaning solvents would penetrate or react with the various coatings so as to alter the nominal surface-insulation resistance of the comb circuit.

2.5.5 Special space materials tests
Suitable samples of each coating material were cut from the flat sheet (Specimen D) and submitted to the following tests (for further information consult the referenced ESA test specification):

Outgassing and Micro-VCM [Ref. 10]
The coating was heated to +125°C under high vacuum and measurements were made of condensable fractions (CVCM) at 25°C, the sample's total mass loss (TML) and, after return to ambient conditions, the sample's recovered mass (RML). Acceptable limits for outgassing are TML < 1.0% and CVCM < 0.10%.

Flammability [Ref.5,11]
Sample strips of coating were mounted vertically in a chamber containing an atmosphere of 24.5% oxygen, the remainder being nitrogen. The lower edge of each strip was ignited by means of a standard chemical igniter of known heat output. The results were recorded on video tape and standard reporting sheets. The criterion of acceptability is whether the material propagates the flame upwards (fail) or not (pass).

Offgassing and Toxicity [Ref.5,12]
Samples were weighed and held in a chamber for an incubation period of 72 hours at 50°C. The enclosed atmosphere was then quantitatively analysed by gas chromatography. The toxicity limits for offgassed sample are 25ppm carbon monoxide and less than 100μg/g for total organics.

2.5.6 Mechanical testing
Mechanical testing was performed with an Instron 1185 tensile test machine incorporating a Grenco environmental chamber capable of heating or cooling the samples between +300°C and −150°C.

Shear tests were made on the Specimen (type E) having a standard overlap of 12.5 mm. Testing was performed at a strain rate of $1.3 \times 10^{-4}s^{-1}$ at temperatures of +100°C, +20°C and −55°C.

Tensile tests used standard 'dumb-bell'-shaped samples stamped out of Specimen D (flat sheet). Sample dimensions were gauge length: 55 mm, gauge width: 12 mm and thickness: 2 mm. These samples were tested with a strain rate of $1.3 \times 10^{-4}s^{-1}$ at temperatures of +150°C, +20°C and −100°C. The test pieces were heated by circulating hot air into the chamber and cooled by blowing in boiling nitrogen through a forced air fan. Accurate temperature control was achieved by a thermocouple attached to the test piece.

2.5.7 Hardness testing
Type F specimens (large blocks) were submitted to RAPA Technology Ltd, for hardness testing according to two standards:

BS 903: Part A26: 1969 using a Wallace Deadload hardness meter (International Rubber Hardness Degrees (IRHD) 20-95 by method N, IRHD 85-100 by method H and IRHD 10-35 by method L).

BS 2782: Part 3: Method 365 B: 1992 employing instantaneous and 15 second readings.

Hardness measurements were made on all coatings with the aid of equipment calibrated to the accuracy required by the appropriate standard and at an ambient temperature of 23°C ± 2°C.

2.5.8 Expansion measurements
The coefficient of thermal expansion of each of the conformal coatings was measured with the aid of a Dupont 9900 Thermal Mechanical Analyser (TMA) system. Each of the silicone coatings proved to be a problem in the TMA; owing to their softness, surface penetration occurred even when a large-based probe was used.

3. Results and discussion

3.1 Observations concerning repair procedures

Repair is defined as a set of operations performed on a non-conforming printed-circuit-board assembly in order to bring it into a usable condition. This might include the replacement of a damaged component or a soldered joint, modification of an electrical circuit or the application of adhesive to a lifted terminal. Repairs to ESA spacecraft assemblies are only permitted when the methods and alternative processes are approved and qualified according to specification ESA PSS-01-728 [Ref.6]. The repair sequences executed during this study were considered to be as important as the material property investigations. It was felt that the results would assist in establishing quality assurance acceptance/rejection criteria for coatings. These criteria include uniformity, tack-free to touch, physical continuity, adhesion, thickness, absence of large or interconnecting bubbles and charring of pcb, coating or components.

Repair to specimen 1 (Leaded Devices)
The main observations concerning the repairs are given in the captions of photographs illustrating the appearance of assemblies from which coating and components had been removed. Each component was then re-mounted and re-coated. See Figures 6 to 12.

The following components were removed from each of the seven conformally coated pcbs:

transistor Q3,
resistor R4,
diode CR3.

Solder extraction was successfully achieved with the aid of a Philips 90-400 sucker with continuous vacuum; other processing details are in the captions.

Repair to Specimen 2 (Leadless Devices)
An orangewood stick was used to remove the conformal coating from the leadless components. Compared with the conventional leaded components, these 28-leadless chip carriers and the leadless chip capacitors (12 × 18 mm) were more difficult to remove. The chip capacitors often broke and in order to remove the LCCs it was necessary to drill two small holes in their lids to locate thin clinched wires. The pcbs were pre-heated to 100°C on a heating plate, the solder joints were fluxed with RMA flux type 601 and then hot air at 350°C was directed on to each joint with a Zervac device (nozzle N28D for the capacitors, and nozzle N45E for the LCCs). A jig was then clamped on to the clinched wires and the LCCs lifted from the board, as shown in Figure 13. The mounting of new devices required the removal of excess solder and coating from the pcb surface and the dispensation of new solder paste. New chips were degolded and pre-tinned, fluxed and positioned on the boards. After oven drying for two hours at 80°C, the Zervac hot air heater was applied (at 350°C) to melt the paste. Cleaning of the newly assembled SMD was followed by recoating. The captions of Figures 14 to 20 summarise the operator's experiences during repair of Specimen 2.

The records documented by the operator during his repair procedures for the leaded and leadless components and Figures 6-20 have been scrutinised. Although somewhat subjective, the coatings can be tabulated in order of repairability (easiest to repair at the top):

CV 1144-0
MAPSIL 213
SYLGARD 184
SOLITHANE 113
URALANE 5750LV
CONATHANE EN11
SCOTCHCAST 280

Note: The same order was derived for the repaired board assemblies of both Specimen 1 and Specimen 2.

3.2 Environmental test results for soldered joints and wedge bonds (Specimens 1, 2 and C; see also Table I)

3.2.1 The effect of thermal cycling

(a) Visual examination

All specimens were visually examined by two inspectors after each series of 200 thermal cycles. A large dossier of observations was compiled and macrophotographs were made to record the progression of surface discontinuities on the fillets of the various soldered joints. In most cases, the joints' visual appearance deteriorated with cumulative thermal fatigue. For many solder joints, the original smooth, bright surface changed to one possessing a dull, orange-peel-like appearance. The formation of local solder shrinkage and folding was difficult to differentiate from wide-mouthed propagating cracks; this could only be substantiated by the destructive metallographic examinations made on the pcb's when they were subsequently withdrawn from the test on reaching 1000 thermal cycles. Figure 21 highlights the most common visual defect on the leaded components' solder fillets.

Three of the open chip carriers that contained aluminium microwire wedge bonds interconnecting adjacent package bonding pads could be seen to suffer some degradation after only 100 thermal cycles. The reference 'empty' packages contained smooth pristine microwires and wedge bonds even after 1000 thermal cycles. Microwires embedded in the various coatings were seen to become kinked and slightly misaligned from their original symmetrical positions between the first and second wedge bonds. The Solithane, Conathane and Scotchcast media produced the greatest thermal stresses on their aluminium microwires which led to early electrical open circuits. One wire fracture is illustrated in Figure 22. Generally it is the wedge bond-to-pad interface that is the first to record an electrical open circuit, but owing to the practically opaque nature of the coatings these failures are impossible to photograph. The fractured wire seen in Figure 22 has a length approximately 100 times its diameter; this is the longest wire dimension in the circuit, being across the package corner, and is at the maximum length-to-diameter ratio recommended for avoidance of mechanical fatigue damage resulting from excitation of the wire (both aluminium and gold) during over-aggressive ultrasonic cleaning cycles.

The visual examination results of solder and wedge bond interconnections can be summarised as follows: the most severe joint degradation was associated with Scotchcast, followed by Solithane and then Conathane. The least damage was associated with the uncoated reference specimens which possessed a small degree of wide-mouth cracking around leaded solder connections, but no real degradation of the leadless solder joints or the aluminium wedge bonds.

(b) Electrical monitoring of interconnections

Only the reference, non-coated, assemblies were easy to examine visually. More effort was required to record photographically the degradation of coated joints by a fine adjustment of the illuminating lights. Although the importance of a complete visual inspection cannot be overemphasised, only the electrical test will verify an electrical failure. The electrical monitoring of each soldered and wedge bond interconnection during temperature cycling has isolated many intermittent failures during their exposure to the 1000 thermal cycle environment.

The full results of the electrical tests are tabulated in Annex 1 for the leaded (Specimen 1) connections and in Annex 2 for the surface-mounted devices (Specimen 2) and wedge bonds (Specimen C). A summary sheet that highlights the occurrence of the first electrical failures on each of the specimens is presented in Table IV.

It is important to note that every non-coated reference specimen survived the complete 1000 cycle programme without producing an electrical failure. For leaded devices, despite the presence of some slight (non-propagating) wide-mouth cracks, the joints associated with uncoated, MAPSIL 213, CV1144 and Sylgard produced no failures throughout the 1000 cycles. The first leaded component failure was associated with Solithane (a transistor after 300 cycles). Transistor lead failures were then noted for Scotchcast (400 cycles), Conathane (500 cycles) and Uralane (600 cycles).

The surface-mounted devices assembled to the matched expansion coefficient Specimen 2 boards were surprisingly resilient to thermal fatigue. Only the Scotchcast-coated board promoted the failure of one leadless chip carrier after 400 cycles, and all these LCCs failed at the end of the 1000 cycle period. None of the chip capacitors completely failed (although certain devices possessed visual cracks).

The most sensitive specimen to thermal fatigue is seen from Table IV to be the wedge bonds. The daisy-chain connections failed after only 100 thermal cycles when Solithane, Conathane and Scotchcast coatings filled these package cavities. Uralane caused a failure after 200 cycles, Sylgard a failure after 300 cycles, Mapsil a failure after 400 cycles and finally CV 1144 caused a failure after 500 cycles.

An 'order of merit' can be established on the basis of these results. The conformal coating listed first is regarded as being the best suited for encapsulating electronic assemblies that may be expected to be subjected to extensive thermal cycling:

CV 1144 MAPSIL 213 SYLGARD 184	All silicones
URALANE 5750 CONATHANE EN-11 SOLITHANE 113	All polyurethanes
SCOTCHCAST 280	Epoxy

(c) Metallographic Examination

A selection of soldered interconnections taken from the Specimen boards 1 and 2 at the completion of 1000 thermal cycles were submitted to metallographic examination. The small devices and their soldered joints were removed from these pcbs with a routing tool, care being taken to ensure that no mechanical stresses were induced.

Cold mounting techniques were employed to pot the devices, which were later ground, polished and etched. Where possible, optical macrophotographs and scanning electron images have been placed next to the metallographic cross-sections of certain interesting thermally stressed solder joints.

Figure 23 illustrates the stand-off height of the leaded diode components. The conformal coating has filled the entire volume between the glass body, the stress relief bent leads and the pcb surface. In Figure 23, some degree of 'wedging' is seen to have occurred, because stresses, induced on the component by the coating during the hot part of the temperature cycle, have pulled the lead and reduced its stud length.

One of the worst cases of solder joint deformation is shown in Figure 24. The stud connection has been severely reduced in height and extensive solder-joint cracking is visible on the cross-sectioned plated-through hole. It is interesting to note that, despite the severe mechanical damage associated with this connection (Specimen 1, Diode CR3, covered with Scotchcast), no electrical failure was recorded. The lead material is Dumet (copper-coated nickel).

The first solder joints to fail electrically were associated with the transistors coated in Solithane (300 cycles) then Scotchcast (600 cycles), and Uralane (600 cycles). Each of the Kovar-leaded transistors possessed a similar solder-joint failure mode for these three coating types. Wide-mouth cracks were seen at the soldering side of these joints (see Figures 25 and 27). Although every one of the three leads on each transistor possessed similar wide-mouth cracks only one joint contained a continuous crack that had propagated throughout the solder (compare Figure 26 with Figure 28). Close examination of the electrically failed solder joint in Figure 28 indicates that the hard Kovar lead has been forced up and down in a direction parallel with the plated-through hole. This can only have been induced by stresses created by the expanding and contracting conformal coating present in the space between the transistor base plate and the pcb.

In contrast to the many cracked soldered joints, some solder fillets remained unaffected by the thermal-cycling environment. One such joint to a resistor lead is shown in Figure 29. It is noted that resistor leads are made of pure copper, which has a coefficient of thermal expansion of 17 ppm per degee Celsius. In this respect, copper is better matched to the glass-polyimide material of the pcb than either Kovar or Dumet (5.0 and 6.0 ppm per degree Celsius, respectively, as listed in Table XII)) and is therefore unlikely to produce orange-peel effects (resulting from microstresses, as seen in Figure 21) on the surface of solder joints.

The leadless devices solder-attached to Specimen 2 pcbs appear to be more resilient to thermal fatigue than the leaded components. The full results are given in Annex 2 and a summarised overview is shown in Table IV. Unstable measurements were first noticed on the leadless chip carrier Z5 (coated with Scotchcast) after 400 cycles. A full open circuit developed on this device, as it also did on Z3 and Z4 after 900 cycles (Annex 2, Specimen 2, No. 4.1). The remaining coating materials did not cause solder-joint degradation, except for an unstable measurement in the case of the Solithane-coated board at 1000 cycles (Annex 2, Specimen 2, No. 4.3).

Photographs of the solder-joint castellations from the first leadless package to produce an electrical open circuit are shown in Figure 30. These photographs (made at the end of the 1000 thermal cycle test) illustrate the problem of crack detection by visual means. The inspection difficulty is compounded by the presence of the Scotchcast coating which, although quite transparent, reflects the illuminating light to such an extent that each visual image has an optical aberration. The pictures shown in Figure 30 were made by video imaging, which was found to probe more efficiently than a conventional stereozoom microscope. Nevertheless, although separations between the Scotchcast, the package and the multilayer board were visible, the solder fillets appeared reasonably undisturbed and 'free from cracks'.

A glancing microsection, made parallel to one of the devices encapsulated in Scotchcast (Z5), after 1000 thermal cycles is shown in Figure 31. Clearly each joint contains a crack. Even more revealing are the transverse microsections made through the apparently perfect solder fillets seen in Figure 30. It is only by this microsectioning method that the true extent of cracking is revealed. The crack paths seen in Figure 32 account for the electrical open circuits that were recorded in Table IV. It is interesting to note that the wide-mouth cracked joints associated with the hard coatings and leaded components (Figs. 24-27) are readily inspectable. However, the same hard coatings appear to have lifted (wedged up) the leadless chip carriers during thermal cycling to produce microcracking of the solder joints, and these defects were so small as to be uninspectable on the castellation solder fillets. Possibly the greatest damage is caused when the epoxy coating expands during the positive temperature excursion, as will be seen in Paragraphs 3.2.6 to 3.2.8. The Scotchcast has the greatest strength of all the coatings tested at room temperature, the greatest hardness and a high coefficient of thermal expansion. As the temperature increases, the crack produces an open circuit but, on returning to room temperature and below, the epoxy contracts, drawing the cracked solder surfaces together so that electrical contact is re-established.

For completeness many of the electrically sound joints were microsectioned after the 1000-thermal-cycle period. Figure 33 shows the leadless chip carrier, Z5, coated with Conathane EN 11. This package has a stand-off height of 280 μm (same order as the Scotchcast package), but there is no indication of any crack initiation on these solder joints.

The final microsection to be reported on is that of a chip capacitor coated with Scotchcast and shown in detail in Figure 34. The caption describes the microstructure, and it is noted that the SEM image allows somewhat more discrimination for the detection of these microcrack initiation sites than the optical microscope.

3.2.2 Humidity test results

Specimen 3 comb patterns had been manufactured on epoxy and polyimide base laminates (see Table II and Para. 2.5.2). The initial surface insulation resistance (SIR) and capacitance properties of three uncoated comb patterns were measured for each pcb laminate **before humidity testing** (i.e. **in dry condition**):

Glass-epoxy laminate, uncoated

SIR	5×10^7 MΩ	Capacitance	18.3 pF
	1×10^5 MΩ		19.1 pF
	1×10^7 MΩ		18.4 pF

Polyimide laminate, uncoated

SIR	9×10^6 MΩ	Capacitance	19.6 pF
	2×10^7 MΩ		20.0 pF
	6×10^6 MΩ		19.6 pF

After coating, but before exposure to humidity, it was found that the SIR and the capacitance of both board types increased, as recorded in Tables V and VI.

The SIR values for each of the coated boards decreased by approximately one decade during the first 8-hour exposure to damp heat (95%RH, 40°C). The capacitance values remained virtually unaltered for every board and coating during the entire 161-hour humidity test (see Tables V and VI).

The SIR values obtained after the 9-hour exposure to humidity show a general increase to the original SIR value of the as-coated comb for the epoxy boards. Similar values are recorded up to the end of the 161-hour test period.

The various coatings have been tabulated in an order which reflects the protection they afford to the underlying comb patterns during exposure to humidity. Whereas the SIR values of the epoxy laminate remain reasonably stable throughout the tests, it is interesting to note that the 'best' and 'worst' coatings applied to the polyimide comb patterns produced ohmic-resistance measurements separated by four orders of magnitude. The reason for this anomaly may be related to the well-known fact that polyimide systems have a higher water absorption than epoxy systems.

3.2.3 Life test results

The comb patterns made from either epoxy or polyimide laminates, coated and then exposed to 125°C for 500 hours were noted to have changed in colour at the end of the test. The Conathane darkened considerably, the Uralane somewhat less and the remaining coatings were only slightly modified.

The SIR values increased by an order of magnitude for the patterns coated with CV 1144, MAPSIL, Scotchcast, Sylgard and Uralane. The pattern coated with Solithane produced a slight increase in ohmic resistance and the Conathane a slight reduction in SIR. These results, together with the unmodified capacitance recordings, are presented in Tables VII and VIII.

3.2.4 Cleaning-solvent resistance

The tabulated results are presented in full in Annex 3. A wide range of SIR values was recorded following the 16-hour solvent-immersion tests.

Both electrical measurement and visual inspection of the comb patterns showed isopropyl alcohol to have had little effect on any of the coating materials. The Freon (Arklone P) solvent had a slight damaging effect on the silicone materials, causing a reduced SIR and some visual degradation. Capacitance values remained essentially the same for all variant types of coatings and laminates.

The most damage was recorded when coated comb patterns were immersed in Propaklone. The silicones and Uralane were visually affected, and after 16 hours Scotchcast was noted to have a reduced SIR value.

It is difficult to draw any conclusions from these results, except that the alcohol solvents will have minimal effect on the coatings. Care must be taken when any of the silicone coatings are immersed in either Freon or Propaklone, as these solvents may permeate the coating and, in the presence of ionic contaminants, there may be a reduction in surface insulation resistance.

3.2.5 Results of special space materials tests

The complete test results have been compiled in Table IX. Some of the more important findings are as follows:

(a) Outgassing and Micro-VCM
All samples passed the ESA requirements [Ref.4] except Sylgard 184, which possessed a high TML and a high CVCM (1.46 and 0.65 respectively).

(b) Flammability
The test sample consisted of a strip of coating mounted vertically in the test chamber. The sample can be considered as a worst case; a more meaningful sample (and one better representing flight electronics) would have been a thinly coated pcb. However, as tested, the following order of merit was obtained:
Passed: All the silicone products (CV-1144, MAPSIL 213 and Sylgard 184);
Failed: All the remaining polyurethane and epoxy samples.

(c) Offgassing and toxicity
Each of the coating products under evaluation passed these tests.

3.2.6 Mechanical test results

Table X lists the mechanical properties of the cast sheets of coatings prepared at the same time and by the same methods as for the coated component-assembled pcbs. The silicone coatings can be seen to have retained their flexibility down to −100°C, which makes them the preferred coating materials when thermal-cycle stresses on solder joints and sensitive components need to be minimised. Although they have a higher coefficient of thermal expansion (see Table XII) than the other coating types, they possess a far lower elastic modulus (*E*) and this greatly reduces the forces imposed on solder joints and resulting in thermal fatigue. This effect has been noted in Paragraph 3.2.1, and these silicones are therefore recommended for both standard conformal coatings and as stress-relief coatings.

The polyurethane coatings exhibit good flexibility, but a rather high strength and elastic modulus at low temperatures. Their mechanical properties are intermediate between those of the silicones and the epoxy coatings.

As can be seen from Table X, the epoxy coating possesses the highest room-temperature strength (both tensile and shear); it also has poor elongation properties (see Figures 30 and 34, where it is the only coating to separate from both component bodies and pcb during thermal cycling). The relatively high coefficient of thermal expansion, coupled with its high hardness value (see Table XI), renders Scotchcast unsuitable for the majority of cases where the thermal cycling of spacecraft conformal coatings is likely to promote stress-induced solder-joint failures.

3.2.7 Hardness test results

Various standard rubber-hardness tests have been made on the seven coatings under evaluation. The results are compiled in Table XI. These results are comparable to the room-temperature mechanical-strength properties shown in Table X, in that the silicones have the lowest hardness, the polyurethanes have an intermediate hardness and the epoxy coating has the greatest hardness.

3.2.8 Coefficient of thermal expansion (CTE)

Some difficulties were experienced during these expansion measurements owing to the extreme softness of certain coatings. The results are presented in Table XII for the sake of completeness, but it is recommended that alternative sources of CTE data be consulted before these results are applied.

4. Conclusions

(1) The ESA 'verification of process' thermal-cycling test ($-55°C$ to $+100°C$) has proved that:

a. All leaded component assemblies (plated-through-hole technology) passed the 200-thermal-cycle requirement set out in ESA PSS-01-708. However, additional thermal cycling to 1000 cycles revealed open circuits in transistor solder joints after a total of 300 cycles (Solithane), 400 cycles (Scotchcast), 500 cycles (Conathane) and 600 cycles (Uralane). Neither the uncoated boards, nor the three silicone-coated boards (Mapsil, CV1144 or Sylgard) promoted failures at 1000 cycles. When these life-to-first-failure data are plotted on the abridged Halpin thermal-fatigue curve shown in Figure 1.c, it is clear that the strongly reduced 'factor of safety' for assemblies coated with Solithane and Scotchcast may be reason to preclude these materials from flight hardware.

b. The surface mount technology boards passed the 500-thermal-cycle requirement set out in ESA PSS-01-738, with the exception of one 400-cycle failure (Scotchcast). Additional Scotchcast-promoted failures were observed at 600, 700 and 800 cycles. One other intermittent failure was also noted at the 1000-cycle end of test (Solithane). The uncoated board and Mapsil-, CV1144-, Sylgard-, Uralane- and Conathane-coated boards survived the 1000 cycles. From these results it is apparent that Scotchcast should be forbidden for use as a spacecraft conformal-coating material, and that Solithane should only be considered if benign thermal-cycling environments are expected.

(2) It is not possible to identify electrically failed solder joints by visual-inspection methods alone. On the one hand, the continual plastic deformation of solder fillets surrounding **conventional component leads** causes surface discontinuities that may be described as folds, ridges, orange-peel effects and wide-mouthed cracks. 'Failures' can only be substantiated by electrical-continuity measurements or destructive metallography (see also [Ref.13]). Real electrical failures only ensue as a result of gross solder-fillet deformation (e.g. Figures 24-28). On the other hand, the hair-line cracks running through the solder fillets connecting the **surface mount devices** are impossible to detect by visual means (e.g. Figures 30-32). These are real catastrophic failures; at room temperature the fillets appear to be cosmetically defect-free, but electrically — particularly at elevated temperatures when the coating expands to lift the components up — these joints are completely open-circuit. ESA approval of all SMT assembly materials and processes [Ref.1] must rely on continuous electrical monitoring of circuits during verification testing.

(3) Microwire wedge bonds are extremely sensitive to the mechanical stresses and strains imposed on them by the conformal coatings during thermal cycling. In the absence of coatings, the wedge bonds survive 1000 thermal cycles. When these aluminium microwire bonds are embedded, however, stretching is caused, resulting in electrical failure after only 100 thermal cycles in the case of Solithane, Conathane or Scotchcast, after 200 cycles in that of Uralane, after 300 cycles in that of Sylgard, after 400 cycles in that of Mapsil and after 500 cycles in that of CV1144.

The influence of each coating type on the order of wedge bond failures is seen to be duplicated in the sequence for solder-joint failures.

(4) Practical exercises that have been performed by operators, trained and certified to follow the ESA repair procedures [Ref.6], have confirmed that the silicone conformal coatings are far easier to remove than the polyurethanes from both conventional and surface-mounted board assemblies. It was extremely difficult to remove the epoxy coating from both leaded and leadless components or to prepare the pcb surfaces for component replacement.

(5) The permeability to water of the various coating materials was evaluated by the humidity test. The epoxy-glass comb pattern laminates are less sensitive to humidity than polyimide-glass since, as is well known, the latter laminate possesses a far higher water-absorption rate. The coatings that withstand highly humid environments best are considered to be, in order of merit, CV1144, Solithane 113, Mapsil 213 and Sylgard 184.

(6) All coatings survived the life test (125°C for 500 hours), although Conathane darkened considerably and caused a slight reduction in surface insulation resistance.

(7) Isopropyl alcohol had very little effect on the surface insulation resistance of comb patterns covered with any of the conformal coatings. In this respect it can be regarded as a suitable cleaning liquid for fabricated spacecraft circuits. Freon is now a non-approved solvent, owing to its ozone-depleting effect in the stratosphere, but in any case it was found to damage the silicone coatings. Trichloroethane with 7% isopropyl alcohol caused the most damage and should be excluded from all applications where it could come into contact with any of the conformal coatings.

(8) The mechanical properties of each coating type have been measured over a range of temperatures from $-100°C$ to $+150°C$. The silicone coatings can be seen to retain their flexibility down to $-100°C$, which makes them the preferred coating materials when thermal-cycling stresses are likely to be imposed on soldered connections. The polyurethane coatings possess good flexibility but a rather high strength and elastic modulus at low temperatures. The epoxy coating has the highest room-temperature strength and a poor elongation which causes it to impose the greatest stress on interconnections during conditions of thermal

fatigue; it also was seen to separate from component surfaces and delaminate from/or cause delamination of pcbs in the vicinity of soldered joints.

(9) The results of this evaluation programme indicate that there is no one conformal coating best suited for all spacecraft applications. However, in order to provide advice on the suitability of each coating for a given service life or environment an 'order of merit' table (Table XIII) has been drawn up. This also includes the question of cost, since it should be noted that the extra processing steps and controls required to ensure a low outgassing of the clean silicone coatings does markedly increase their price per kilo. Table XIII can be consulted if one wishes to discover any particularly advantageous or unfavourable feature of a given coating, details of which can then be located in the text of this report.

5. Recommendations for further work

The reliability of both conventional leaded components and leadless surface-mount devices, solder-assembled on to pcbs has been studied by numerous authors and attempts have been made, with some degree of success, to correlate experimental thermal-cycling test data with three-dimensional nonlinear finite-element analysis. The thermal-fatigue life of such joints has been calculated on the basis of plastic strain, Coffin-Manson law and isothermal fatigue data on solder alloy [Ref.14]. Zafran, Engelmaier and Solomon have presented data relating shear strain range to solder fatigue life [Ref.15-17]. In all these studies, the test sample has consisted of component-assembled pcbs **without the presence of a conformal coating**.

The severity of the service environment of particular spacecraft electronic assemblies depends on dozens of factors. These are, to start with, the thermal excursions undergone during production (i.e. wave soldering, bake-out, curing of conformal coating etc.), while others operate during testing (ground operation at elevated temperatures), during launch (acceleration, shock, vibration and acoustic noise) and during operation (thermal cycling due to exposure to sun and eclipse, power cycling in vacuum where heat flux is dissipated by conduction through the solder joint).

Numerous laboratory failure analyses performed by the present authors have identified vibrational fatigue failures during launch simulation testing of spacecraft electronics; both leaded and leadless components have broken free from pcbs in locations either where conformal coatings were absent or where the bodies of leaded components had stood proud of the coatings. In the light of this experience, coatings are considered to be important for enhancing the overall reliability of spacecraft electronics.

The authors wish to make the following recommendations for further work:

(a) Existing mathematical models should be reviewed and adaptations and developments should be made with the aim of developing improved expressions for the simulation of conformally coated assemblies.

(b) The results of the present study suggest that silicone conformal coatings are to be preferred as a means of minimising the coatings' contribution to thermal fatigue. These materials have a low modulus of elasticity and are relatively weak. They need to be further assessed to ensure that they provide mounted components with sufficient support to avoid failure as a result of vibrational fatigue.

(c) It is possible that legislation will be introduced to restrict or even eliminate the use of lead in electronic solders. Moreover, on the technical side, it may be possible to produce solder joints that are more resistant to fatigue by utilising non-standard solder alloys, including those based on bismuth-tin. Many new lead-free solder alloys have already been evaluated and presented at recent meetings ('Brasage 93' in Lannion, France, 14-16 September 1993, and the Eighth Electronic Materials and Processing Congress, San José, CA, USA, 30 August-2 September 1993). Although, at the time of writing, none of the proposed alloys have been found to possess an overall performance as good as tin-lead eutectic, some effort should be made to identify alternative viable lead-free electronic solders.

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TABLE I
Flow diagram of test programme with reference to Specimens 1, 2 & C

Specimen 1	**Specimen 2**
Solder assembly of conventional components into plated-through holes of glass-polyimide double-sided pcbs (Figure 2)	Vapour-phase assembly of surface-mounted devices, including open leadless chip carrier containing ultrasonic-bonded wires (referenced **SPECIMEN C**), onto multilayer (mlb) pcbs having quartz-polyimide laminate with Cu-Mo-Cu interlayers (Figs 3 & 4)
8 boards	**8 boards**

↓

- 1 board kept uncoated (e.g. one Specimen 1 and one Specimen 2 supporting two Specimen C's unfilled with coating).
- 7 coating materials were applied to Specimens 1, 2 and C.

↓

***Simulated repair* of every component type on each pcb and mlb** (i.e. coating removal, component removal/replacement and further coating application)

↓

Thermal cycling ($-55°C$ to $+100°C$, ΔT of $10°C$ per minute with 15 minute dwell time)
Electrical monitoring of each component and connection on Specimens 1, 2 and C, at intervals of every 100 thermal cycles until 1000 cycles.

↓

Visual inspection, macrophotography of joints and metallography of interesting features on interconnections as they developed during thermal cycling.

TABLE II
Identification of specimens 3, D, E & F

All specimens were manufactured within the shelf life of the unmixed coatings and in the same time period.

Specimen 3 (Comb patterns)
Comb patterns for the surface insulation resistance (SIR) and capacitance testing of glass-epoxy and polyimide laminates, either bare or supporting one of the seven conformal coatings under evaluation.

Set 1	Set 2	Set 3
Humidity exposure	High temperature storage	Resistance to cleaning solvents

Specimen D (Flat sheet)

Outgassing	Flammability	Offgassing and Toxicity

Tensile Testing at −100°C, +20°C and +150°C
Coefficient of thermal expansion

Specimen E
Shear Testing at −55°C, +20°C and +10°C

Specimen F (Large blocks)
Hardness testing (4 different methods)

Table III: Conformal coating processing parameters and summarised observations

Varnish	From manufacturer's data sheets	Actual specimen preparation (all applied with paint brush)	Observations during preparation
CV 1144-0	Type: silicone Temperature range: −115 to +200°C Mixture: 1 part Polymerisation: 25°C/24h Working time: 30 g/15mn Glass transition: $T_g = -100$°C	Application to component side of pcb with pre-curing polymerisation of 1 h at 25°C, then application to solder side (back) with full polymerisation of 24 h at 25°C	Colour: transparent Odour: petrol Very soft varnish; spray application possible Application: easy Cost (1994) for 1 kg: 18 000 FF
MAPSIL 213	Type: silicone Temperature range: −100 to +200°C Mixture: 100 parts A + 10 parts B Polymerisation: 65°C/24 h Working time: 2 h/25°C Glass transition: $T_g = -117$°C	Two parts were mixed for 4 mn, vacuum degassed at 0.1 torr until bubbles disappeared. Application to component side of pcb with pre-curing polymerisation of 5 h at 65°C, then application to solder side (back) with full polymerisation of 24 h at 65°C	Colour: transparent Odour: none MAPSIL is refined SYLGARD 184 Application: easy Cost (1994) for 1 kg: 12 000 FF
SYLGARD 184	Type: silicone Temperature range: −65 to +200°C Mixture: 10 parts A + 1 part B Polymerisation: 65°C/18 h Working time: 2 h/25°C Glass transition: $T_g = -110$°C	Two parts were mixed for 4 mn, vacuum degassed at 0.1 torr until bubbles disappeared. Application to component side of pcb with pre-curing polymerisation of 3 h at 65°C, then application to solder side (back) with full polymerisation of 5 h at 65°C	Colour: transparent Odour: none Used normally for manned spacecraft Application: easy Cost (1994) for 1kg: 800 FF
SCOTCH-CAST 280	Type: epoxy Temperature range: −55 to +130°C Mixture: 10 parts A + 15 parts B Polymerisation: 65°C/18 h Working time: 5 h/25°C Glass transition: $T_g = -70$°C	Two parts were mixed for 4 mn, preheated to 60°C, vacuum degassed at 0.1 torr until bubbles disappeared. Application to component side of pcb after preheating to 50°C. Polymerisation of 3 h at 65°C. Then application to solder side (back) with full polymerisation of 1 h/50°C + 1 h/60°C + 16 h/80°C	Colour: transparent Odour: none Application: difficult Cost (1994) for 1 kg: 400 FF
CONA-THANE EN 11	Type: polyurethane Temperature range: −70 to +135°C Mixture: 10 parts A + 5.5 parts B Polymerisation: 60°C/24 h Working time: 2 h at 25°C Glass transition: $T_g = -65$°C	Two parts were mixed for 4 mn, preheated to 60°C, vacuum degassed at 0.1 torr until bubbles disappeared. Application to component side of pcb with pre-curing polymerisation of 4 h at 65°C, then application to solder side (back) with full polymerisation of 24 h at 60°C	Colour: transparent (amber) Odour: strong after polymerisation Application: easy Cost (1994) for 1 kg: 300 FF
SOLI-THANE 113	Type: polyurethane Temperature range: −65 to +120°C Mixture: 100 parts A + 73 parts C 113 300 Polymerisation: 65°C/12 h Working time: 2 h at 25°C Glass transition: $T_g = -10$°C	Two parts were mixed for 4 mn, preheated to 60°C, vacuum degassed at 0.1 torr until bubbles disappeared. Application to component side of pcb with pre-curing polymerisation of 3 h at 65°C, then application to solder side (back) with full polymerisation of 12 h at 65°C	Colour: transparent (amber) Odour: strong after polymerisation; dangerous to health Application: easy Cost (1994) for 1 kg: 720 FF
URALANE 5750LV	Type: polyurethane Temperature range: −65 to +100°C Mixture: 18 parts A + 100 parts B Polymerisation: 65°C/9 h Working time: 2 h at 25°C Glass transition: $T_g = -65$°C	Two parts were mixed for 4 mn, vacuum degassed at 0.1 torr until bubbles disappeared. Application to component side of pcb with pre-curing polymerisation of 3 h at 65°C, then application to solder side (back) with full polymerisation of 9 h at 65°C	Colour: transparent (pink) Odour: petrol Difficult to find in France Application: easy Cost (1994) of 1 kg: 500 FF

Table IV(A): Summary of electric failures for each conformal coating under study as a function of number of thermal cycles (plated-through hole type pcb)

Specimen	*Cycles*	100						200						300						400						500					
		T1	T2	T3	D1	D2	D3	T1	T2	T3	D1	D2	D3	T1	T2	T3	D1	D2	D3	T1	T2	T3	D1	D2	D3	T1	T2	T3	D1	D2	D3
	Uncoated assembly																														
	MAPSIL 213																														
1	CV 1144-0																														
plated	SYLGARD 184																														
through	URALANE 5750LV																														
hole	SOLITHANE 113													X						X	X	X				X	X	X			
	CONATHANE EN11																										X				
	SCOTCHCAST 280																			X	X	X				X	X	X			

Specimen	*Cycles*	600						700						800						900						1000					
		T1	T2	T3	D1	D2	D3	T1	T2	T3	D1	D2	D3	T1	T2	T3	D1	D2	D3	T1	T2	T3	D1	D2	D3	T1	T2	T3	D1	D2	D3
	Uncoated assembly																														
	MAPSIL 213																														
1	CV 1144-0																														
plated	SYLGARD 184																														
through	URALANE 5750LV		X					X	X	X				X	X	X				X	X	X				X	X	X			
hole	SOLITHANE 113	X	X	X				X	X	X				X	X	X				X	X	X				X	X	X			
	CONATHANE EN11	X	X	X				X	X	X				X	X	X				X	X	X				X	X	X			
	SCOTCHCAST 280	X	X	X				X	X	X				X	X	X				X	X	X				X	X	X			

Note: X = open circuit

Table IV (B1 & B2): Summary of electrical failures for each conformal coating under study versus the number of thermal cycles (surface mounting technique pcb)

Specimen	*Cycles*	100								200								300								400								500							
		Z1	Z2	Z3	Z4	Z5	C1	C2	C3	Z1	Z2	Z3	Z4	Z5	C1	C2	C3	Z1	Z2	Z3	Z4	Z5	C1	C2	C3	Z1	Z2	Z3	Z4	Z5	C1	C2	C3	Z1	Z2	Z3	Z4	Z5	C1	C2	C3
	Uncoated assembly																																								
	MAPSIL 213																										X							X	X						
2	CV 1144-0																																	X							
surface	SYLGARD 184																	X	X							X	X							X	X						
mounting	URALANE 5750LV									X								X								X								X							
tech-	SOLITHANE 113	X	X							X	X							X	X							X	X							X	X						
nology	CONATHANE EN11	X	X							X	X							X	X							X	X							X	X						
	SCOTCHCAST 280	X	X							X	X							X	X							X	X			X				X	X			X			

Note: Specimens Z1 and Z2 have daisy-chained internal connections identical to those on Z3, Z4 and Z5, but are without a package lid and, unless 'uncoated', are filled with the coating being tested.
(? = intermittent open circuit. X = totally open circuit

Specimen	*Cycles*	600								700								800								900								1000							
		Z1	Z2	Z3	Z4	Z5	C1	C2	C3	Z1	Z2	Z3	Z4	Z5	C1	C2	C3	Z1	Z2	Z3	Z4	Z5	C1	C2	C3	Z1	Z2	Z3	Z4	Z5	C1	C2	C3	Z1	Z2	Z3	Z4	Z5	C1	C2	C3
	Uncoated assembly																																								
	MAPSIL 213	X	X							X	X							X	X							X	X							X	X						
2	CV 1144-0	X								X								X	?							X								X	?						
surface	SYLGARD 184	X	X							X	X							X	X							X	X							X	X						
mounting	URALANE 5750LV	X								X								X	X							X	X							X	X						
tech-	SOLITHANE 113	X	X							X	X							X	X							X	X							X	X			?			
nology	CONATHANE EN11	X	X							X	X							X	X							X	X							X	X						
	SCOTCHCAST 280	X	X	X		X				X	X	X	X	X				X	X	X	X	X				X	X	X	X	X				X	X	X	X	X			

Note: Specimens Z1 and Z2 have daisy-chained internal connections identical to those on Z3, Z4 and Z5, but are without a package lid and, unless 'uncoated', are filled with the coating being tested.
(? = intermittent open circuit. X = totally open circuit

Table V: Results of humidity test on epoxy comb pattern

	Humidity test on epoxy (classification after 161 h)									
	$R_{insulation}$ ($\times 10^7$ MΩ)					Capacity (pF)				
Varnish type	before	after 8 h	after 9 h	after 160 h	after 161 h	before	after 8 h	after 9 h	after 160 h	after 161 h
SYLGARD 184	6	0.35	4	4	4	24.3	24.4	24.1	24.9	24.6
URALANE 5750LV	4	0.4	3.5	5	4	23.7	23.5	23.3	24	23.6
MAPSIL 213	2	0.5	2.5	3	3	25.2	24.6	24.5	25.2	25.4
CONATHANE EN 11	5	0.8	3	1	2.5	24.4	24.7	24.5	26	24.9
SCOTCH-CAST 280	5	0.45	3	1.5	2	23.9	24.2	23.4	24.4	24.4
CV 1144-0	3	0.4	3	1	1	23.2	23	22.9	23.3	23.3
SOLITHANE 113	2	0.35	0.8	0.3	0.6	24.9	25.7	25.3	26.4	25.5

Three uncoated samples: $R_{insulation} = 5 \times 10^7$ MΩ capacity = 18.3 pF
1×10^5 MΩ 19.1 Pf
1×10^7 MΩ 18.4 pF

Table VI: Results of humidity test on polyimide comb pattern

	Humidity test on polyimide (classification after 161 h)									
	$R_{insulation}$ ($\times 10^7$ MΩ)					Capacity (pF)				
Varnish type	before	after 8 h	after 9 h	after 160 h	after 161 h	before	after 8 h	after 9 h	after 160 h	after 161 h
SYLGARD 184	3	0.6	0.65	0.09	0.2	25.3	25.1	24.8	25.8	25.7
URALANE 5750LV	2	0.45	0.45	0.06	0.1	23.7	23.4	23.2	25.1	23.9
MAPSIL 213	1.5	0.5	0.4	0.15	0.2	24.5	24.1	24	24.6	25
CONATHANE EN 11	1.5	0.3	0.3	0.025	0.045	24.6	25.5	24.7	26	25.3
SCOTCH-CAST 280	1.5	0.5	0.45	0.1	0.15	24.6	24.6	24	25	24.6
CV 1144-0	2	45	35	15	25	23.2	23.4	22.7	24	23.4
SOLITHANE 113	2	0.35	0.35	0.3	0.45	24.5	25.5	25	26.4	25.6

Three uncoated samples: $R_{insulation}$ = 9×10^6 MΩ capacity = 19.6 pF
2×10^7 MΩ 20.0 Pf
6×10^6 MΩ 19.6 pF

Table VII: Results of life test on epoxy comb pattern

Life test epoxy (125°C for 500 h)				
Varnish type	$R_{insulation}$ ($\times 10^7 M\Omega$)		Capacity (pF)	
	before	after	before	after
CONATHANE EN11	2	1	25.5	25.4
CV 1144-0	3	60	23.6	23.7
MAPSIL 213	2	30	24	24.3
SCOTCHCAST 280	4	20	23.4	22.9
SOLITHANE 113	3	5	25.9	25.7
SYLGARD 184	2	20	25.2	24.7
URALANE 5750LV	10	>100	22.8	23.7

Table VIII: Results of life test on polyimide comb pattern

Life test polyimide (125°C for 500 h)				
Varnish type	$R_{insulation}$ ($\times$ 10^7MΩ)		Capacity (pF)	
	before	after	before	after
CONATHANE EN11	2	1.5	24.6	23.8
CV 1144-0	2	>100	23.1	21.8
MAPSIL 213	2	30	24.9	23.9
SCOTCHCAST 280	2	>100	24.4	22.9
SOLITHANE 113	1.5	8	24.8	24.7
SYLGARD 184	2	20	24.8	23.7
URALANE 5750LV	4	>100	22.7	22.9

Table IX: Results of special space materials tests on conformal coatings

			RESULTS						
			Polyurethane			Silicone varnish			Epoxy
Test	*Test specification*	*Accept/reject criteria (if any)*	*Conathane EN11*	*Solithane 113*	*Uralane 5750LV*	*CV1144*	*Mapsil 213*	*Sylgard 184*	*Scotchcast 280*
Outgassing* under vacuum	ESA PSS-01-702	Total mass loss (TML $\leq$ 1.0%)	0.50	0.45	0.60	0.28	0.44	1.46	0.63
		Recovered mass loss (RML)	0.33	0.26	0.51	0.28	0.44	1.45	0.43
		Collected volatile condensed material (CVCM) $\leq$ 0.1%	0.00	0.02	0.00	0.03	0.10	0.65	0.04
Offgassing and toxicity	NASA NHB 8060-1B	ppm CH_4	2.33	2.68	2.47	2.44	5.36	14.50	2.47
		μg/g CO $\leq$ 25 ppm	0.63	0.31	0.39	0.83	0.40	0.59	0.85
		μg/total organics $\leq$ 100 μg/g	38.23	17.65	52.48	59.30	25.42	19.95	46.37
Flammability in 24.5% oxygen, rest nitrogen	NASA NHB 8060-1B (Test 1)	Whether the material propagated flame upwards or not	Failed (thick smoke, large heat output)	Failed (burning droplets expelled)	Failed thick smoke, large heat output)	Passed (extinguished itself)	Passed (extinguished itself)	Passed (extinguished itself)	Failed (thick smoke, large heat output)
Thermal cycling (Para. 3.2.1)	ESA PSS-01-738	After application to surface-mount technology pcbs	Intermediate	Poor	Good	Good	Good	Good	Poor
Repairability (Para. 3.1)	ESA PSS-01-728	Ease of removal/reapplication	Difficult	Intermediate	Difficult	Good	Good	Good	Very difficult

* Test runs 1716 and 1717, see Ref. 10 for results on other batches.

Table X: Mechanical properties of conformal coatings at various temperatures

			RESULTS						
			Polyurethane			Silicone varnish			Epoxy
Test	*Sample characteristics*	*Test temperature (degrees Celsius)*	*Conathane EN11*	*Solithane 113*	*Uralane 5750LV*	*CV1144*	*Mapsil 213*	*Sylgard 184*	*Scotchcast 280*
Shear strength	Aluminium plate 25 mm wide with 12 mm overlap containing coating (units: N mm^{-2})	+100	0.6	2.0	1.9	1.9	2.2	4.2	1.7
		+20	2.6	5.2	5.8	2.7	2.9	5.5	17.4
		−55	13.1	29.5	22.0	1.7	3.5	6.8	30.6
Tensile tests	Dumbbell having 60 mm gauge length, 12 mm wide								
Ultimate tensile strength	UTS (units: N mm^{-2})	+150	0.5	0.6	0.4	0.3	1.2	2.7	–
		+20	2.8	1.8	1.4	0.3	1.3	3.6	10.6
		−100	56.8	79.5	59.0	0.5	12.1	9.6	35.1
Modulus	E (units: N mm^{-2})	+150	2.1	5.4	1.7	0.6	1.2	2.8	–
		+20	3.7	4.1	3.8	0.6	1.1	1.7	445.0
		−100	2606.0	1661.0	1923.0	0.8	529.0	27.7	1859.0
Elongation	(unit: %e)	+150	45.0	11.2	36.3	47.5	93.6	69.9	–
		+20	260.0	55.0	85.0	83.3	104.1	70.8	42.0
		−100	50.0	14.3	83.6	166.6	149.3	141.0	2.0

T9 T8
-75 -6

Table XI: Results of room temperature hardness measurements

Sample designations	Readings (IRHD)						Test condition
	1	2	3	4	5	Average	
CV 1144-0	33	29	28	28	31	29	IRHD
	23	22	22	21	22	22	Instantaneous A
	23	22	22	21	22	22	15 seconds A
MAPSIL 213	32	33	33	33	33	33	IRHD
	34	35	35	34	35	35	Instantaneous A
	34	35	35	34	35	35	15 seconds A
SYLGARD 184	50	50	50	50	50	50	IRHD
	53	53	53	53	54	53	Instantaneous A
	53	53	53	53	54	53	15 seconds A
SCOTCHCAST 280	>99.5	>99.5	>99.5	>99.5	>99.5	>99.5	IRHD
	99	99	99	99	99	99	Instantaneous A
	99	99	99	99	99	99	15 seconds A
CONATHANE EN11	56	55	57	57	55	56	IRHD
	68	73	72	64	69	69	Instantaneous A
	58	60	61	57	56	58	15 seconds A
SOLITHANE 113	63	63	63	63	63	63	IRHD
	63	64	65	64	64	64	Instantaneous A
	63	64	65	64	64	64	15 seconds A
URALANE 5750 LV	59	58	59	60	59	59	IRHD
	59	57	60	57	60	59	Instantaneous A
	58	57	59	57	59	58	15 seconds A

IRHD — International Rubber Hardness Degrees
A — Indentation hardness using a shore A durometer

Table XII: Results of coefficient of thermal expansion measurements
(CTE: $1 \times 10^{-6}\ °C^{-1}$)

Material	**Temperature (°C)**					
	−100	**−55**	**+20**	**+100**	**+150**	**+200**
Conformal coating*						
Polyurethane						
Conathane EN11	66	66	120	229	229	n/a
Solithane 113	87	87	transition	212	softening	n/a
Uralane 5750 LV	120	120	172	270	270	n/a
Silicone						
CV-1144			Too soft to measure			
MAPSIL 213	576	245	310	263	145	n/a
Sylgard 184	696	804	309	205	278	n/a
Epoxy						
Scotchcast 280	78	78	78	213	207	n/a
Printed circuit board*						
Glass-epoxy G10						
x direction	13	13	13	13	13	13
z direction	39	39	39	50	340	340
Glass-polyimide						
x direction	14	14	15	15	15	15
z direction	37	37	38	42	41	41
Quartz polyimide						
Cu-Mo-Cu						
x direction	9	9	8	8	7	6
z direction	28	28	28	34	65	73
Metals						
Solder 63Sn37Pb	17	16	15	15	15	15
Kovar	5	5	5	5	5	5
Dumet	6	6	6	6	6	6
Copper	17	17	17	17	17	17
Brass, 70Cu30Zn	19	19	19	19	19	19
Aluminium (6061T-6)	24	24	24	24	24	24
Molybdenum	5	5	6	6	6	6
Ceramics						
Alumina	6	6	6	7	7	7
Beryllia	9	9	9	9	9	9
Silicon carbide	3	3	4	4	4	4

* From present study n/a not available

Table XIII: Overall order of merit table

Coating type	Cost	Process	Repair	Solvent resistance	Humidity	Life test	Resistance to thermal cycling environment: Surface mount	Resistance to thermal cycling environment: Leaded components	Resistance to thermal cycling environment: Microwire bonds	Outgassing	Manned spacecraft	Total
	7=dear 1=cheap	7=com-plicated 1=simple	7=difficult 1=easy	1=good 7=poor	1=good 7=poor	1=good 7=poor	1=best 7=poor			1=good 7=fail	1=good 4=fail	
CV 1144-0	7	2	1	5	1	1	1	1	1	1	1	22
MAPSIL 213	6	1	2	6	3	4	1	1	2	6	1	33
URALANE 5750 LV	3	3	5	1	6	1	1	4	4	4	4	36
SYLGARD 184	5	6	3	7	3	5	1	1	3	7	1	42
CONA-THANE EN11	1	5	6	1	7	7	1	5	5	1	4	43
SOLITHA-NE 113	4	4	4	1	2	6	6	7	6	1	4	45
SCOTCH-CAST 280	2	7	7	1	5	1	7	6	7	4	4	51
Details in Para.	2.2	2.2	3.1	3.2.4	3.2.2	3.2.3	3.2.1			3.2.5	3.2.5	4

ANNEX I

Electrical results for the leaded components (specimens 1) during thermal cycling to 1000 cycles

REFERENCE		
Varnish: **none**	Phase: **THERMAL CYCLES**	

cycles	T1 mV	T2 mV	T3 mV	D1 mV	D2 mV	D3 mV
0	63	59	67	677	688	678
100	61	59	69	675	687	676
200	62	59	67	679	690	681
300	62	59	67	677	688	678
400	62	58	67	674	685	678
500	62	59	67	676	687	677
600	62	59	67	682	693	682
700	62	59	67	677	688	678
800	62	59	67	676	687	677
900	62	59	68	676	687	677
1000	62	62	68	678	689	679

X = connection open   * = unstable measurement

SILICONE	Specimen no. **1**	**no. 1.4**
Varnish: **CV 1144-0**	Phase: **THERMAL CYCLES**	

cycles	T1 mV	T2 mV	T3 mV	D1 mV	D2 mV	D3 mV
0	57	65	66	678	675	664
100	57	65	67	674	671	661
200	57	65	67	678	675	665
300	57	65	67	676	673	662
400	57	65	65	678	675	665
500	58	64	68	675	672	661
600	57	65	65	673	671	660
700	57	65	66	676	673	663
800	57	65	65	681	678	667
900	57	65	66	676	674	663
1000	57	65	66	675	672	661

X = connection open   * = unstable measurement

SILICONE	Specimen no. **1**	**no. 2.3**
Varnish: **MAPSIL 213**	Phase: **THERMAL CYCLES**	

cycles	T1 mV	T2 mV	T3 mV	D1 mV	D2 mV	D3 mV
0	68	62	63	661	669	690
100	63	62	63	662	670	691
200	63	62	63	664	672	692
300	63	62	63	661	668	689
400	64	62	63	662	670	690
500	64	62	62	659	666	687
600	62	62	63	660	667	688
700	63	62	63	661	669	689
800	64	62	63	667	674	695
900	63	62	63	661	669	689
1000	63	62	63	661	668	689

X = connection open * = unstable measurement

SILICONE	Specimen no. **1**	**no. 3.1**
Varnish: **SYLGARD 184**	Phase: **THERMAL CYCLES**	

cycles	T1 mV	T2 mV	T3 mV	D1 mV	D2 mV	D3 mV
0	64	56	67	679	677	662
100	64	56	67	679	677	662
200	64	56	67	679	676	662
300	64	56	67	676	670	656
400	64	56	67	679	677	662
500	65	56	67	678	676	661
600	64	56	68	675	673	658
700	64	56	67	677	675	661
800	63	56	68	682	680	665
900	65	56	66	676	677	659
1000	64	56	67	677	675	660

X = connection open * = unstable measurement

POLYURETHANE	Specimen no. 1	no. 2.2
Varnish: **CONATHANE EN11**	Phase: **THERMAL CYCLES**	

cycles	T1 mV	T2 mV	T3 mV	D1 mV	D2 mV	D3 mV
0	62	66	60	665	671	672
100	62	65	61	663	671	673
200	63	65	61	666	674	675
300	62	66	61	664	673	674
400	61	66	63	665	673	674
500	63	*	61	663	671	671
600	X	X	X	663	671	672
700	X	X	X	665	672	673
800	X	X	X	670	678	679
900	X	X	X	665	673	673
1000	X	X	X	665	673	674

X = connection open   * = unstable measurement

POLYURETHANE	Specimen no. 1	no. 1.3
Varnish: **SOLITHANE 113**	Phase: **THERMAL CYCLES**	

cycles	T1 mV	T2 mV	T3 mV	D1 mV	D2 mV	D3 mV
0	63	58	65	680	683	683
100	63	58	65	681	684	684
200	65	57	64	683	685	686
300	*	51	57	680	682	683
400	*	*	*	682	685	684
500	*	*	*	678	684	684
600	X	X	X	678	682	682
700	X	X	X	680	683	683
800	X	X	X	685	688	688
900	X	X	X	679	682	682
1000	X	X	X	680	683	683

X = connection open   * = unstable measurement

POLYURETHANE	Specimen no. **1**	**no. 1.2**
Varnish: **URALANE 5750 LV**	Phase: **THERMAL CYCLES**	

cycles	T1 mV	T2 mV	T3 mV	D1 mV	D2 mV	D3 mV
0	59	67	60	667	676	684
100	58	68	60	663	671	679
200	59	67	59	668	676	685
300	59	68	60	665	673	682
400	58	67	60	666	675	684
500	59	68	59	666	674	682
600	58	*	58	664	672	680
700	*	X	*	665	673	682
800	*	X	*	669	678	686
900	*	X	X	664	673	680
1000	X	X	X	665	674	682

X = connection open   * = unstable measurement

EPOXY	Specimen no. **1**	**no. 2.4**
Varnish: **SCOTCHCAST 280**	Phase: **THERMAL CYCLES**	

cycles	T1 mV	T2 mV	T3 mV	D1 mV	D2 mV	D3 mV
0	56	68	68	681	686	692
100	57	67	67	678	683	688
200	63	67	66	682	687	693
300	59	69	68	678	684	688
400	65	*	74	681	686	692
500	*	X	X	678	683	688
600	*	X	X	676	680	686
700	X	X	X	680	685	691
800	X	X	X	684	689	695
900	X	X	X	677	683	689
1000	X	X	X	679	685	690

X = connection open   * = unstable measurement

ANNEX II

Electrical results for the surface mounted devices (specimens 2) and the wedge bonds (specimens C) during thermal cycling to 1000 cycles

REFERENCE	Specimen no. **2**	**no.3.1**
Varnish: **none**	Phase: **THERMAL CYCLES**	

cycles	Z1	Z2	Z3	Z4	Z5	C1		C2		C3	
	mΩ	mΩ	mΩ	mΩ	mΩ	pF	D	pF	D	pF	D
0	2529	2724	2299	2440	2744	2731	0,0010	2753	0,0011	2806	0,0012
100	2707	2521	2289	2437	2739	2735	0,0018	2757	0,0018	2811	0,0020
200	2708	2521	2288	2434	2736	2732	0,0014	2754	0,0017	2807	0,0018
300	2702	2521	2302	2443	2743	2732	0,0015	2754	0,0017	2807	0,0018
400	2722	2539	2302	2450	2757	2730	0,0015	2752	0,0018	2805	0,0019
500	2726	2542	2311	2468	2772	2731	0,0016	2752	0,0018	2805	0,0018
600	2744	2553	2324	2476	2778	2731	0,0014	2753	0,0016	2806	0,0018
700	2726	2539	2314	2467	2770	2732	0,0014	2754	0,0017	2807	0,0018
800	2716	2534	2323	2468	2767	2731	0,0012	2753	0,0015	2806	0,0017
900	2758	2560	2344	2497	2794	2730	0,0015	2752	0,0017	2805	0,0019
1000	2756	2565	2352	2498	2799	2730	0,0017	2752	0,0017	2805	0,0019

SILICONE	Specimen no. **2**	**no. 2.2**
Varnish: **CV 1144-0**	Phase: **THERMAL CYCLES**	

cycles	Z1	Z2	Z3	Z4	Z5	C1		C2		C3	
	mΩ	mΩ	mΩ	mΩ	mΩ	pF	D	pF	D	pF	D
0	2333	2554	2438	2699	2397	2766	0,0009	2824	0,0010	2788	0,0013
100	2346	2568	2450	2728	2418	2765	0,0015	2820	0,0018	2787	0,0019
200	2338	2558	2441	2719	2411	2765	0,0015	2820	0,0017	2788	0,0019
300	2337	2558	2440	2718	2415	2770	0,0016	2825	0,0018	2793	0,0020
400	2331	2549	2429	2720	2416	2766	0,0014	2821	0,0016	2789	0,0018
500	*	2573	2441	2730	2430	2766	0,0015	2821	0,0017	2789	0,0018
600	X	2582	2457	2752	2452	2764	0,0015	2720	0,0017	2788	0,0020
700	X	2585	2458	2758	2460	2765	0,0016	2820	0,0018	2788	0,0020
800	X	2614	2475	2778	2475	2765	0,0014	2821	0,0016	2789	0,0018
900	X	2597	2468	2781	2475	2766	0,0015	2821	0,0016	2789	0,0019
1000	X	2608	2475	2793	2488	2765	0,0013	2821	0,0016	2789	0,0018

X = Connection open

* = Unstable measuremnt

SILICONE	Specimen no. **2**	**no. 3.4**
Varnish: **MAPSIL 213**	Phase: **THERMAL CYCLES**	

cycles	Z1	Z2	Z3	Z4	Z5	C1		C2		C3	
	mΩ	mΩ	mΩ	mΩ	mΩ	pF	D	pF	D	pF	D
0	2395	2531	2663	2459	2300	2786	0,0011	2737	0,0014	2743	0,0013
100	2417	2549	2683	2475	2312	2785	0,0015	2736	0,0018	2742	0,0019
200	2400	2540	2676	2470	2306	2785	0,0015	2736	0,0017	2743	0,0019
300	2415	2543	2677	2473	2307	2790	0,0016	2741	0,0018	2748	0,0021
400	2409	*	2663	2456	2292	2786	0,0014	2737	0,0016	2744	0,0019
500	X	X	2703	2497	2327	2786	0,0016	2738	0,0018	2744	0,0020
600	X	X	2694	2486	2323	2785	0,0016	2736	0,0018	2743	0,0021
700	X	X	2706	2499	2330	2785	0,0016	2736	0,0018	2743	0,0020
800	X	X	2699	2499	2328	2785	0,0013	2737	0,0016	2743	0,0018
900	X	X	2700	2502	2333	2786	0,0015	2737	0,0017	2744	0,0019
1000	X	X	2712	2511	2338	2785	0,0014	2737	0,0016	2743	0,0019

X = Connection open   * = Unstable measuremnt

SILICONE	Specimen no. **2**	**no. 3.3**
Varnish: **SYLGARD 184**	Phase: **THERMAL CYCLES**	

cycles	Z1	Z2	Z3	Z4	Z5	C1		C2		C3	
	mΩ	mΩ	mΩ	mΩ	mΩ	pF	D	pF	D	pF	D
0	2471	2739	2614	2670	2569	2751	0,0009	2768	0,0011	2739	0,0012
100	2476	2744	2628	2683	2580	2751	0,0015	2768	0,0016	2739	0,0018
200	2468	2726	2614	2666	2564	2751	0,0015	2768	0,0017	2739	0,0019
300	*	X	2625	2672	2566	2755	0,0017	2773	0,0017	2744	0,0019
400	X	X	2605	2660	2553	2752	0,0013	2769	0,0015	2740	0,0017
500	X	X	2635	2686	2574	2752	0,0016	2769	0,0017	2741	0,0018
600	X	X	2634	2692	2584	2750	0,0015	2767	0,0018	2739	0,0015
700	X	X	2641	2703	2587	2751	0,0016	2768	0,0018	2739	0,0020
800	X	X	2669	2731	2611	2751	0,0015	2768	0,0016	2740	0,0019
900	X	X	2652	2709	2591	2752	0,0014	2769	0,0017	2740	0,0018
1000	X	X	2652	2713	2592	2750	0,0014	2767	0,0015	2740	0,0017

X = Connection open   * = Unstable measuremnt

POLYURETHANE	Specimen no. **2**	**no. 3.2**
Varnish: **CONATHANE EN11**	Phase: **THERMAL CYCLES**	

cycles	Z1	Z2	Z3	Z4	Z5	C1		C2		C3	
	mΩ	mΩ	mΩ	mΩ	mΩ	pF	D	pF	D	pF	D
0	2317	2838	2592	2053	2575	2776	0,0009	2795	0,0013	2799	0,0013
100	X	X	2643	2067	2589	2775	0,0016	2794	0,0018	2798	0,0020
200	X	X	2598	2048	2567	2775	0,0015	2794	0,0018	2799	0,0020
300	X	X	2613	2064	2584	2780	0,0017	2799	0,0018	2804	0,0021
400	X	X	2602	2061	2575	2776	0,0014	2795	0,0016	2800	0,0019
500	X	X	2634	2085	2581	2776	0,0015	2796	0,0018	2800	0,0020
600	X	X	2634	2092	2608	2775	0,0016	2794	0,0019	2799	0,0021
700	X	X	2634	2086	2599	2775	0,0017	2794	0,0019	2799	0,0021
800	X	X	2653	2099	2607	2776	0,0015	2795	0,0017	2800	0,0019
900	X	X	2650	2098	2602	2775	0,0016	2796	0,0017	2800	0,0020
1000	X	X	2647	2104	2607	2776	0,0015	2795	0,0017	2799	0,0019

X = Connection open   * = Unstable measuremnt

POLYURETHANE	Specimen no. **2**	**no. 4.3**
Varnish: **SOLITHANE 113**	Phase: **THERMAL CYCLES**	

cycles	Z1	Z2	Z3	Z4	Z5	C1		C2		C3	
	mΩ	mΩ	mΩ	mΩ	mΩ	pF	D	pF	D	pF	D
0	2322	2406	2743	2658	2569	2812	0,0009	2759	0,0012	2713	0,0012
100	X	X	2748	2663	2586	2811	0,0016	2758	0,0019	2712	0,0018
200	X	X	2746	2661	2583	2811	0,0015	2758	0,0018	2712	0,0019
300	X	X	2747	2660	2582	2817	0,0016	2763	0,0019	2717	0,0020
400	X	X	2755	2665	2584	2813	0,0015	2759	0,0017	2713	0,0018
500	X	X	2758	2674	2600	2813	0,0015	2759	0,0017	2713	0,0019
600	X	X	2771	2686	2612	2811	0,0016	2758	0,0018	2712	0,0020
700	X	X	2789	2684	2615	2811	0,0016	2758	0,0018	2712	0,0020
800	X	X	2803	2711	2636	2812	0,0015	2759	0,0017	2713	0,0018
900	X	X	2793	2696	2630	2813	0,0015	2759	0,0017	2713	0,0019
1000	X	X	2799	2713	*	2811	0,0013	2758	0,0017	2712	0,0018

X = Connection open   * = Unstable measuremnt

POLYURETHANE	Specimen no. **2**	**no. 2.4**
Varnish: **URALANE 5750 LV**	Phase: **THERMAL CYCLES**	

cycles	Z1 mΩ	Z2 mΩ	Z3 mΩ	Z4 mΩ	Z5 mΩ	C1 pF	C1 D	C2 pF	C2 D	C3 pF	C3 D
0	2689	2656	2633	2324	2582	2785	0,0010	2741	0,0009	2743	0,0013
100	2687	2673	2654	2343	2601	2784	0,0017	2740	0,0018	2747	0,0019
200	X	2663	2653	2341	2597	2784	0,0015	2740	0,0018	2743	0,0019
300	X	2652	2641	2328	2584	2789	0,0015	2745	0,0017	2748	0,0019
400	X	2650	2640	2326	2583	2785	0,0014	2741	0,0017	2744	0,0020
500	X	2663	2658	2340	2598	2786	0,0015	2742	0,0018	2744	0,0020
600	X	2666	2679	2358	2621	2784	0,0015	2740	0,0018	2743	0,0021
700	X	2675	2360	2358	2619	2784	0,0016	2740	0,0018	2743	0,0020
800	X	X	2704	2375	2634	2785	0,0014	2741	0,0017	2743	0,0019
900	X	X	2710	2383	2642	2785	0,0015	2741	0,0018	2744	0,0019
1000	X	X	2672	2355	2613	2795	0,0014	2741	0,0015	2743	0,0018

X = Connection open   * = Unstable measuremnt

EPOXY	Specimen no. **2**	**no. 4.1**
Varnish: **SCOTCHCAST 280**	Phase: **THERMAL CYCLES**	

cycles	Z1 mΩ	Z2 mΩ	Z3 mΩ	Z4 mΩ	Z5 mΩ	C1 pF	C1 D	C2 pF	C2 D	C3 pF	C3 D
0	2261	2695	2518	2394	2585	2726	0,0009	2751	0,0011	2759	0,0011
100	X	X	2529	2403	2595	2726	0,0015	2750	0,0017	2758	0,0018
200	X	X	2523	2394	2591	2727	0,0015	2750	0,0017	2758	0,0017
300	X	X	2512	2388	2594	2731	0,0015	2755	0,0015	2763	0,0015
400	X	X	2512	2387	2719	2728	0,0013	2751	0,0014	2759	0,0016
500	X	X	2554	2438	*	2728	0,0015	2752	0,0016	2759	0,0018
600	X	X	2604	2463	*	2726	0,0016	2750	0,0017	2758	0,0019
700	X	X	2836	*	*	2727	0,0015	2750	0,0018	2758	0,0019
800	X	X	*	*	*	2727	0,0014	2751	0,0015	2759	0,0017
900	X	X	X	X	X	2728	0,0015	2752	0,0016	2759	0,0018
1000	X	X	X	X	X	2727	0,0014	2759	0,0015	2759	0,0018

X = Connection open   * = Unstable measuremnt

ANNEX III

Results of tests to determine rèsistance to solvents

ANNEX III.a
Resistance of various varnishes to industrial solvents
(failure determined by visual inspection, all passed unless otherwise indicated)

Type of pcb	37 EPOXY GLASS			37 POLYIMIDE GLASS		
Type of varnish	Propaklone	Freon	Isopropyl alcohol	Propaklone	Freon	Isopropyl alcohol
Reference (uncoated)						
MAPSIL 213	failed	failed		failed	failed	
CV 1144-0						failed
SYLGARD 184	failed	failed		failed	failed	
URALANE 5750LV	failed					
SOLITHANE 113						
CONATHANE EN 11						
SCOTCHCAST 280						

ANNEX III.b
Results of tests on epoxy comb pattern to determine resistance to industrial solvents (effect on electrical resistance)

	Resistance to solvent test on epoxy comb (immersion for 5 min at 23°C)									
	$R_{insulation}$ ($\times 10^7$ MΩ)									
	Freon			Isopropyl alcohol			Propaklone			Witness
Varnish type	before	after	after 16 h	before	after	after 16 h	before	after	after 16 h	
CONATHANE EN11	8	15	20	5	30	6	4	4	10	2
CV 1144-0	4	1.5	2	4	0.2	1	3	0.00035	1	4
MAPSIL 213	2	0.8	2	2	0.4	1	1.5	0.04	1	1
SCOTCHCAST 280	3	10	10	5	0.9	4	3	0.002	0.4	3
SOLITHANE 113	2	6	4	2	1	3	1.5	0.5	2	2
SYLGARD 184	3	0.4	5	2	0.05	4	2	0.05	2	3
URALANE 5750LV	6	20	8	10	6	20	9	0.05	10	3
Blank	1	4	0.04	0.01	0.015	0.35	0.5	2	3	

ANNEX III.c
Results of tests on epoxy comb pattern to determine resistance to industrial solvents (effect on capacity)

	Resistance to solvent test on epoxy comb (immersion for 5 min at 23°C)									
	Capacity (pF)									
	Freon			Isopropyl alcohol			Propaklone			Witness
Varnish type	before	after	after 16 h	before	after	after 16 h	before	after	after 16 h	
CONATHANE EN11	24.5	23.9	24.3	24.5	23.6	24.3	25.2	24.2	23.7	23.9
CV 1144-0	22.8	22	22.3	23.6	22.8	22.2	24.6	24.7	23.8	23.8
MAPSIL 213	23.6	23	23.1	23.4	22.4	22.7	23.3	23	22.7	24.3
SCOTCHCAST 280	24.9	23.6	23.7	24.5	22.9	22.7	24.1	25.6	24.5	23.3
SOLITHANE 113	24.5	23.9	23.9	25	24.9	24.5	24.3	25.9	24	25.3
SYLGARD 184	23.5	20.8	20.9	25.3	24.1	24	25.8	21.7	21.6	24.9
URALANE 5750LV	23.4	22.8	23.3	23.1	22.8	22.4	23	24.9	22.8	23.4
Blank	18.4	18	18.6	19.1	18.4	17.9	18.3	17.7	18	

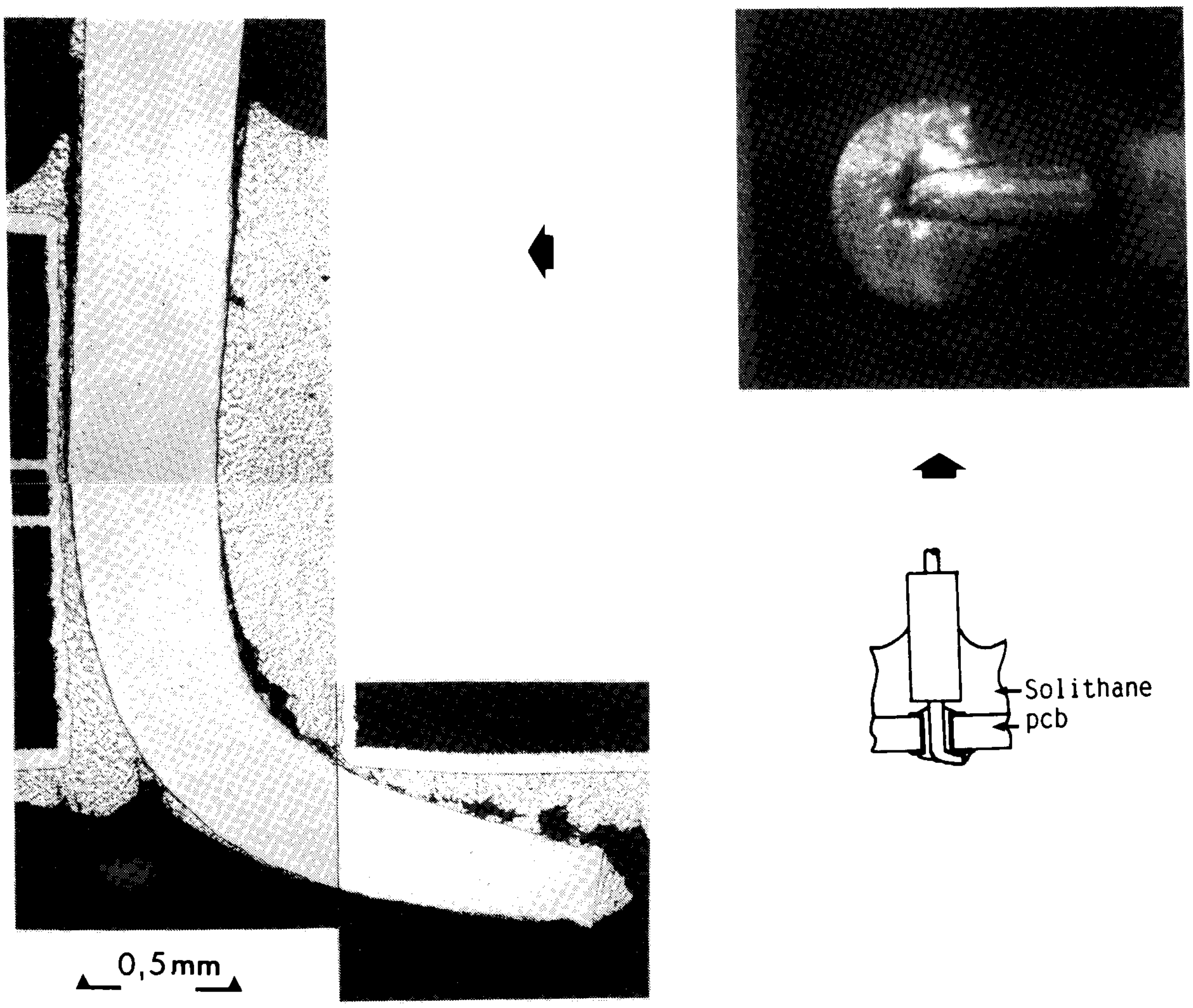
ANNEX III.d
Results of tests on polyimide comb pattern to determine resistance to industrial solvents (effect on electrical resistance)

	Resistance to solvent test on polyimide comb (immersion for 5 min at 23°C)									
	$R_{insulation}$ ($\times 10^7$ MΩ)									
	Freon			Isopropyl alcohol			Propaklone			Witness
Varnish type	before	after	after 16 h	before	after	after 16 h	before	after	after 16 h	
CONATHANE EN11	1.5	15	10	3	10	5	2	3.5	4	2
CV 1144-0	2	2	2	2	1.5	1.5	2	0.9	1.5	3
MAPSIL 213	2	1	2.5	1.5	0.15	1.5	1	0.025	1	1
SCOTCHCAST 280	3	1.5	2	2	0.8	4	1.5	0.35	0.5	3
SOLITHANE 113	1.5	4	2	2.5	3.5	5	2	0.015	2	2
SYLGARD 184	4	2	1.5	1.5	0.15	3	0.05	0.03	1.5	1.5
URALANE 5750LV	3	20	3	2	10	3	3	0.2	2.5	3
Blank	0.9	2	0.05	2	0.2	2	0.6	0.08	0.15	

ANNEX III.e
Results of tests on polyimide comb pattern to determine resistance to industrial solvents (effect on capacity)

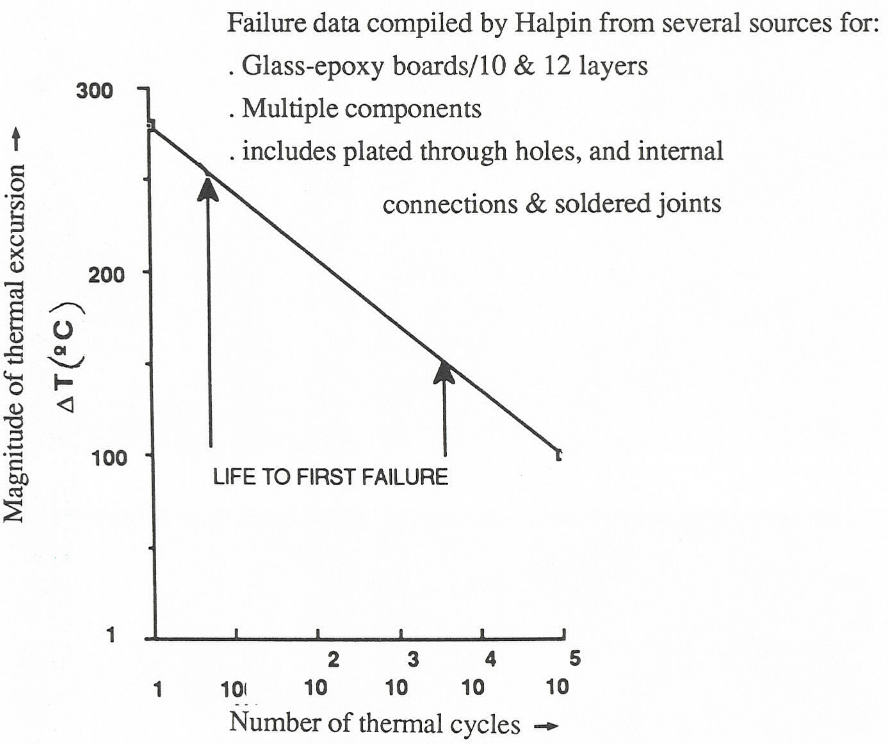
	Resistance to solvent test on polyimide comb (immersion for 5 min at 23°C)									
	Capacity (pF)									
	Freon			Isopropyl alcohol			Propaklone			Witness
Varnish type	before	after	after 16 h	before	after	after 16 h	before	after	after 16 h	
CONATHANE EN11	25.3	24.3	24.2	24.9	23.2	23.8	24.5	24.1	23.6	23.9
CV 1144-0	23.8	22	22	23.7	21.6	22.1	22.3	20.7	21.3	23.8
MAPSIL 213	24.2	22.8	23.2	25.2	23.3	23.2	24.5	23.5	23.1	24.3
SCOTCHCAST 280	24	22.2	22.3	24.4	23	23.2	25.5	25.9	24.9	23.3
SOLITHANE 113	25.1	23.5	24	25.6	24.5	24.5	24	26.5	23.3	25.3
SYLGARD 184	24.3	23.5	22.5	24.7	23.1	23.5	25.2	24.9	23.7	24.9
URALANE 5750LV	23.1	22.7	22.4	23.6	22.9	23.1	24	25	22.7	23.4
Blank	19.6	18.6	17.7	20	18.6	17.7	19.6	18.5	18.3	

FIGURES

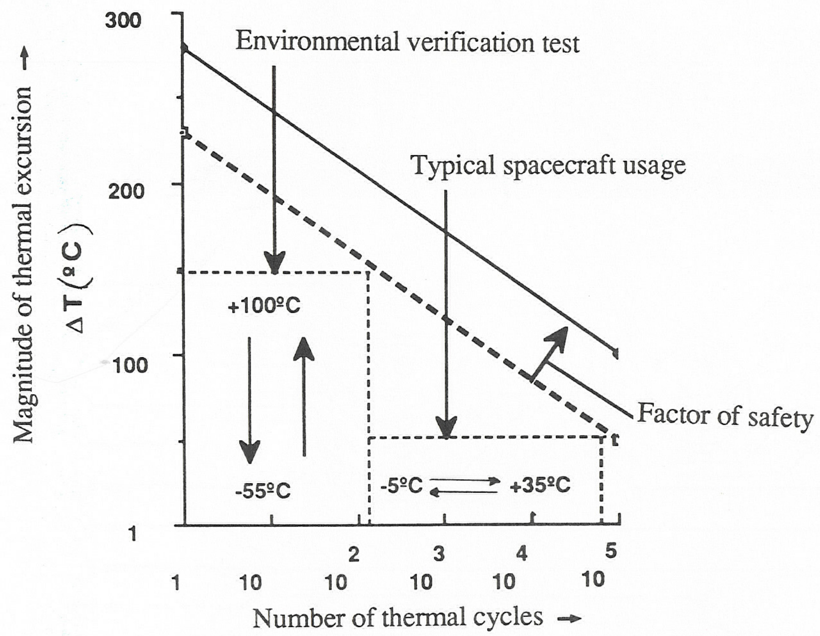


(a) Thermal cycling of a spacecraft flight-spare multilayer board (1000 cycles between $-55\,^{\circ}C$ and $+100\,^{\circ}C$) that had been coated with a thick layer of Solithane 113 polyurethane produced extensive cracking of plated-through hole soldered joints. A typical joint (vertically mounted axial leaded component) shown here indicates that electrical continuity is only maintained at the lower left solder-to-copper lead interface

Figure 1: Thermal fatigue failures in printed circuit board assemblies and the concept of using thermal cycling as a verification test [Ref.3]

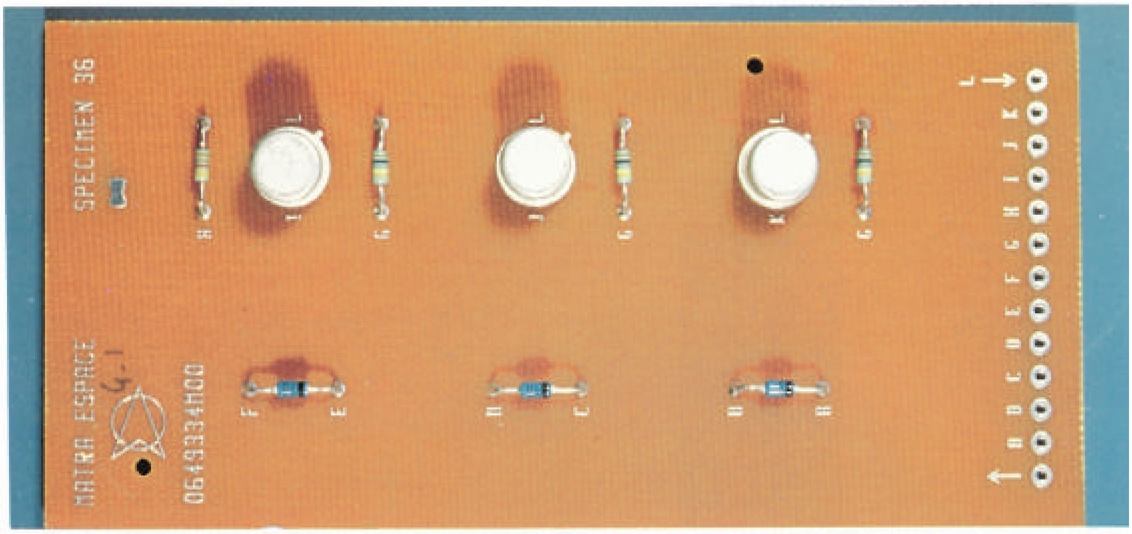


(b) Fatigue curve for printed circuit assemblies from Reference 2



(c) Prediction of service life based on the successful completion of verification testing

(a)



(b)

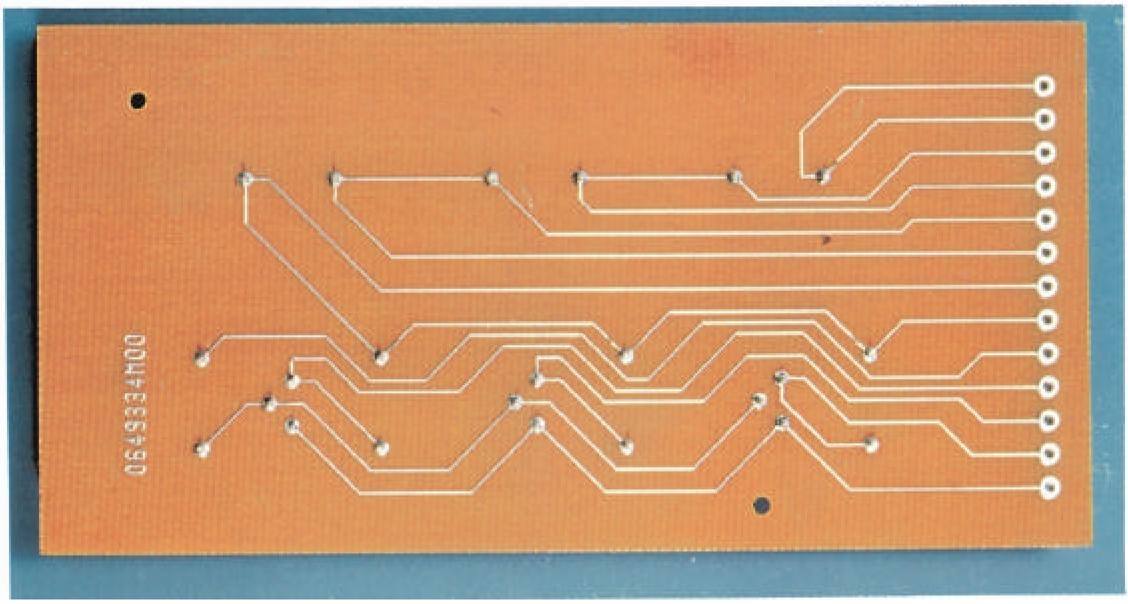
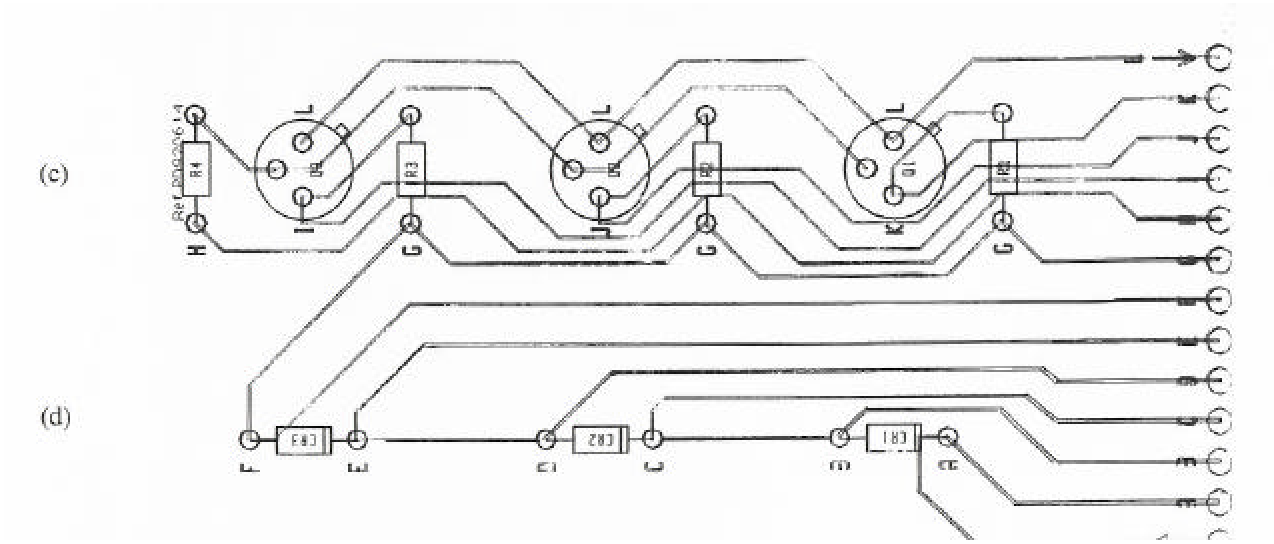


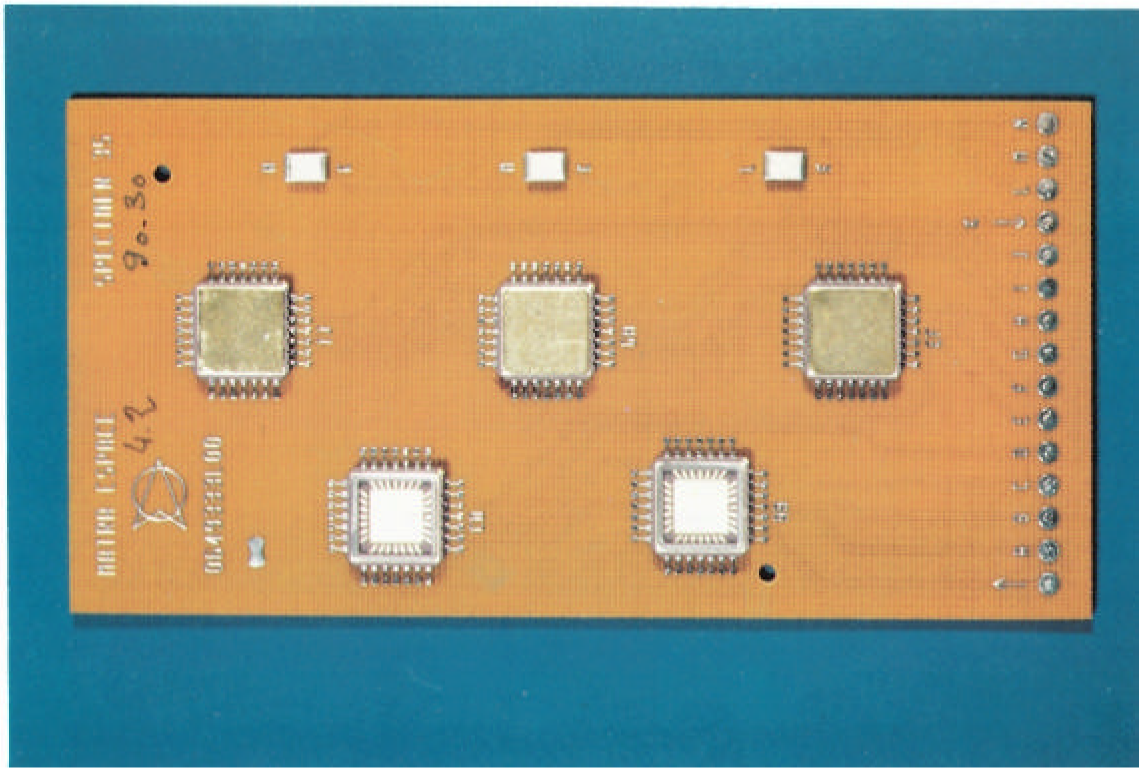
Figure 2: Specimen

(c)

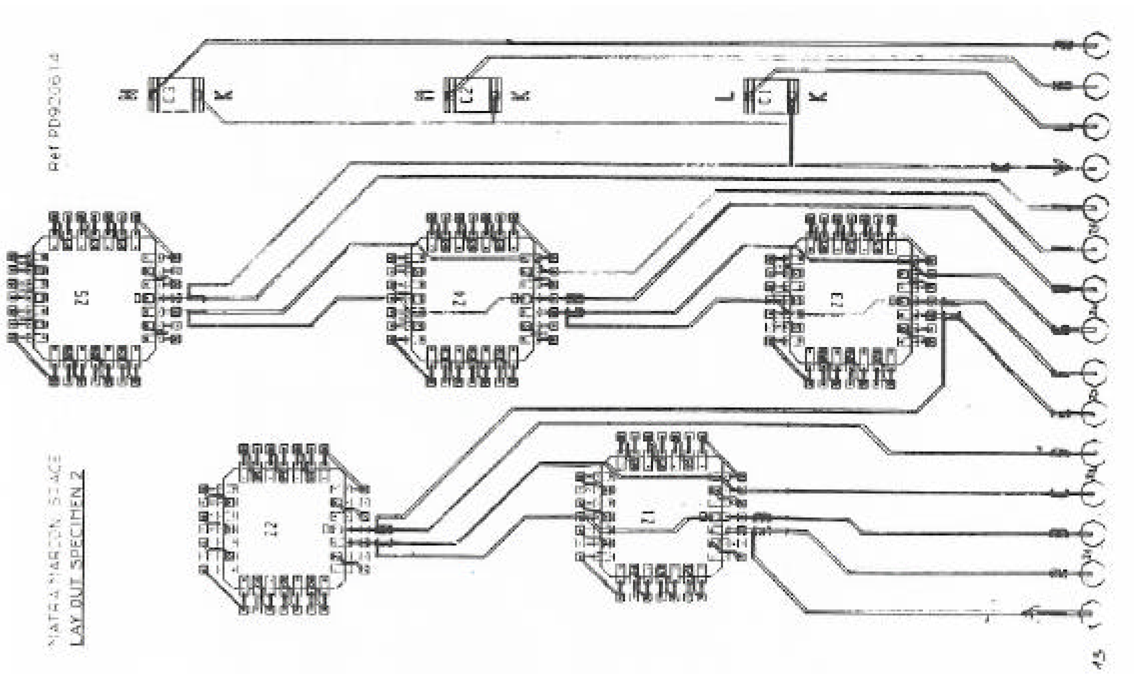
(d)



1 - (a) Photograph of top side; (b) Photograph of solder side; (c) and (d) the electrical circuit for conventionally manually soldered double-sided pcbs



(a)



(b)

Figure 3: Specimen 2 - (a) Photograph of assembled mlb supporting chip carriers and chip capacitors; (b) electrical monitoring circuit

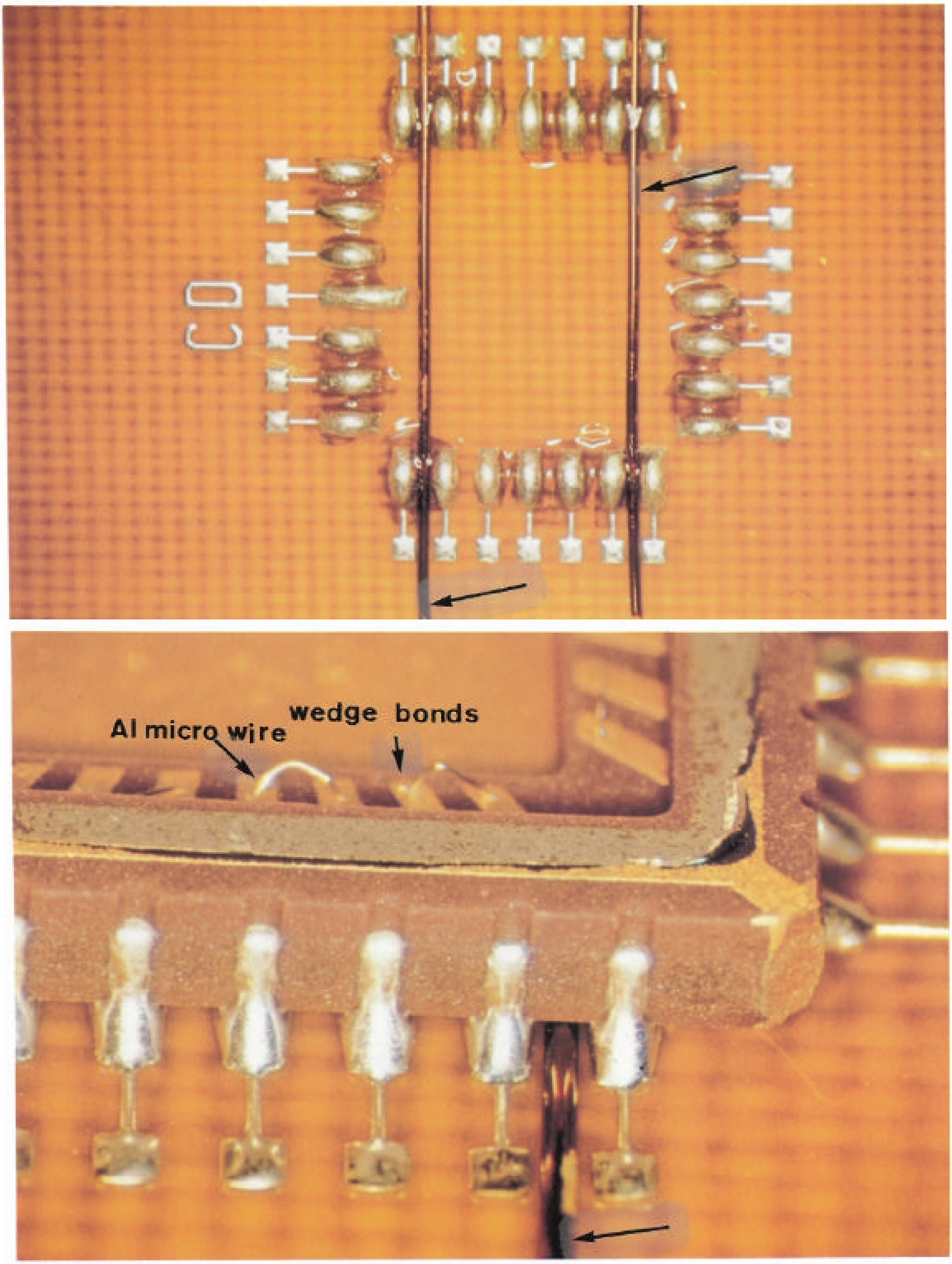


Figure 4: Close-up view of enamel wires used to maintain a constant stand-off height of 0.3 mm. Photograph of Specimen 2 shows the solder joint castellations immediately after vapour-phase soldering and cleaning

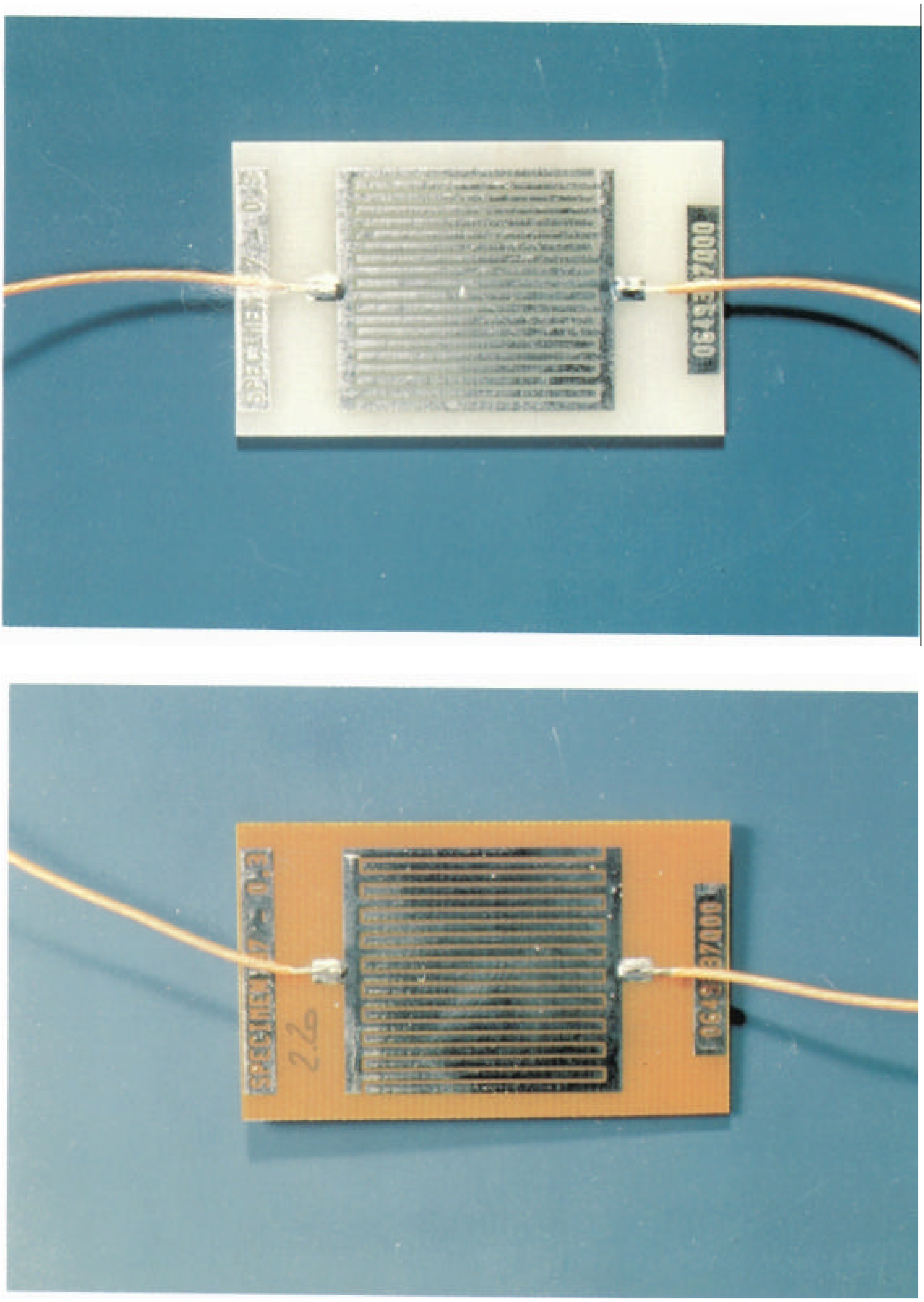


Figure 5: Appearance of (a) epoxy and (b) polyimide pcb comb patterens

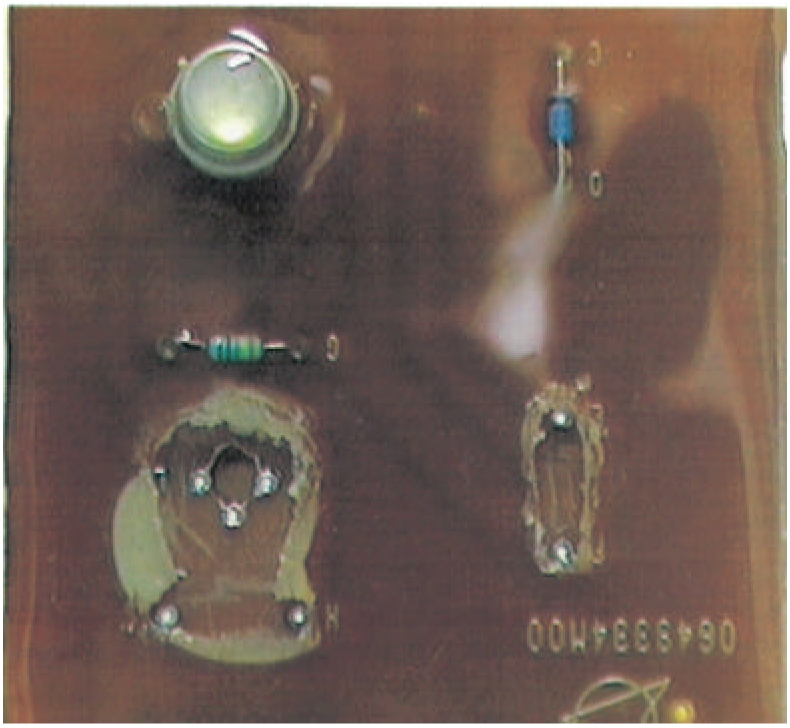


Figure 6: Conathane EN I 1 - Coating removed by tip of soldering iron at 300°C. A disagreeable odour was continually released as the coating became soft. It was possible, albeit with some difficulty, to remove small chips of coating with an orange stick (wooden probe). Adjacent coating was partially lifted

Figure 7: Solithane 113 - Hot air was needed to heat coating locally to about 100°C and it was then possible to prise of the coating with an orange stick

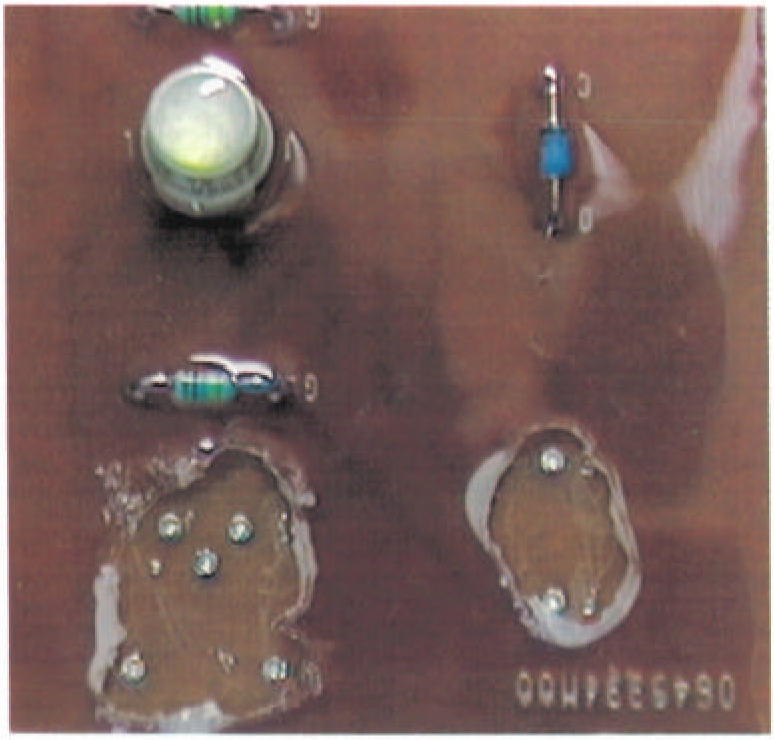


Figure 8: Uralane 5750 LV - Local hot-air heating was required to heat the coating to 100°C. this coating was difficult to remove

Figure 9: CV 1144-0 - Coating was easy to remove with the aid of an orange stick at ambient temperature. There was minimal lifting of adjacent coating

figures

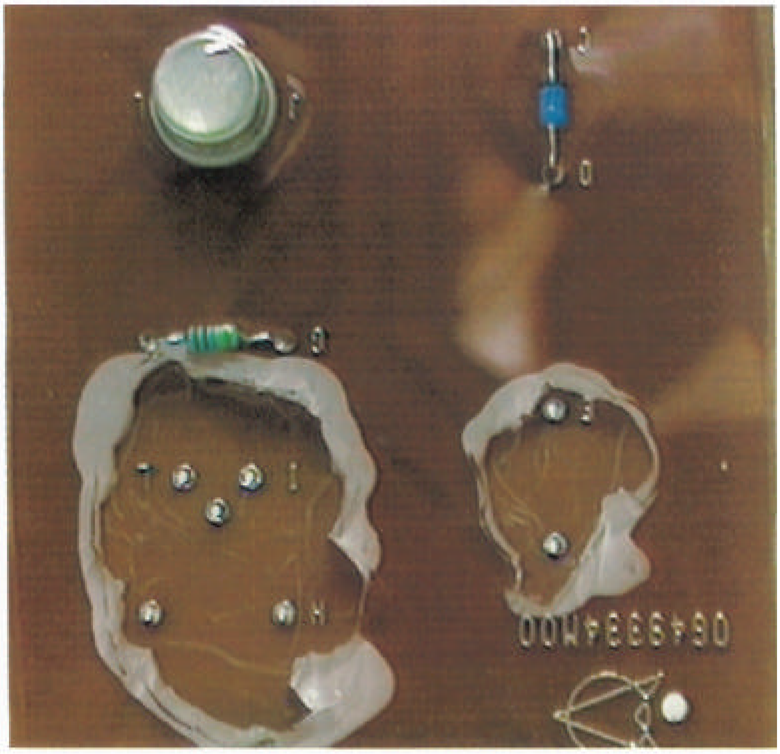


Figure 10: Mapsil 213 - The coating was easily removed with the aid of an orange stick at ambient temperature. Care had to be taken to avoid lifting adjacent coating (worst case visible in photograph)

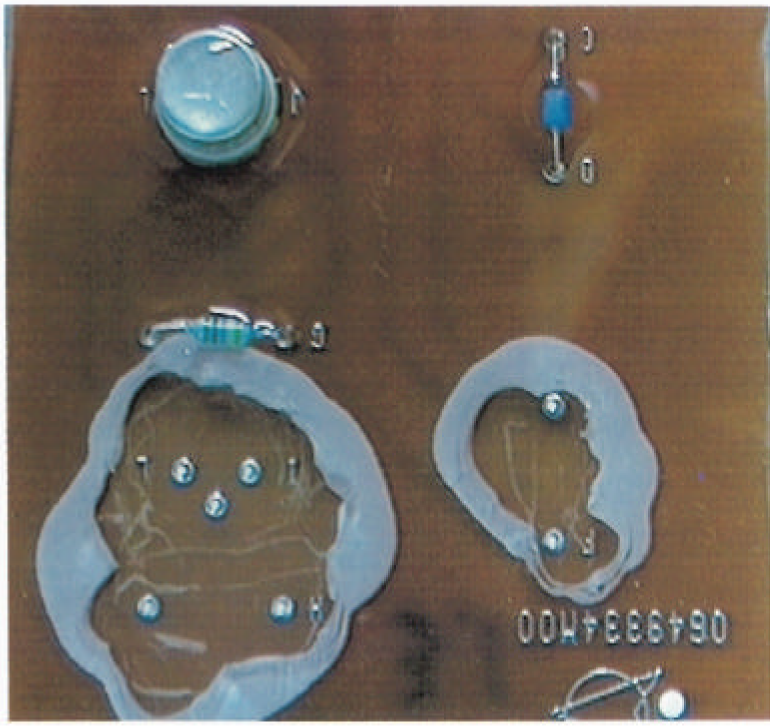


Figure 11: Sylgard 184 - Coating was quite easy to remove at room temperature with the aid of an orange stick, but lifting of adjacent area of coating was difficult to avoid

Figure 12: Scotchcast 280 - A soldering iron tip at 300°C was required to heat and slightly soften this coating. It was then possible to remove very small pieces with an orange stick. The coating hardened rapidly and application of heat caused the release of an unpleasant odour

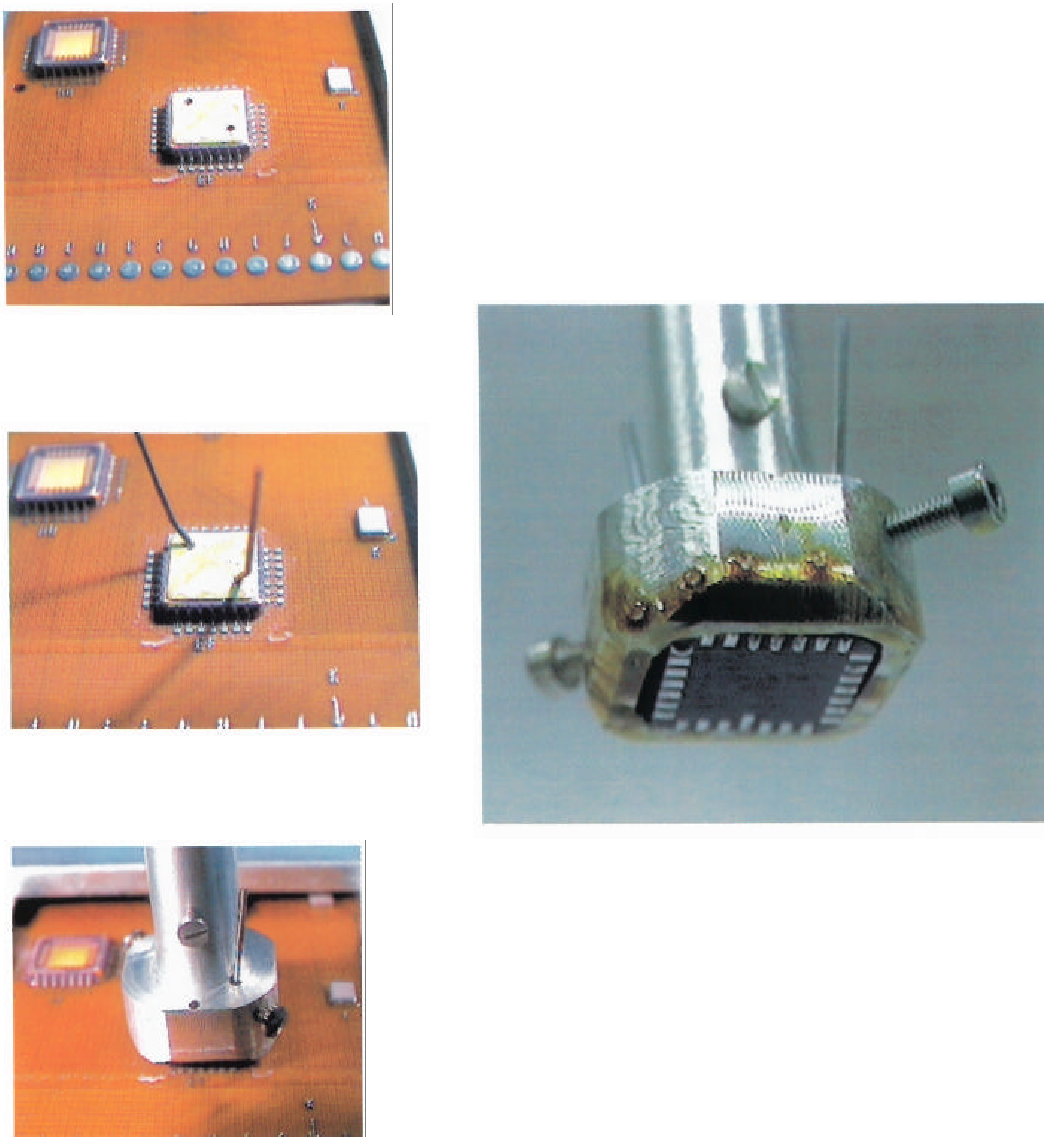


Figure 13: Illustrations of method for removing leadless chip carriers from pcb 68

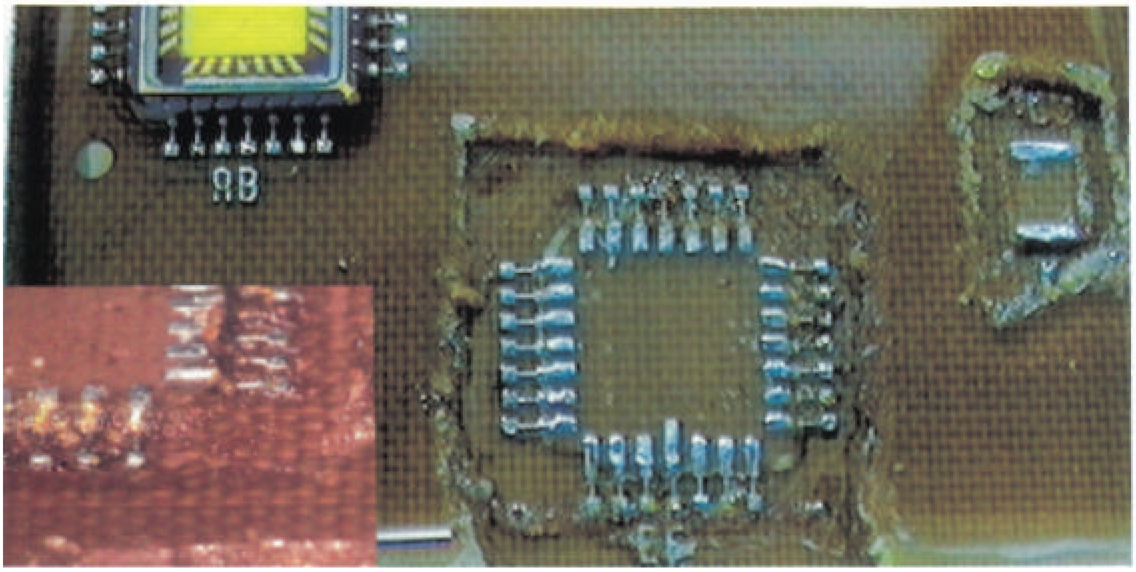


Figure 14: Conathane EN 11 - Coating was melted with a soldering iron at 300°C. Unpleasant odour was released. The coating was difficult to remove with the aid of an orange stick. Lifting and removing a chip carrier required nine seconds

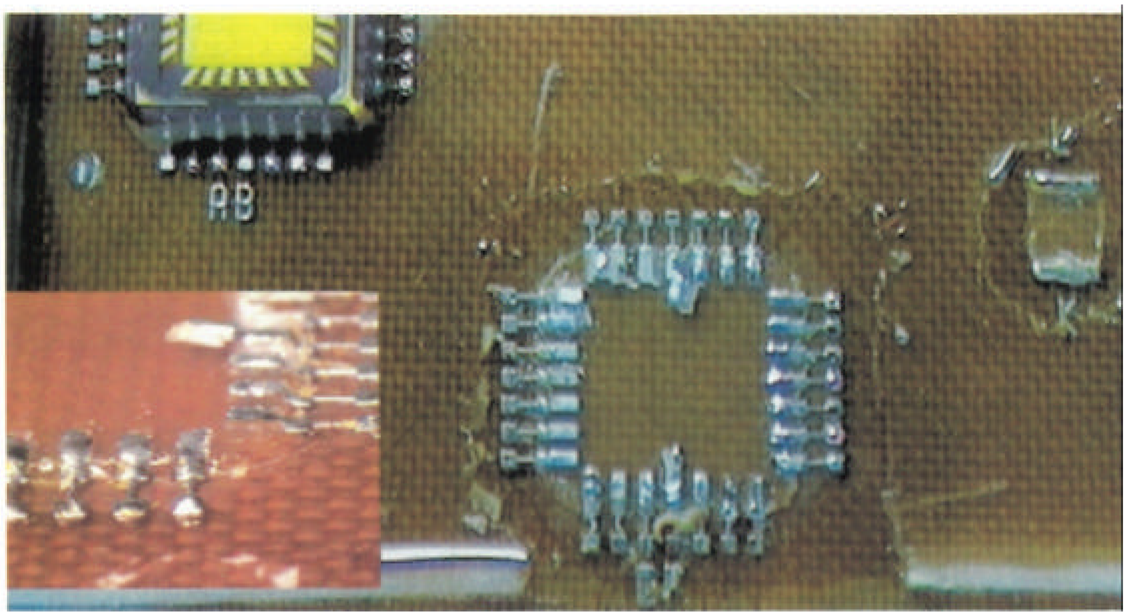


Figure 15: Solithane 113 - Hot air at 100°C was needed to soften the coating, which was then peeled off with an orange stick. Lifting and removal of a chip carrier required six seconds

figures

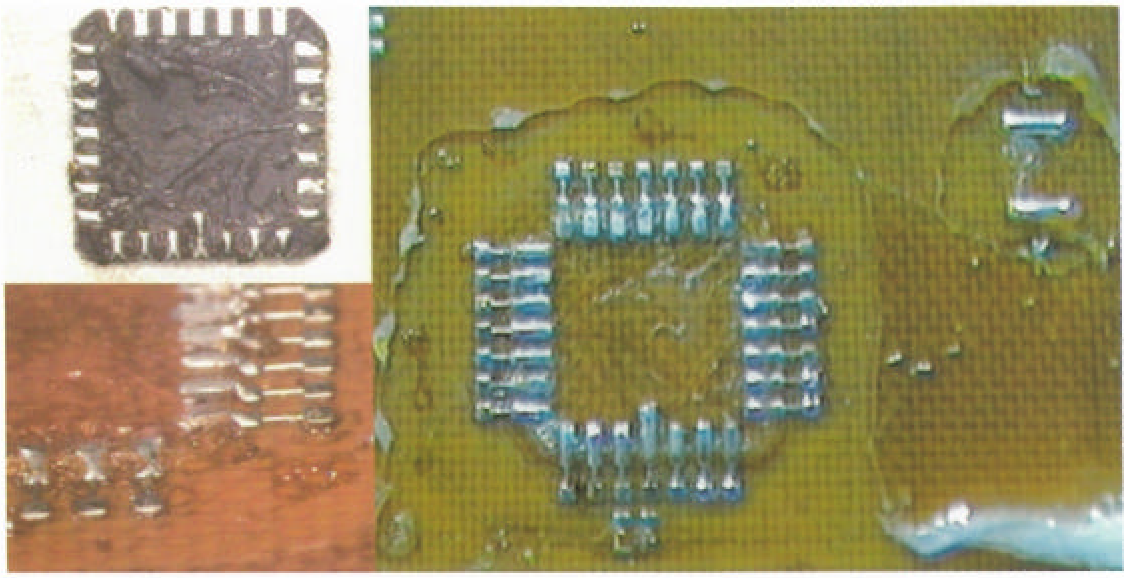


Figure 16: Uralane 5750 LV - The coating is quite hard even when heated to 100°C with hot air. Removal of a chip carrier required seven seconds

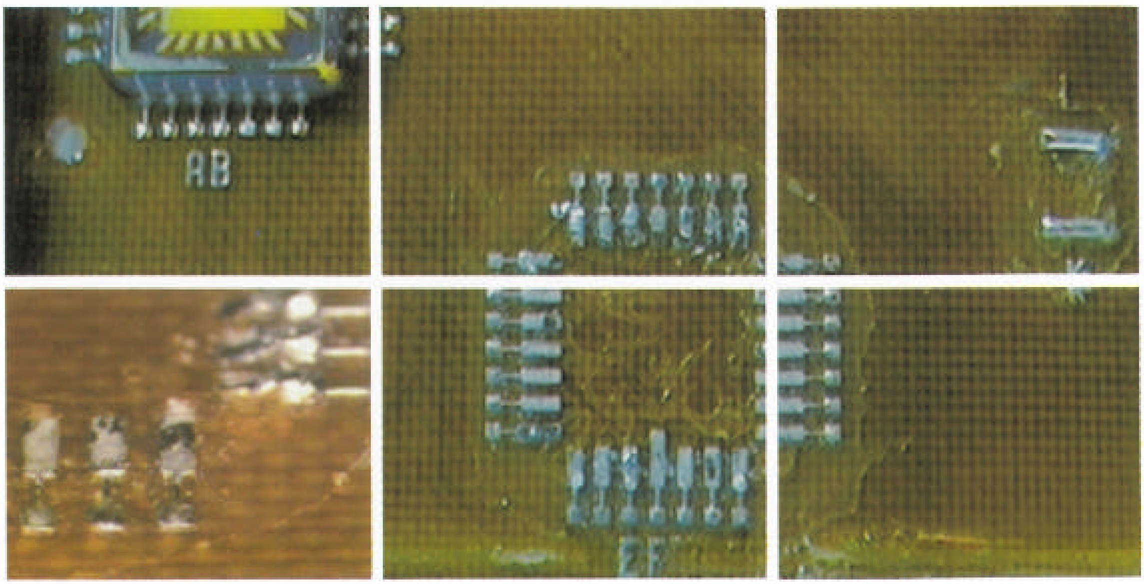


Figure 17: CV 1144-0 - The coating was quite easy to remove at ambient temperature. Removal of a chip carrier required five to six seconds

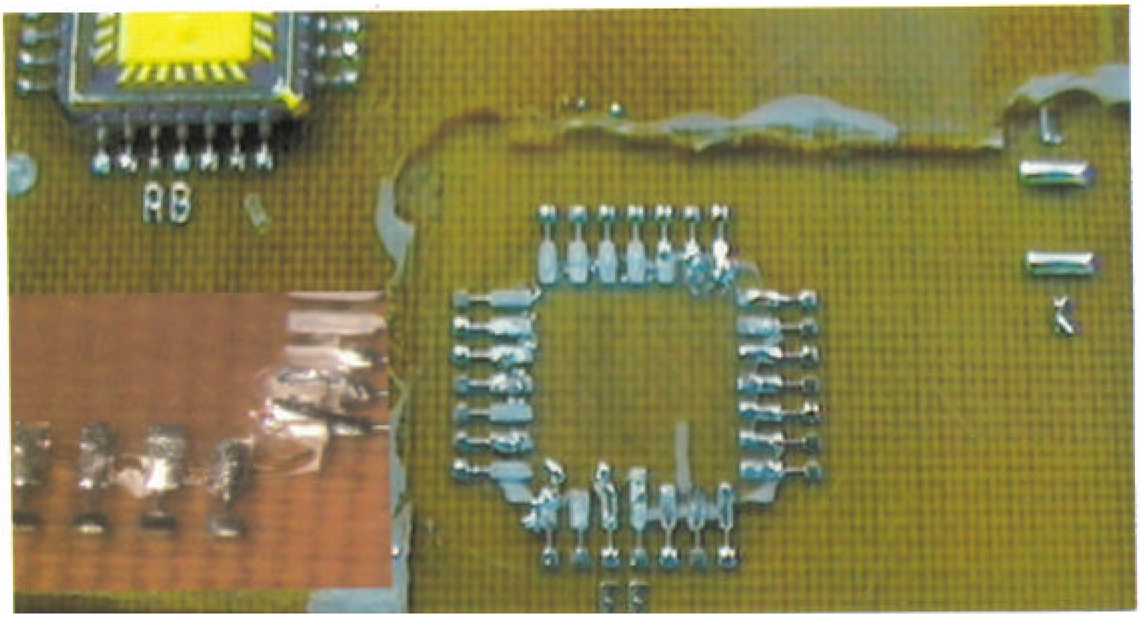


Figure 18: Mapsil 213 - The coating was easily removed at ambient temperature. Removal of a chip carrier required five to six seconds

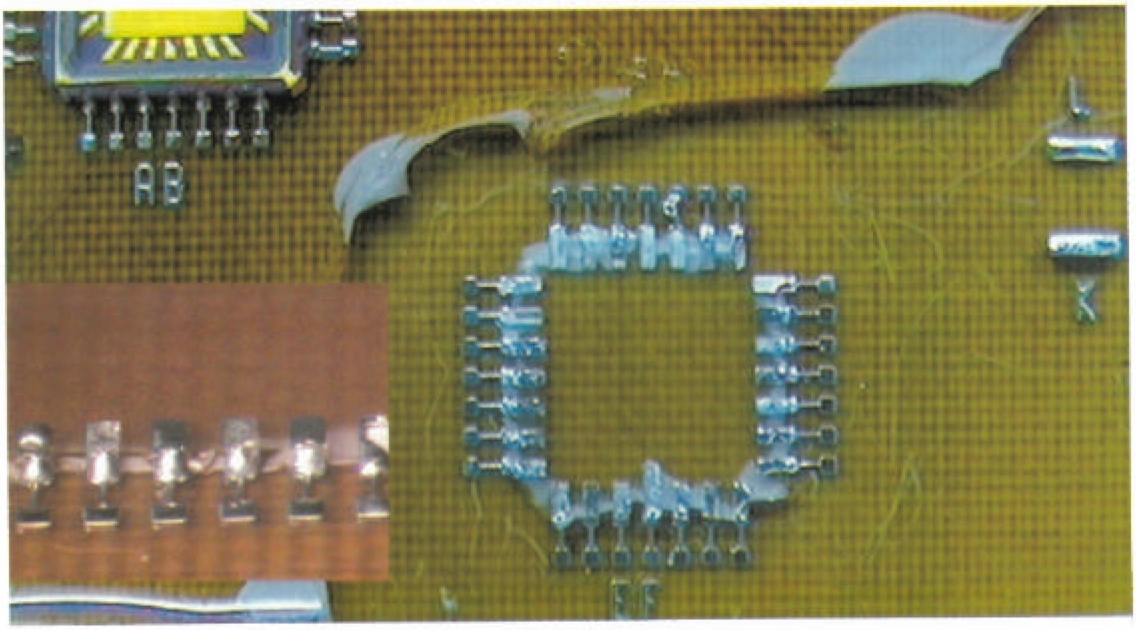


Figure 19: Sylgard 184 - Clean removal of all coating at room temperature was a little more difficult. Removal of a chip carrier required five to six seconds

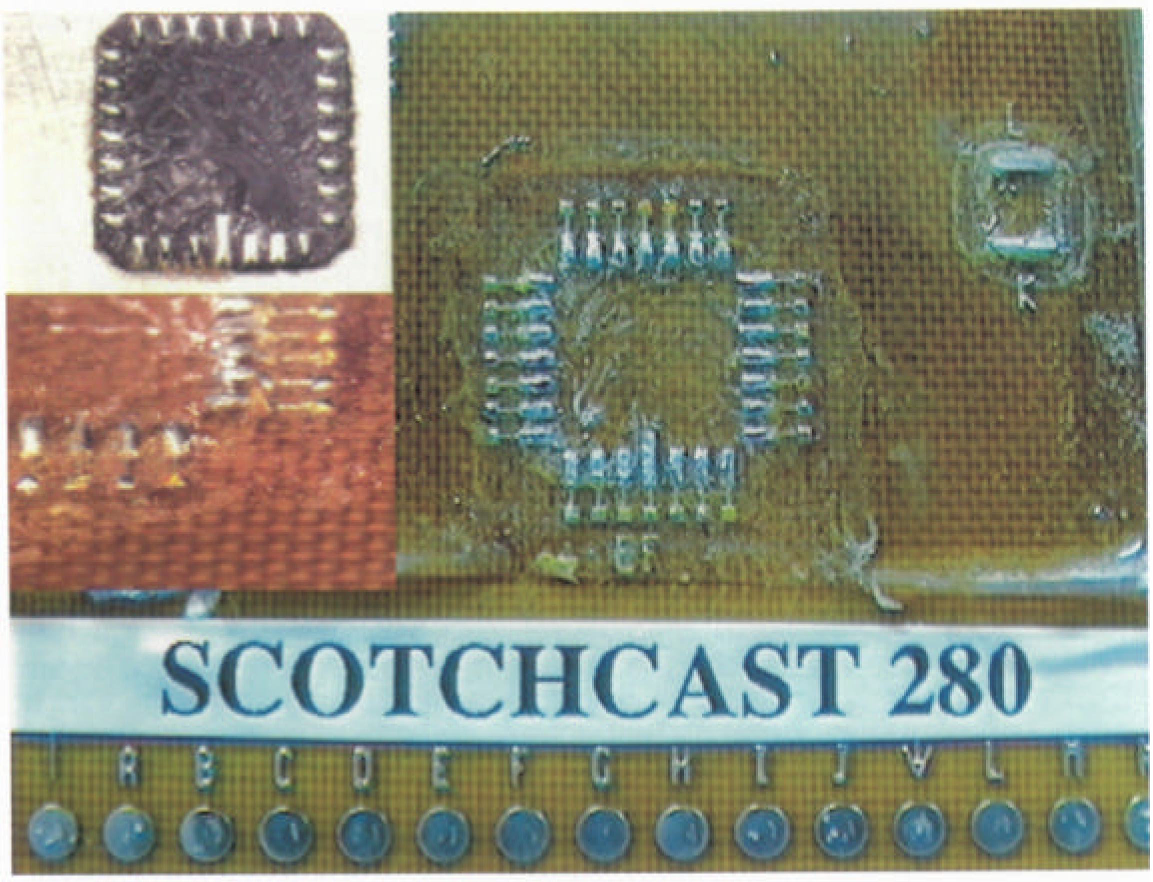


Figure 20: Scotchcast 280 - Only with a soldering iron at 300°C was it possible to remove this coating. Complete removal of material from the pcb was very difficult. Removal of a chip carrier required nine seconds

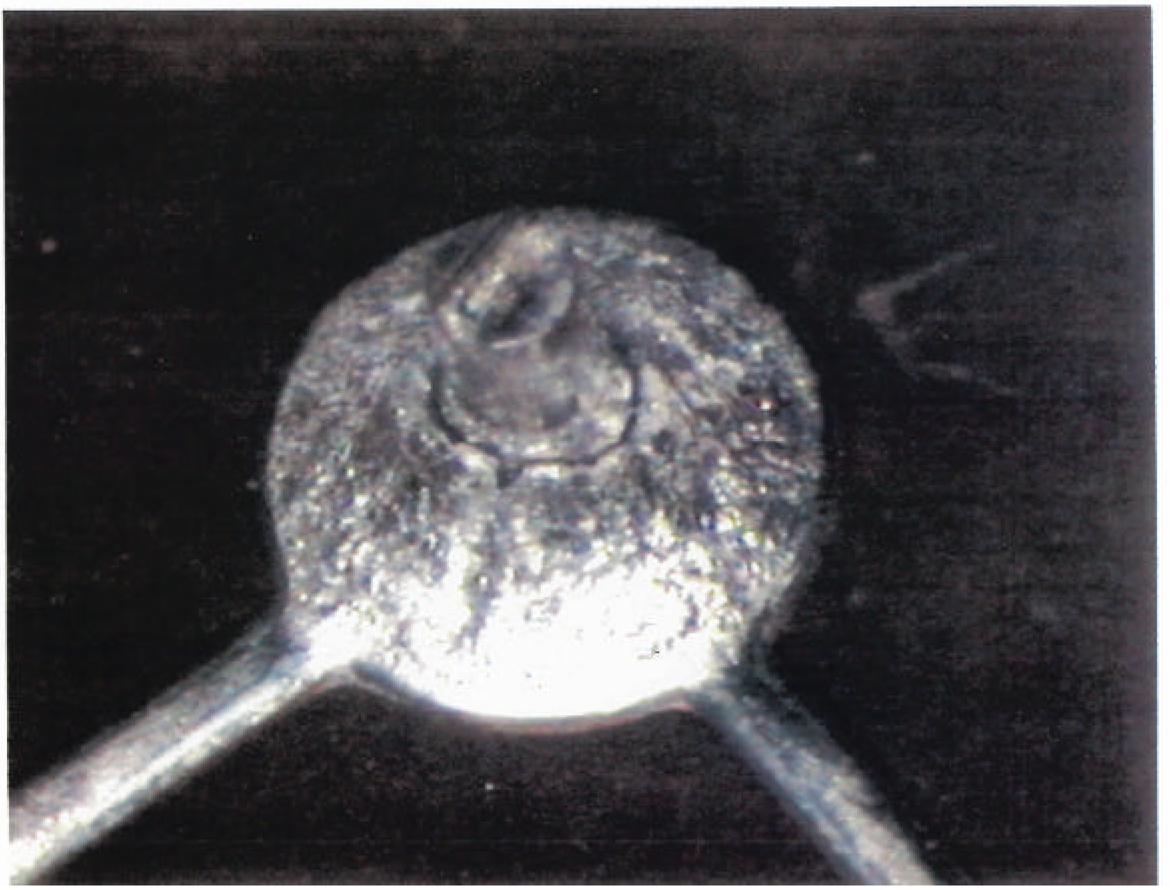


Figure 21: Orange-peel appearance and wide-mouthed cracking after 1000 thermal cycles (Transistor, Solithane 113)

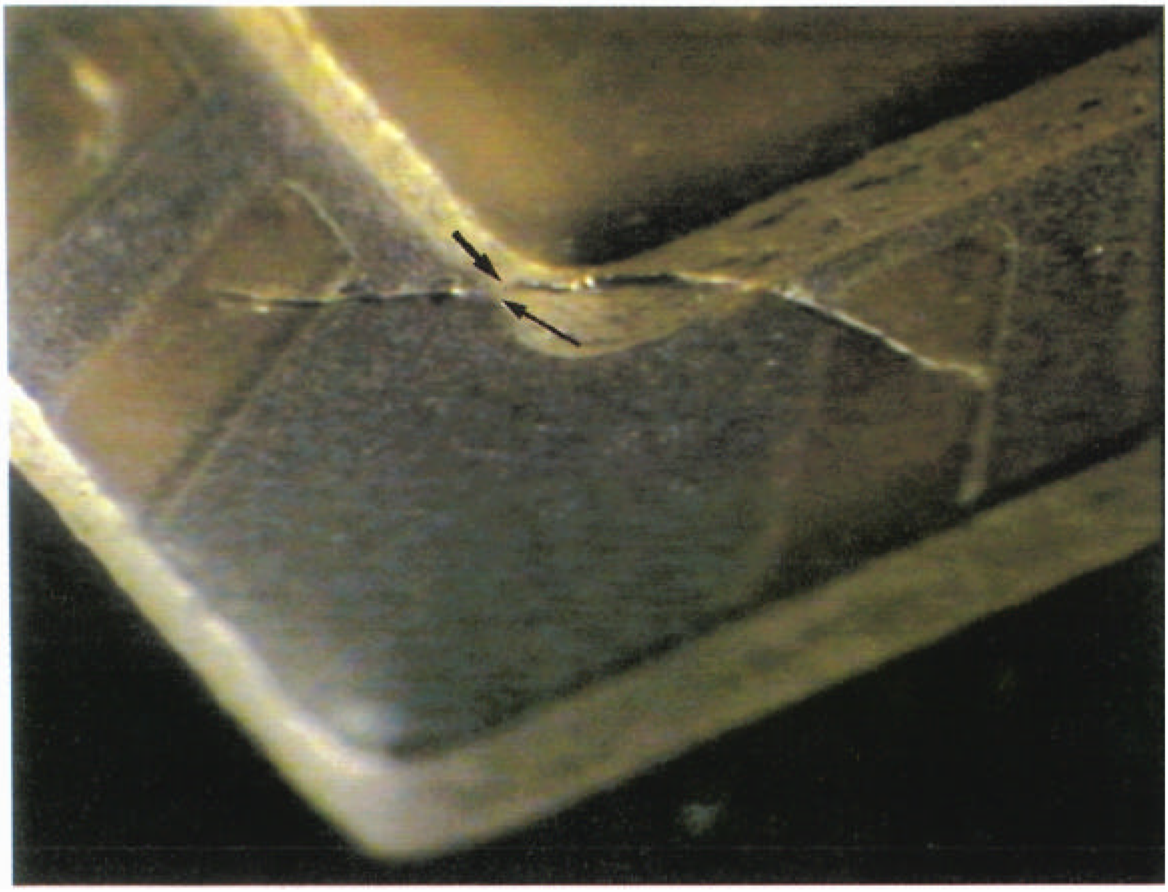


Figure 22: Top view of wedge-wedge bonded 38µm diameter aluminium wire after 800 thermal cycles. The original form of the wire was a symmetrical loop. Thermal mismatch has produced twists and kinks in the wire that are typical of all wires encapsulated in Solithane, Conathane or Scotchcast. The wire fracture surfaces (arrowed) on this Solithane sample exhibit necking and a reduced wire cross-sectional area of approx. 50%

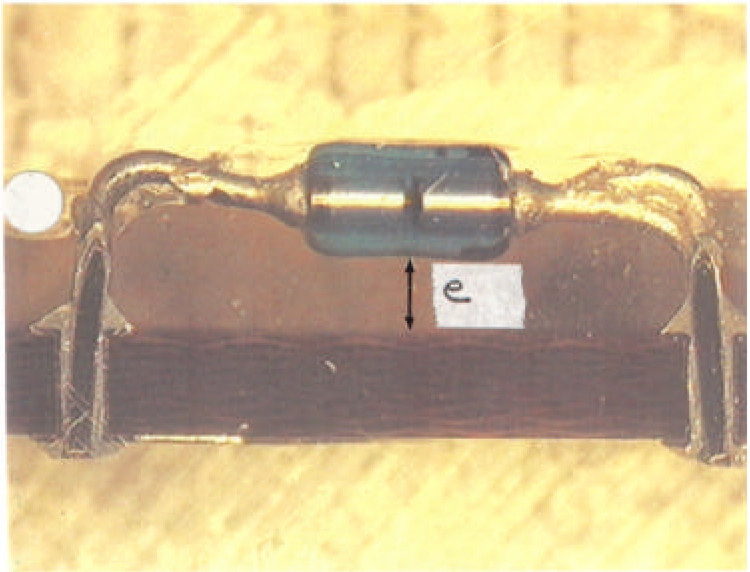


Figure 23: Microsection of a typical glass-bodied diode, confirming that the thick conformal coating had encased the lower part of this component and its leads. The stand-off height, e, is 0.9mm. After 1000 thermal cycles, the large cyclic strains produced by the expanding and contracting coating have cracked the plated through hole soldered joint and wedged up the component to reduce the height of the stud connection leads on the underside of this pcb

figures

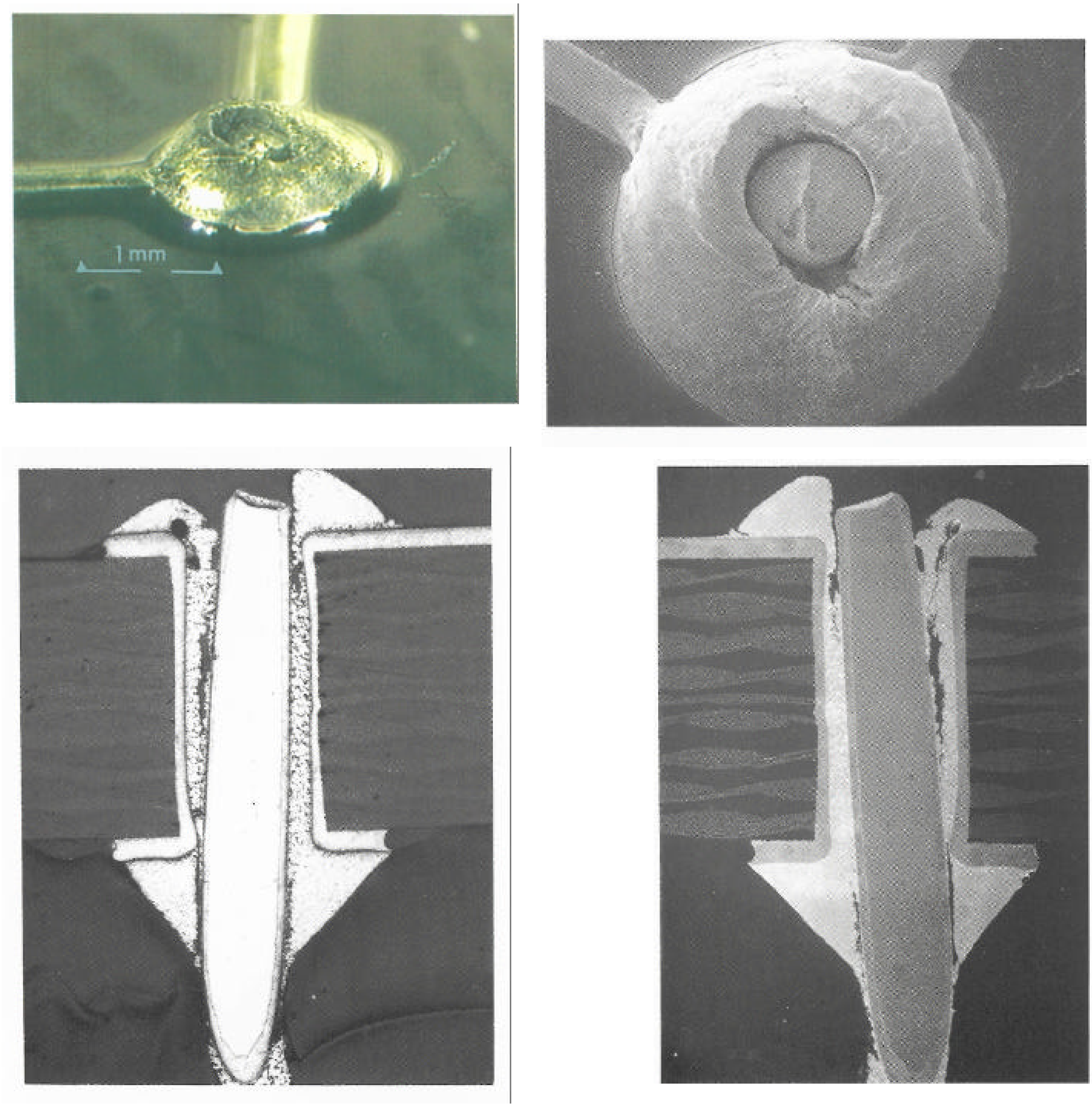


Figure 24: Optical (left-hand side) and SEM images of extensively damaged solder joint. The ratcheting effect of the coating during each thermal cycle has pulled the lead towards the component side of the board. Sample is Diode CR3, coated with Scotchcast, after 1000 thermal cycles. Electrical continuity is maintained within the plated through hole

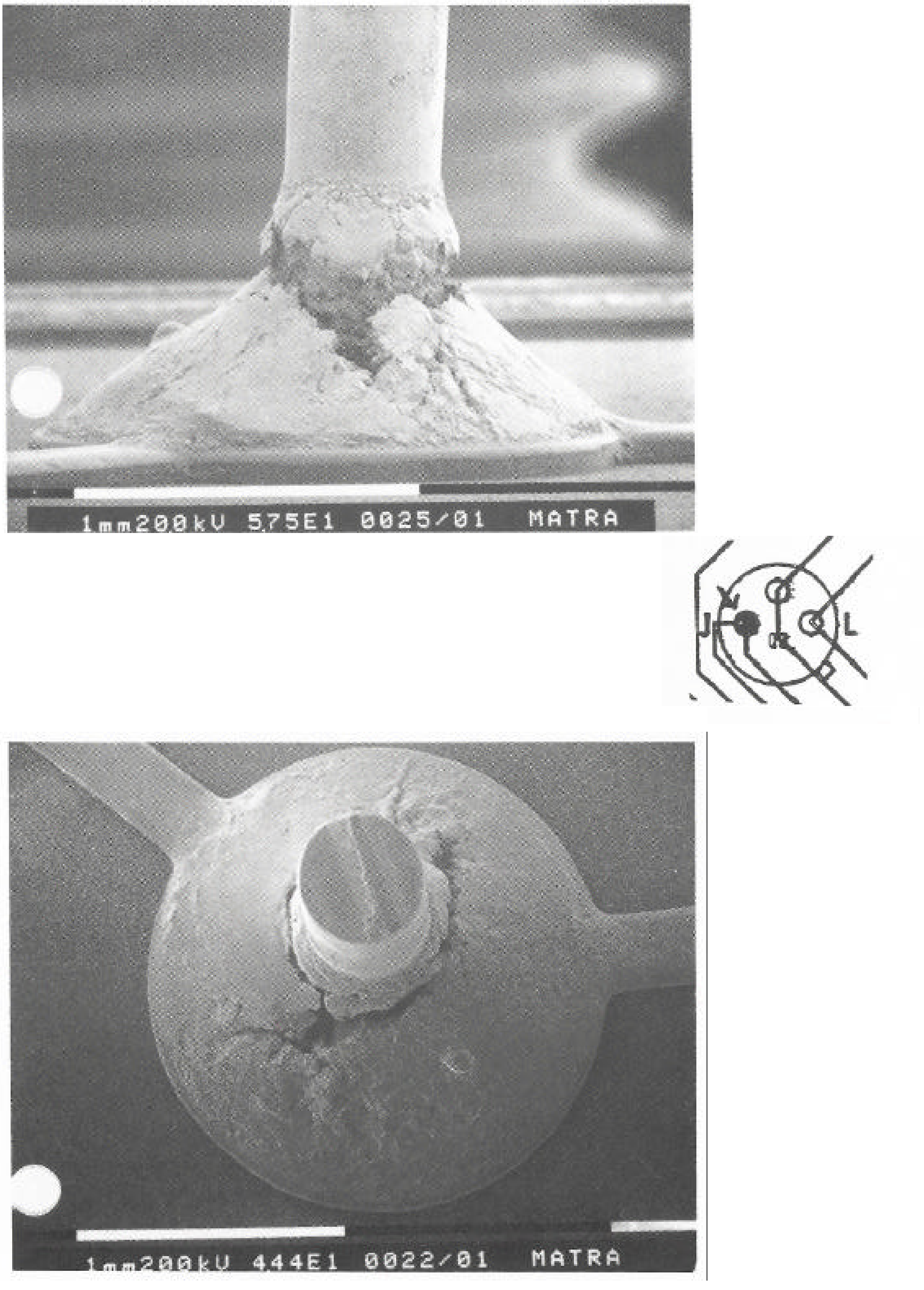


Figure 25: SEM views of stud-leaded Transistor Q2 coated with Uralane following 1000 thermal cycles (J lead)

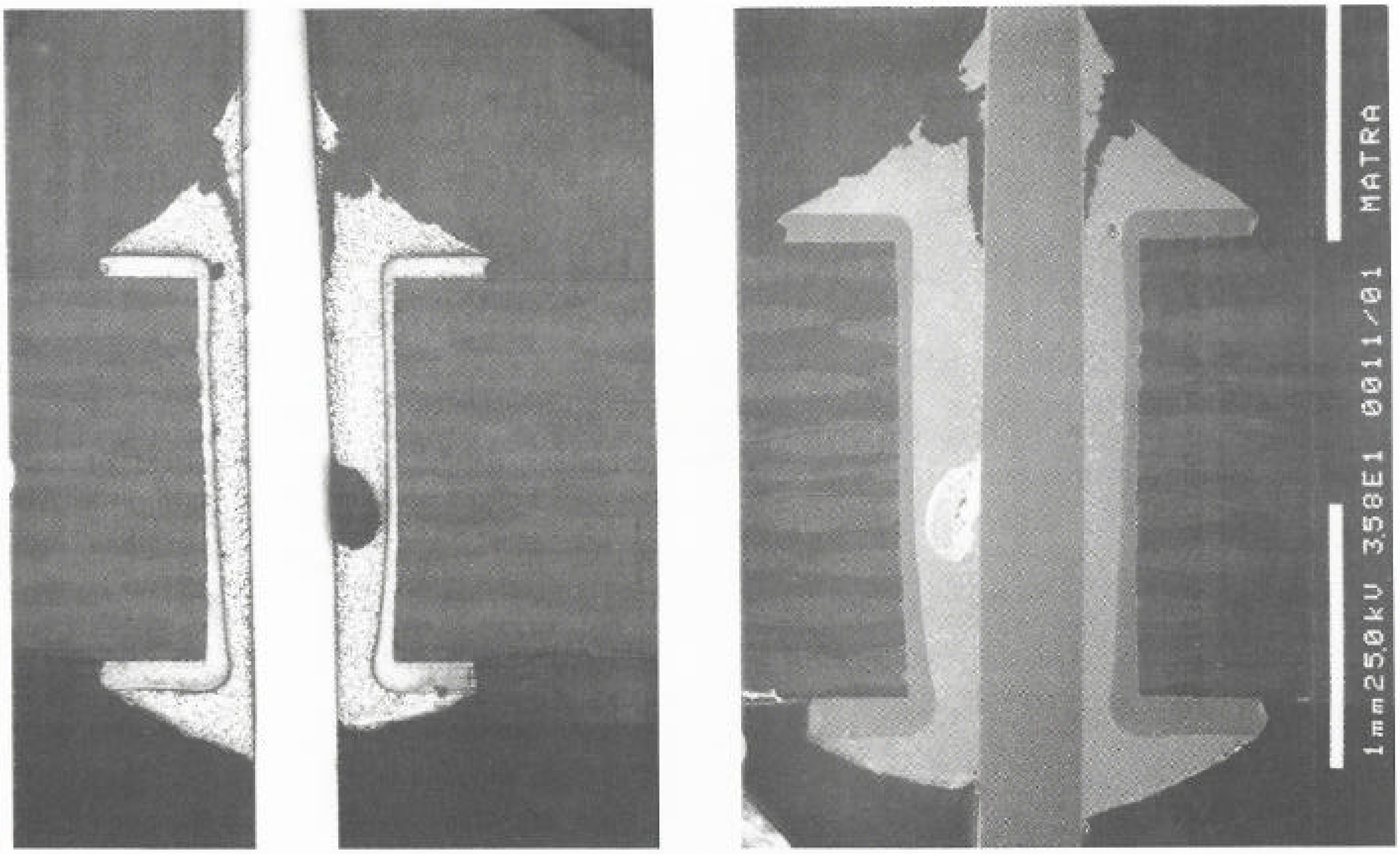


Figure 26: Optical (left-hand side) and SEM views of microsectioned Transistor Q2 lead J shown in Figure 25. Crack propagation has not entered the plated through hole region and is confined to the stud fillet. Cracking is not present at the transistor side of the joint or in the vicinity of the entrapped gas pocket.

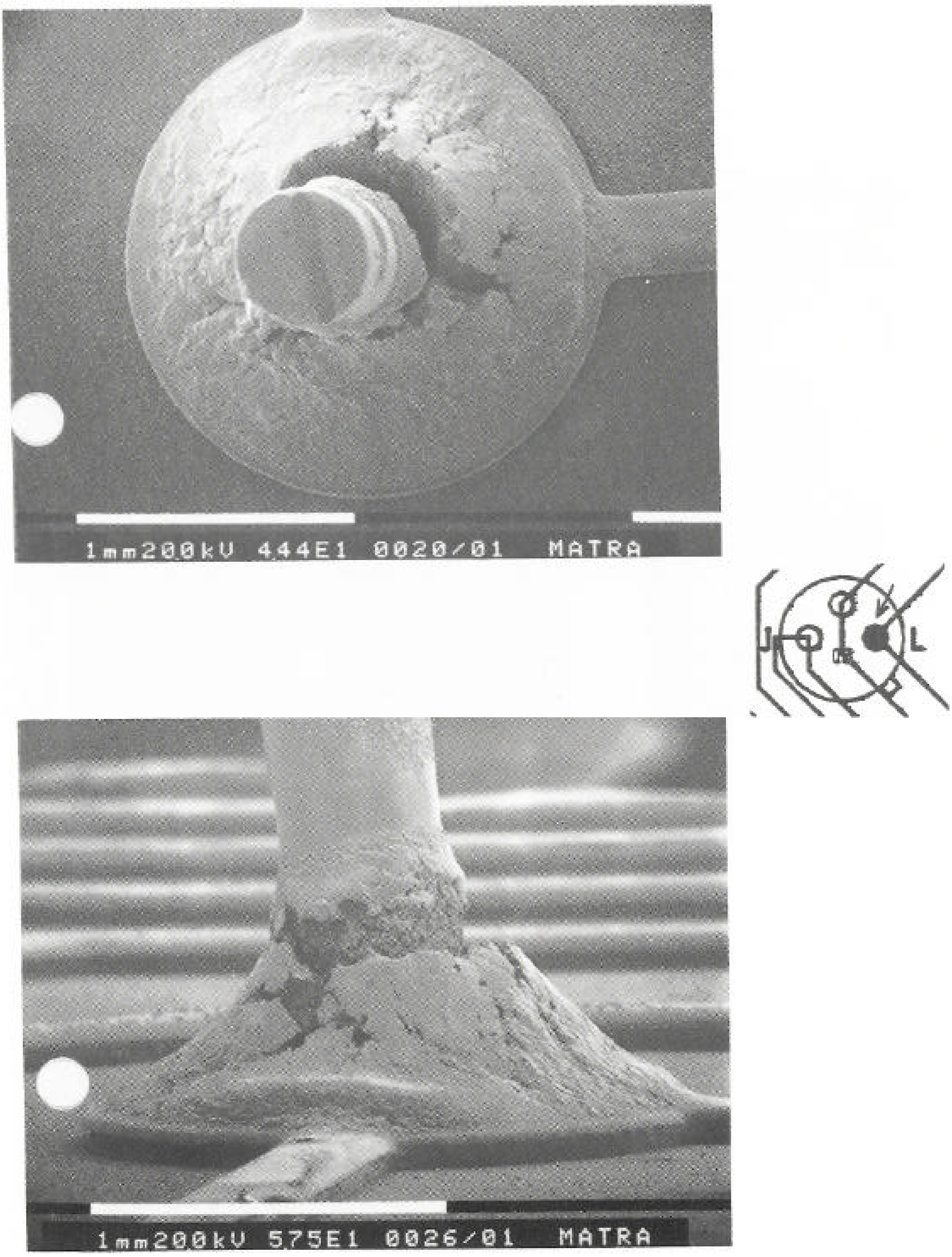


Figure 27: SEM views of stud-leaded Transistor Q2 coated with Uralane following 1000 thermal cycles (L lead). This is the same component as that shown in Figure 25.

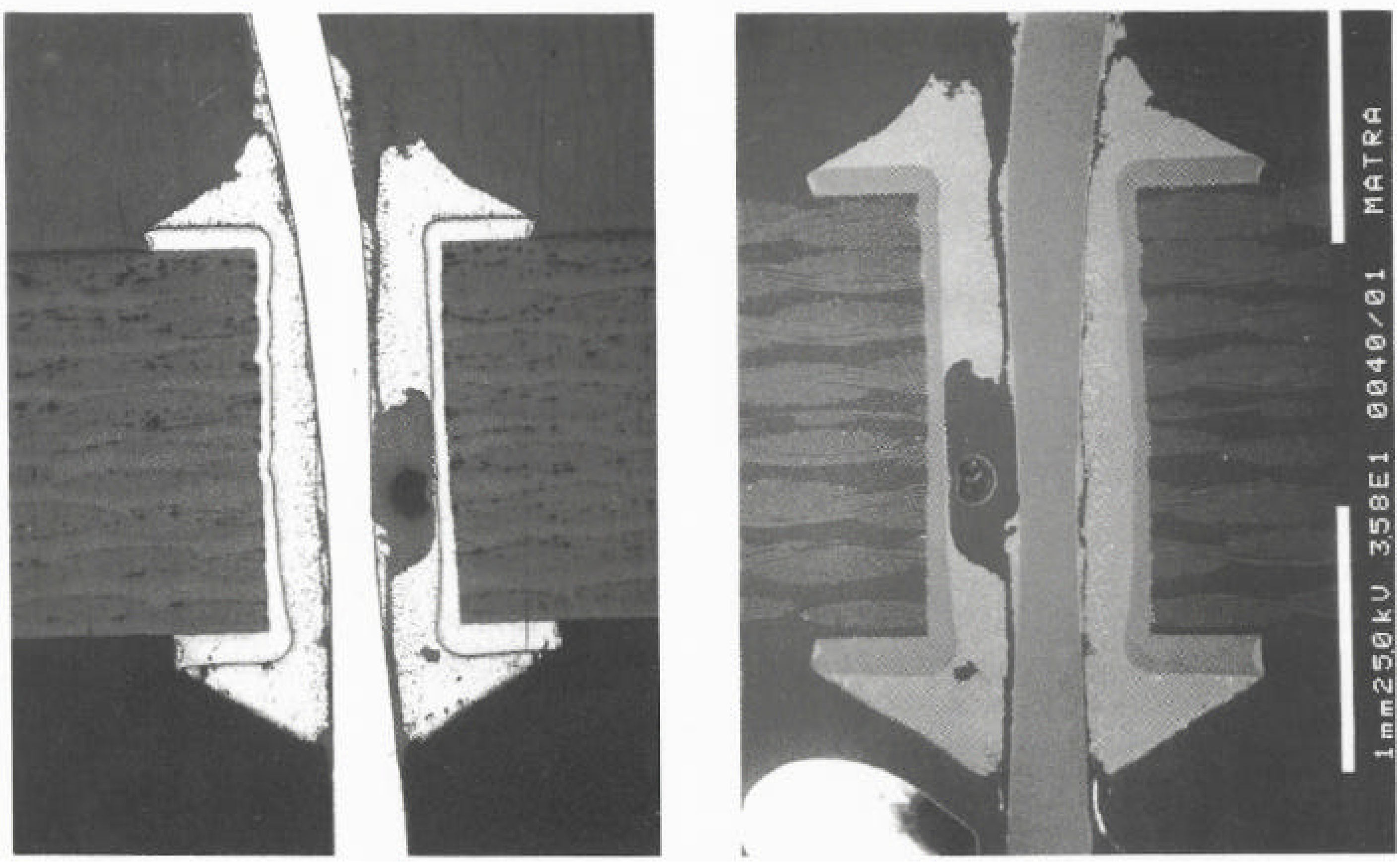


Figure 28: Optical (left-hand side) and SEM views of microsectioned Transistor Q2 lead L shown in Figure 27. Cracks have propagated completely through this solder joint to produce an electrical open circuit after 600 thermal cycles (micrograph made after 1000 cycles)

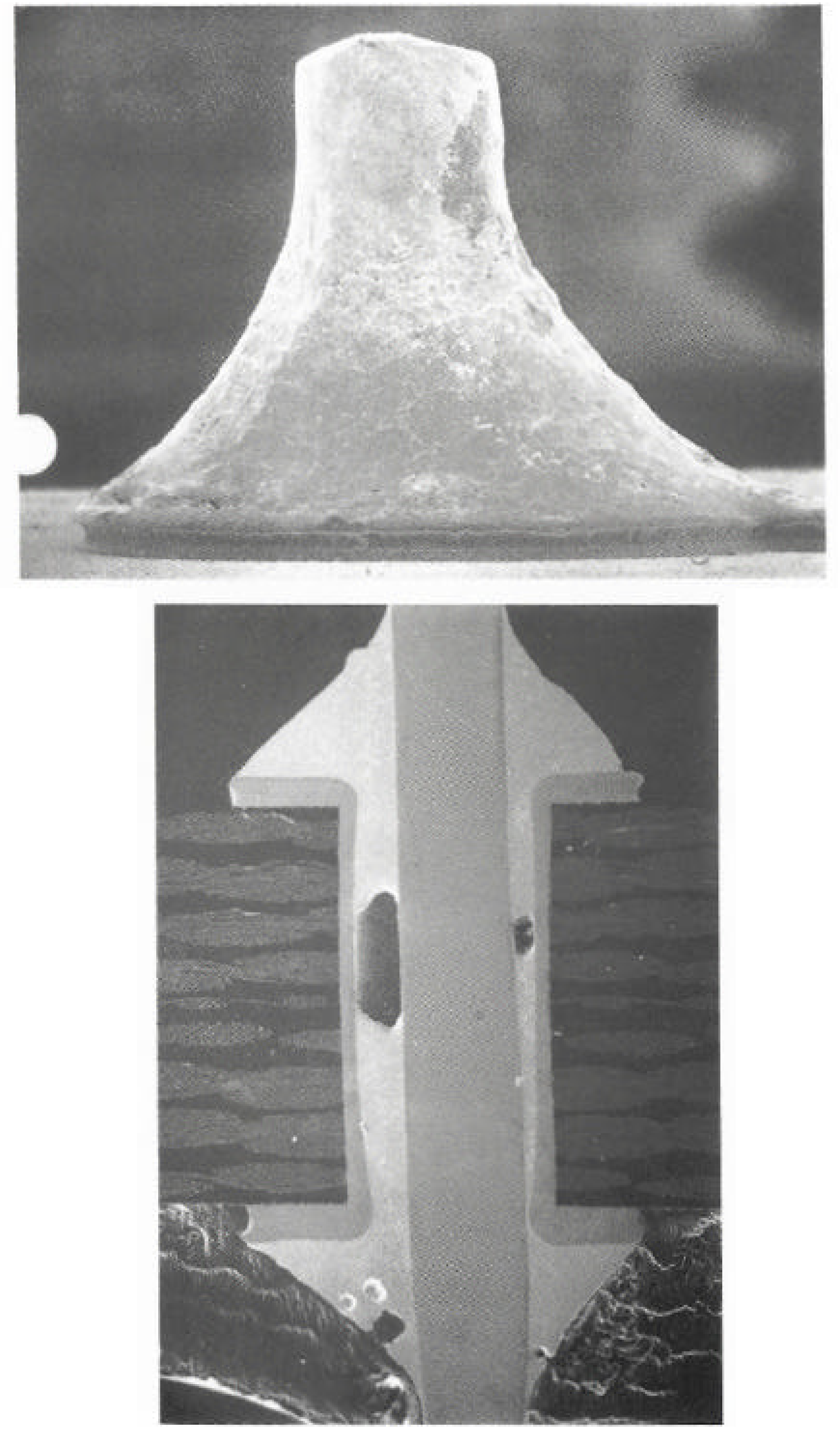


Figure 29: SEM views of lead on Resistor R4, coated with CV 1144, after 1000 thermal cycles. Very little surface movement has occurred

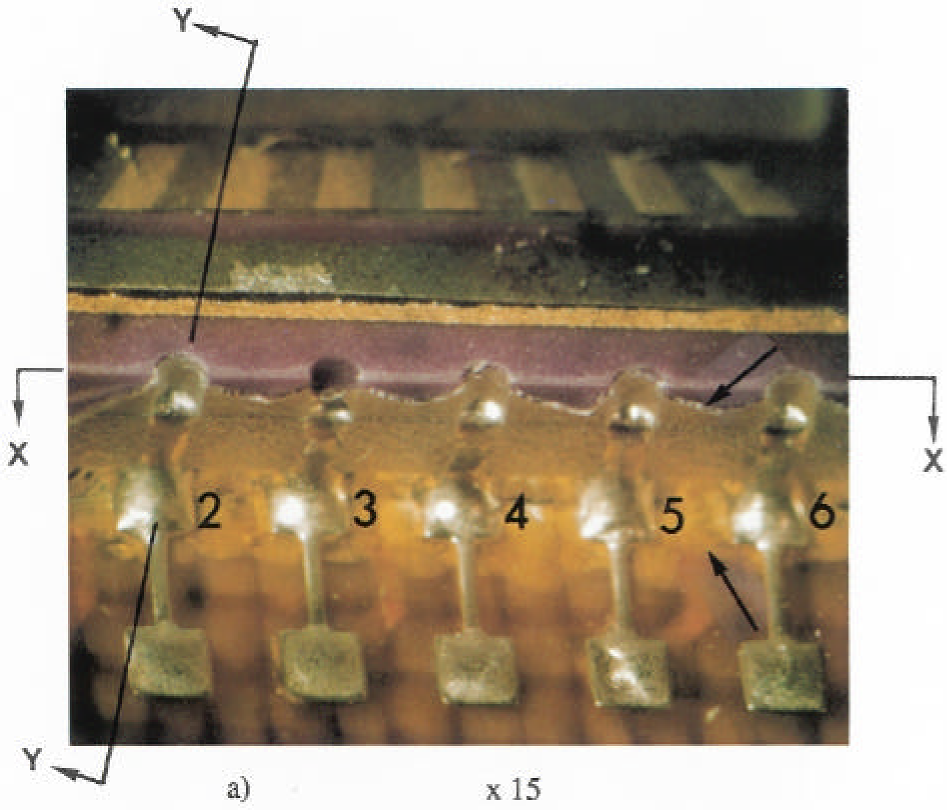
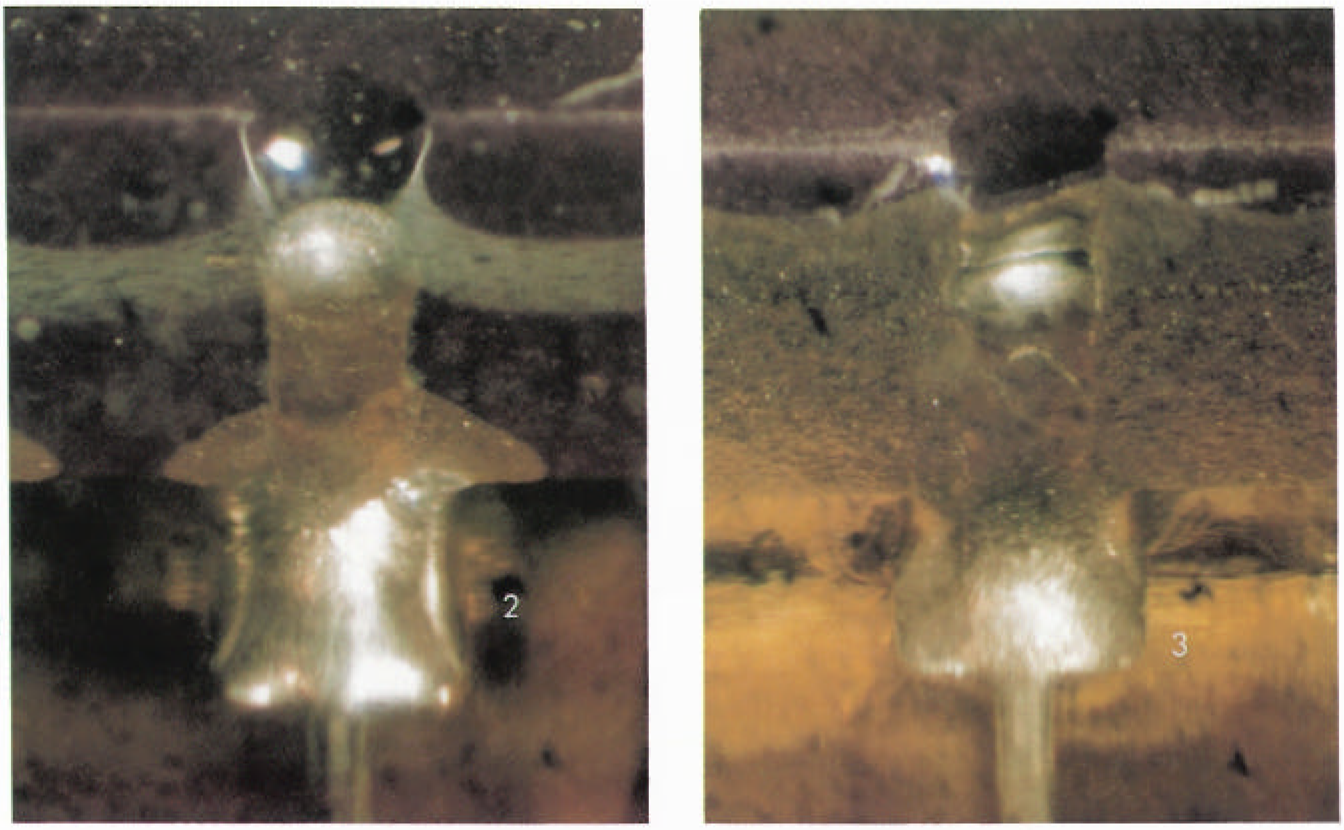
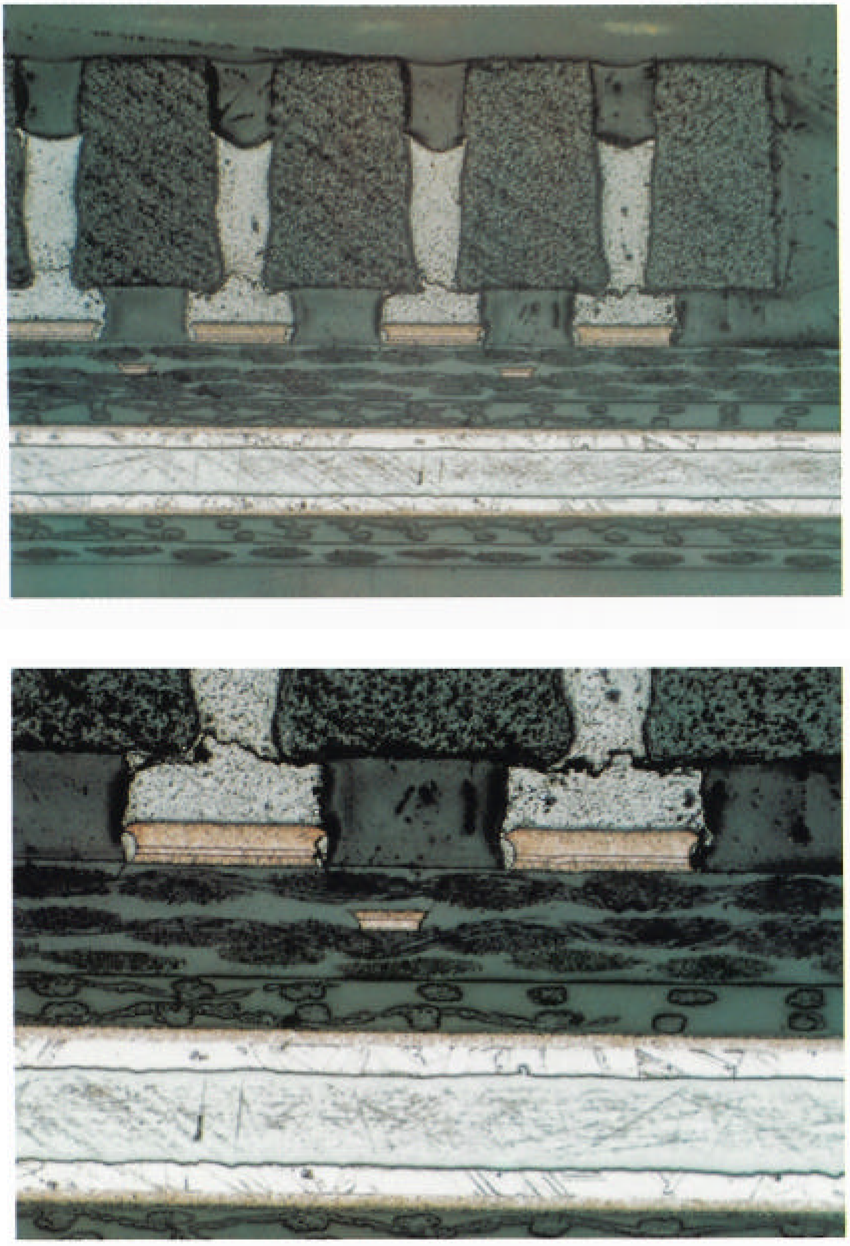


Figure 30: Leadless chip carrier coated with Scotchcast, device Z 5 (see Fig. 3 for location on polyimide pcb) after 1000 thermal cycles.
Overall view (a) shows some detachment of Scotchcast from upper side face of ceramic package and some delamination from pcb surface (arrows). The castellations 2 and 3 are detailed at x40 magnification (b and c) but, even with the best inspection optics, the fillets of these soldered joints cannot be seen to contain cracks which account for the electrical open circuits



b) x 40 c) x 40

tr



<--- Scotchcast

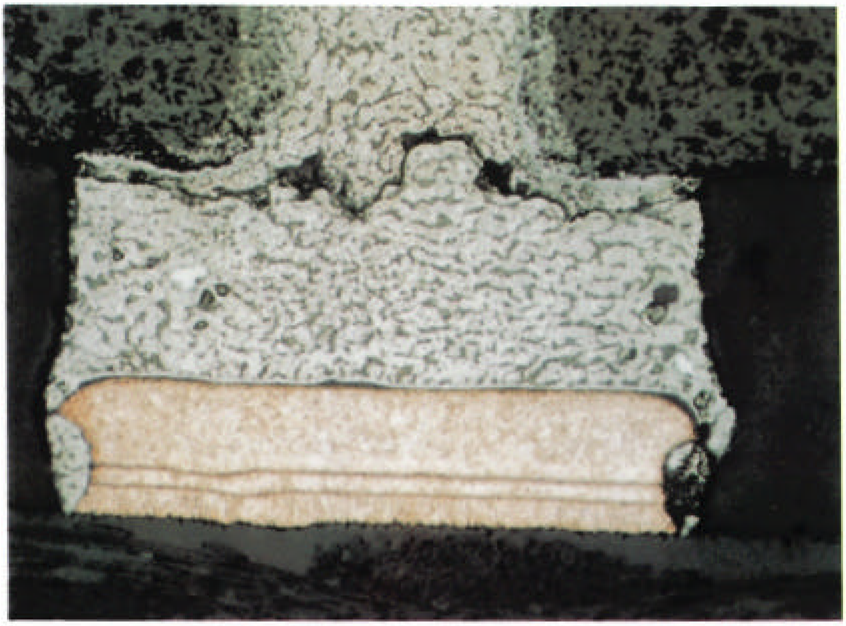
<--- Polyimide-glass

<--- Copper-coated molybdenum

(a) ×15

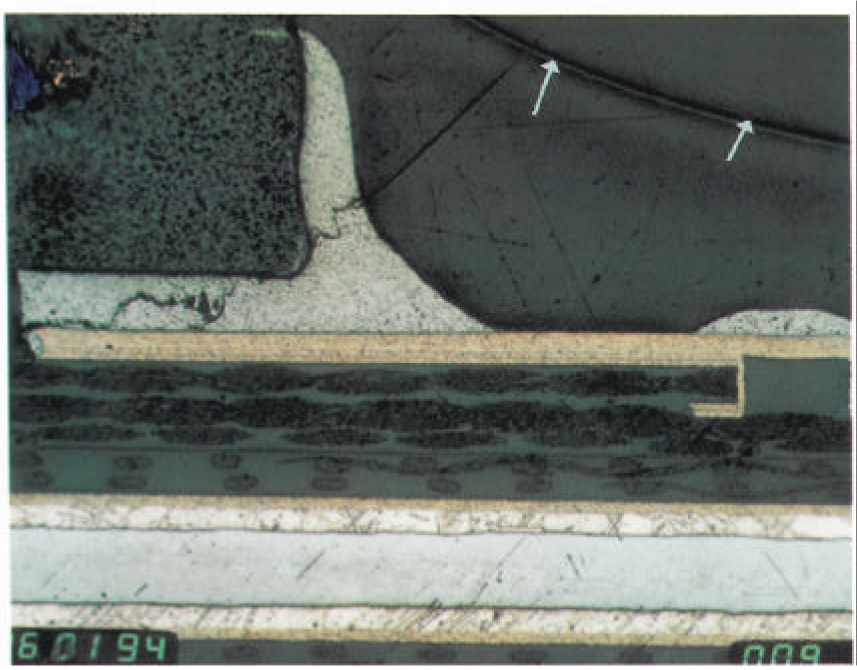
(b) ×30

Figure 31: Optical micrographs made parallel to a row of solder joint castillations (shown as section XX in Figure 30). Scotchcast after 1000 cycles. All castellations contain cracked soldered joints



< --- Crack location is at level of
metallised base of the castellation

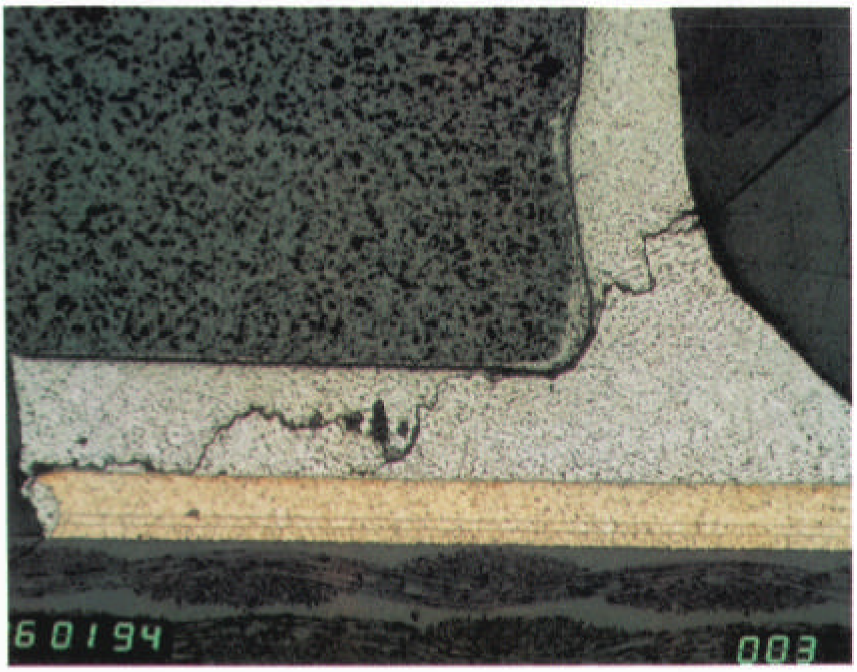
(c) x 130



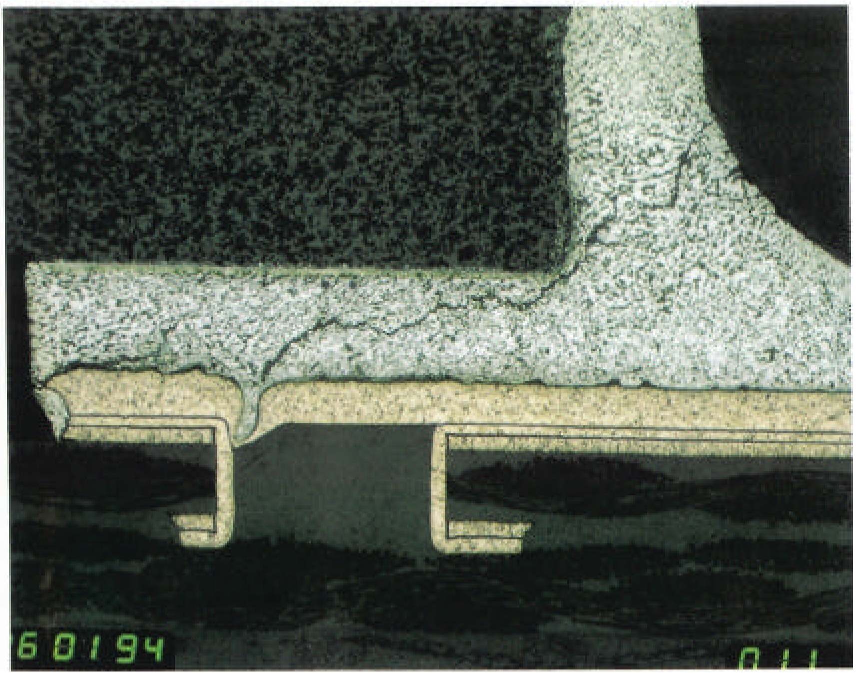
(a) General transverse view through cracked joint, also showing physical construction of the multilayer polyimide board with copper-coated molybdenum inner layer. The Scotchcast surrounds the package (arrows) and fills the stand-off volume (x 32)

(b) Detail of the irregular crack path. Zones of maximum shear strain have an

Stand-off height
= 220 μm --->



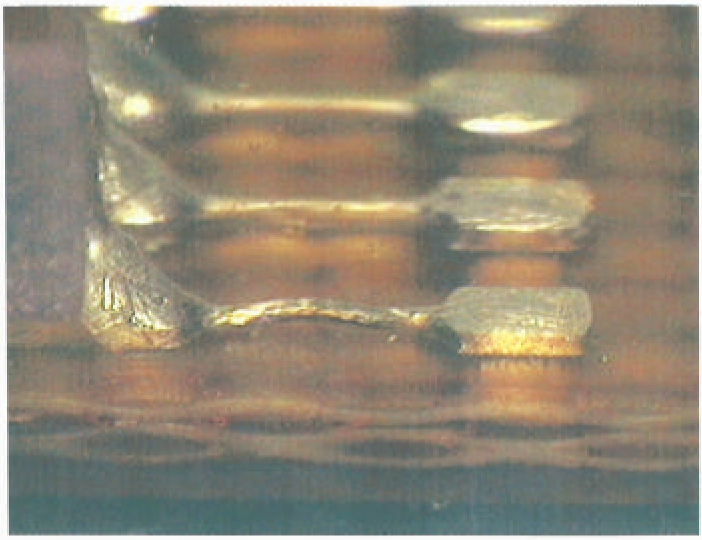
enlarged tin-lead grain structure. This is castellation No. 3 (x64)



(c) Similar picture of the irregular crack path. Zones of maximum shear strain have an enlarged tin-lead grain structure. This is castellation No. 3 (X64)

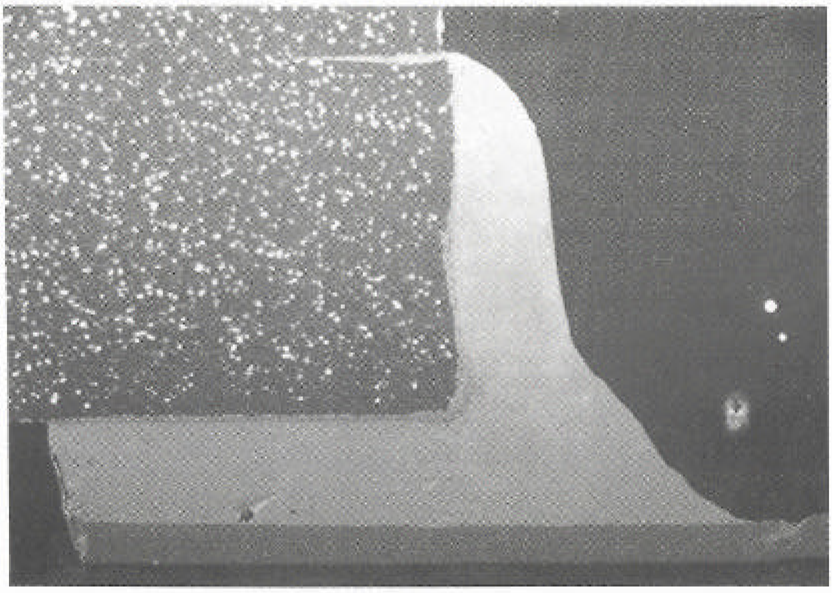
Figure 32: Microsection made progressively across the solder fillets shown in Figure 30 (section YY). Every joint was electrically open circuit, but because these defects do not emerge as wide-mouthed cracks they are not visible through the Scotchcast coating during inspection at high magnification

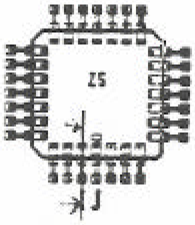
tr



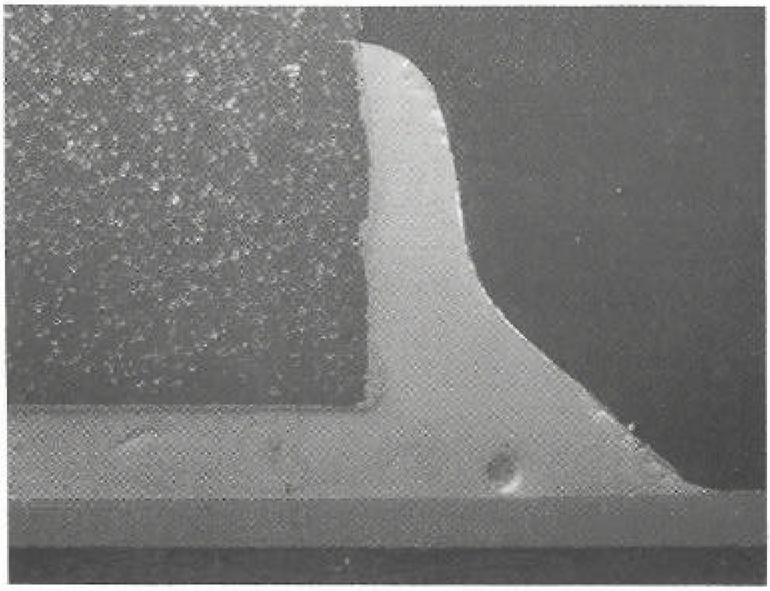
(a)

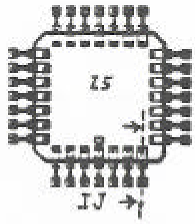
Figure 33: Leadless chip carrier coated with Conathane EN 11. Visual appearance (a) shows slight surface roughness of fillets, but microsections (SEM images b and c) confirm that no cracks were initiated during exposure to 1000 thermal cycles.



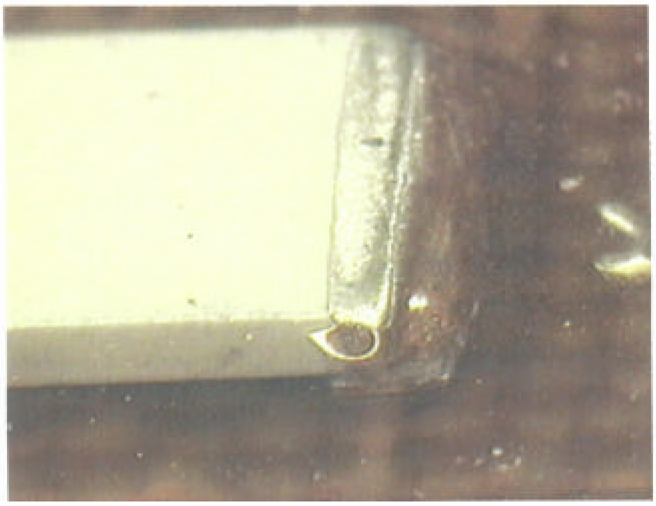


(b) ×50

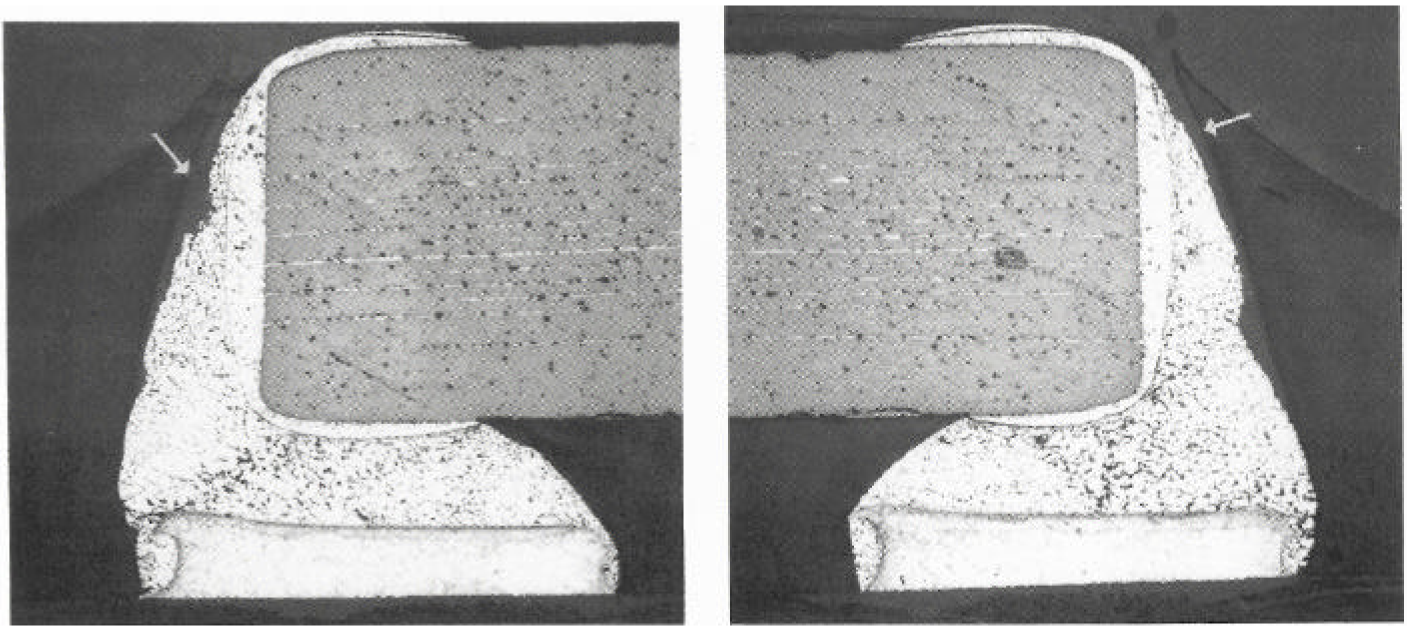




(c) ×50



(a) Optical image of capacitor



(b) Optical view of microsectioned capacitor showing stand-off height to be 200 µm. Note: Scotchcast has separated from upper (arrowed) part of solder fillet and has flowed in to fill the space beneath the component. The tin-lead microstructure has recrystallised in zones of high shear strain (see following SEM images). Magnification: X60

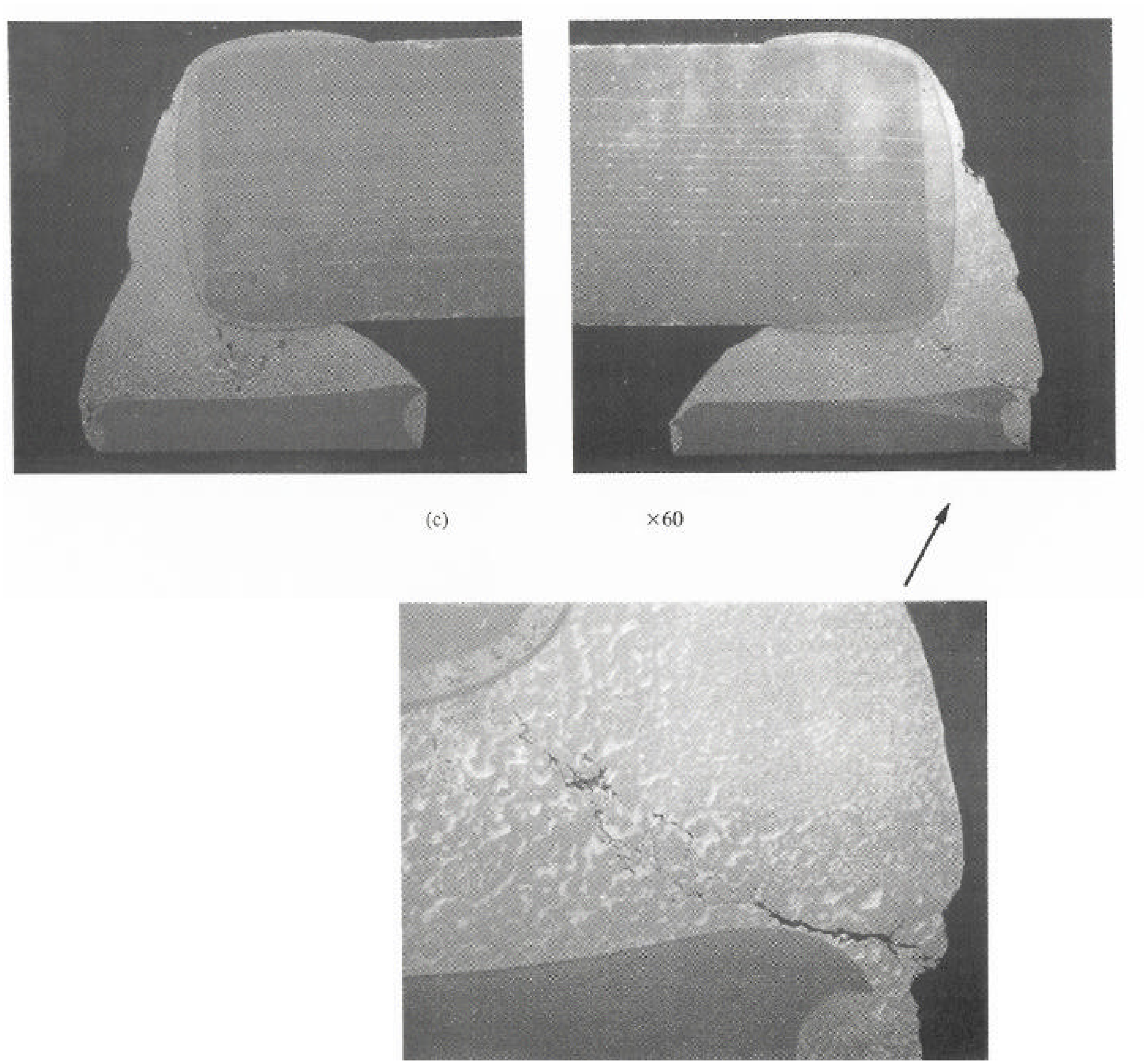


Figure 34: Ceramic chip capacitor (Specimen 2, C2) coated with Scotchcast, shows no electrical discontinuities after 1000 thermal cycles. The SEM images show surface roughening of fillets and some microcracks inside the solder (in zones of large grain size).