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**SUMMARY**

The surface insulation resistance (SIR) of double comb patterns on substrates manufactured from FR-4 laminates, ceramic and flexible polyimide have been used to assess the efficacy of conformal coatings to protect circuitry from exposure to harsh environmental conditions. A variety of different finishes have been used (copper/organic solderable preservative (Cu/OSP), hot air solder leveling (HASL), gold, silver and resist) to determine whether or not these have any affect on the performance of coatings. Several examples of conformal coatings representing each of the main generic types currently used by industry (acrylics, silicones and polyurethanes) have been studied together with a paraxylene. These coatings have been chosen to assess the potential variability that may exist between different formulations of equivalent generic types.

Measurements of the SIR of both coated and bare boards have been made during exposure to alternating dry (10% RH) and damp (90% RH) atmospheres as a function of increasing test temperature. Exposure of the boards to this pattern of environmental conditions enables the performance of coatings to be assessed with respect to both temperature and humidity. Rates of recovery or decay of the SIR in response to changes in humidity can also be monitored.

# 1 INTRODUCTION

The reliability of circuitry exposed to a variety of different environmental conditions is of paramount importance particularly that used in safety critical applications. This can be significantly improved by coating circuit assemblies with a thin layer of plastic i.e. a conformal coating. The function of this physical barrier is to shield boards from dust, process solvents e.g. acetone, moisture, fuels, hydraulic fluids and abrasion from handling[1,2].

Whilst this technology has been used in manufacture for some thirty years the problem of how to assess the performance of different coatings using a short-term *accelerated* test method remains. In this study we compare the performance of twelve different coatings that represent acrylics, silicones, polyurethanes and paraxylenes exposed to a profile of increasing temperature coupled with alternating low and high humidity. The performance of the coatings has been assessed by measuring the surface insulation resistance of comb patterns that have been produced in different finishes on different substrates i.e. FR-4 laminate, ceramic and flexible board.

## 1.1 THE MECHANISMS RESPONSIBLE FOR FAILURE OF CIRCUIT BOARD ASSEMBLIES

Before describing the experimental programme it is worthwhile to recall the mechanisms responsible for circuit assemblies failing when exposed to harsh or humid environments. Circuit failure can occur as a result of electrochemical migration, corrosion and or cracking of solder joints.

Electrochemical migration occurs when ions flow through an electrolyte from one conductor to another that is at a different electrical potential. This ion flow represents a current leakage between the two conductors that can be measured as a fall in the surface insulation resistance (SIR). The flow of positively charged metallic ions between two conductors can lead to dendrites being formed on the negatively charged conductor and subsequent short circuiting[3]. Typically the electrolytic medium through which the ions travel is water. The amount of water on the surface of a board immediately after manufacture is normally very little if the board has been suitably cleaned and dried. However this can change significantly with time especially if the board is exposed to damp atmospheres during service. The presence of organic residues such as the surfactants found in fluxes and other cleaning agents can facilitate the growth of dendrites due to their hygroscopic nature or their ability to form soluble complexes with metal ions.

Electrochemical migration results in corrosion of the circuitry although this process can also occur in the absence of an applied voltage. Corrosion of circuitry can lead to loss of conductor, cracking of solder joints and current leakage due to bridging between adjacent conductors by corrosion products. Cracking of solder joints can also occur as a result of thermal cycling due to differences in the thermal expansion coefficients of the board material, conductor and solder. This is a particular problem at low temperatures. There is some evidence to suggest that this susceptibility to cracking can be reduced by conformal coatings[4]. However the efficacy of the coating in this role depends on its chemistry and how well it coats the soldered junction.

## 2 EXPERIMENTAL

### 2.1 BOARD DESIGNS AND MATERIALS

Tests designed to probe the moisture resistance and thermal behaviour of conformal coatings have to account for potential variations arising from:

- the bonding between each coating and different substrates e.g. FR-4 laminate, ceramic and flexible boards.
- interactions between the coating and the board finish e.g. hot air level soldering (HASL), resist.
- the degree of cure of the coating.
- differences in the coating thickness.
- differences in the composition of ‘generically equivalent’ coatings supplied by different manufacturers e.g. water or solvent based acrylics.
- pre- and post-treatment of the boards i.e. cleaning procedures, storage and handling.
- different test conditions.

Given this complexity we have chosen to measure the surface insulation resistance of a simple board design comprising of three double comb patterns. The influence of that these different conditions have on the SIR values can then be studied by depositing the comb patterns on to different types of board and finishes. This simplistic arrangement avoids the additional problems that arise during conformal coating of boards that have dummy components mounted on them i.e. ensuring that soldered joints are effectively shrouded.

#### 2.1.1 Selection of board materials and test patterns

The test coupons consisted of a square board of length 100 mm manufactured from epoxy FR-4 laminate or ceramic or flexible polyimide. FR-2 laminate has also been used for some limited aspects of the investigation that are described in section 3.3. The design of the test pattern (NPL TB15) is shown in Figure 1. The test pattern comprises of three double combs of dimensions 25 mm x 25 mm. The track width is 0.35 mm and the pitch and gap are 0.3 and 0.15 mm respectively. The SIR was monitored via a 32 way edge connector. The 25 mm square metallised pad on the board can be used to compare the adhesion of different coatings to this area and the bare board by cross-hatch or similar measurement techniques.

#### 2.1.2 Selection of finishes and resist

FR4 boards were finished with copper/organic solder preservative (Cu/OSP), gold and HASL whilst ceramic boards were finished with silver or gold. A gold finish was used on the flexible board. Probimer 52 was used as a resist material for FR-4 boards.

#### 2.1.3 Selection of coatings

The twelve coatings selected for this investigation represent acrylics, polyurethanes, silicones and paraxylene. A number of examples from each generic type were chosen so as to include water and solvent based materials and those cured by heat and UV. The paraxylene was deposited by vacuum deposition. The application method and curing route for these materials are listed in Table 1. Most boards were coated on both sides i.e. dipped as is apparent from the final column of Table 1 with the coating covering approximately 92.5 % of the board. (The products have been classified only according to material type as the manufacturers supplied them under a confidential agreement.)

| Resin Type | Code | Method of application | Method of Cure | Coated on one or both sides |
|---|---|---|---|---|
| Acrylic | AC1 | Dip/Spray | Solvent | Double |
| | AC2 | Dip/Spray | Ambient/Heat | Double |
| | AC3 | Dip/Spray | Ambient/Heat | Double |
| | AC4 | Dip/Spray | UV | Single |
| | AC5 | Dip/Spray | Solvent | Double |
| Paraxylene | XY | Vacuum Deposition | None | Double |
| Urethane | UR1 | Dip/Spray | Water/Heat | Double |
| | UR2 | Dip/Spray | Solvent | Double |
| | UR3 | Dip/Spray | Solvent | Double |
| Silicone | SR1 | Dip/Spray | Water | Double |
| | SR2 | Dip/Spray | Heat | Double |
| | SR3 | Dip/Spray | Heat | Double |
| | SR4 | Spray | UV/Water | Single |

Table 1: Conformal coating materials.

Where possible coatings were applied in different thickness i.e. nominally 25, 50 or 75 μm. There is some evidence to suggest that the thickness of the coating plays an important role in protecting circuitry during exposure to harsh conditions[4]. However it has also been reported that thicker coatings are more susceptible to in-service cracking and tend to inadequately cover soldered joints[4].

### 2.1.4 Pre- and post-coating treatments

Initial tests on the bare connector assembly showed that cleanliness of the wiring assembly, particularly around the solder lugs is important in maintaining high values of SIR. In a comparison of ultrasonic and iconographic cleaning of the wiring assembly the latter proved to be more successful at removing stray ionic contamination. Hence prior to coating the boards were cleaned with an isopropyl alcohol/water mixture where necessary, baked at 125 $^{o}$C for 1 hour and then subjected to a typical reflow oven profile for eutectic SnPb solders. After cleaning the boards were handled only by their edges by operators wearing latex gloves to avoid contamination prior to coating. After coating and curing the boards were packaged into moisture-proof bags containing desiccant material. Sheets of paper were used to prevent the boards from coming into contact with each other.

### 2.1.5 Curing procedure

The coatings were cured following the manufacturers recommended procedures.

During manufacture it is not uncommon to encounter coated boards that have not been fully cured. This is a particular problem with polyurethanes and heat cured silicone. To simulate this scenario a limited number of FR-4 laminate boards were prepared with partially cured coatings.

## 2.2 SURFACE INSULATION RESISTANCE MEASUREMENTS

A Concoat AutoSIR (Mk II) that has a current sensitivity $1 \times 10^{-11}$ A was used to monitor the SIR values on 16 channels at intervals of either 5 or 10 minutes during the 48 hour period of the test. This sampling frequency enables changes in SIR to be closely monitored under different environmental conditions. A $10^6$ $\mathbf{\Omega}$ limiting resistor was included in each measurement channel. During the test period a +50 V DC biased voltage was continuously applied across the double comb patterns.

The edge connector was masked on both sides of the board to ensure that the SIR measurements were a true reflection of the resistance of the test pattern and not contaminated by the edge connector. The measured SIR values discussed here represent the average value for the three double combs contained on each board and are not given in ohm squares.

### 2.2.1 Test conditions

Typically SIR values for clean boards are well in excess of $10^{12}$ ohms at room temperature and relative low humidity (<30% RH) and are beyond the measurement range of testing equipment[5]. Previous investigators have overcome this problem by raising both the temperature and the relative humidity until the SIR falls within the measurement capability of their test equipment. This approach whilst enabling the performance of different coatings to be assessed is limited in that the data are restricted to the test conditions at which the measurements are made. In this study the test coupons were exposed to alternating wet and dry environments over a range of different temperatures to ascertain how the conformal coatings perform as a function of these two variables. This procedure has the potential to provide valuable information concerning the expected in-service performance of coatings applied to circuit assemblies.

A typical measured profile for humidity and temperature during a test is shown in Figure 2A. From this figure it is evident that the humidity is cycled over a two hour period from 10% RH to 90% RH. This humidity cycle is superimposed on to a stepped temperature profile where each step is maintained for a period of four hours. The temperature and humidity conditions within the environmental chamber (Sanyo Format 550 Programme[6]) were monitored by wet and dry platinum resistance thermometers.

# 3 RESULTS

## 3.1 VISUAL APPEARANCE

After exposure to the temperature – humidity profile the boards were visually examined using an optical microscope. In general there was very little evidence of track corrosion or dendritic growth although a small number of boards (8) did show some localized track damage as shown in Figure 3. However there are no obvious links between damaged boards and different types of coating, board finish or substrate.

## 3.2 SIR RESULTS

Figure 2B shows the dependence of log SIR (averaged over the three double comb patterns) on temperature and humidity for FR-4 board with a resist finish. The bare board has a SIR in excess of $10^{13}$ ohms under low temperature dry conditions (below 60 $^{o}$C and at 10% RH). This resistance is associated with a current that is beyond the measurement capability of the equipment. However during the damp phase of the humidity cycle the SIR progressively falls to below $10^{10}$ ohms as the test temperature increases. Note that recovery of the SIR during the dry phase of the humidity initially recovers to a level of around $10^{13}$ ohms but then falls with increasing test temperature.

The ability of the SIR to recover after exposure to a damp environment appears to depend on the chemistry of the conformal coating, the finish applied to the board and on the type of board. This phenomenon is illustrated in Figure 4 which shows the variation in SIR behaviour with different coatings applied to a resist finished FR-4 board. From this figure it appears that the SIR value for the control board takes more time to recover than for most of the coated boards. This is probably a reflection of the measuring equipments limitations in detecting resistances in excess of $10^{13}$ ohms. This argument appears to be supported when the SIR values become measureable during the dry phase of the humidity cycle at higher temperatures. The data in Figure 4 show that the SIR of the coated boards exceeds that of the bare board for this combination of board type and finish.

Although plots of log SIR versus time are graphically informative they are not particularly useful for assessing the relationships between different coatings, substrates and finishes. This requires the development of metrics that can describe how:

- log SIR varies with temperature and humidity.
- log SIR varies with time under different humidity and temperature conditions.

The development of these metrics and their interpretation is described below.

### 3.2.1 The variation of log SIR with temperature and humidity

There is a definite decrease in log SIR with increasing temperature under damp conditions (90% RH) as shown in Figure 2B. This trend can be described by fitting a straight line to the average log SIR value as measured during each period of exposure to a damp environment. The data shown in Figure 2B is somewhat unusual in that all the averaged SIR values measured during exposure to the damp environment lie on a straight line. In many cases the SIR values at 90% RH and at the lower temperatures are beyond the measurement range of the AutoSIR equipment. This limitation causes plots of log SIR versus temperature to plateau. This problem can be overcome by only considering mean SIR data at temperatures in excess of 50 $^{o}$C in linear least-squares fits.

The bar charts of Figure 5 show the log SIR and its temperature dependence varies for each of the coatings applied to Cu/OSP finished FR-4 boards and with the uncoated board. The log SIR values are those predicted by least-squares fits to the data at 50 $^{o}$C. The error bars reflect the variation in the predicted log SIR values generated from measurements on duplicate boards. In subsequent sections the variation in log SIR with different board finishes and types of substrate will be discussed.

3.2.2 The dependence of log SIR on the surface finish of epoxy FR-4 boards.

Table 2 shows how the predicted log SIR at 50 $^{o}$C under damp conditions is affected by the finish used to prepare bare FR-4 boards. The data are ranked from high to low SIR.

| Generic coating type | Specific coating | Log SIR ranking of bare board and board finishes | Temperature dependence of log SIR as function of different board finishes |
|---|---|---|---|
| - | - | Cu/OSP > Au > Resist > HASL | Cu/OSP ≡ Au > Resist > HASL |
| Acrylic | AC1 | Au > Cu/OSP > HASL > Resist | Cu/OSP > Au > Resist > HASL |
| | AC2 | Au > Cu/OSP > Resist > HASL | Au > Resist > Cu/OSP > HASL |
| | AC3 | Cu/OSP > Au > Resist > HASL | Cu/OSP > Au ≡ Resist > HASL |
| | AC4 | Au > Cu/OSP > Resist > HASL | Cu/OSP > Resist > Au |
| Polyurethane | UR1 | Resist > Au > HASL > Cu/OSP | Au > Resist > HASL > Cu/OSP |
| | UR2 | Cu/OSP > Au > HASL > Resist | Cu/OSP ≡ Au ≡ Resist > HASL |
| | UR3 | Resist > Cu/OSP > HASL > Au | Cu/OSP > Au ≡ Resist ≡ HASL |
| Silicone | SR1 | Au ≡ Cu/OSP > HASL ≡ Resist | Cu/OSP > Au ≡ Resist > HASL |
| | SR2 | Au ≡ Cu/OSP > HASL > Resist | Cu/OSP ≡ Au > Resist ≡ HASL |
| | SR3 | Cu/OSP > Au ≡ HASL > Resist | Cu/OSP ≡ HASL > Au ≡ Resist |
| | SR4 | Cu/OSP > Au ≡ HASL > Resist | Cu/OSP > Resist > HASL > Au |
| Paraxylene | XY | Cu/OSP > HASL ≡ Au | Cu/OSP > Au > HASL |

Table 2: Ranking of the predicted log SIR at 50 $^{o}$C and the temperature dependence for different board finishes under ***damp*** conditions.

In general Cu/OSP or gold finishes give a superior SIR to resist or HASL finishes irrespective of the conformal coating type. Note that the resist finish appears to give higher SIR values than HASL finished boards coated with acrylics, a trend that is reversed for boards coated with silicones. The SIR of Cu/OSP or gold finished boards is more sensitive to temperature than those finished by HASL or resist.

### 3.2.3 The influence of conformal coatings applied to different surface finishes of FR-4 laminate on log SIR

The data shown in Table 2 can be re-presented according to the efficacy of different coatings in maintaining SIR with respect to different types of coating. These data are shown in Table 3. From this table it is apparent that the predicted log SIR value at 50 $^{o}$C under damp conditions depends on both the generic and specific type of conformal coating material. The bare board, for example, has a higher log SIR value than boards coated with any of the polyurethane materials examined in this study. In contrast the performance of bare board in comparison with boards coated with silicone varies with different suppliers materials.

| Board Finish | Generic coating type | Log SIR ranking of bare board and specific coatings | Temperature dependence of log SIR as function of different coatings |
|---|---|---|---|
| Au | Acrylic | AC1 > Bare > AC3 > AC4 > AC2 | Bare ≡ AC1 ≡ AC2 ≡ AC3 > AC4 |
| Cu/OSP | | AC1 ≡ Bare ≡ AC3 > AC4 >AC2 | Bare ≡ AC1 ≡ AC2 ≡ AC3 > AC4 |
| HASL | | AC1 ≡ AC3 > Bare > AC4 > AC2 | Bare ≡ AC1 ≡ AC3 > AC2 ≡ AC4 |
| Resist | | AC3 > Bare ≡ AC1 > AC4 > AC2 | AC4 ≡ AC3 > Bare ≡ AC1 ≡ AC2 |
| Au | Polyurethane | Bare > UR2 > UR3 ≡ UR1 | Bare > UR1 ≡ UR2 ≡ UR3 |
| Cu/OSP | | Bare > UR2 ≡ UR3 > UR1 | Bare ≡ UR2 ≡ UR3 > UR1 |
| HASL | | Bare > UR2 ≡ UR3 > UR1 | UR3 > UR2 ≡ Bare > UR1 |
| Resist | | Bare ≡ UR3 > UR2 > UR1 | UR3 > UR1 > UR2 ≡ Bare |
| Au | Silicone | SR2 > Bare ≡ SR3 > SR1 > SR4 | Bare ≡ SR2 ≡ SR3 > SR1 ≡ SR4 |
| Cu/OSP | | Bare ≡ SR2 ≡ SR3 ≡ SR4 > SR1 | Bare ≡ SR2 ≡ SR3 ≡ SR4 > SR1 |
| HASL | | SR2 > SR3 > Bare > SR4 > SR1 | SR2 > SR3 > Bare > SR1 ≡ SR4 |
| Resist | | SR2 > SR3 ≡ SR4 > Bare > SR1 | SR2 > SR3 ≡ Bare ≡ SR4 > SR1 |
| Au | Paraxylene | Bare ≡ XY | Bare ≡ XY |
| Cu/OSP | | Bare ≡ XY | Bare ≡ XY |
| HASL | | XY > Bare | XY > Bare |
| Resist | | - | - |

Table 3: A comparison of the predicted log SIR values at 50 $^{o}$C and the temperature dependence of log SIR measured under ***damp*** conditions.

Although the ranking order is of limited statistical validity there are indications of trends within the data shown in Table 3, for example, the predicted log SIR values can be ranked for the:

- acrylic materials as AC1 > AC3 > AC4 > AC2
- silicone coatings as SR2 > SR3 > SR4 > SR1
- polyurethane coatings as UR3 and UR2 > UR1
- paraxylene as bare board ≡ XY

***irrespective*** of the finish used on the FR-4 board. The ranked temperature dependencies of the mean log SIR's measured for different coatings on differently finished FR-4 boards under damp conditions essentially mirror those of the predicted log SIR values at 50 $^{o}$C. It should be noted that in many cases the temperature dependence of log SIR of coated boards is equivalent to that of the bare board within experimental error.

Whilst it is important to ensure that the SIR is maintained during exposure to damp atmospheres over a range of temperatures it is also necessary for any losses in SIR to be rapidly recovered if the board is exposed to a dry atmosphere. For some coating/board combinations log SIR repeatedly and rapidly recovers to values in excess of 13 during each dry period of the environmental cycling (e.g. coating SR3 figure 4). Other coatings show a progressive decrease in log SIR during the dry phase of the cycling programme e.g. the bare board shown in figure 4.

The temperature at which the board no longer recovers its initial low temperature dry value for SIR at 40°C and 10% RH can be used as a means of ranking the performance of different coatings on different finishes. These data are shown in Table 4.

| Board Finish | Generic coating type | Log SIR ranking of bare board and specific coatings |
|---|---|---|
| Au | Acrylic | AC4 = AC3> Bare = AC2 = AC1 |
| Cu/OSP | | Bare > AC4 = AC3 = AC3 = AC1 |
| HASL | | Bare = AC4 = AC3 = AC2 = AC1 |
| Resist | | AC2 = AC4 > AC3 = AC1 > Bare |
| Au | Polyurethane | Bare = UR3 = UR2 > UR1 |
| Cu/OSP | | Bare > UR2 > UR3 > UR1 |
| HASL | | Bare > UR3 = UR2 > UR1 |
| Resist | | UR3 > UR1 > UR2 = Bare |
| Au | Silicone | SR3 = SR2 = Bare > SR4 = SR1 |
| Cu/OSP | | Bare = SR3 = SR2 > SR4 = SR1 |
| HASL | | SR4 = SR3 = SR2 = SR1 = Bare |
| Resist | | SR4 = SR3 > SR2 = SR1 > Bare |
| Au | Paraxylene | XY = Bare |
| Cu/OSP | | Bare > XY |
| HASL | | XY = Bare |
| Resist | | - |

Table 4: Ranking of the SIR of bare and coated boards under ***dry*** conditions.

Some coating/finishes gave SIR values that exceeded the measurement capabilities of the AutoSIR equipment throughout the temperature/humidity cycling test e.g SR3 coated FR-4 laminate. Other coating/finish combinations show a dramatic drop in SIR after one exposure to damp atmosphere e.g UR1 coated HASL finished FR-4.

Table 4 shows that the performance of conformal coatings during the dry phase of the humidity cycle is less sensitive to different types of coating than the data obtained from measurements made during the damp phase of the humidity cycle. However it is interesting to note that the log SIR values for FR-4 boards finished with a resist are lower for bare board than for coated boards. The opposite is true for boards finished with Cu/OSP with the exception of silicone coated boards where the performance of the bare board is equivalent to those coated with SR3 and SR2.

### 3.2.4 The variation of log SIR with different board substrates

Table 5 shows that the SIR is higher for patterns deposited on FR-4 laminate than for the same patterns deposited on ceramic board irrespective of the conformal coating used to shield the pattern. The same trend is also observed for the temperature dependence of log SIR.

| Generic coating type | Specific coating | Log SIR ranking of bare board based on different substrates | Temperature dependence of log SIR as function of different substrates |
|---|---|---|---|
| - | Bare Board | FR-4(Au) > CERAM | FR-4(Au) > CERAM |
| Acrylic | AC1 | FR-4(Au) > CERAM | FR-4(Au) > CERAM |
| | AC2 | FR-4(Au) > CERAM | FR-4(Au) > CERAM |
| | AC3 | FR-4(Au) > CERAM | FR-4(Au) > CERAM |
| | AC4 | FR-4(Au) > CERAM | FR-4(Au) > CERAM |
| Polyurethane | UR1 | FR-4(Au) > CERAM | FR-4(Au) > CERAM |
| | UR2 | FR-4(Au) > CERAM | FR-4(Au) > CERAM |
| | UR3 | FR-4(Au) > CERAM | FR-4(Au) > CERAM |
| Silicone | SR1 | FR-4(Au) > CERAM | FR-4(Au) > CERAM |
| | SR2 | FR-4(Au) > CERAM | FR-4(Au) > CERAM |
| | SR3 | FR-4(Au) > CERAM | FR-4(Au) > CERAM |
| | SR4 | FR-4(Au) > CERAM | FR-4(Au) > CERAM |
| Paraxylene | XY | FR-4(Au) > CERAM | FR-4(Au) > CERAM |

Table 5: The SIR of FR-4 laminate exceeds that of ceramic board irrespective of the coating applied to it. This behaviour is mirrored by the temperature dependence of log SIR.

The performance of equivalent coatings on different substrates during the dry phase of the humidity cycle is shown in Table 6. Here coatings perform equally well on both FR-4 and ceramic which out-perform flexible polyimide.

| Generic coating type | Specific coating | Log SIR ranking of bare board based on different substrates |
|---|---|---|
| - | Bare Board | CERAM > FR-4(Au) = FLEX |
| Acrylic | AC1 | - |
| | AC2 | FR-4(Au) = CERAM > FLEX |
| | AC3 | FR-4(Au) = CERAM > FLEX |
| | AC4 | FR-4(Au) = CERAM |
| Polyurethane | UR1 | FR-4(Au) > CERAM |
| | UR2 | FR-4(Au) = CERAM > FLEX |
| | UR3 | - |
| Silicone | SR1 | FR-4(Au) = CERAM > FLEX |
| | SR2 | FR-4(Au) = CERAM > FLEX |
| | SR3 | FR-4(Au) = CERAM > FLEX |
| | SR4 | FR-4(Au) = CERAM = FLEX |
| Paraxylene | XY | FR-4(Au) = CERAM = FLEX |

Table 6: Ranking of SIR values for different coating/substrate combinations measured during the dry phase of the humidity cycle.

### 3.2.5 Influences of coating thickness and degree of cure on SIR

Measurements of the SIR of partially cured coatings were equivalent within experimental error to those determined for fully cured materials. Similarly there are no obvious links between SIR measurements and the thickness of different coatings that nominally ranged from 25 µm to 75 µm.

## 3.3 THE PERMEABILITY OF CONFORMAL COATINGS TO WATER VAPOUR

There are a number of issues that have been identified as a result of this investigation that merit a more detailed discussion. In general the decrease of SIR observed under damp conditions implies that the conformal coatings used in this study ***are not*** behaving as efficient moisture barriers. Indeed the SIR results clearly show that the SIR of polyurethane coated boards is less than that of bare board. This appears to conflict with some manufacturers claims that conformal coatings are ‘moisture resistant’, a finding that has also been observed by others[2,4].

Measuring the permeability of conformal coatings to water directly is not an easy task. However it is possible to infer something about the moisture permeability of coatings by monitoring changes in the weight of boards exposed to different humidity environments. Table 7 shows the difference in weight of both coated and un-coated FR-2 and FR-4 laminate boards after exposing the boards to a hot dry atmosphere for a period of 24 hours. These results show, as expected, that the weight loss is greater for FR-2 laminate than FR-4. The weight gains after a single period of exposure to a hot damp atmosphere (65% RH, 65 $^{o}$C) are identical within experimental error. These results imply that both coatings are permeable to moisture.

| Board material | Coating | Weight *loss* (%) (24 hours, 125 $^oC$) | Weight *gain* (%) (24 hours (65% RH, 65 $^oC$) |
|---|---|---|---|
| FR-2 | - | 3.0 | 2.3 |
| FR-2 | AC5 (both sides) | 3.5 | 2.2 |
| FR-4 | - | 0.29 | 0.11 |
| FR-4 | SR4 (single side) | 0.11 | 0.15 |

Table 7: Changes in weight of bare and coated boards after drying and exposure to a warm damp environment.

The SIR was measured during the period that the boards were exposed to a hot damp environment. These results are shown in Figure 6. From this figure it is apparent that the SIR value of both coated and bare FR-4 laminate falls to a relatively stable level within approximately 30 minutes of the exposure time. FR-2 boards show the same pattern of behaviour although the time required to achieve a ‘stable’ SIR value is approximately 8 – 10 hours. This difference in behaviour is likely to be a reflection of the water content of the different boards.

## 3.4 THE ABILITY OF CONFORMAL COATINGS TO PROTECT CIRCUITRY FROM CORROSION.

Figures 7A and 7B show the change in appearance of bare and conformally coated FR-4 boards during immersion in deionised water for a period of approximately 17 hours. From these figures it is evident that the silicone conformal coating provides an effective barrier against corrosion of the comb patterns. The corresponding SIR patterns shown in Figure 7c illustrate the very significant fall in log SIR that occurs during the first hour of immersion. Corrosion of the bare board begins almost instantaneously and is responsible for the subsequent increase in log SIR that occurs. This increase in log SIR with time is due to loss of corroded tracking that becomes detached from the comb patterns, thereby increasing resistance.

This appears to be a paradoxical result in that although the SIR data and weight measurements suggest that conformal coatings are permeable to moisture immersion in water shows that they can protect the circuitry from corrosion. This phenomenon could be explained by assuming that corrosion is constrained by the coating that would have to debond from the substrate to allow the growth of dendrites or build up of corrosion products.

## 3.5 THE SURFACE APPEARANCE OF FR-4 LAMINATE AND CONFORMAL COATINGS

Figure 8 shows the surface appearance of bare FR-4 laminate as seen under by a scanning electron microscope. From this figure it is evident that the surface is highly cratered and appears to cover a honeycomb structure within the laminate. In contrast the bare ceramic board (which is not shown here) appeared as a smooth undulating surface.

Most of the conformal coatings are featureless when viewed under the electron microscope with the exception of polyurethane coating UR1. The photomicrographs of this material shown in Figures 9 and 10 show a morphology that depends on the surface of the substrate. The coating covering the honeycombed epoxy appears as an aggregate of spherical balls that become distended forming sausage like structures on the gold tracking.

## 4 DISCUSSION

Log SIR progressively declines with increasing test temperature during the damp phase of the humidity cycle, this sensitivity appears to be linked to the chemistry of the conformal coatings and the finish used on different boards. Similar results are obtained under low humidity conditions. These findings suggest that the claims made by some manufacturers that conformal coatings are acting as ‘moisture barriers’ may be excessive, although there is no doubt that these coatings can protect circuitry from corrosion in harsh environments. Sbar et al[7] has suggested that the ‘moisture resistance’ of silicone rubber encapsulants is due to the strength of the bond between the coating and the substrate. In this scenario the adhesion between the coating and both the substrate and electrodes inhibits hydrolysis, interfacial conduction and metal dissolution kinetics. Wargold[2] and Tautscher[1] have also observed that conformal coatings act as semipermeable membranes allowing some moisture penetration to occur when boards are exposed to a damp atmosphere or immersed in water that reduces the SIR. Despite the decline in SIR the coating will stop the circuit from water bridging and hence causing signal cross talk or short circuits. This finding implies that although water is able to penetrate the coating it is unable to form a continuous film between the conductors.

The fall of SIR with increasing temperature during exposure to a damp environment could be attributed to the solubility of water in epoxy that would provide an additional conduction path for ion movements. The maximum solubility of water in epoxies is of the order of a few percent[3] at 80 $^{o}$C. Takahashi[8] has observed a jump in both electrochemical and bulk coating properties at 70% humidity (80C) indicating greatly increased ionic mobility as measured by ac impedance.

The efficiency of different coatings in preserving high values of SIR during exposure to increasingly harsh environments depends both on the generic type of coating and the specific chemistry of the formulation. Coatings based on polyurethanes are, for example, constantly out-performed by uncoated boards as measured by SIR. Sandoz[9] has also recorded falls of more than one decade in SIR to giga-ohm levels for comb patterns coated with polyurethane. In general HASL and resist finished boards have a lower SIR than those finished with either gold or Cu/OSP. HASL fluid can contain polygycol and hydrobromic acid both of which have been shown to penetrate the epoxy matrix at high temperature (around Tg)[7,11]. Due to the hygroscopic nature of glycol residues this enhances the absorption of moisture by the matrix[12]. This observation may well provide an explanation as to why HASL and resist coated boards give poorer SIR results than gold or Cu/OSP finished boards. This effect may not be limited to HASL finished boards. Wargold et al[2] also note that any water soluble residues in the vicinity of the board surface will be readily activated by the absorbed moisture indicating that board cleanliness is essential in maintaining high SIR values.

SIR testing at high temperatures can volatize or decompose organic residues yielding electrical behaviour that is not a true measure or indicator of ultimate electrical performance. This problem has been discussed by Sohn[13]. A contaminated surface can also cause a conformal coating to blister as a result of moisture passing through it leading to loss of adhesion, track corrosion and the growth of conductive anodic filaments. Damage to the interface between the coating and the substrate can also be triggered by thermal cycling particularly where there is a substantial difference in the coefficients of thermal expansion between the coating and the substrate. This is a particular problem for coatings that cover soldered joints[14]. The surface of the substrate can also play a significant role in trapping water by virtue of its structure. Many inorganic substances such as natural or synthetic zeolites or some forms of silica and some organic ones can have microfissured surfaces. If these cracks are similar in size to water molecules then they will accumulate in the vicinity of the surface thus lowering the SIR[15].

Tegehall[4] in a study of the link between conformal coatings and circuit degradation has noted that there is no obvious correlation between the capability of different coatings to prevent corrosion and the large variation in SIR observed during humidity tests. On the basis of this finding he has suggested that water condensation tests provide a better measure of coating capability than exposure to a damp environment. Tegehall claims the water will penetrate poor coatings through pin-holes or cracks within them if a thin film of water (~22 um) is sprayed directly onto test circuits. If water penetrates the coating then electrochemical migration can occur within a minute.

The rate at which log SIR increases after the chamber switches from damp to dry conditions is also a measure of coating/board performance. Most of the board coating combinations show a rapid recovery of SIR although a number of systems showed a delayed recovery particularly at higher temperatures. This behaviour is presumably a reflection of the rate at which water is absorbed by the matrix.

## 5 CONCLUSIONS

Surface insulation resistance (SIR) measurements from conformally coated substrates can give information on:

10 The absolute values for resistance and its temperature dependence as indicated by SIR temperature indices.
11 The recovery of performance during exposure to dry environment.
12 The performance of coatings in the absence of any visible corrosion.
13 The relative performance of different coatings with similar or dissimilar chemistry.
14 The performance of coatings covering different finishes and substrates.

The performance of a conformal coating can be assessed by surface insulation resistance temperature indices that give a value for the log SIR at 50C and describe how it changes with both temperature and time. From these measures it appears that the surface insulation resistance is insensitive to the degree of cure and the thickness of coatings. The resistance of bare board FR-4 laminate is superior to that of ceramic boards. In general Cu/OSP or gold finishes give a superior SIR to resist or HASL finishes irrespective of the conformal coating type. A resist finish appears to give higher SIR values than HASL finished boards coated with acrylics a trend that is reversed for boards coated with silicones. The SIR of Cu/OSP or gold finished boards is more sensitive to temperature than those finished by HASL or resist. The type of finish also affects the absolute value of SIR and its temperature sensitivity:

10 Gold finished FR-4 laminates have a higher SIR than those finished with HASL.
11 The SIR of gold or CU/OSP finished boards is more sensitive to temperature than HASL or resist.

Measurements of SIR of conformally coated FR-4 and ceramic boards indicate that the coatings are water permeable although this does not appear to affect their ability to protect circuitry from corrosion. The SIR of both coated and bare boards decreases with temperature particularly when exposed to a damp atmosphere of 90 % RH

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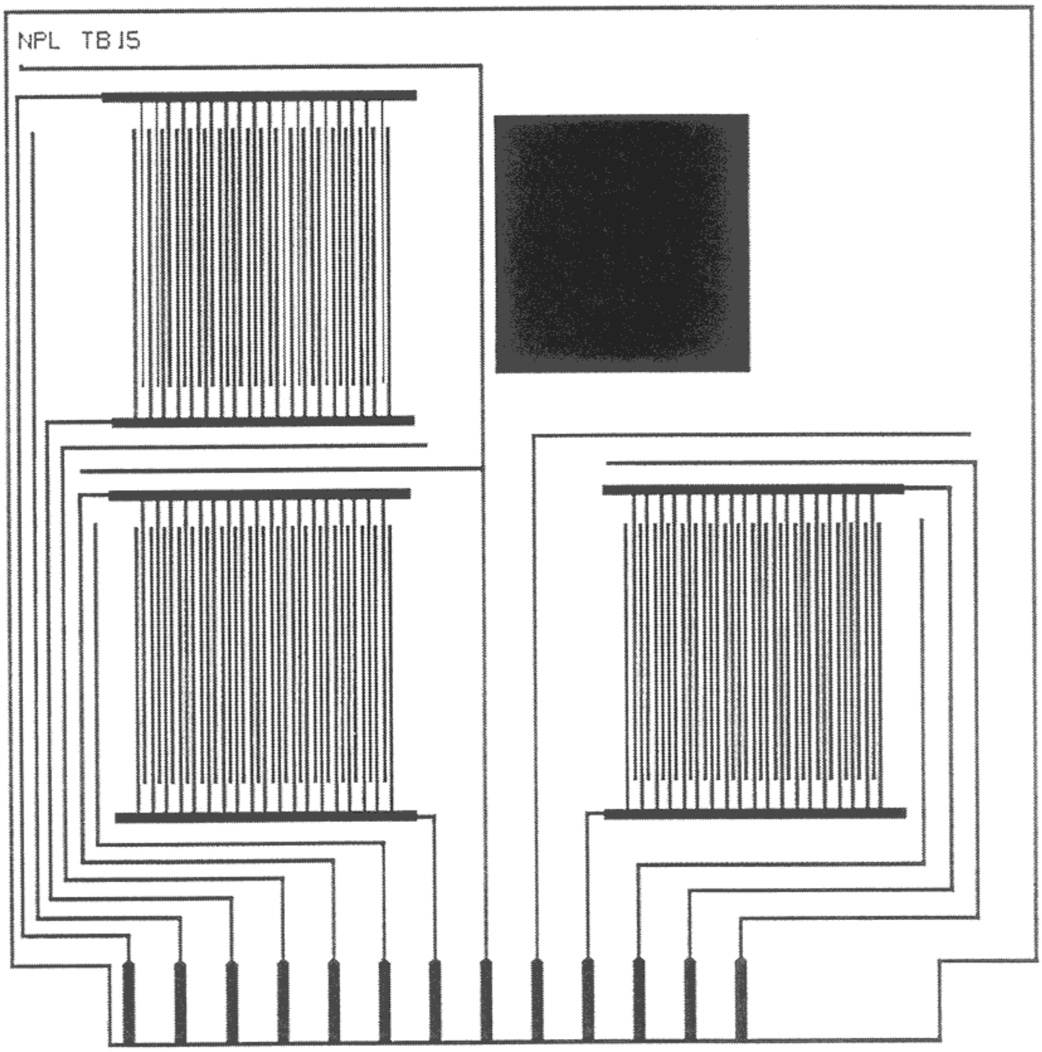
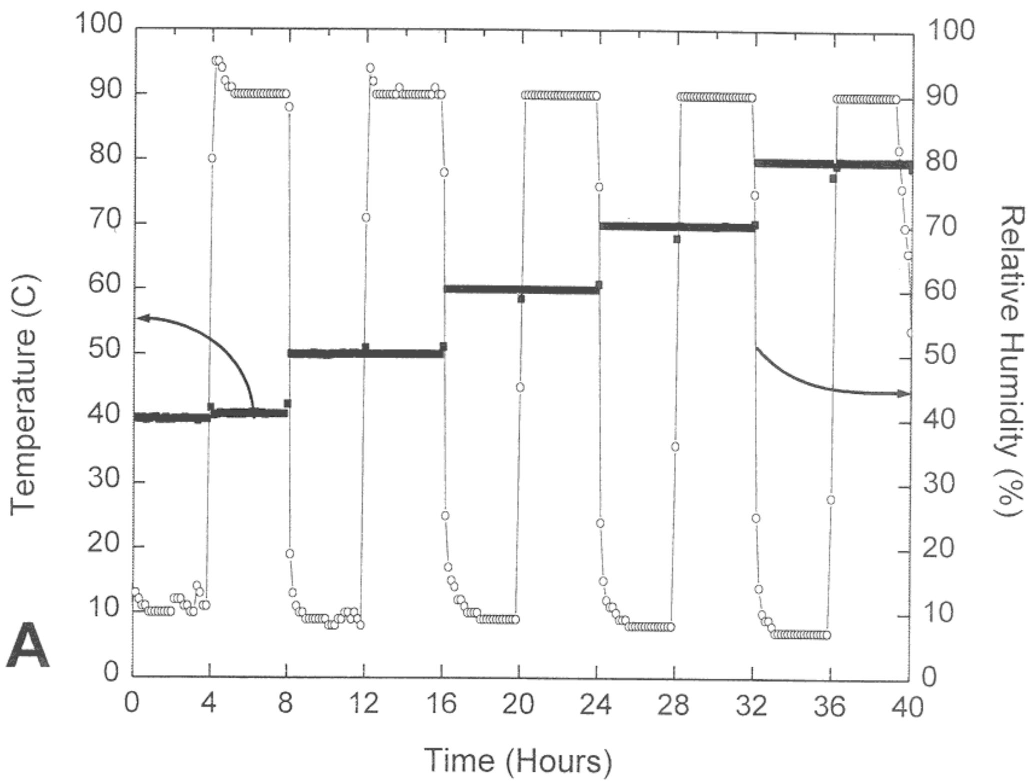



Fig. 1 The test patterns used for SIR measurements of finishes on FR-4 laminate and ceramic.



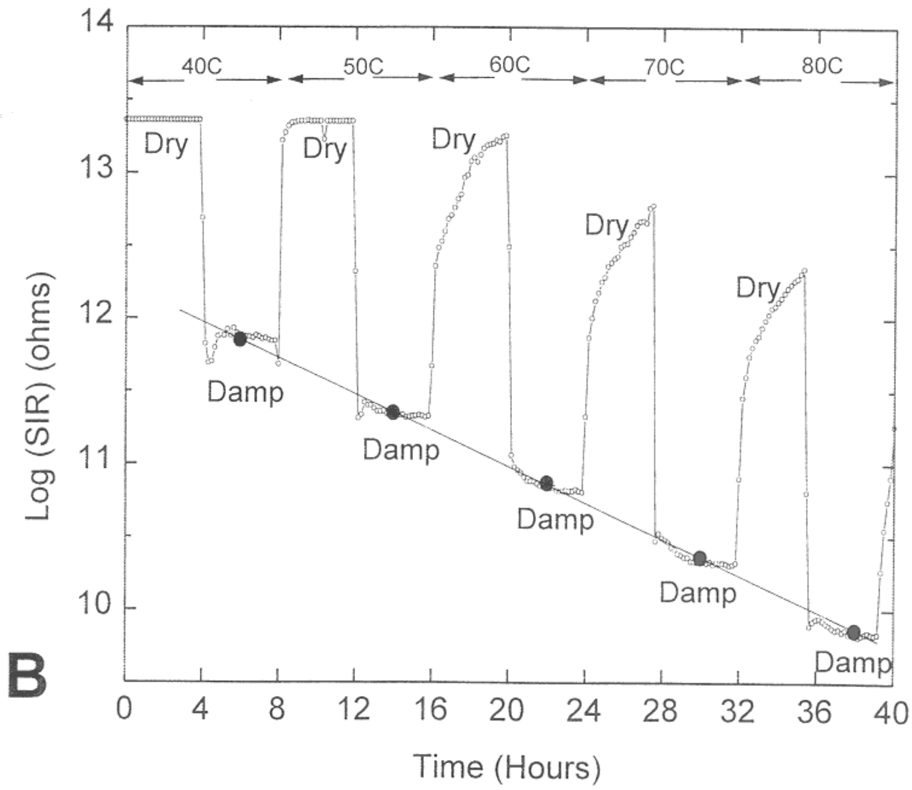
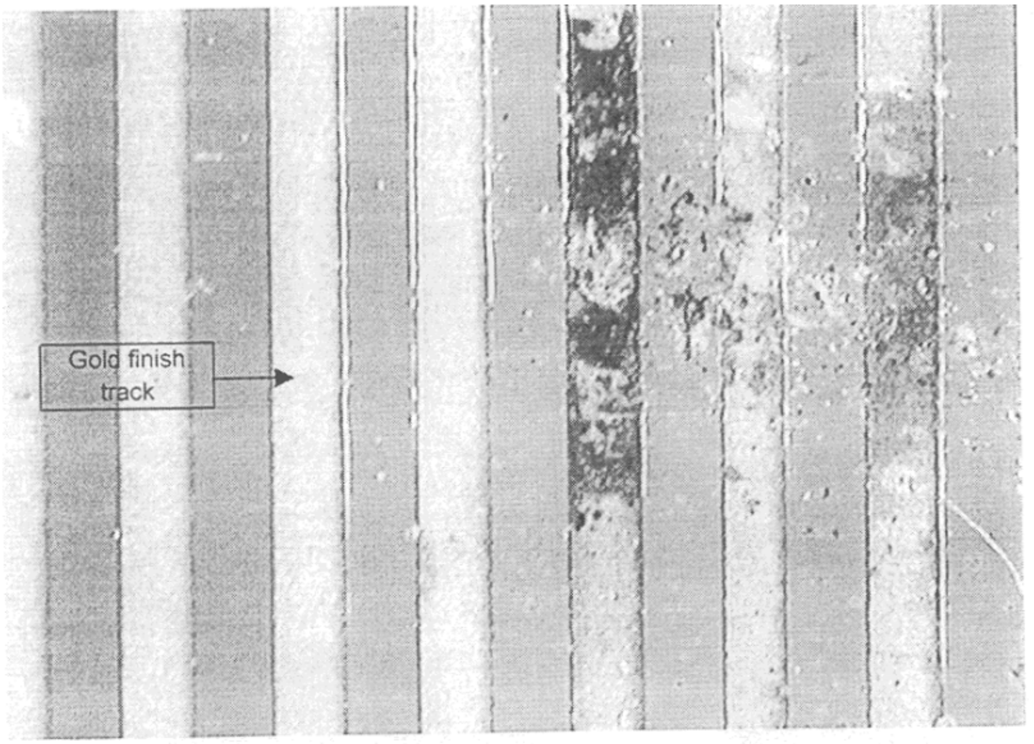
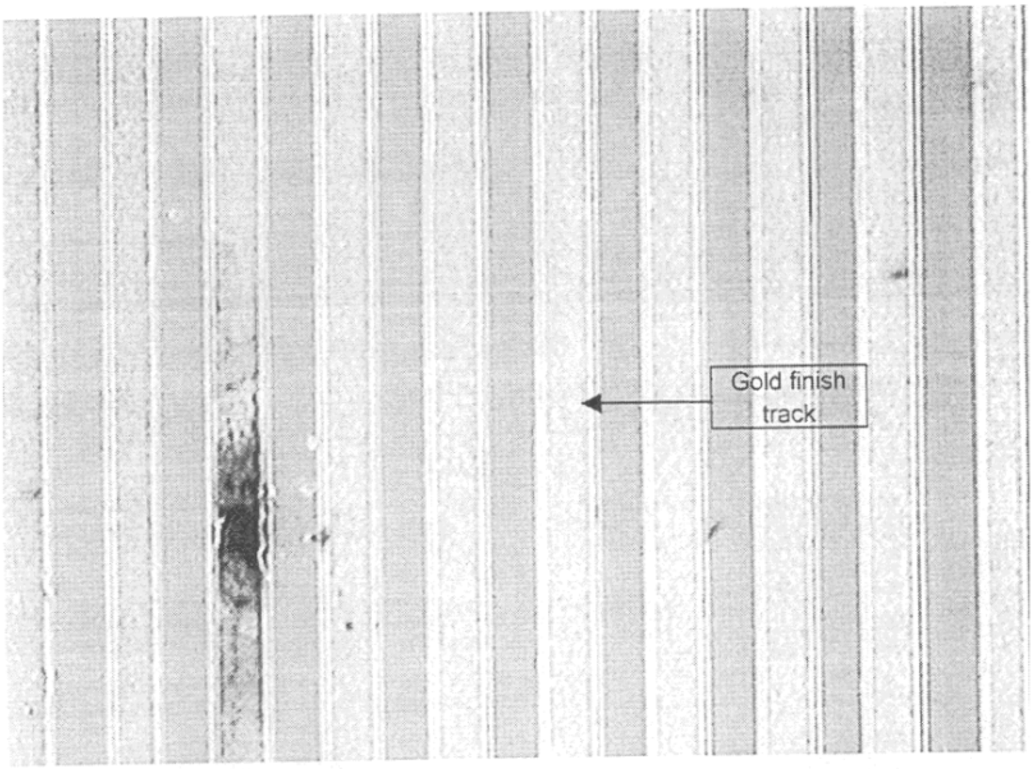




Fig. 2 The variation in log SIR (B) with temperature and humidity (A) for resist coated FR-4 bare board. The solid line in Figure 1B is the 'best fit' to the average log SIR values (●) measured during exposure to high humidity.




A: Local corrosion of FR-4 laminate coated with SR4.




B: Local corrosion of FR-4 laminate coated with AC1

Fig. 3 Corrosion of coated boards exposed to a harsh environment

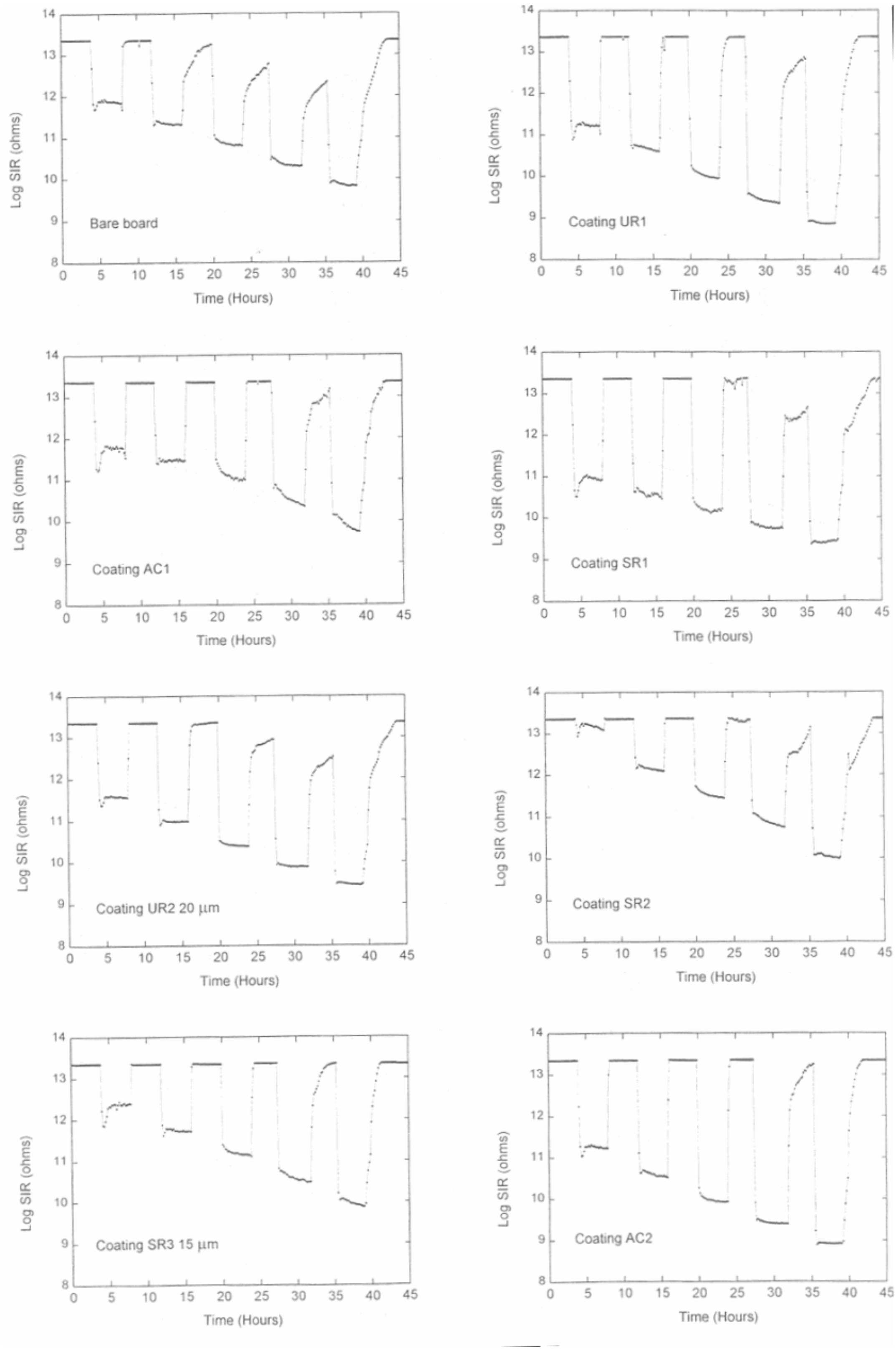



Fig. 4 Log SIR plots of double comb patterns following exposure of FR-4 laminate boards coated with resist to the temperature-humidity profile shown in Figure 2A. The dotted lines represent the average value of log SIR measured for the control uncoated board during the damp phase of each thermal step.

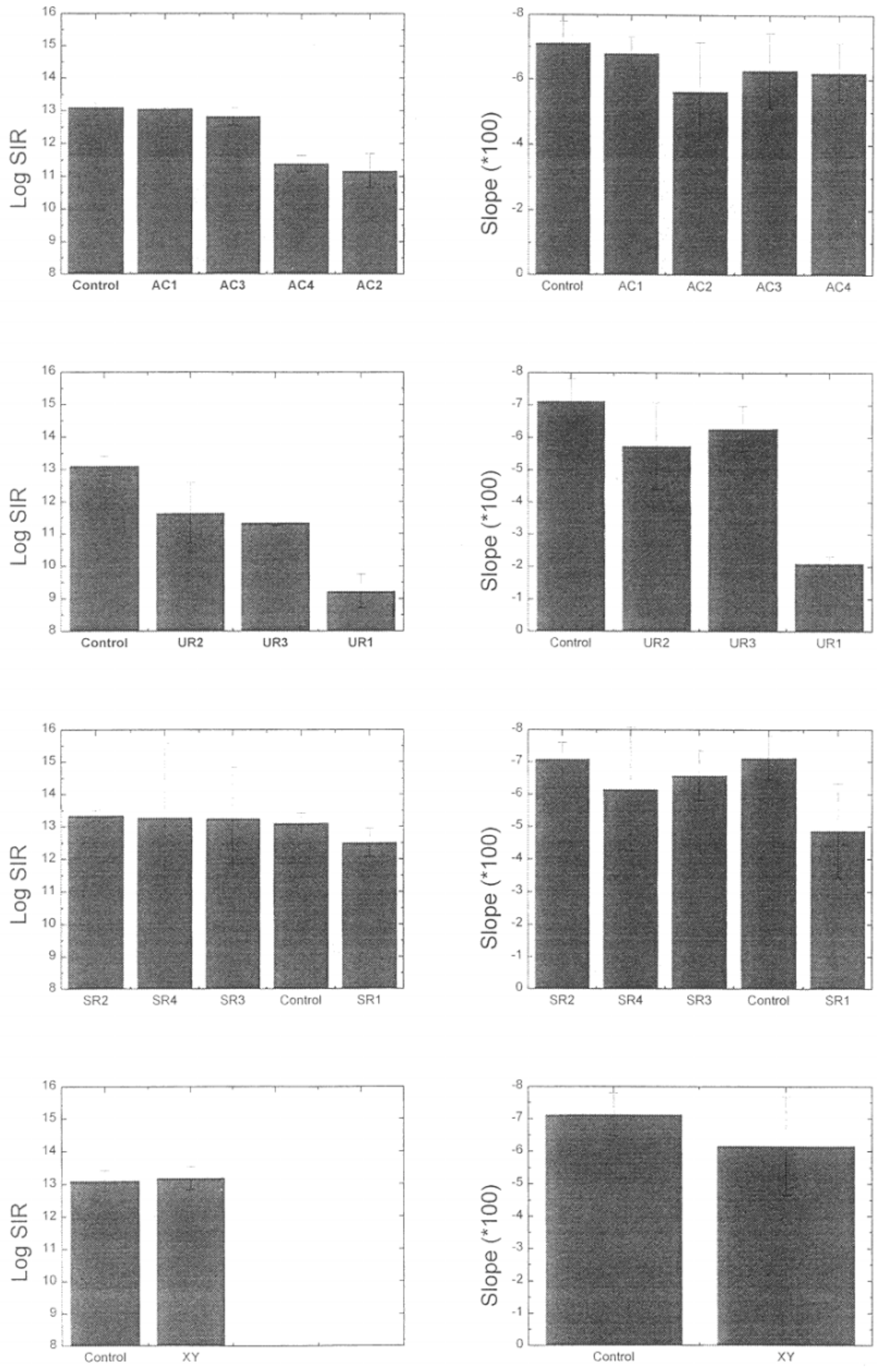



Fig. 5 The variation in the mean log SIR and its temperature dependence for different coatings applied to Cu/OSP FR-4 laminate boards. These data are generated for SIR measurements during the damp phase of the humidity cycle. Higher values for the slope indicate the SIR falls more rapidly with increasing temperature.

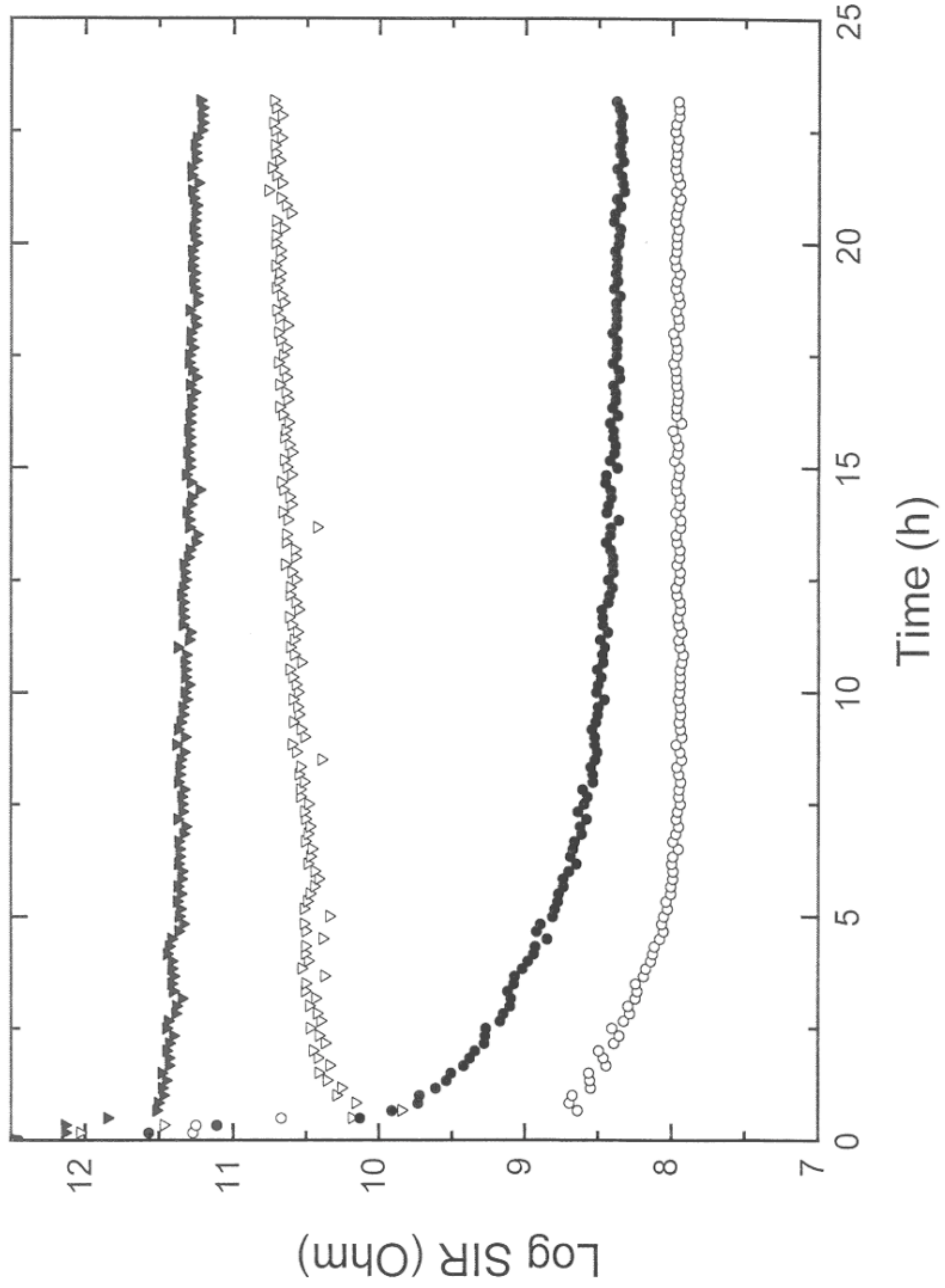
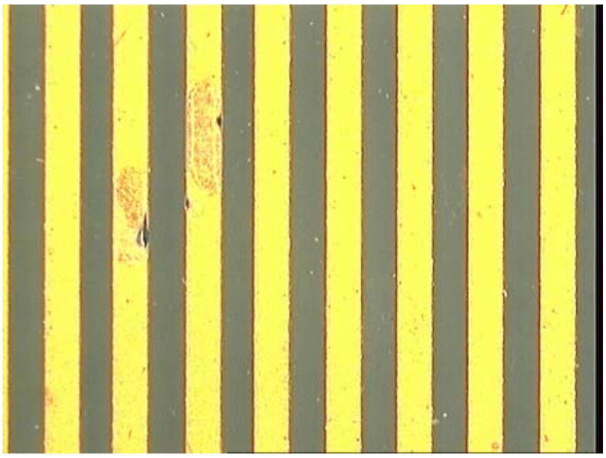
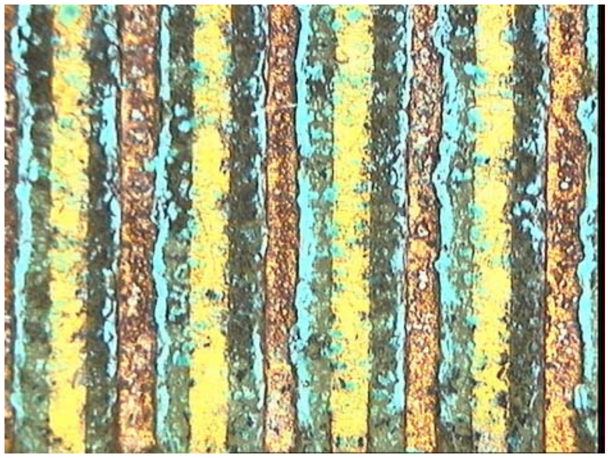


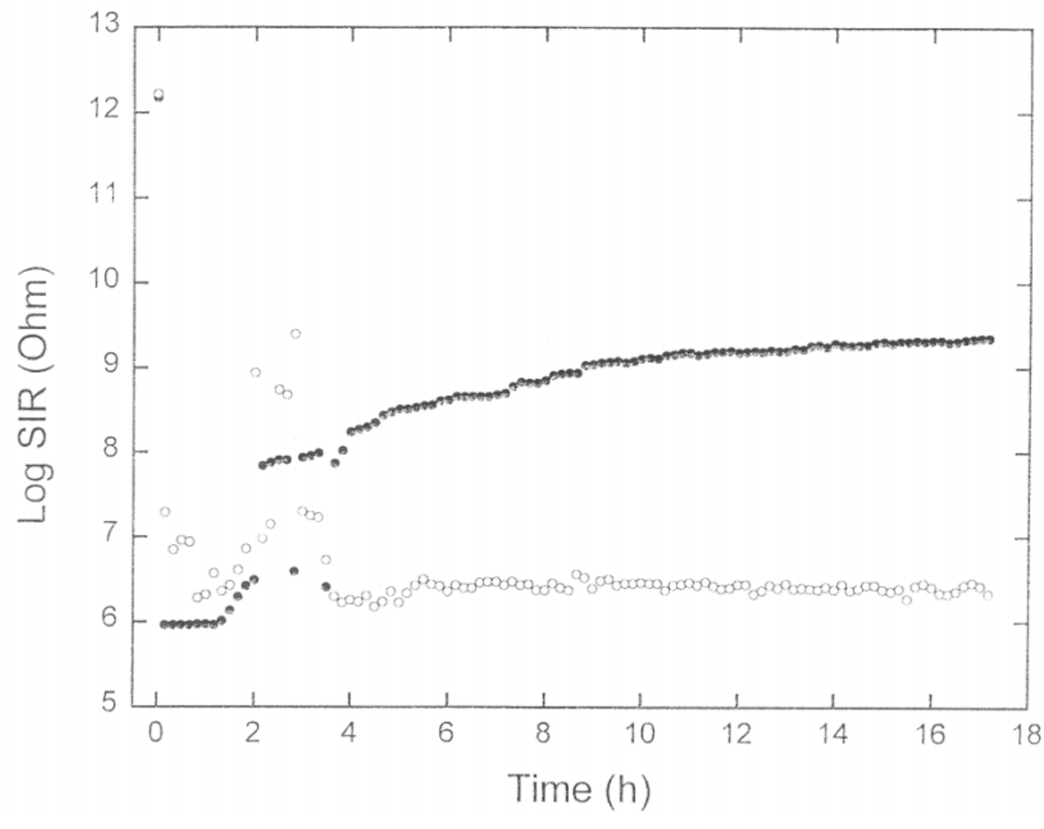

Fig. 6    A comparison of the SIR behaviour of bare FR-4 (∇) and FR-2 (O) laminate with conformally coated boards FR-4, SR4 (▼) and FR-2 IB31 (●).



A



B




**C**

Figure 7 : A silicone coating (SR3) applied to FR-4 board inhibits corrosion of the gold SIR pattern (**A**). In contrast the bare FR-4 board is severely corroded. The corresponding SIR patterns are shown in **C**:

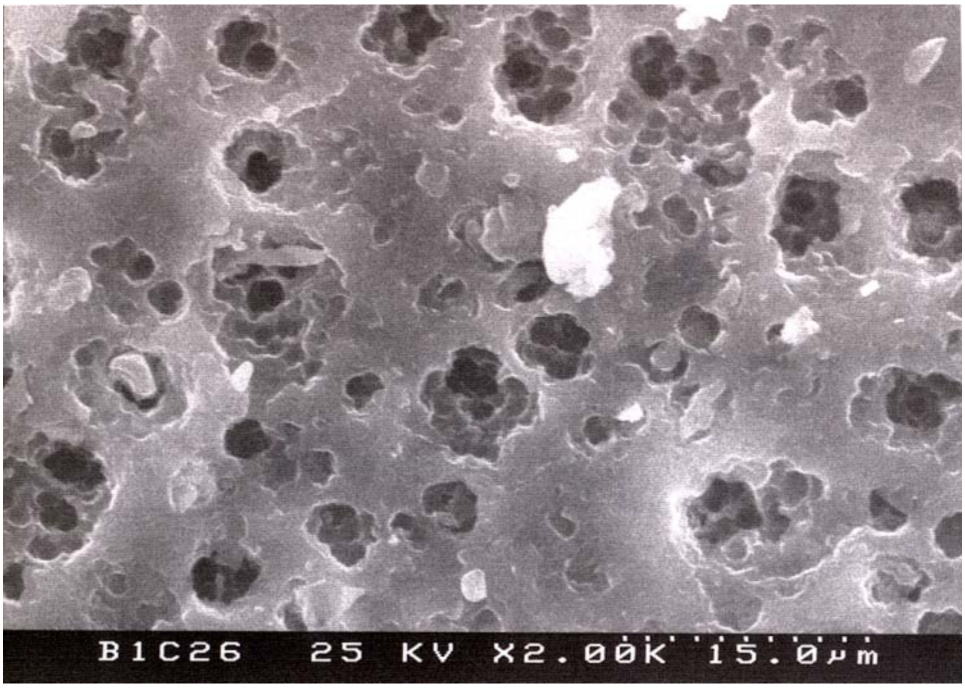



Figure 8 : Scanning electron micrograph of un-coated FR-4 laminate (x 2000)

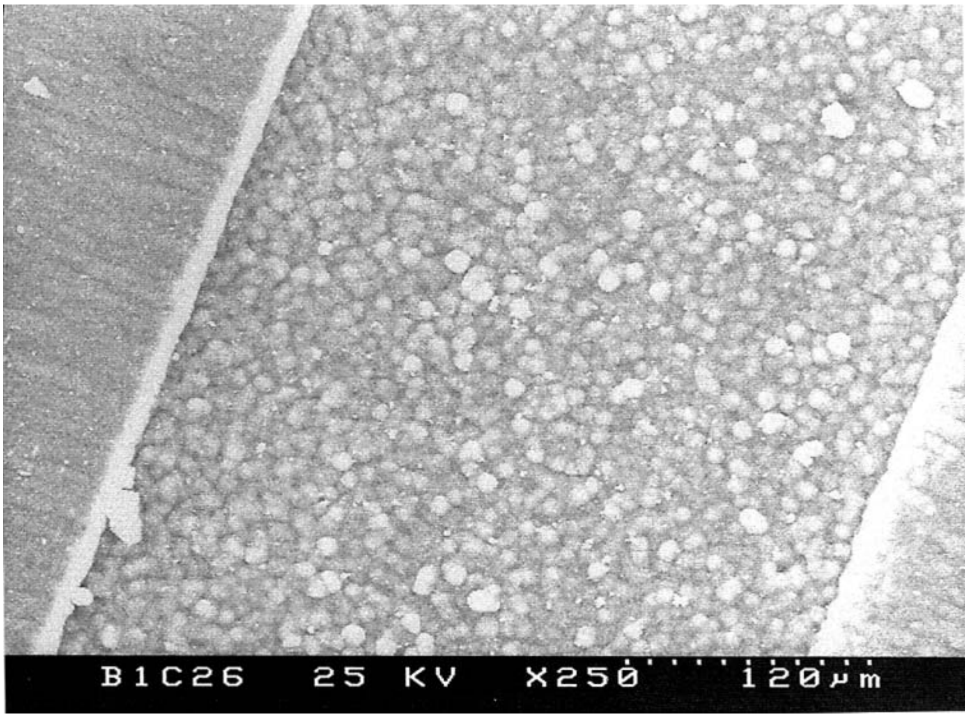



Figure 9 : Scanning electron micrograph of FR-4 laminate coated with polyurethane UR1 (x 250). Morphological detail between gold tracks.

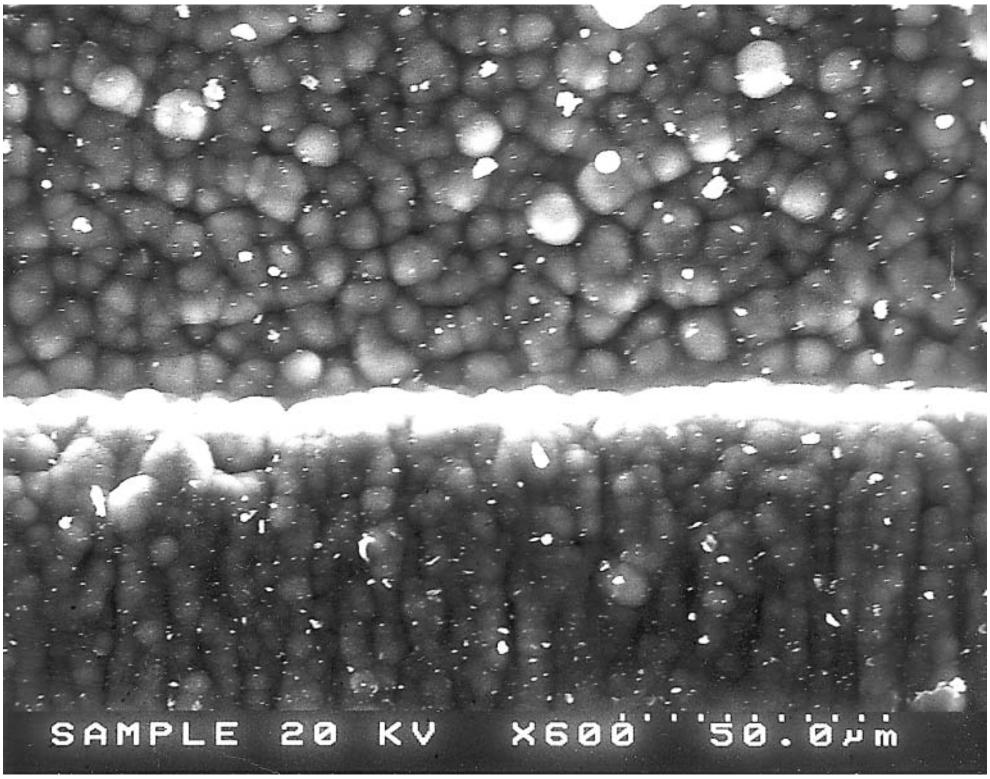



Figure 10 : Detail of coating UR1 showing the differences in morphology between that covering the track (sausage shaped objects) and the inter-track region (spherical objects) (* 600).