Condensation Testing – A New Approach

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Conformal coatings are applied to protect electronic assemblies from adventitious environmental factors, which include, for example, corrosive gases, corrosive fluids and high humidity. Whenever there is a significant level of humidity, there is always the opportunity for parts of the assembly to drop beneath the dew point, thus resulting in the formation of condensed water on the surface of the assembly, which can significantly reduce the insulation resistance of the boards surface, resulting in malfunctioning electronics.

While the characterisation of coating performance under high humidity conditions is detailed, in well accepted IPC and IEC standards, the performance and testing under condensing conditions is not so well developed.

This situation largely reflects the hardware challenge. Most humidity chambers are designed to achieve stable, well controlled humidity and temperature conditions, but none of these offer condensing options. Therefore the user has to improvise. A common approach to attempt to achieve condensing conditions is to ramp at a fast enough rate to cause condensation, a feature the humidity chamber designers have by and large, successfully managed to remove. Alternatively chambers run very close to 100% relative humidity and hence at this condition condensation will occur in various parts of the chamber. An immediate drawback of these approaches is that chambers of different designs will perform differently, and will be sensitive to small drops in cooling performance.

There are many alternative approaches to achieving condensation, and these are described in ISO, IEC, ASTM and others, and commonly attempt to drive a chamber into producing condensation, against the anticipated use condition, and hence sensors in the chamber detect the additional moisture and will work to reduce the humidity level to the required set-point. Thus, the level of experimental control will be very dependent on the chamber performance, and variability across chamber manufacturers can be expected.

A new approach has been developed where the test board is mounted on a substrate whose temperature can be independently controlled without changing the ambient condition. Thus, the temperature of the test board can be depressed below ambient to any desired point and hence, produce condensation at different levels. It is then, therefore, straightforward to cycle between condensing and non-condensing conditions on the test board in a constant ambient environment. The technique has been demonstrated to be repeatable and controllable, with the user able to select a temperature differential that matches their worst in-use conditions, or to understand the performance of their system under a range of condensing conditions.

The data for a range of conformal coatings are presented, and correlated back to the conformal coating material type, and coverage and thickness by cross-sectioning.

Introduction
Condensation is the change of physical state of matter from the gas phase to the liquid phase. It is most often caused when gaseous matter is in contact with a substrate that is at a lower temperature. The temperature at which condensation will form is known as the dew point. The dew point is the temperature at which the water vapour in a sample of air at constant barometric pressure condenses into liquid water at the same rate at which it evaporates. At temperatures below the dew point, water will leave the air. The condensed water is commonly called dew when it forms on a solid surface.

All things being equal, as the temperature falls, the relative humidity rises, reaching 100% at the dew point, at least at substrate level. The dew point temperature is never greater than the ambient temperature, since the relative humidity cannot exceed 100%.

The dew point then, is the saturation temperature for water in air, and the dew point will be dependent on the relative humidity. A high relative humidity implies that the dew point is closer to the current air temperature. Relative humidity of 100% indicates the dew point is equal to the current temperature and that the air is maximally saturated with water. When the moisture content remains constant and temperature increases, relative humidity decreases.

Conformal coatings are thin, polymeric coatings, intended to preserve the condition of a printed circuit board (PCB) under a wide range of operating environments, including high humidity, corrosive gases, dust and other contaminants.

Conformal coatings are often evaluated in high humidity environments, typically 40°C / 93% RH, 65°C / 95% RH or 85°C and 85% RH. Until recently, little attention has been paid to the characteristics of conformal coatings under condensing environments. Table 1 shows the dew point at several conditions, including those of the common evaluation test methods.

Table 1 – Temperature, Relative Humidity and Dew point

Ambient Temperature °C	Humidity % RH	Dew Point / °C in () °C below ambient
25	75	21 (-4)
30	90	28 (-2)
40	85	37 (-3)
40	95	39 (-1)
65	95	64 (-1)
85	85	81 (-5)

As can be seen, the dewpoint is within a few degrees of the ambient conditions at all of these conditions. At 30°C and 90% RH, a common enough condition in South East Asia, and North East America for example, the dewpoint is only 28°C, i.e. if the substrate is just 2°C cooler than the ambient air, condensation can begin to form.

As condensation proceeds from the formation of droplets and then coalescence to the formation of a continuous water layer, with the surface then saturated, it is essentially the same as if it were submerged in water, although there will not be the same dilution effect of ionic contamination. Conformal coatings are known to protect poorly in such immersion conditions.

The reasons for this are easy enough to understand. Conformal coatings are typically applied in the liquid state and dry by a variety of mechanisms. During the drying process, the materials are subject to gravity and capillary forces, making it difficult to ensure uniform and even thickness of the applied coating. When the surface is covered by a continuous water layer, any uncoated, partially coated or defectively coated areas will immediately be exposed to liquid water. Whilst liquid water is not a very good conductor of electricity (5.5×10^{-8} S/m), the presence of ionic species greatly increases the conductivity of water. In today's no-clean chemistry dominated production process, the presence of ionic species is impossible to avoid.

The combination of lack of coating coverage (or sufficient thickness), the presence of ionic species and the presence of even nano-layers of moisture can have a devastating effect on electronics, resulting in short-circuits or even permanent corrosion.

Given the proximity of the dew point to ambient conditions in a variety of common working environments, the impact of condensation on the reliable operation of conformal coated PCBs requires more thorough examination.

There are existing methods for generating condensing conditions within humidity chambers, utilising differing approaches. The biggest challenge to creating condensation in humidity chambers is related to the chamber hardware itself. It is designed to produce a stable, condensation free environment. The most simplistic method, and one that will struggle to generate condensation, is to ramp the temperature and humidity condition as quickly as possible causing a condensation event. However chamber design is continually improving, and striving to avoid any such condensation event. A second approach is to introduce moisture by a secondary moisture source. This can be either by an independent heated water tray (as in test K15 from GS 95024-3-1) [1] or direct jetting of atomised water droplets. A third approach uses a multi-chamber approach where the working area climatic environment is rapidly changed by injecting an alternative environment from a reservoir chamber.

There are a number of standards that are based around the above approaches and some of these are given here:
- IEC 60068-2-30, Environmental testing - Part 2-30: Tests - Test Db: Damp heat, cyclic (12 h + 12 h cycle)
- IEC 60068-2-38, Environmental testing - Part 2-38: Tests - Test Z/AD: Composite temperature/humidity cyclic test
- ISO 6270-2, Paints and varnishes -- Determination of resistance to humidity -- Part 2: Procedure for exposing test specimens in condensation-water atmospheres
- ISO 16750-4, Road vehicles -- Environmental conditions and testing for electrical and electronic equipment -- Part 4: Climatic load.
- ASTM D1735, Standard Practice for Testing Water Resistance of Coatings Using Water Fog Apparatus
- ASTM D2247, Standard Practice for Testing Water Resistance of Coatings in 100 % Relative Humidity
- ASTM D4585 – Standard Practice for Testing Water Resistance of Coatings Using Controlled Condensation
- JIS 5600-7-2 – moisture resistance (continuous condensation method) utilising aerosol water injection
- JASO D 001-94 (Japanese Automobile Standard): General rules of environmental testing methods for automotive electronic equipment

While these methods can demonstrate controlled condensation the control and ease by which they generate condensation remains challenging. Almost all of these approaches generate condensation in humidity chambers, and this leads to a challenge, since the chamber systems are developed to minimise condensation. In these cases chambers are run very close to 100%RH, inducing condensation. However, the uniformity of this condensation within the chamber is unknown. Hence, reproducibility of the given approaches will be variable between different chambers from different manufacturers, and furthermore with time developments in chambers will make them less prone to suffering from condensation events. The approach developed overcomes many of these difficulties.

None of these approaches control the sample temperature condition, and hence the uniformity of the condensed water layer is unknown and the stability of the condensed water film with time may not be constant, as the chamber control system attempt to compensate for the variance in the nominal conditions set for the chamber.

The approach adopted for achieving condensation in this study is one that can be realised in any humidity chamber and shows good correlation with the calculated dew point.

Experimental setup

In this approach the temperature of the circuit board under test is lowered, and hence within a high humidity environment condensation will occur. To achieve this condition the test boards are mounted on a platen whose temperature can be independently controlled. Hence by lowering the platen temperature below the chamber ambient, condensation will occur on the platen, and by the thermal coupling of the test board to the platen, condensation will occur on that as well. There is an assumption that the circuit board under test has a flat unimpeded under side so that it can make good contact with the platen. In Figure 1 we show four PCBs mounted on the platen.
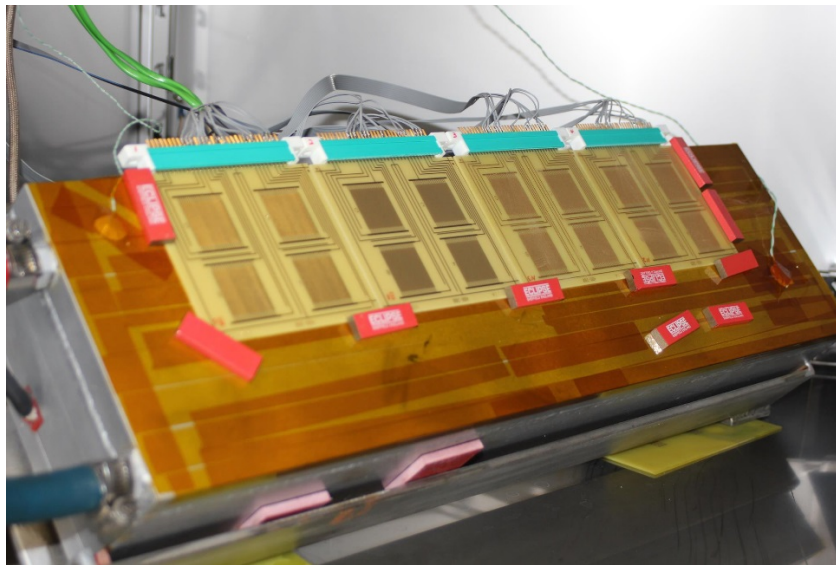

Figure 1: Test boards on platen

The mounting technique is very simple, the boards are held in position on the platen surface which is at 45° by magnets. The PCBs under test can be connected by the common technique of using connectors, since these are off the platen. In future PCB designs the tabs to the connectors will be extended away from the PCB area in contact with the platen to minimise further any tendency to cause condensation on the connectors themselves. In Figure 2 the ability of the system to control the test board temperature is shown.
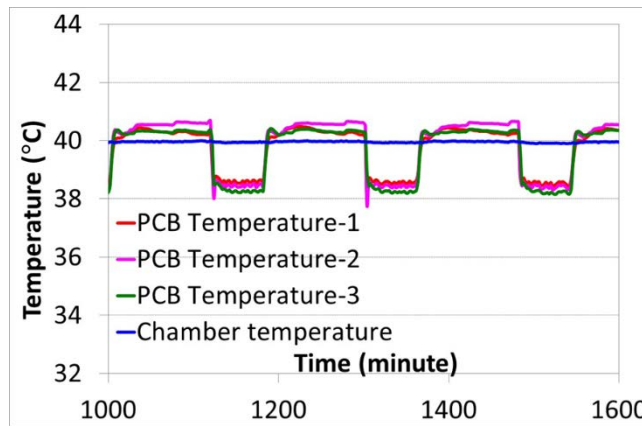
Figure 2: PCB temperature profile during platen thermal cycling

The temperature profiles in Figure 2 include the chamber temperature, and it can be clearly seen that this does not change as the platen and PCBs cycle up and down by 2ºC, with a nominal chamber temperature of 40ºC. This is an important advantage of this approach in that there is no attempt to use transitioning in the humidity chamber condition to create temporary condensing conditions. Furthermore, it can be seen that the transition is rapid in the cooling and heating phase of the cycle, and additionally the low temperature part of the cycle can be sustained indefinitely, or as long as set in the programme cycle.

The effect on surface insulation resistance (SIR) on a test PCB with 4 SIR patterns with a 400µm track and 200µm gap in an ambient condition of 40ºC / 85% relative humidity (RH) is now explored. This PCB is not conformally coated, the ENIG finished copper is fully exposed. In Figure 3 the effect of cycling to increasingly lower temperatures is presented.

Five sets of data are shown, in which the minimum temperature diminishes by 0.5ºC from set to set. In each set the temperature returns to the ambient 40ºC. These results show that it is not until the bottom temperature of the cycle reaches 37ºC does the reduction in SIR become particularly significant. For the 1.5 to 2.5ºC depression of the PCB temperature the level of condensation is only having a minimal effect, but for 3.0 and 3.5ºC the condensation is clearly having a significant impact. From this it is clear that the 0.5ºC steps provide a fine level of control and that a range of condensing conditions can be readily controlled. The interaction between the ambient condition and the platen temperature can be seen in the comparative results given in Figure 4. At the ambient condition of 40ºC/93%RH a platen temperature of 38.5ºC now causes significant condensation, which at 85%RH took a platen temperature of 36.5ºC. Hence with this experimental arrangement the ambient temperature and humidity and the platen temperature are all independently controlled, and the impact of these factors can be assessed independently. It is also pertinent to note that the platen temperature at which condensation occurs closely agrees with the dew points given in Table 1.
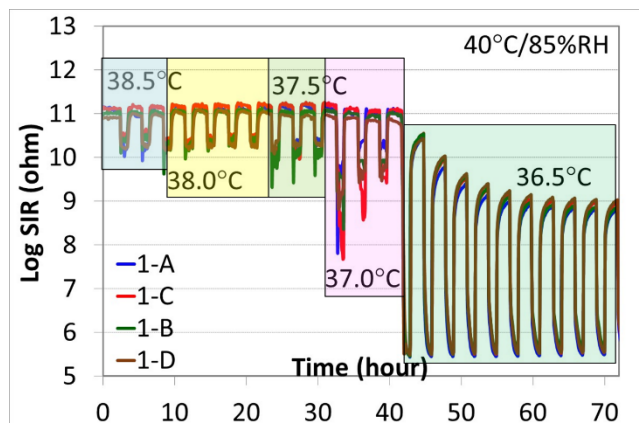

Figure 3: SIR response as the platen was cycled to cooler temperatures
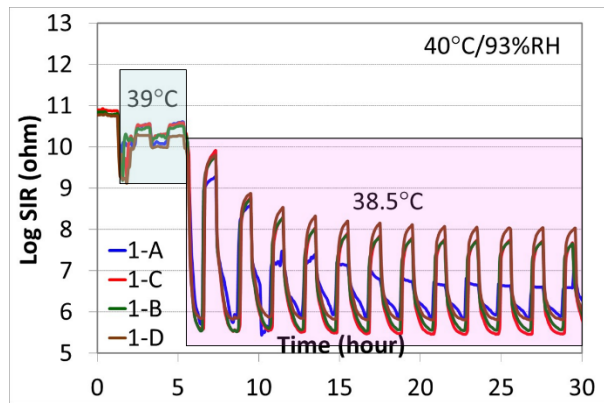
Figure 4: SIR response at 40ºC/93%RH under condensing conditions

An indication that an even level of condensation is achieved is shown in Figure 5. Here features of the water film can be seen across the entire surface and crossing the track and gap without hindrance.
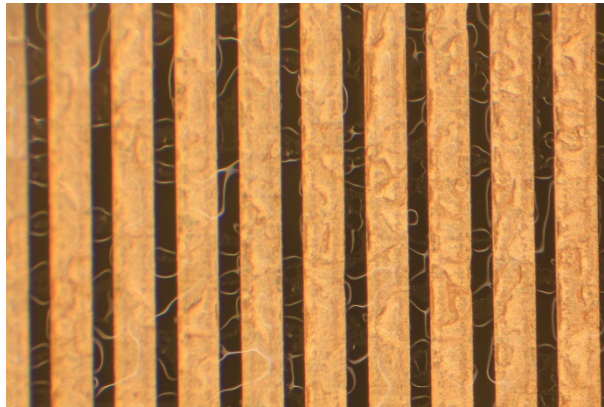

Figure 5: Uniform condensation across the SIR pattern

Assessing conformal coating performance

In this study the same test vehicle was used as described above, but manufactured with 1 and 3oz copper, corresponding to track heights of approximately 35 and 105µm. The test vehicle is shown in Figure 6. The applied coatings included one of the new super hydrophobic nano coatings, two types of acrylic, and two types of polyurethane. The first acrylic was also tested after a double spray process, and both polyurethanes were tested in a thick form. Cross sections of the coatings are shown in Figure 7, the copper thickness is approximately 35µm, from which the coating thickness can be gauged. Both polyurethanes can be seen to amply cover the track, whereas the acrylic coatings are just managing to do this, and it is not clear whether the nano coating has covered the track.

The impact of the double spray process is clear for acrylic-2, where there is clearly a thicker coating on the track. The results of a SIR test, 40ºC/93%RH and 5V bias, for the coated boards are shown in Figure 8. These results clearly show that the uncoated board, along with the nano coated board and one of the polyurethane materials have the highest SIR, and one of the thick polyurethanes has the lowest SIR. It is well know that polyurethane coatings can have lower SIR, due to the less hydrophobic backbone, since the absorbed moisture provides an additional conduction path lowering the SIR.
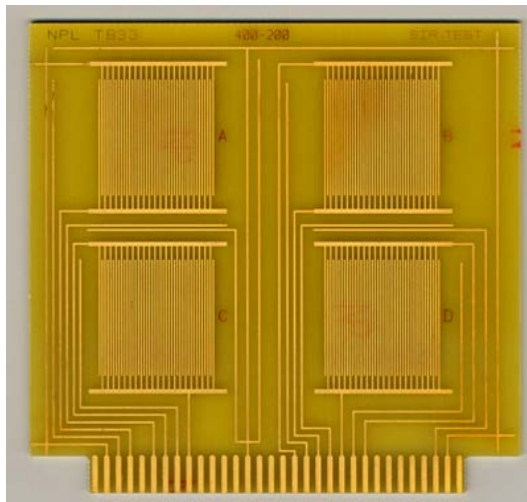
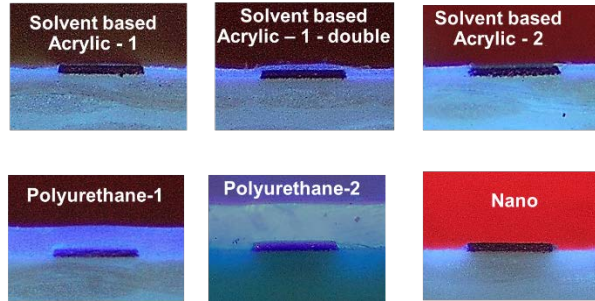*Figure 6: SIR test coupon used for coating studies*

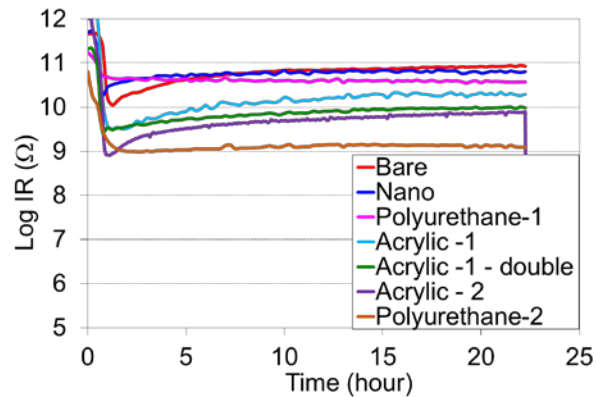*Figure 7: Coating coverage on the 1oz copper tracks of the SIR patterns*

Figure 8: SIR testing of conformal coated boards

The effect of using the condensing condition is now explored, using a platen temperature of 38.5ºC and a 3 hour cycle time with the same environmental condition of 40ºC/93%RH and 5V bias. The results of this test are shown in Figure 9 and Figure 10 for all the coatings, and include an uncoated test board. The nano-coating now performs very poorly with little difference between the results and the bare board. All three acrylic results follow the condensation cycle but have less than a two decade drop in SIR, with the values always above $10^8\Omega$. The polyurethanes are far less susceptible to the condensation cycle, particularly polyurethane-1. For all coating results the response from the four SIR patterns on each test coupon are very

similar. Clearly all the coatings, except the nano coating, are working to prevent a large drop in SIR as seen with the bare test board. This is contrary to the SIR results seen in Figure 8.
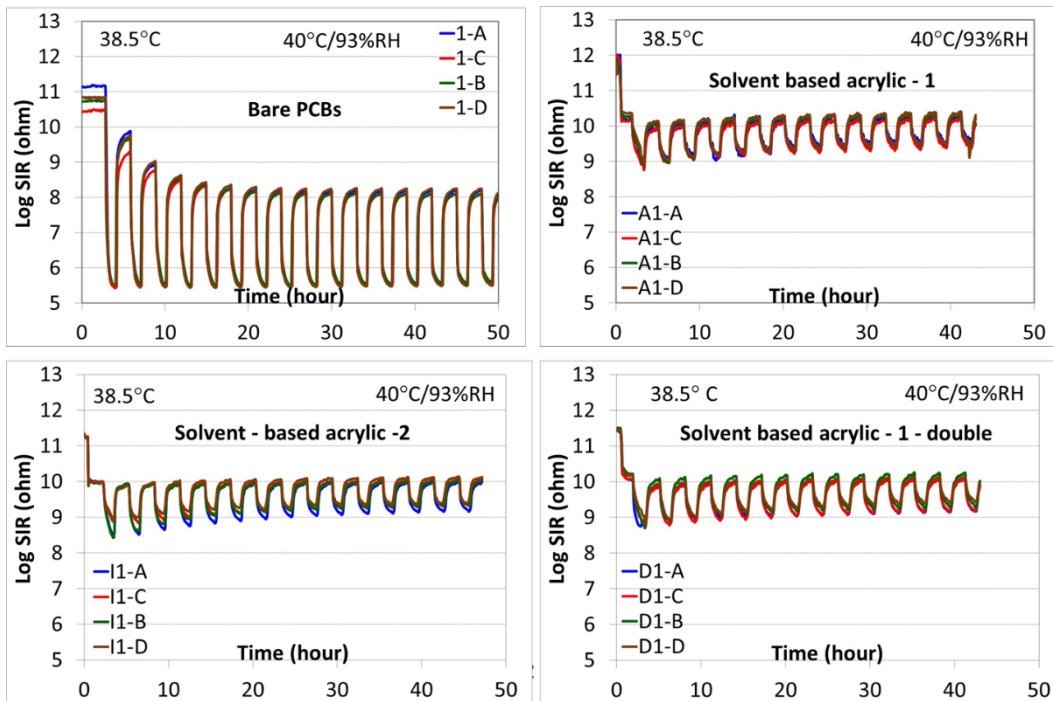

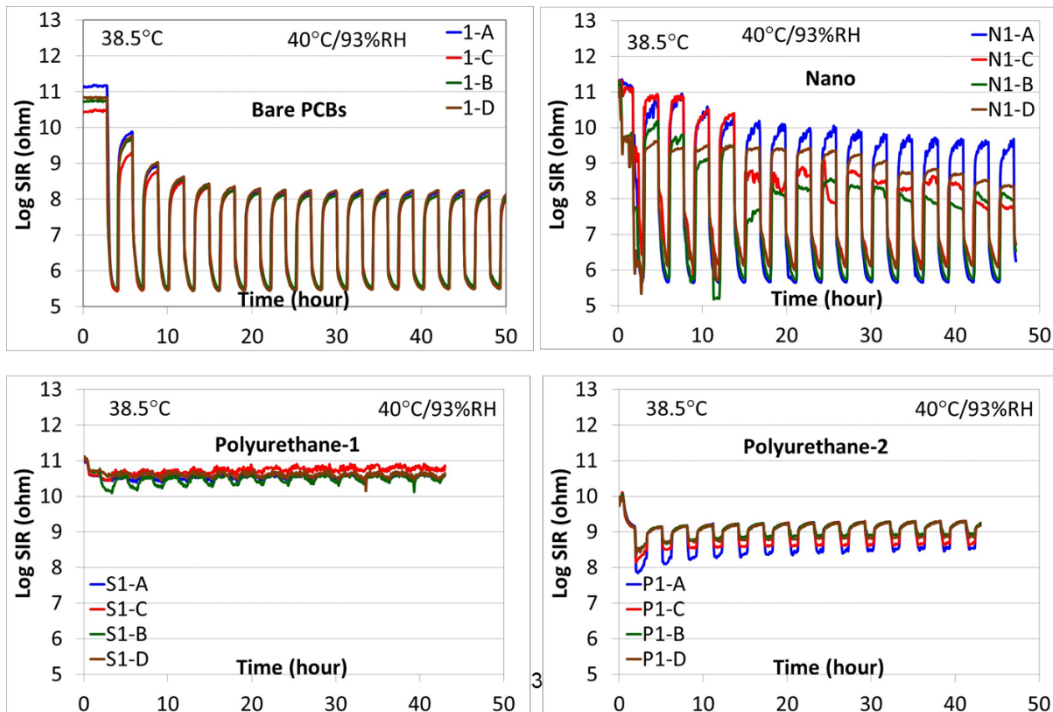Figure 9: Condensing conditions with the 1oz copper tracks and the acrylic coatings

Figure 10: Condensing conditions with the 1oz copper tracks with the nano and polyurethane coatings

The coating coverage on the 3oz copper test boards are shown in Figure 11. Again the polyurethanes are easily covering the copper tracks, and with the nano coating again there is no evidence of coating. However with the acrylic, acrylic-2 was not used on the 3oz copper SIR boards, it is difficult to determine from these images if the acrylic coating has covered the copper

track and in particular whether the corners are coated. The results from the condensation testing of these coated boards are presented in Figure 12.
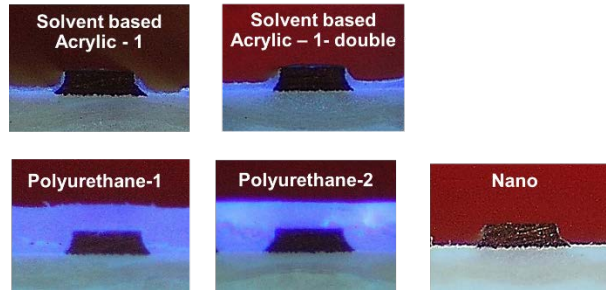

Figure 11: Coating coverage on the 3oz copper tracks of the SIR patterns
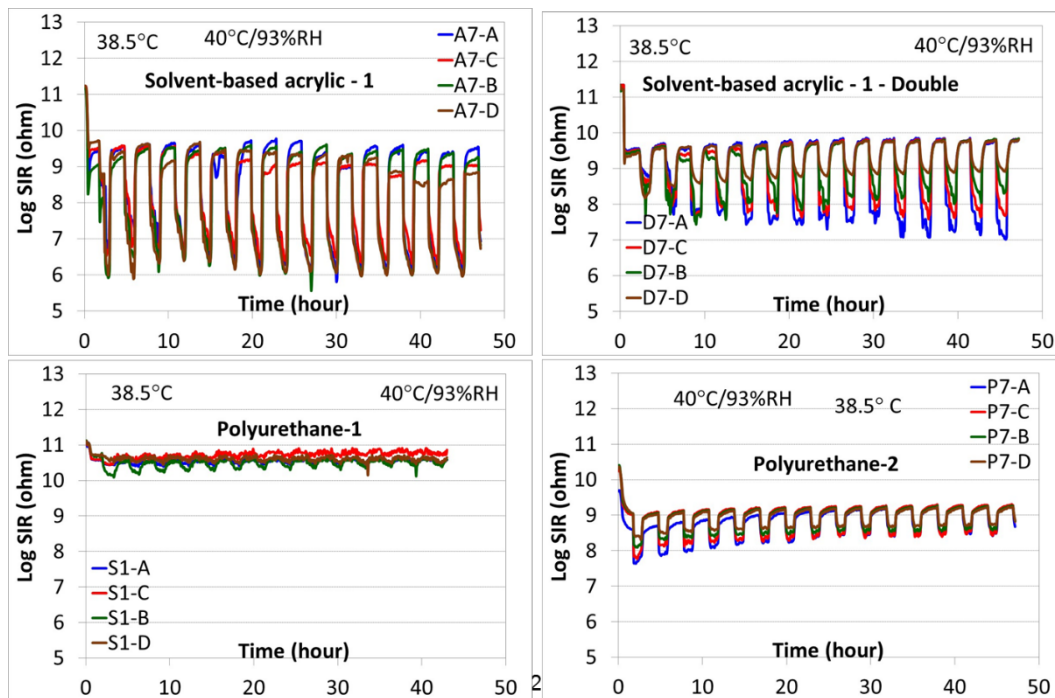

Figure 12: Condensing conditions with the 3oz copper tracks with the acrylic-1 and polyurethane coatings

The results in Figure 12 show that the two polyurethane coatings behave in a very similar mode as shown in Figure 10. The nano coating results are not shown here as they also performed similarly to before. However, now the two acrylic results are different, with the single coated acrylic showing a large drop in SIR, indicating that the corners of the tracks are not covered. Supporting this conclusion, the image in Figure 13 shows corrosion at the track edge, and with corrosion products forming across the top of the coating between the anode and cathode. The acrylic-1 results show the SIR dropping to $10^6\Omega$ from the first condensation event, with the behaviour remaining broadly consistent through the following condensation cycles. With the double coated acrylic the SIR results are not as bad, but SIR values are dropping below $10^8\Omega$, and with a trend of decreasing SIR with each condensation cycle. The 1oz copper SIR pattern boards the results in Figure 9 do not show any difference between the single and double coated boards, but with the 3oz copper SIR pattern boards the results do show a clear difference, and furthermore the acrylic coating can be seen to failing in either single or double coated condition. Hence the geometry challenge of the 3oz copper tracks for the acrylic-1 coating has been shown by it failing the condensation test. From above this coating passed the humidity test at 40ºC/93%RH, and the same coating with the 1oz copper tracks also passed. Thus the incremental geometry challenge and the fine control of the condensing condition in this experimental arrangement allows detailed and robust characterisation of coating performance.
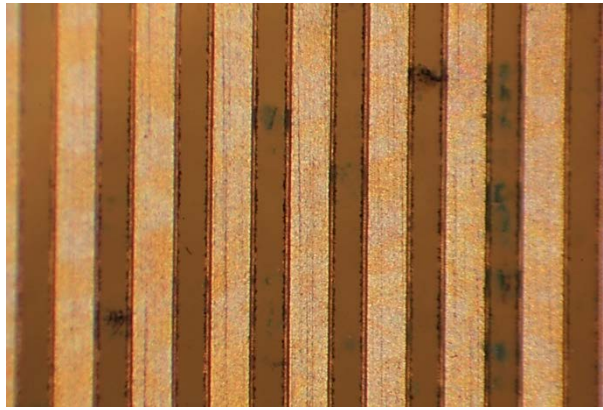
Figure 13: The 3oz SIR pattern coated with acrylic-1 with evidence of corrosion from the track edges

Discussion

It is well known that water films will lead to anodic corrosion on powered circuitry and that conformal coatings are a suitable mitigator. However, this requires complete coverage of all the parts so that the water film has no access to the energised parts of the boards. Hence there is an issue with achieving complete perfect conformal coating coverage.

The technique described here that has just been developed and offers a wide range of flexibility in the test conditions. In the current setup controlled levels of condensation can be achieved above 30ºC and a range of humidities. A crucial aspect of any condensation technique is the ability to achieve a number of aims: repeatability, controllable and stable conditions, and maintain those conditions over any desired time period. Within the many existing testing methods that were mentioned above there is a great challenge to achieve a fully controlled condensing condition across the wide range of equipment manufacturers, and hence there is a struggle to achieve all four aims in the wider context of standards testing. However, the approach described here has this ability, and furthermore these four aims are easily met.

The challenge of achieving stable and controlled condensing conditions over large areas is understood by a consideration of the dew point and the onset of condensation. This work shows that the SIR of the uncoated coupons, begins to drop noticeably when the temperature of the platen was dropped below the dewpoint. At 40°C and 85% RH the dewpoint is 37°C, and the onset of degradation was noticeable at 36.5°C. At 40°C/93% the dewpoint is 39°C and the SIR drop was noticeable at 38.5°C. These results are important in showing that there is good agreement between the platen and dew point temperature, and confirms that the platen arrangement is performing as expected.

The experiments described here show clearly that while test boards may pass simple humidity testing, as the geometry of the surface becomes more challenging test boards will fail under condensing conditions if complete coverage is not achieved, as was observed with the acrylic-1 results. In Figure 8 the SIR results for acrylic-1 are very good, for the 1oz copper tracks in Figure 9, there is some susceptibility to condensation cycles but the SIR values are still high and above $10^9\Omega$. However in Figure 12 with the 3oz copper track the SIR values are now at the $10^6\Omega$ level, which is classed as an SIR failure. Hence, the difficulty in achieving good coverage with these acrylic materials became apparent as the copper track thickness increased, and even with the application of two separate coating layers the performance was problematic.

These results clearly demonstrate the need for condensation type testing for finding the weaknesses in coating coverage, and furthermore the control that can be achieved with this experimental setup allows this to be readily achieved than has hitherto been possible. However, while specific condensing conditions can be achieved the desired test parameters still need to be developed, and this will be the scope of further work.

Conclusions

A review of condensation testing reveals that there are many approaches to achieving the required condition. These approaches struggle to achieve a known and uniform steady state across the test vehicle, and typically attempt to achieve condensation while fighting the inherent control system of the humidity chamber

This paper presents a new technique for achieving condensing conditions on circuit boards, and utilises an approach of using a platen as an independent means of controlling the substrate temperature to induce condensation, which has been shown to be uniform. Hence complete control of the condensing conditions can be achieved in a wide range of temperature and relative humidity climatic conditions, and the level of condensation can be easily adjusted and maintained over long periods of time

and readily cycled through those conditions. Since the whole test board is cooled on a platen the condensation film that forms will be uniform across the surface.

This paper has shown that as the test becomes more severe the condensing conditions will find weaknesses in the coating quickly. While humidity SIR and a low profile condensing test, the test vehicle passed, as the geometry became more challenging weaknesses and failures were observed. The results confirmed the susceptibility of exposed edges under condensing conditions, and that complete coating coverage is crucial

The thicker polyurethane materials demonstrated much greater resistance to condensing environments, with polyurethane-1 in particular showing little change in SIR during the condensation events.

It was surprising how quickly the insulation resistance of the acrylic materials and polyurethane-2 dropped with the onset of condensation – the drop in SIR being almost instantaneous. Condensation conditions will find weaknesses in the coating quickly.

Of particular surprise was the poor performance of the nano-coating. It showed no resistance to the condensing environments whatsoever, and corrosion was evident on the traces at both 1oz and 3oz copper track thickness. Although the coating contained a fluorescent trace it was impossible to determine coverage by cross-section.

Therefore it is clear from both the SIR results, the cross-sections and the visual inspection that conformal coating coverage is crucial in providing protection under condensing environments. There was a clear correlation between coating thickness and coverage and SIR under condensing environments.

References

1. BMW GS 95024-3-1 (Test K15).