Entrapment in food-grade transglutaminase cross-linked gelatin-maltodextrin microspheres protects Lactobacillus spp. during exposure to simulated gastrointestinal juices

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Humidity Build-Up in a Typical Electronic Enclosure Exposed to Cycling Conditions and Effect on Corrosion Reliability

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Abstract—The design of electronic device enclosures plays a major role in determining the humidity build-up inside the device as a response to the varying external humidity. Therefore, the corrosion reliability of electronic devices has direct connection to the enclosure design. This paper describes the internal humidity build-up in a typical enclosure prescribed for electronic applications as a function of external humidity conditions and enclosure-related parameters. Investigated parameters include external temperature and humidity conditions, the temperature and time of the internal heating cycle, thermal mass, and port/opening size. The effect of the internal humidity build-up on corrosion reliability has been evaluated by measuring the leakage current (LC) on interdigitated test comb patterns, which are precontaminated with sodium chloride and placed inside the enclosure. The results showed that the exposure to cycling temperature causes significant change of internal water vapor concentration. The maximum value of humidity reached was a function of the opening size and the presence of thermal mass inside the enclosure. A pumping effect was observed due to cycling temperature, and the increase in the level of absolute concentration. The maximum value of humidity reached was a sudden increase in LC.

Index Terms—Electronic reliability, enclosures, humidity, internal climate, temperature, thermal mass.

I. INTRODUCTION

TODAY, electronic products are exposed to various kinds of climatic conditions; therefore, the protection of interior parts from external conditions is a critical factor. The interaction of humidity with internal parts, such as printed circuit board assemblies (PCBAs), can cause several functionality issues due to corrosion [1]–[5]. The corrosion of electronic products due to humidity exposure is a serious issue today, leading to the reduced life span of the products and heavy economic loss due to failures.

The design of enclosure plays a huge role in determining the interaction of electronic device interior parts to the harsh environmental conditions. The enclosure body needs to be designed for providing holes/openings for cooling, input–output ports for electrical connectors, hinges, screw locations, and so on [6]. The geometrical and relative arrangement of various electronic parts, such as the PCBAs, is another important design factor. An electronic enclosure is seldom perfectly sealed, and the moisture ingress is dependent on the material of the enclosure and openings. Polymer enclosures cause moisture diffusion through the walls, while the moisture can also enter through the sealants and other openings as part of the design, such as cable openings and so on [7].

Heat sinks are commonly used in electronics as part of the PCBA or as a base, where they are expected to extract the heat from the devices under working conditions. Heat sinks and other heavy metallic parts can act as a thermal mass, causing a time delay in the heating up and cooling down processes, thus introducing a differential temperature with respect to the surroundings. Under varying temperature conditions, the high thermal conductivity of the heat sink material combined with its heat capacity and volume leads to a delayed response to the temperature fluctuations, and therefore affects the interaction of humidity with the surface of the attached PCB surface. This is the reason for condensation in most cases, especially on the PCBAs if they are attached to a heat sink or a metallic frame.

Corrosion occurs on PCBAs surfaces when a water layer forms due to humidity in addition to other driving forces, such as applied potential bias and contamination. The presence of ionic residues on the surface of the PCBAs can arise from the soldering process [8]–[12], degassing from PCB materials or deposited species from external environment (gases, aggressive ions, dust, and so on) [13]–[18]. The ionic residues on the PCBA surface are hygroscopic [10], [11], [19], and therefore, significantly reduce the level of critical humidity level needed for the substantial thickness of the water layer formation and initiation of corrosion failures [for example, leak current and electrochemical migration (ECM)] on the PCBAs.

Only few papers investigate the experimental study of humidity build-up inside the electronic enclosures [7], [20], [21], whereas huge focus is on the improvement of the thermal management of electronic devices, and thus on the performance of the heat sink, by improving its geometry and design [22]–[26]. However, its effect on local humidity build-up has not been investigated.

In this paper, the response of internal humidity level in a standard polycarbonate enclosure is monitored as a function...
of various parameters with an aim to understand the humidity build-up and its effects on actual electronic equipment. Possible effect of humidity build-up on leak current and corrosion reliability was assessed by placing a test PCB pattern, which measures the leakage current (LC) between comb-shaped electrodes with the build-up of humidity. The placement of the test PCB was to simulate appropriately the arrangements of the PCBAs in electronic devices, such as with and without heat sink acting as thermal mass. Other parameters used for testing were the opening size on the enclosure, the volume of thermal mass inside the enclosure, and the concentration of NaCl contamination on the test board. The internal heating and external cycling of temperature were used to simulate the alternate power/temperature extremities under the functioning of the device.

II. MATERIALS AND METHODS

A. Details of Enclosure and Humidity Profile for Testing

The enclosures used for investigations were made of polycarbonate with dimensions: \(280 \times 190 \times 130\) mm\(^3\) and an IP rating \([27]\) of 66/67. Holes through the casing material of 1 or 3 mm diameter were drilled on one side of the enclosure in order to simulate a possible leakage or an opening. Calibrated humidity and temperature sensors were placed inside the enclosure at appropriate places on the heating element, on the heat sink, and on the PCB surfaces as shown in the schematic in Fig. 1.

Sensors used for monitoring the temperature and relative humidity (RH) were PT1000 and HIH4021 from Honeywell. A data logging system using Keithley Model 2700 multi-meter was used for recording the data. In order to generate internal heating that simulates a functioning device, a heating element (silicon mat type) was placed inside the enclosure. During testing, the heating element inside the enclosure was switched ON for the duration of 45 min and OFF for the duration of 2 h 15 min to create a time lag with the external temperature cycle. The enclosure was exposed to a constant RH condition of 98% in an Espec, Escorp PL-3KPH climatic chamber, while the temperature of the chamber was cycled between 10 °C (for 2 h, which is 15 min less than the OFF time for the heating element inside the enclosure) and 50 °C (for 1 h, which is 15 min higher than the ON time for heating element) as shown in Fig. 2. Therefore, the temperature in the chamber increases from 10 °C to 50 °C, 15 min before the heating element inside the enclosure is switched ON. This will simulate the conditions necessary for condensation due to lower temperature inside the device, while ramping up the temperature outside. The simulated conditions can be correlated to a spring morning when outside temperature is increasing at high humidity level, while the temperature of the device placed outside lag behind in equilibrating the temperature due to its thermal mass.

B. Water Layer Formation and Resulting Leak Current Measurement

Possible effect of humidity build-up inside the enclosure on the electrical functionality of the electronics was assessed by measuring the LC across a test surface insulation resistance (SIR) PCB comb pattern. The test SIR PCB was made in accordance with IPC-4101/21 using FR4 substrate with the dimensions of \(80.5 \times 23.1\) mm\(^2\) and a thickness of 1.6 mm (Fig. 3). The surface finish of the SIR comb pattern was Sn–Pb finish, and the pattern dimension was \(13 \times 25\) mm\(^2\) with a pitch distance of 0.3 mm. The overlapping area was 10.8 mm in height, and there were 41 sets of common overlap providing 442.8 mm as the total length of the opposing faces. The ratio of the total length of the opposing faces and
A constant potential bias of 5 V dc was applied to the test SIR PCB used for the testing can be found elsewhere [28].

The SIR comb patterns were precontaminated with 1.56 or 15.6 μg·cm⁻² of NaCl. For reference, a comb pattern which specify a maximum allowed surface contamination level of 1.56 μg·cm⁻² of NaCl equivalent for the assembled electronic components [29].


table

<table>
<thead>
<tr>
<th>Arrangement inside enclosure</th>
<th>Test using 1 mm diameter hole at the bottom</th>
<th>Test using 3 mm diameter hole at the bottom</th>
</tr>
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<tbody>
<tr>
<td>empty</td>
<td>No SIR PCB</td>
<td>No SIR PCB</td>
</tr>
<tr>
<td>No thermal mass</td>
<td>SIR PCB with 1.56 μg·cm⁻² of NaCl</td>
<td>SIR PCB with 1.56 μg·cm⁻² of NaCl</td>
</tr>
<tr>
<td>Small thermal mass</td>
<td>SIR PCB with 15.6 μg·cm⁻² of NaCl</td>
<td>SIR PCB with 15.6 μg·cm⁻² of NaCl</td>
</tr>
<tr>
<td>40 cm³</td>
<td>SIR PCB with 0 μg·cm⁻² of NaCl (Clean)</td>
<td>-</td>
</tr>
<tr>
<td>Big thermal mass</td>
<td>SIR PCB with 1.56 μg·cm⁻² of NaCl</td>
<td>SIR PCB with 1.56 μg·cm⁻² of NaCl</td>
</tr>
<tr>
<td>80 cm³</td>
<td>SIR PCB with 15.6 μg·cm⁻² of NaCl</td>
<td>SIR PCB with 15.6 μg·cm⁻² of NaCl</td>
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The results of the temperature profile [temperature T and dew point (DP)] and moisture ingress [RH and absolute humidity (AH)] into the enclosures with 1- and 3-mm-diameter hole exposed to the cycling condition are shown in Fig. 4. The DP temperature was calculated according to [30]

\[
DP = ((0.66077 - s) \cdot 237.3) / (s - 0.816077) \quad (1)
\]

where \( s = 0.66077 + 7.5 \cdot T / (237.3 + T) + (\log (\%RH - 2)) \); \( \%RH \) = relative humidity (%); and \( T \) = temperature (°C).

The cycling of temperature in the chamber between 10 °C and 50 °C at 98% RH caused a similar cyclic increase and decrease of humidity profile inside the enclosure, as shown in Fig. 4. However, the temperature cycling inside the enclosure has caused the increase of RH above saturation level (at 10 °C) and the increase of residual humidity in the enclosure with time (number of cycles).

The residual AH content in the enclosures has increased with time, showing an irreversible effect of the build-up of water content as the temperature increased to 50 °C. The build-up of water inside the enclosure with 3-mm hole size was faster due to easy transfer of humidity in and out from the chamber. The internal temperature followed the external cycling temperature, while the internal humidity showed a different profile. Even if the external RH condition was constant (98% RH), a continuous increase of RH at each cycle was observed when the external temperature raised to 50 °C. Under this condition, the water vapor inside the enclosure did not reach the saturation value after 24 h (at 50 °C, the AH is 81 g·m⁻³ according to Mollier diagram), while at 10 °C excess water was present (RH profile from the sensor shows AH = 10 g·m⁻³). The amount of water vapor during the last cycle at 10 °C was ~10 g·m⁻³, while it was about 36 and 51 g·m⁻³ at 50 °C inside the enclosures with 1- and 3-mm-diameter hole, respectively. A change in the hole diameter from 1 to 3 mm has increased the build-up of water vapor of almost 1.5 times. The constant AH level under 10 °C showed the possibility of condensation, while the RH sensor showed the saturation value. Therefore, with a 3-mm hole size, one expects more condensation due to the higher level of water build-up at 50 °C. The DP was equal to the air temperature inside the enclosures at 10 °C, while the increased hole size has raised the DP temperature at 50 °C closer to the air temperature inside the enclosures (with a difference of only 11 °C). This resulted in the increased risk of build-up of water layer.

B. Effect of Internal Heating and Thermal Mass on Internal Temperature and Humidity Profile

A thermal mass was introduced inside the enclosure to simulate the actual placement of PCBA as well as internal heating of the device under working conditions. The results of the temperature profile and moisture ingress into the enclosure with 1- and 3-mm-diameter hole with an internal heater and an SIR PCB placed on a thermal mass of volume 40 or 80 cm³ are shown in Fig. 5. The thermal conductivity of the thermal mass material (aluminum) is 205 W·m⁻¹·K⁻¹ (at 25 °C).

Due to the internal heating, the temperatures on the PCB and on the thermal mass were slightly above 50 °C when the chamber temperature was at 50 °C. Similarly, during the cooling cycle, the temperature did not drop to 10 °C despite chamber temperature was at 10 °C.

Similar to the empty enclosure, the humidity profiles show that the residual humidity level (RH and AH) increased at each
Fig. 4. Internal T, DP, RH, and AH inside an empty polycarbonate enclosure exposed to cycling conditions with a controlled leakage size of (a) 1-mm diameter and (b) 3-mm diameter.

Fig. 5. Internal humidity profile in a polycarbonate enclosure exposed to the cycling conditions with an internal heater and an SIR PCB: i) with a controlled leak size of 1-mm diameter: (a) no thermal mass (b) a thermal mass of 40 cm$^3$, and (c) a thermal mass of 80 cm$^3$; and ii) with a controlled leak size of 3-mm diameter: (d) a thermal mass of 80 cm$^3$.

cycle. At the last cycle, the AH range inside the enclosures with 1-mm-diameter hole and a thermal mass of 40 and 80 cm$^3$ was between 12–51 g · m$^{-3}$ and 12–58 g · m$^{-3}$, respectively [Fig. 5(b) and (c)], while it was between 12 and 56 g · m$^{-3}$ for the enclosure with 3-mm-diameter hole and a thermal mass of 80 cm$^3$ [Fig. 5(d)]. A stable AH value at 10 °C showed that there might have been excess water, which has condensed during each cycle, keeping the air humidity at saturation level.

The DP on the surface of the PCB was very close to its surface temperature when the external temperature was at 10 °C, and the level of humidity reached beyond the upper detection point of the RH sensor showing a flat line. Overall, the level
of AH increased in comparison with the level of humidity inside the enclosure without thermal mass, where the internal AH was between 9 and 34 g \( \cdot \) m\(^{-3} \) [Fig. 4(a)]. The larger thermal mass increased the humidity level inside the enclosure [Fig. 5(b) and (c)], while the transition part of the humidity profile was broader inside the enclosure with the bigger leak size [Fig. 5(d)]. The effect of thermal mass on humidity build-up reduced with increase in hole size to 3 mm. The overall effect of the thermal mass on the AH content inside the enclosure when the temperature was 50 °C is shown in Fig. 6. The AH content inside the box doubled with a minimal hole size of 1 mm with thermal mass, while the difference reduced with a hole size of 3 mm. The AH level in both the boxes with 1- and 3-mm holes was almost similar after eight cycles. However, with 1-mm hole size and a thermal mass of 80 cm\(^3\), the AH content in the box increased by \(~5\) units.

The temperatures on the surface of the SIR PCB and on the thermal mass are compared in Fig. 7. The temperature of the thermal mass was approximately 2 °C–3 °C warmer than the surrounding air temperature in the chamber. For the enclosure with an opening of 1-mm diameter, the cooling temperature on the PCB surface had a delay compared to the thermal mass temperature, while their temperatures are similar when placed inside the box with 3-mm diameter. The increase of airflow over the thermal mass due to a wider 3-mm hole has promoted the cooling of the PCB laminate.

### C. Effect of Hole Size, Thermal Mass, and Level of Contamination on Leakage Current

The correlation of the LC, size of thermal mass, hole size, and the level of contamination as a function of cycling time is shown in Fig. 8. The SIR patterns were precontaminated with 1.56 and 15.6 \( \mu \)g \( \cdot \) cm\(^{-2}\) of NaCl together with a clean SIR and placed at the center of the enclosure with 1- and 3-mm-diameter hole. The SIR patterns were attached to the thermal mass of different volumes, namely, 40 or 80 cm\(^3\).

The profile obtained on the noncontaminated sample shown in Fig. 8(a) indicates that the fast change of temperature from 10 °C to 50 °C led to a high increase of AH during each cycle inside the enclosure. The increased humidity level with repeated cycling caused higher LC on the SIR pattern. The leak current value increased as the temperature in the enclosure increased from 10 °C to 50 °C because the temperature on the PCB lags behind the increase in temperature to 50 °C with
Fig. 8. AH on PCB surface and corresponding LC profile as a function of NaCl precontamination on various volumes of thermal mass in a polycarbonate enclosure with 1- and 3-mm-diameter leak hole: 1-mm-diameter leak, thermal mass of 80 cm$^3$, and SIR pattern precontaminated with (a) 0 μg · cm$^{-2}$ of NaCl, (b) 1.56 μg · cm$^{-2}$ of NaCl, and (c) 15.6 μg · cm$^{-2}$ of NaCl; and (d) 1-mm-diameter leak, thermal mass of 40 cm$^3$, and SIR pattern precontaminated with 1.56 μg · cm$^{-2}$ of NaCl, (e) 3-mm-diameter leak, thermal mass of 40 cm$^3$, and SIR pattern precontaminated with 1.56 μg · cm$^{-2}$ of NaCl, and (f) 3-mm-diameter leak, thermal mass of 80 cm$^3$, and SIR pattern precontaminated with 1.56 μg · cm$^{-2}$ of NaCl.

Fig. 9. Effect of hole size, the volume of thermal mass, and the contamination level on maximal LC measured on SIR comb pattern placed inside polycarbonate enclosures.

Fig. 10. AH on PCB surface and corresponding LC profile as a function of NaCl precontamination on various volumes of thermal mass in a polycarbonate enclosure with 1- and 3-mm-diameter leak hole: 1-mm-diameter leak, thermal mass of 80 cm$^3$, and SIR pattern precontaminated with (a) 0 μg · cm$^{-2}$ of NaCl, (b) 1.56 μg · cm$^{-2}$ of NaCl, and (c) 15.6 μg · cm$^{-2}$ of NaCl; and (d) 1-mm-diameter leak, thermal mass of 40 cm$^3$, and SIR pattern precontaminated with 1.56 μg · cm$^{-2}$ of NaCl, (e) 3-mm-diameter leak, thermal mass of 40 cm$^3$, and SIR pattern precontaminated with 1.56 μg · cm$^{-2}$ of NaCl, and (f) 3-mm-diameter leak, thermal mass of 80 cm$^3$, and SIR pattern precontaminated with 1.56 μg · cm$^{-2}$ of NaCl.

The introduction of the NaCl contamination of 1.56 μg · cm$^{-2}$ [Fig. 8(b)] on the surface of the PCBA did not lead to an increase of the LC under low temperature conditions (10 °C), while with higher temperature the LC reached values as high as 1 mA. The increase of contamination level to 15.6 μg · cm$^{-2}$ has increased the current level ∼10 times. Similarly, a comparison of Fig. 8(b) and (d) shows the effect of thermal mass. The LC levels are ∼10 times higher for the PCB attached to the thermal mass with a volume of 80 cm$^3$ compared to the thermal mass volume of 40 cm$^3$. Fig. 8(d) and (e) and 8(b) and (f) show the effect of the hole size on the AH and LC profile. Irrespective of the thermal mass, the increased hole size has increased the AH response, therefore causing a higher LC.

Fig. 9 shows the data extracted from Fig. 8 to show the combined effect of the hole size, volume of the thermal mass, and the contamination level on the LC as a function of cycling. It shows that the contamination was the most important factor in increasing the LC on the board, while the change in temperature profile due to the thermal mass further led to an increase in the LC. Increase in opening size also slightly increased the LC due to higher AH build-up.

The images of the SIR PCB comb patterns after the cyclic exposure are shown in Fig. 10. The test with no contamination on the PCB did not show any degradation of the comb pattern, while corrosion products appeared on the SIR PCBs placed on the thermal mass and contaminated with NaCl.

The presence of thermal mass has clearly increased the corrosion level of the electrodes, while the worst case is observed with the high-volume thermal mass and the high contamination level of 15.6 μg · cm$^{-2}$ of NaCl. The SEM images of the SIR pattern after climatic testing show clear differences between the effect of thermal mass and the contamination level (Fig. 10). The Sn–Pb solder finish on the FR4 laminate can be observed in Fig. 10(b) and at higher magnification in Fig. 10(c). It shows a typical microstructure of the Sn–Pb eutectic. The bright-appearing phases are rich in Pb (α-Pb), whereas the dark-appearing phases are pure Sn (α-Sn). After exposure to the cycling conditions, the dissolution of Sn and Pb from the SIR pattern and the contamination of the FR4 laminate with corrosion products of Sn and Pb can be observed [Fig. 10(e)]. The higher magnification image in Fig. 10(f) shows the formation of pits on the Sn–Pb solder finish and a preferential pitting on the Pb-rich phase is observed. This tendency of pitting corrosion increases...
with the presence of thermal mass of 80 cm$^3$, as observed in Fig. 10(i).

The SIR pattern precontaminated with $15.6 \mu g \cdot cm^{-2}$ of NaCl, and placed on a thermal mass of 80 cm$^3$ shows even higher degree of corrosion of the Sn–Pb SIR pattern. In Fig. 10(k), alternating bright- and dark-appearing SIR pattern lines indicate the formation of corrosion products on Sn and Pb (like oxides) on the anodes, whereas the cathodes are relatively cleaner and show only pitting in the Pb-rich phase. In addition, severe corrosion is observed at certain locations [see Fig. 10(l)], where the Cu layer below the Sn–Pb solder finish is leached out and results in the formation of Cu-based blue corrosion products [appear blue in Fig. 10(j)].

### IV. DISCUSSION

The results clearly show the effect of the combination of enclosure opening, thermal mass, and contamination in the humidity build-up and condensation regime inside the enclosure as a response to device heating and change in the external temperature. The aim here was to simulate the cycling
climatic conditions, such as day and night cycles together with device ON and OFF, although the level of temperature change used was higher to accelerate the process similar to accelerated humidity testing. The rate of change of internal temperature was fast as shown in Fig. 4, while the change of internal humidity was slower due to mass transfer restrictions depending on the opening size of the enclosure. Even though the external humidity condition was maintained at 98% RH, the level of water vapor inside the enclosure did not reach the saturation level (within the test time of 24 h) when the temperature was at 50 °C. Warmer air has a greater capacity to hold water vapor than cold air; therefore, at 50 °C, air can hold 81 g ⋅ m⁻³, while at 10 °C, the amount decreases to 9 g ⋅ m⁻³. The pumping effect due to the change in temperature and the humidity entry through the opening did not reach the maximum value of 81 g ⋅ m⁻³ (saturation level at 50 °C) within the number of cycles extending for 24 h. In this experiment, the time of the cycle was shorter than the time constant for water vapor to diffuse through the leak and reach the equilibrium. Therefore, at each cycle at 50 °C, the AH increased but did not reach its maximal value, while at 10 °C, the AH was close to its saturation value. The rate of change in the humidity plot in Fig. 5(a) and (d) shows that in the presence of the thermal mass of 80 cm³ and a 3-mm-diameter hole leak, the AH increased up to 1.2 g ⋅ m⁻³/cycle, while it increased only up to 0.7 g ⋅ m⁻³/cycle in the case of no thermal mass and 1-mm-diameter hole leak; therefore, the saturation level at 50 °C would have been reached after 41 and 83 h, respectively.

Heat sinks are included in electronic products to extract the heat produced from components during the operation of the device especially for the components with higher heat output. Therefore, the heat sinks are designed to maximize their surface area that is in contact with the surrounding cooling medium, such as air. The choice of material, its surface area, and the air velocity are the primary factors [22], [24], [26] that affect the performance of the heat sink, which essentially acts as a thermal mass to assist the transfer of heat from the component to the cooling medium. The most commonly used heat sink material is aluminum, which has a thermal conductivity of 205 W ⋅ (m ⋅ K)⁻¹ (at 25 °C) [22]. However, under cyclic conditions with varying temperature, a thermal mass can act as a site for local humidity build-up due to its slow heating during the cycling of temperature. The area of heat sink acting as a thermal mass is prone to condensation when the surrounding air temperature is high with a high water content, while the temperature on the thermal mass can lag behind, for example below the DP [31], where water vapor will condense on its subcooled surface.

By comparing the temperature profiles inside the empty enclosure [Fig. 5(a)] and with the thermal mass [Fig. 5(c)], the interior of the enclosure responds to the temperature change instantaneously, while the thermal profile over the thermal mass shows a time delay. Fig. 11 shows a magnified view of the surface temperature of the PCB without thermal mass and with a thermal mass of 80 cm³. It is clear that the temperature of the PCB without thermal mass reached the air temperature of 50 °C, while the temperature on the PCB in presence of thermal mass under similar condition was only 30 °C. While the air temperature increased to 50 °C, the temperatures on the thermal mass and on the attached PCB are lower. This contributes to the accumulation of condensed water or water vapor inside the enclosure at each cycle.

The presence of the larger thermal mass (80 cm³) has led to an AH value of 58 g ⋅ m⁻³ at the last cycle, while only a level of 51 g ⋅ m⁻³ of AH has been measured in the presence of thermal mass of 40 cm³ (Fig. 5). The rate of change of humidity was faster with a higher leak size (3-mm-diameter hole) than with a smaller leak size (1-mm-diameter hole). Tests performed at the constant condition of 40 °C and 98% RH have shown that the time constant to reach the humidity fraction of 0.63 of 98% RH [20] is 70 h and 32 h for the enclosures with 1- and 3-mm-diameter hole, respectively. The bigger leak size allowed also a better airflow due to the temperature difference between inside and outside (natural convection). The higher air flow and the higher thermal conductivity of the thermal mass combined with its large surface area resulted in the rapid transfer of thermal energy and cooled the PCB at the same rate as for thermal mass, which is in direct contact with it [Fig. 7(b)].

At 10 °C, the AH reached its saturation limit inside the enclosures and led to a thin water layer on the surface of the PCB, and resulted in a low resistance of the water layer forming on the surface. Verdingovas et al. [10] showed that in condensing conditions, the level of the LC on similar SIR test pattern was similar, about 0.01 μA at 5 V bias. The following sudden increase of the LC on the SIR PCB is a result of the increased moisture content of the vapor phase at higher temperature (50 °C), which led to more moisture adsorption by the board [32].

The introduction of NaCl contamination on the surface of the PCBA has caused the increase of the LC as much as three to four orders of magnitude, representative of high level of moisture condensation. The NaCl contamination layer added to the SIR surface is a crystalline solid and can form a discontinuous layer between the electrodes. Upon adsorption of water onto the surface, a few of the salt crystals dissolve...
and dissociate to form an ionic conduction pathway, thereby increasing the resulting LC. The higher concentration of ionic residues will increase the water layer thickness (due to their hygroscopic nature) and increase the conductivity of the electrolyte. Verdingovas et al. [10] found similar level of the LC, i.e., about 1 mA, in the case of the presence of NaCl and harsh conditioning conditions, when the SIR PCB was biased with 5 V, exposed to 98% RH and cooled down to about 8 °C below the surrounding air temperature. The measured LC values showed that the adsorbing water layer was very thick when the temperature was 50 °C.

The overview of the corroded SIR patterns (Fig. 10) did not show any ECM, confirming that dendrites did not cause the intermittent drops of the LC and that the high levels of NaCl contamination have led to the higher amount of corrosion products that bridge the gap between the oppositely biased electrodes of the SIR pattern. The lack of dendrite formation due to ECM might be due to the total time of higher water layer thickness and time needed for dendrite formation. This is highly significant from the point of view of the application of electronic devices, as it indicates that the temperature differential that leads to a significant level of water layer formation on the surface can be reduced due to the presence of ionic contamination [10], [33], [34]. The bigger leak size, the bigger volume of thermal mass, and the higher contamination level caused the highest level of internal AH, and also the highest level of the LC. Overall, the effect of internal thermal mass creating the temperature gradient is evident, and the experimental data can be used for calculating the time delay in equilibrating the temperature and dew formation.

V. CONCLUSION

The results in this study showed that:

1) The time constant for achieving temperature equilibrium in the tested conditions was shorter than the time constant for humidity equilibrium. Even at constant humidity, the outdoor cycling temperature led to a cycling humidity inside the electronic device. In the presence of openings, such as feedthrough of cables, or ventilation, the humidity equilibrium reaches faster than without openings.

2) The level of humidity increased at each temperature cycle, both with and without thermal mass in the enclosure. The increase in the level of the AH was higher in the enclosures with thermal mass in comparison to the level of humidity inside the enclosure without thermal mass, where the internal AH (with 1-mm hole size) was between 9 and 34 g · m⁻³ at the last cycle, and were between 12 and 51 g · m⁻³, and 12 and 58 g · m⁻³ with a thermal mass of 40 and 80 cm², respectively. Increased hole size led to a broader transition part of the humidity profile.

3) While the saturated level of humidity has been reached at low temperature (10 °C—AH = 10 g · m⁻³), the delay of temperature change due to the thermal mass attached to the PCB during the increase and decrease of the chamber temperature has caused the accumulation of water vapor or condensed water inside the enclosure at each increase in temperature, known as the pumping effect.

4) The maximum current levels on clean SIR pattern reached 1 μA (at high temperature and high AH), while the introduction of NaCl contamination of 1.56 and 15.6 μg · cm⁻² on the surface of the PCB caused the LC to peak to 1 and 10 mA. The LC levels are ~10 times higher for a PCB attached to a thermal mass with a volume of 80 cm³ compared to the thermal mass volume of 40 cm³. Irrespective of the thermal mass, increased hole size has increased the AH response, therefore caused higher LC.

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REFERENCES


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