SURFACE INSULATION RESISTANCE OF NO-CLEAN FLUX RESIDUES UNDER VARIOUS SURFACE MOUNT COMPONENTS

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ABSTRACT

No-clean fluxes present great benefits for the Electronic assembly industry, but the activity of the unwashed process residues must be tightly controlled in order to meet high reliability standards. The pervasive miniaturization trends of the industry, coupled with a complexification of the component architectures profoundly affect the nature and the reactivity of the flux residues. A series of customized Surface Insulation Resistance Experiments under various SMT components demonstrate the dramatic impact of the partial activation of the fluxes, unevaporated solvents and non-decomposed activators on the reliability of the final assembly. Mainstream no-clean pastes and liquid fluxes, which are qualified under all the standard SIR and ECM reliability tests, present SIR values several decades lower than the 100MΩ limit mandated by IPC J-STD-004B when tested under QFNs. Different surface mount components (Passive, QFP, BGA) can be more or less forgiving depending on the induced heat gradients and resistance to outgassing. From this perspective, we demonstrate how a thorough examination of the interplay between assembly architecture, processing conditions and flux formulation is the necessary condition for the design of reliable fluxes mitigating the risks of in-field failures of the final assembly. This study forms the background for the proposal of new reliability testing standards for the electronic assembly industry.

Key words: Reliability, Surface insulation resistance, electrochemical migration, dendrites, liquid fluxes, solder pastes, activators

INTRODUCTION

The electronic assembly industry is perpetually evolving to satisfy the ever-increasing needs for computing power, versatility, and system integration in robust and cost-effective packages. From the big data revolution to energy efficiency problematics, from consumer to industrial applications, these driving forces result in growing system complexities. From an assembly process perspective, interconnect densities are constantly increasing, while form-factors, stand-off heights, and component layouts at various scales are always more challenging. These trends, associated with the needs for mobility and end-use in challenging environments, greatly increase the sensitivity of modern electronics to in-field failures. Meanwhile, there has been little progress in the definition of reliability qualification protocols for these assemblies. The certification standards do not reflect the current design trends and the industry as a whole is calling for more predictive tests. Due to the component and architecture complexity, and the great variety of assembly materials and processes, it is of paramount importance to design model testing vehicles and protocols allowing the study of specific reliability failure modes. This paper represents such an attempt, in focusing on the dramatic influence of surface mount components on reliability failures from assembly materials (solder pastes and fluxes). The design of testing boards involving multiple component types in various configurations allows a methodical study of the interaction of materials, components and assembly processes. It also allows us to analyze the multiple chemical mechanisms at play during the assembly process, which will ultimately drive the reliability of the electronic device during its operating life. It therefore contributes to a fundamental understanding of the in-field failure of complex electronic architectures, which is a necessary condition for the design and testing of robust products.

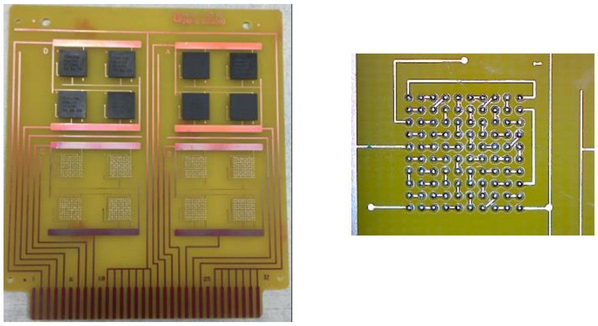
EXPERIMENTAL

Temperature calibration study: Local temperatures conditions experienced by the assembly materials (flux and solder pastes) were recorded by means of a Mole thermal profiler, whose thermocouples were placed in the interconnecting area between a standard IPC-B-24 SIR board and conventional Quad Flat Packages (QFP208). The assemblies were subjected to various reflow profiles using a Speedline Electrovert OmniExcel 7-zone oven.

Surface Insulation Resistance (SIR): All tests were executed according to the joint industry standard IPC J-STD-004B, under test method IPC-TM-650 §2.6.3.7, involving SIR monitoring over a period of 7d of an IPC-B-24 board exposed to a moist environment (40C, 90% RH) under a constant bias of 12,5VDC. This board is made of bare copper on an FR-4 epoxy laminate. It consists of four comb patterns formed by interdigitated Cu traces (width:0.4mm, spacing: 0.5mm). A Vitronics Delta3 industrial-scale wave soldering machine was used for the application of pattern-up / pattern-down soldering profiles. All other flux preconditioning and reflow protocols were carried-out in the 7-zone oven described above.

SIR assessments under BGA components: The standard IPC-B-24 board was customized by replacing the interdigitated connector pattern with a daisy-chained pad structure (figure 1). This architecture enables the measurement of the surface insulation resistance of laminate sections located between the interconnections underneath the BGAs.

Figure 1. Custom-designed SIR Board under BGA's



Solder paste was stencil-printed on the pads in a Speedline MPM Momentum Printer equipped with a 4mil laser-cut stainless steel stencil. BGA100 components were then positioned with a Juki KE-1080LN pick-and-place system. The assembly was reflowed under air in the 7-zone reflow oven, using a conventional IPC LF242C reflow profile. It was then subjected to the same environmental conditions (T, RH, Voltage Bias) and duration as the standardized SIR tests described above.

SIR assessments under QFN components and resistors: The second board showcases a more radical departure from the conventional designs used in reliability assessment (figure 2). This test vehicle was developped to be more representative of current trends in the electronic assembly industry, while providing a challenging environment to discriminate the reliability of chemical fluxes and solder pastes in realistic application conditions. It features a series of resistors of various dimensions (2512, 1210, 0805) and a matching board pattern, where additional interdigitated traces were placed in the central body area to serve as local sensors for biasing and surface insulation resistance measurements (figure 2.1). In a similar fashion, two Quad Flat No-Leads packages (QFN44, QFN100) are connected to a pattern featuring an additional sensor loop in the channel between the thermal pad and the perimeter I/O's (figure 2.2). This sensor enables SIR data collection across the channel (loop-to-thermal pad and loop-to-I/O's biasing).

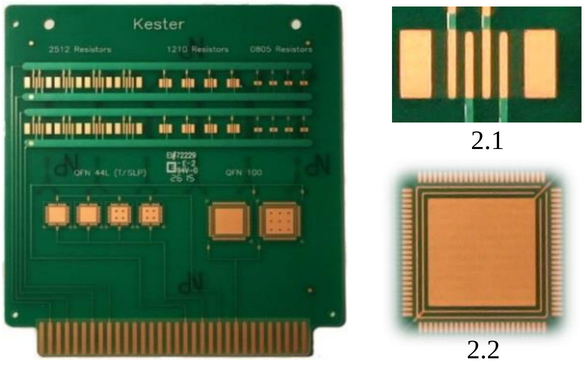


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Figure 2. Custom-designed SIR board under Passives/QFNs

Various no-clean solder pastes were used to assemble these test boards. A 5mil laser-cut stainless steel stencil was used in conjunction with the Momentum printer to transfer the paste on the regular pad structures of all components. The sensors traces under the resistors were also stencil-printed to ensure enough flux was deposited in this area. The assemblies were then reflowed in air using a conventional profile. Their surface insulation resistance was monitored over a period of 7d under a moist environment (85C, 85% RH) considered as challenging conditions for these no clean pastes, based on an earlier study [1]. An 8VDC Bias was applied to achieve the desired voltage gradients under the components, as will be discussed in the following section.

RESULTS AND DISCUSSION

Partial Activation Effects

One fundamental impact of the board components is their disturbance of the thermal transfer in the interconnection area. This region consists of a shallow layer of flux and solder intercalated between the devices and the epoxy laminate. These materials have radically different heat transfer coefficients, and tend to "shadow" the convective transfer of heat from the reflow oven to the interconnection. We quantified this effect in real application conditions by executing the temperature calibration study described in the experimental section, under the various reflow profiles reported on figure 3.

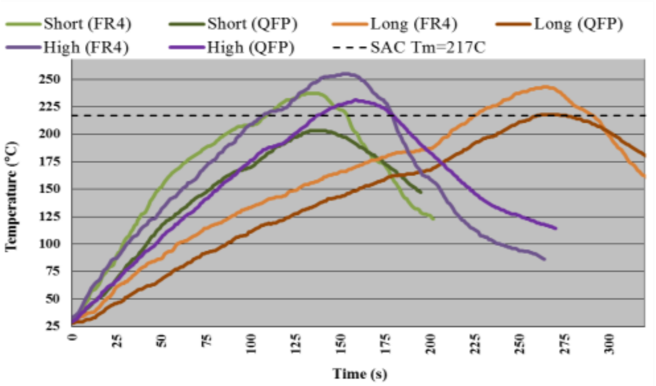

Figure 3. Reflow Profiles for temperature calibration

Both the baseline conditions (labelled FR4) acquired on unpopulated IPC-B24 SIR boards and the local temperatures collected under the QFP208 components (QFP) are represented. One can visualize the heat gradients by comparing curves of the same color. These temperature drops between bare and populated boards vary in fonction of the reflow profile: long profiles provide more time for the temperature under the components to equilibrate, while temperature gradients as high as 40C can be experienced on short profiles, regardless of the peak temperature. These heat heterogoneities could be dramatic enough to drop the temperature below liquidus for some profiles (green curve), resulting in non-reflowed solder under the QFP components.

It is therefore likely for fluxes located under massive components to experience thermal conditions differing significantly from the original profile. In these conditions, the energy transferred to the flux by the reflow oven is much lower then expected. Therefore, the physical state of the flux residue differs from the one obtained in equilibrated conditions as described by the IPC standards. This so-called "partially activated state" can have drastic effects on the reliability of the final assembly, as demonstrated in the following series of experiments. Four fluxes were reflowed in various conditions on IPC-B24 boards prior to being submitted to the standard SIR testing protocol.

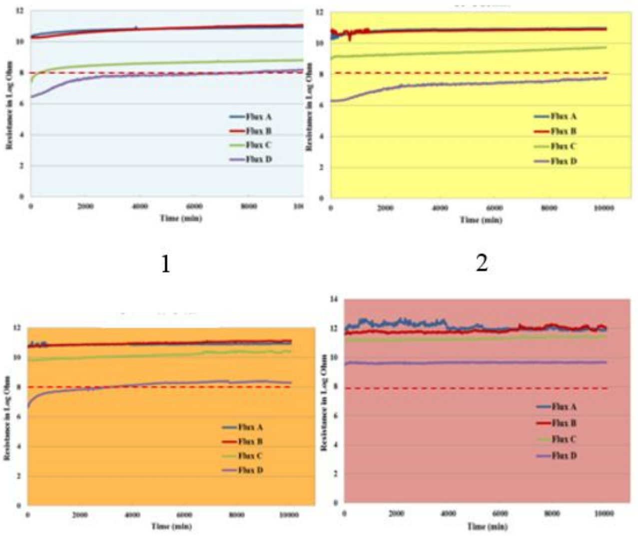

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Figure 4. SIR studies under various activation conditions

(1) Flux dried at room temperature / 24h
(2) Flux preheated at 80C / 10min
(3) Flux wave soldered pattern-up (120C preheat + 200C/5s)
(4) Flux wave soldered pattern-down

The conventional fluxes (represented by Flux D) are extremely sensitive to the activation conditions: these fluxes need to be soldered pattern-down (where the scrubbing action of the wave removes the majority of the residues) to pass the IPC standard. It is interesting to note that partial activation (modeled by condition (2)) actually degrade the reliability of the final assembly compared to the unheated state (condition (1)). More advanced fluxes were developped to guarante a better process window, two of them (fluxes A and B) being highly reliable under all activation conditions.

These effects are modeled by the chemical reactions describing the fluxing process of Cu substrates by Halogen-free activator packages [2-4]:

$$Cu_2O + 2RCOOH = Cu(RCOO)_2 + Cu + H_2O \quad (1)$$
$$CuO + 2RCOOH = Cu(RCOO)_2 + H_2O \quad (2)$$

The fluxing residues are made of organometallic compounds, as represented in equations (1-2), combined with unreacted activators, as well as their dehydration and decomposition products resulting from reactions (3) and (4):

$$R(COOH)_2 \rightarrow (RCO)_2 + H_2O \quad (3)$$
$$R(COOH)_2 \rightarrow 2R'COOH \quad (4)$$

All these chemical equilibria will be impacted by the actual temperature conditions experienced by the flux. Therefore, the nature and physical characteristics of the residues produced by the reflow process will strongly depend on the heat gradients described in our experiment. As an example, Figure 5 visualizes the evolution of flux D under the various activation conditions.

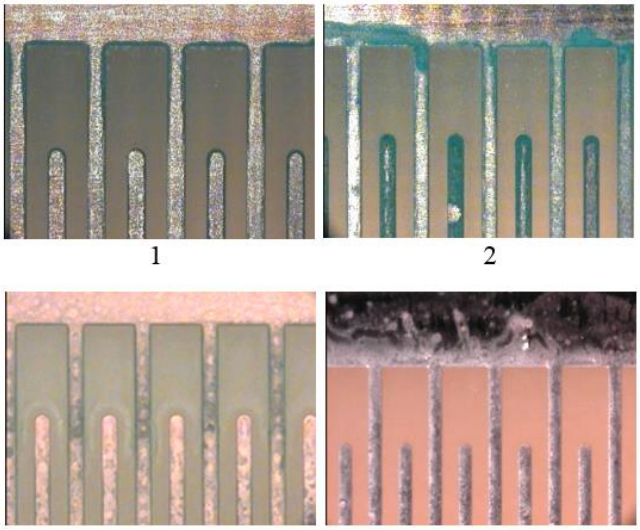

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Figure 5. Microscopic analysis of residue from flux D after reflow on IPC-B24 board under the 4 conditions of Figure 4.

The change in coloration of the residue, as well as the evolving amounts found on the board, constitute a visual representation of the chemical processes described by equations (1-4).

The second fundamental impact of a deviation from the calibrated reflow profile is not captured in these equations. The flux formulations generally contain a complex set of solvents, and a change in the reflow conditions will affect their respective evaporation rates. Consequently, flux residues can contain significant amounts of solvents when local thermal gradients result from the placement of large components acting as thermal sinks. Area array components with large form factors, low stand-off and a dense I/O pattern can produce the same effects by compromising the solvent outgassing channels. These residual solvents will mediate the electrochemical processes responsible for all reliability failure modes. Their impact is a function of the solvent polarity and moisture sensitivity. For a discussion around these mechanisms, the authors refer the readers to their recent communication on the topic [5].

Reliability assessments under BGA components

The concepts described earlier were applied to real-life application conditions. In a first set of experiments, we studied the influence of ball grid array components on the activation level of flux residues. These components were selected to discriminate the heat “shadowing” impacts (thermal gradients), from the solvent-trapping effects. The relatively open interconnection structure (0.8mm pitch, 0.34mm space) and high stand-off (0.36mm initial) of the BGA100 test vehicle do not put significant restrictions to solvents venting off from the flux. The equipment setup and experimental protocol are described in the experimental section.

Various solder pastes were screened with this method. We reported in figure 6 the results obtained with the most reliable one as a baseline (Paste A). This paste was designed to minimize the electrochemical activity of its residues in moist environments. These flux residues are essentially inert under all reflow and activation conditions, as demonstrated by a minimal drop of the SIR values under BGAs over the whole duration of the test. The specific impact of pastes on reliability will be described in the next series of experiments. The assembly was then contacted with various fluxes to focus the discussion on the contribution of chemical packages to the reliability under components.

The colored lines represent the impact of three different flux formulations added in large excess to the assembled device. These fluxes were either dried for 12h in ambient conditions (solid lines) or partially activated (dotted lines). Partial activation corresponds to condition (2) of the previous set of experiments (10 min preheat at 80C). Under these BGA components, the conventional flux D remains significantly less reliable than the more advanced fluxes A and C, with drops in surface insulation resistance values averaging 2 decades (hence a factor 100 in linear scale). Under this experimental setup, the impact of partial activation was only seen with flux A, which still presents high SIR values however. One can also observe that Flux D presents an improved SIR performance than when tested on standard boards. These effects are attributed to the significantly larger pad spacing for the BGA100 components compared to conventional IPC-B-24 boards, resulting in a 60% decrease of the voltage gradient across conductors (for an identical voltage bias of 12.5V). As reported in an earlier communication ([5]), voltage gradients are a critical factor of electrochemical failures, therefore the nominal voltage bias should systematically be normalized for data analysis.

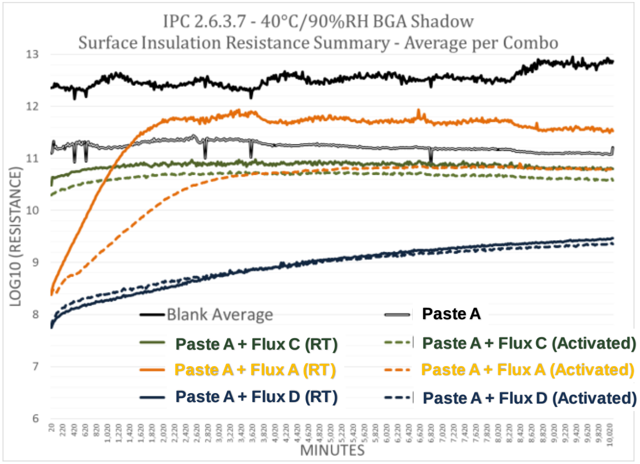


Figure 6. SIR study under BGA components. Various fluxes and activation conditions are plotted.

Overall, one can observe the same classification between fluxes A, C and D as in the previous series of experiments executed on unpopulated IPC-B-24 boards and reported in Figure 4. The current IPC testing standards are therefore a good model for open structures like resistors, capacitors or BGA’s, provided thermal gradients are taken into consideration. The testing protocol can simply be adapted by taking partial activation conditions into consideration as described in the previous section: a proper calibration of the temperature drops under components will enable a standard SIR testing under representative conditions.

Reliability assessments under various components

Following these observations, a more elaborate board was designed, where various voltage gradients and component complexities were tested. The experiment intended to represent mainstream applications; the selected components are currently used in high-volumes in our industry. The custom-designed board described in the experimental section uses capacitors and QFNs with various pitches, resulting in voltage gradients ranging from 16 to 45 V/mm and 27 to 57 V/mm respectively. The current IPC standard for SIR calls for a value or 25V/mm (down from 100V/mm in the older version). The resistors represent low-complexity components, from which solvents can easily vent off. The QFNs represent a more complex architecture, with a greater thermal mass creating the temperature gradients discussed earlier. In addition, the small clearance underneath these components and the tortuosity of the open channels compromise the outgassing of solvents and decomposition products. The large amounts of solder paste deposited on the thermal pads at the center of the structure, amplify these confinement effects. For these reasons, the QFNs represent ideal test vehicles to assess the impact of the multiple component-driven reliability failure mechanisms described earlier.

Indeed, this new test vehicle is capable of discriminating solder pastes very efficiently as demonstrated in Figure 7. The two commercial pastes reported here present radically different reliability levels under both QFN components. The application of Paste B results in a surface insulation resistance drop of more than 4 decades, while the other paste maintains a rather standard performance level under components. The combination of a greater thermal mass and the resistance to outgassing make these QFNs a challenging environment for Paste B. Meanwhile, the chemical package used in Paste A turns into reliable residues under the same conditions.

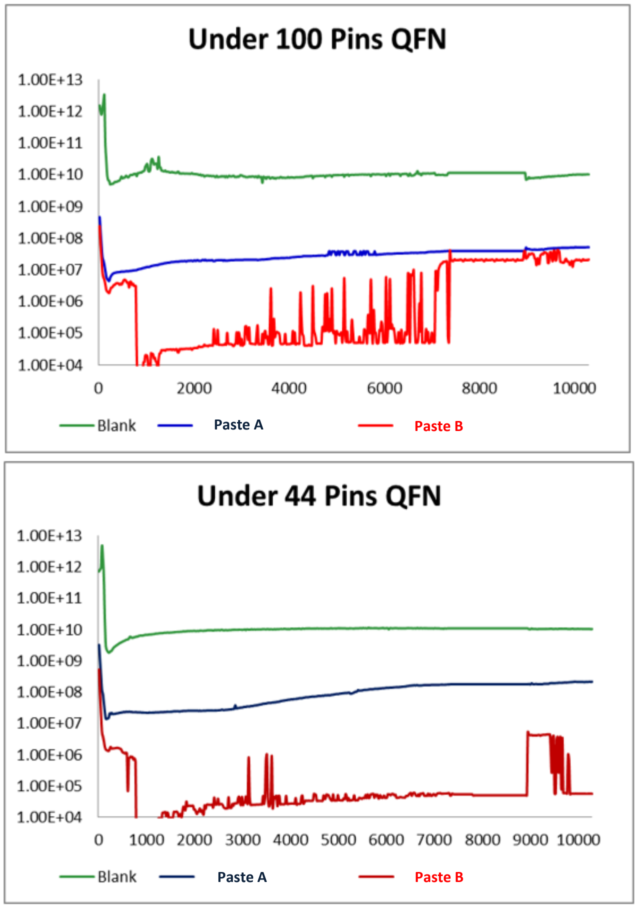


Figure 7. Reliability performance of 2 commercial pastes under QFN components.

In contrast, the voltage gradient effects assessed under the resistors were minor (e.g. less than one decade) compared to the major SIR drops observed for Paste B under QFNs. Moreover, these two pastes behave similarly and acceptably under the passives (figure 8), a direct demonstration of the critical impact of the component characteristics on the reliability of the final assembly. This also highlights the limitations of the industry standards using unpopulated boards: both pastes are classified as ROL0 under IPC-J-STD 004B.

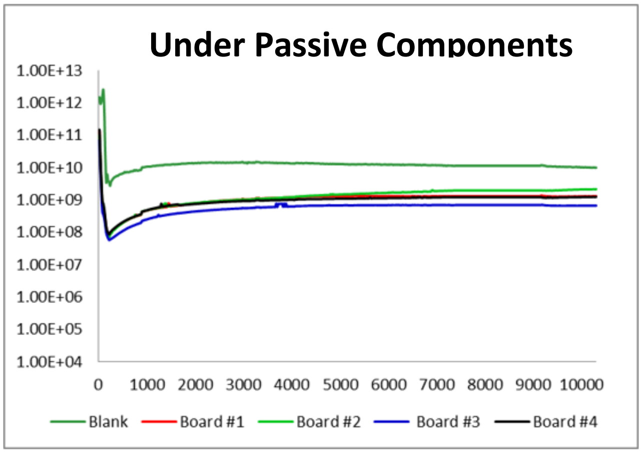


Figure 8. Reliability performance of 2 commercial pastes under passive components.

In an effort to discriminate the heat gradient effects from the resistance to outgassing, we dispensed an additional amount of fluxes onto the components, following the conventional SMT assembly process of passives and QFNs with solder paste. The fluxes migrated underneath the components due to their low surface tension, and the assembly was subsequently dried at room temperature. The area under the resistors was saturated with unheated residues, which had plenty of clearance to outgas the volatile portion of the solvents. This “combo” configuration didn’t change the outcome of the test significantly, as observed on Figure 9.

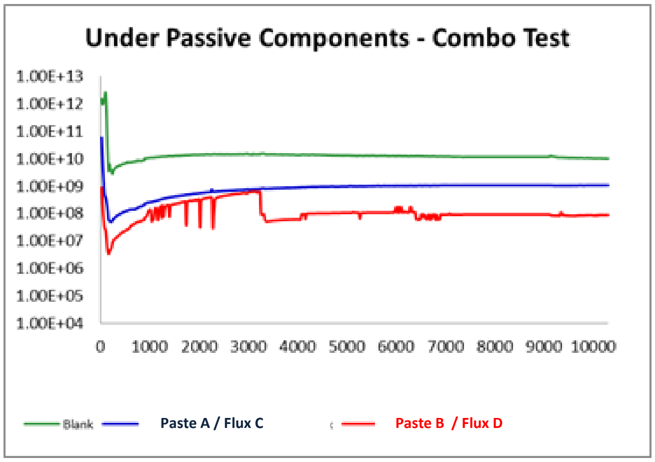
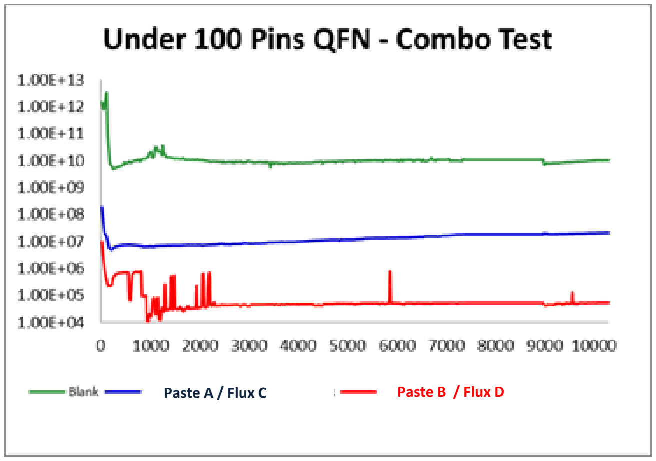


Figure 9. Reliability performance of the pastes/flux “Combo” under passive components.

Similar results were obtained under the QFN components, the performance of Paste A remaining at the same level (figure 10).

These results indicate that the reliability failure mechanisms at play under surface mount components are complex and convoluted. The dramatic variation in the reliability performance of Paste B, when tested under various devices, results from a complex process associating multiple mechanisms, from physical solvent outgassing to fluxing and decomposition reactions, all affected by local temperature gradients and component architectures at various extents.



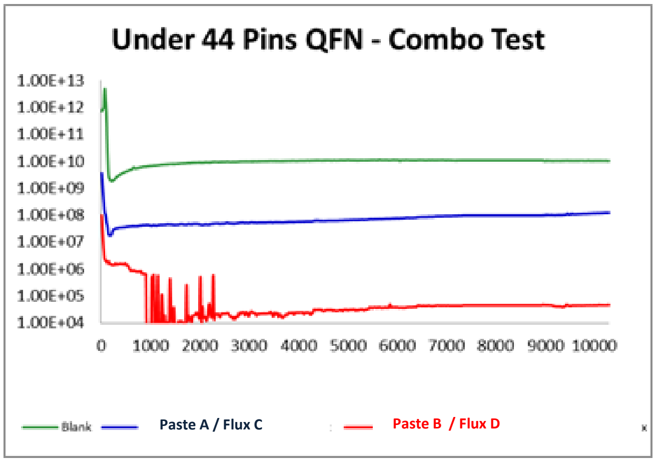


Figure 10. Reliability performance of the pastes/flux "Combo" under QFN components.

CONCLUSIONS

This study demonstrates the strong interaction between solder materials and components in determining the reliability of an electronic assembly. The multiple mechanisms at play were described, and their dramatic impact was assessed through the comparison of simple and open structures (capacitors, BGAs) with more complex architectures (QFNs). The latter creates a challenging environment for some commercial pastes, who dramatically fail reliability tests while performing adequately under current industry standards. On the other hand, it is demonstrated that solder material suppliers are able to design robust formula performing reliably under various environmental conditions and with a large set of components.

We showed that complex leadless devices like QFNs create specific issues due to their greater thermal mass, low stand-off, and the tortuosity of their outgassing channels. This architecture is prone to trap solvents and decomposition products, and also creates thermal gradients altering the complex chemical processes at play during reflow. While these processes were studied in detail, it is difficult to discriminate their impact. Regardless, the general differences observed between open architectures (BGAs, capacitors, open conditions) and QFNs indicate that the outgassing effects are prevalent.

These results highlight the importance of the design of representative qualification protocols for electronic assemblies, in terms of architecture and end-usage environment (T, RH, Voltage Gradients). This requirement becomes critical when low stand-off components are to be used, a common trend of today's electronics industry. Consequently, there is a need to update the testing and qualification standards, and we certainly hope the customized boards presented here will participate to this reflection.

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