DfR- DESIGN FOR RINSE-ABILITY: EFFECT OF SMT COMPONENT PACKAGE DESIGN ON CLEANING EFFECTIVENESS*

Norman J. Armendariz, Ph.D.
Raytheon Company
Andover, MA, USA
norman.j.armendariz@raytheon.com

ABSTRACT
Recent CCAs-circuit card assemblies manufactured using SMT-surface mount technology processes were exhibiting cleaning residues remaining on the surface and within electronic component / package housings with discoloration (degradation) of Cu-wire insulation and (oxidation) of metal contacts observed, which may compromise the surface conformal coating properties, and possibly degrade the component's electrical performance and long-term reliability.

Certain components or package configurations exhibited more entrainment and/or entrapment of cleaning residues. It appears that the component housing design is a major factor that in certain configurations, that either readily entrain cleaning solutions, and/or limit the ability of aqueous rinsing to effectively remove any remaining cleaning agents and residue from the electronic materials housed within. In other words, certain components have more "rinse-ability" than others.

This paper will discuss the "physics" of liquid entrainment / entrapment / cleaning / rinsing and their effects on component materials validated with experiments performed to determine the minimum amount of component housing vent area required to adequately rinse components of their cleaning residues with the objective of providing electronic component designers a DfR or "Design for Rinse-ability" specification or guidelines to deploy.

Key words: SMT, PCB, Components, Electronic Packaging, Cleaning, Contamination, Design

INTRODUCTION
Given that military applications require a high level of performance and reliability, a CCA-circuit card assembly typically undergoes a conformal coating process after SMT-surface mount technology assembly.

This conformal coating serves to protect the circuit card and attached electrical components from exposure to moisture and harsh environments. CCAs are manufactured to meet Class 3 military-grade requirements – they must work the first time, every time.

Prior to conformal coating, the surfaces of the circuit cards and electronic components must be in a suitable surface condition in order for the conformal coating to properly adhere and protect the electronic components as intended.

Before conformal coating, the circuit card assemblies and components undergo an aqueous chemical cleaning process after SMT in order to properly prepare them for the conformal coating process.

However, if any active cleaning constituents and reacted by-products are not removed or rinsed completely, then the surface may not be suitable for subsequent conformal coating.

Moreover, if the cleaning residue and by-products are entrapped within the components, then this contamination may result in latent materials degradation and / or corrosion, which may detrimentally affect the electrical performance of the components.

INITIAL OBSERVATIONS:
Initial product exhibited a yellow-brown substance near component vent holes, which are used for internal epoxy curing during component fabrication. Conformal coating was also found to be missing in these areas. This discoloration, which is also considered FOD-foreign object debris along with a subsequent initial disassembly and cross-sectioning revealed significant discoloration and materials degradation, which required further investigation, Figures 1 and 2.

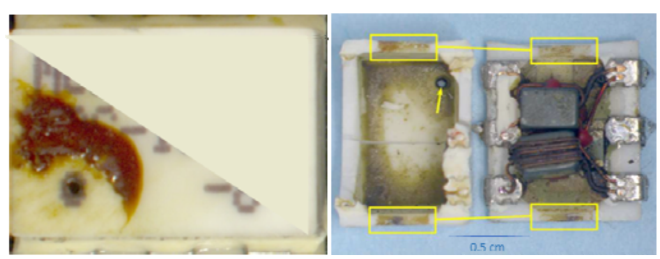


Figure 1. Initial electronic transducer component from production builds that exhibited a brownish / yellowish residue, which was later identified as mostly cleaning chemistry residue, on the surface associated with the vent hole, where pin 1 mark is also placed (L). Upon opening component, severe contamination observed within housing and on the two (2) sides where cover is not bonded (R).

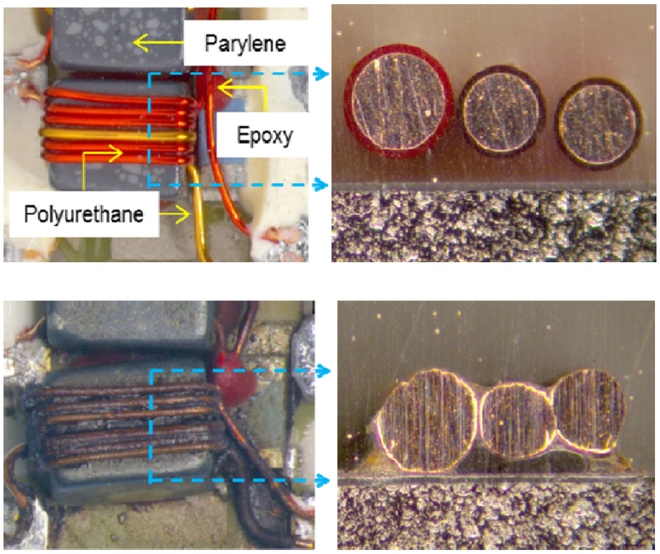


Figure 2. Materials used in an as-received (not cleaned) inductor component (top) and same component type after SMT cleaning processes (bottom). SEM/EDS and FTIR chemical analysis confirmed the presence of entrapped cleaning agents and ionic residues with significant degradation of the polyurethane insulation and Cu-wire.

APPROACH

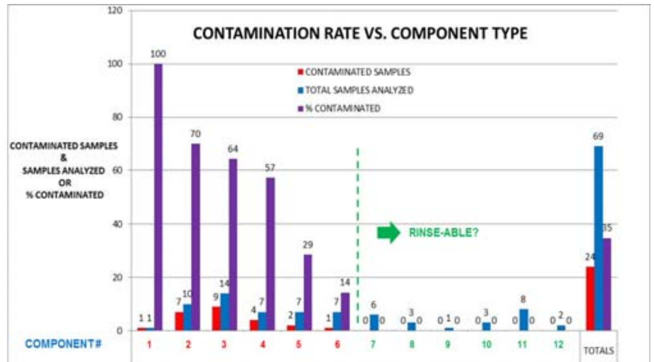
A focused investigative team was formed with members from supply chain, manufacturing, process, product, engineering design, testing and materials analysis groups and tasked to formulate a containment, preventative and corrective strategy to how best to address the residue observed on CCA products.

The initial phase focused on a certain supplier's electronic components, which initially exhibited contamination, to better identify which component types to target to either exonerate, "quarantine" or circumvent automatic machine cleaning processes in favor of manual cleaning processes.

Each suspected component was electrically characterized, followed by removing the covers to inspect for any signs of contamination or degradation. If any were suspected of cleaning residue entrained contamination, then these were submitted for further material / chemical analysis to better disposition.

Previous databases were reviewed for any previous occurrences similarly observed to understand the severity, as well as, gauge the potential for imminent field failures. This process allowed for a multitude of components that did not exhibit entrained contamination, to be exonerated, and not have to delay product from active builds, or returned from field unnecessarily.

More importantly, the on-going analysis began to reveal that some components showed a high-risk for entrained contamination, and other components showed no evidence of entrained contamination and appeared to have been rinsed of any entrained cleaning residue, and thus were considered "rinse-able," Figure 3.



COMPONENT#	1	2	3	4	5	6	7	8	9	10	11	12	TOTALS
CONTAMINATED SAMPLES	1	7	9	4	2	1	0	0	0	0	0	0	24
TOTAL SAMPLES ANALYZED	1	10	14	7	7	7	6	3	1	3	8	2	69
% CONTAMINATED	100	70	64	57	29	14	0	0	0	0	0	0	35

Figure 3. Contamination rate vs. various component types. Six (6) exhibited evidence of cleaning residue contamination and six (6) others did not.

Furthermore, it was observed that the non-contaminated components had covers with more venting or openings and, the contaminated components had covers with tight gaps / seams, Figures 4 and 5.

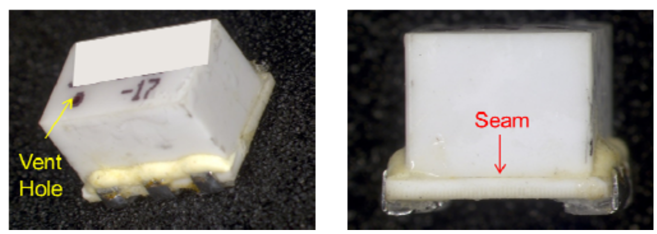


Figure 4. A component that exhibited a high-rate of entrained residue with a cover and a vent hole (L) epoxy bonded to its base on only 2 sides, with the other 2 sides left with a seam or gap (R).

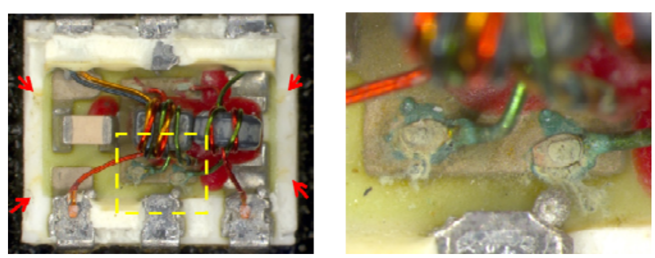


Figure 5. After SMT RF and cleaning process, the cover was removed, which showed the presence of, and entry points of residue (arrows) on the surface of the exposed seams (L) with oxidation of the metal contacts (R).

CHEMICAL / MATERIALS REACTIONS

Additional analysis in terms of the effect of various cleaning bath chemistries or solutions on the materials used in components was performed based on vendor supplied data and cleaning bath chemical analysis to determine if certain materials are non-compatible or more prone to degradation and / or corrosion.

Two (2) major chemical and material interactions were identified that were most likely occurring with the electronic component materials when cleaning bath solutions enter and are not rinsed-out, Figure 6.

1) Cleaning agents; that primarily degrade polymers (wire insulation) Figure 7.

2). Ionics / halides from cleaning bath; primarily chlorine (catalyst) that primarily oxidize metals (contact pads). Figure 8.

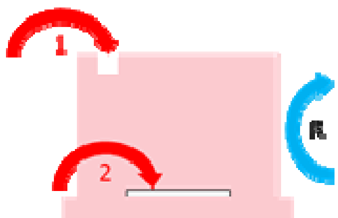


Figure 6. A component with small vent holes or small openings appear to entrain both cleaning agents and ionic constituents from the cleaning bath.

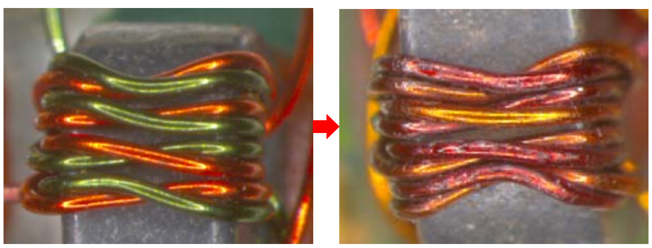


Figure 7. Cu-wire insulation from a non-contaminated component (L) as compared to contaminated insulation, that appeared degraded, discolored, soft, pliable and easy to remove, and attributed to the cleaning chemistry (R).

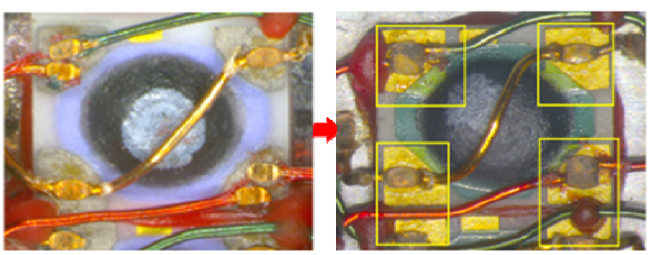


Figure 8. Internal component metal contacts of wires and pads are shown on a non-contaminated component (L). Compare to an equivalent component with metal contacts that appeared discolored and oxidized, and attributed to cleaning bath ionic contamination (R).

MATERIALS NON-COMPATIBILITY

Based on cleaning chemistry supplier data sheets, three (3) cleaning chemistries were compared to each other in terms of their non-compatibility on various polymeric materials, if exposed at 160°F for 8 weeks. For metals used in electronic components, i.e., Sn, Pb, Cu, Ni, etc., all were similarly tested with the cleaning agents listed as benign.

This study was not to determine the cleaning effectiveness of the individual cleaning agents A and B, as they have both been successfully used in removing the materials that remain from SMT processes that use semi-aqueous cleaning machines. C is used in vapor degreasing equipment.

However, it appears that cleaning agent B affects fewer materials as compared to cleaning agent A, Table-1.

Table 1. Materials vs. Cleaning Chemistry

	MATERIALS NON-COMPATIBILITY	CLEANING CHEMISTRY		
NO.	PLASTIC (POLYMER-BASED)	A	B	C
1	acetal	x		
2	nylon	x		
3	polyester	x		
4	Fluoroelastomer (VitonA/B)	x	x	
5	polyurethane	x		
6	polyester/polyether	x		
7	PTFE	x		
8	polyethylene	x		
9	polyetherimide	x		
10	silicone	x		
11	PVC	x		
12	polycarbonate	x	x	x
13	Buna-S	x	x	
14	Buna-N	x	x	
15	acrylic	x	x	x
16	butylstyrene(ABS)	ND	ND	x

In addition to the cleaning chemistry, the cleaning baths also contain ionic constituents. Table-2 shows major ionic anions and cations concentrations (ppm) of a typical SMT cleaning bath.

The anions primarily react with metals, with Cl-chlorine considered the most reactive in oxidation reactions and functions as a catalyst.

Table 2. Cleaning Bath Ionic Constituents (ppm)

Date	SMT Line #1										
	Anions					Cations					
	Cl	SO4	Br	NO3	PO4	Li	Na	NH4	K	Mg	Ca
1/7/2015	**74.9**	81.8	n.a.	5.9	n.a.	n.a.	56.9	n.a.	18.0	n.a.	n.a.
1/12/2015	**66.0**	39.7	n.a.	11.2	n.a.	n.a.	52.7	n.a.	15.9	n.a.	n.a.
1/19/2015	**100.5**	27.8	n.a.	9.6	n.a.	n.a.	63.6	n.a.	15.3	n.a.	n.a.
2/10/2015	**54.5**	17.1	n.a.	8.4	2.1	n.a.	38.4	n.a.	8.2	n.a.	n.a.
2/25/2015	**55.1**	16.3	n.a.	6.5	n.a.	n.a.	40.0	n.a.	38.4	n.a.	1.4
3/4/2015	**56.0**	16.4	n.a.	8.2	n.a.	n.a.	41.6	n.a.	17.3	n.a.	n.a.
3/9/2015	**81.4**	24.5	8.8	9.3	n.a.	n.a.	64.0	n.a.	16.3	n.a.	n.a.
3/11/2015	**71.6**	21.1	7.5	9.9	n.a.	n.a.	56.5	n.a.	18.6	n.a.	1.4
3/18/2015	**102.5**	134.0	10.0	10.6	n.a.	n.a.	81.3	n.a.	225.4	n.a.	n.a.
3/25/2015	**158.0**	36.0	n.a.	15.0	n.a.	n.a.	123.0	n.a.	232.0	n.a.	2.3
4/1/2015	**219.2**	65.3	38.0	21.3	n.a.	n.a.	176.9	n.a.	29.2	0.3	4.7
4/6/2015	**244.1**	52.0	42.0	23.6	n.a.	n.a.	192.1	n.a.	24.7	0.5	10.9
4/13/2015	**388.0**	112.8	61.9	27.1	n.a.	n.a.	285.9	n.a.	387.2	n.a.	1.7
4/15/2015	**329.7**	71.7	58.3	32.9	n.a.	n.a.	252.0	n.a.	41.0	0.3	6.1
4/20/2015	**334.5**	69.6	65.6	34.4	n.a.	n.a.	240.3	n.a.	33.2	n.a.	7.6
4/29/2015	**211.7**	49.2	35.8	20.1	n.a.	n.a.	152.3	n.a.	46.0	n.a.	0.5
5/11/2015	**129.2**	33.9	23.7	12.3	n.a.	n.a.	80.0	n.a.	32.5	n.a.	0.0
5/20/2015	**93.9**	24.2	13.4	7.8	n.a.	n.a.	67.6	n.a.	63.0	n.a.	1.1
5/28/2015	**75.0**	16.8	9.6	6.9	n.a.	n.a.	56.5	n.a.	52.0	n.a.	n.a.
6/1/2015	**76.9**	32.8	8.5	7.2	n.a.	n.a.	54.5	n.a.	87.8	n.a.	n.a.

ENTRAINMENT / ENTRAPMENT MECHANISM

The cleaning process is basically a combination of first W-washing with cleaning agents (soap), and then R-rinsing (water) away the cleaning agents / by-products. Cleaning agents are designed as surfactants / saponifiers with low-surface tension, enabling the active chemistry to penetrate small and tight form-factors or features. Figure 9.

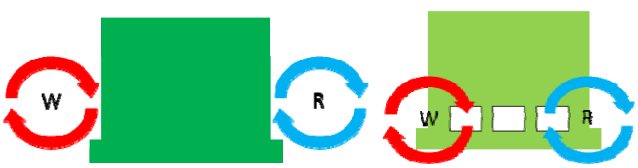


Figure 9. Components that are either hermitically sealed (L) or have ample vents or openings (R), then the washing / rinsing process will result in a "clean" component.

If these small features are also in the component housing in the form of open gaps, seams or small vent-holes, then both the cleaning agents + bath ionic residues are entrained via "capillary forces," but not readily rinsed-out by subsequent DI water rinse.

These openings are also too small for rinsing with water, which has a higher surface tension than the cleaning agents, and do not readily enter and / or "rinse-out" the cleaning agents and / or "ionic" residues, Figure 10.

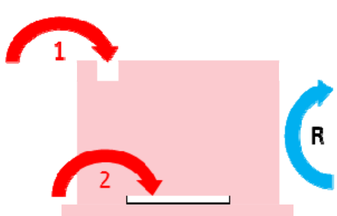


Figure 10. A component with small vent-holes, gaps, seams, etc., where both cleaning agents and ionics from the bath are entrained via capillary forces and the residues are not readily diluted or rinsed by DI water.

In addition, if the open areas are large enough to avoid capillary entrainment, the part would still require large enough openings or minimum vent area openings for water to still adequately flow in and out to adequately remove cleaning solutions, Figure 11.

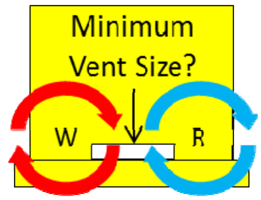


Figure 11. Component housing constructions have various designs and sizes. A minimum vent size is required for the part to be effectively washed / RINSED clean.

SMT / CLEANING PROCESS EXPERIMENTS

Various component cover / attachment constructions with a range of vent open areas form the basis of this study to compare to the occurrence of cleaning residue observed when subjecting the components to actual SMT and cleaning processes.

Experiments were performed to confirm if a relationship exists between a component's vent area and its susceptibility to fluid entrainment / entrapment, and if a minimum vent area specification can be determined to ensure future components can be effectively cleaned and rinsed.

Vent Area Measurements

Each of the twenty-eight (28) components with various vent areas or openings was measured and summed using a microscope with area measurement capability, Figure 12.

Figure 12. Component vent or opening areas measured.

Test Vehicle

Twenty-eight (28) components, each with various housing designs from two (2) vendors, including the same types from initial field failures, were dimensionally characterized, then epoxy-attached and cured on to six (6) 5 x 7" bare PCBs with ENIG plated pads, Figure 13.

Figure 13. Illustrates the placement of various components with the different housing configurations that were epoxy attached to a common PCB as the test platform or vehicle.

The six (6) test vehicles (PCB + components) with various component covers and measured vent areas, were then processed through the current SMT RF / Wash / Rinse / Dry / Bake assembly steps and cycled accordingly, Figure 14.

- Two (2) PCBs were processed 3 times
- Two (2) PCBs were processed 2 times
- One (1) PCB was processed once
- One (1) PCB was retained as a control.

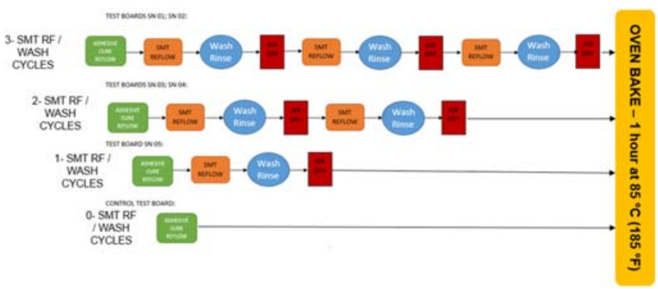


Figure 14. Test boards were processed up to 3 SMT RF / Wash-Rinse / Dry cycles and then baked for 1 hr. at 85 °C.

After SMT and cleaning, the CCAs were baked to remove any moisture, and then components covers were removed and inspected for evidence of cleaning bath fluid entrainment or contamination that did not rinse-out.

Contamination Severity
The amount of contamination was ranked to a qualitative criteria defined as; none, low and high at 15X magnification. The low and high contamination severities were further consolidated to simplify analysis. In other words, if all 5 components on each PCB showed either low or high levels of contamination, then a 100% overall contamination severity would be assigned, or if only 2 components exhibited either high or low levels, then a 40% overall severity would be assigned, Table 3.

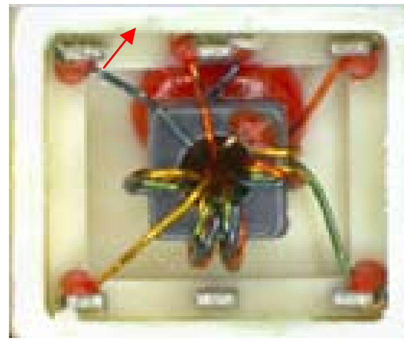


Figure 16. A component with its cover removed, exposing the materials within, that exhibited a viscous / clear fluid, later identified as cleaning bath solution, that was entrapped after SMT and cleaning processes.

EFFECT OF VENT AREA & CLEANING CYCLES ON CONTAMINATION
Each components vent area and the number of SMT RF/ Wash / Clean Cycles 1, 2, or 3 were compared to the % overall contamination severity observed. The severity of the contamination strongly decreased with increasing vent area and the contamination slightly decreased with increasing wash / rinse cycles, Table-3, Figures 16 and 17.

Table 3. Vent Area & Clean Cycles vs. Contamination

LEGEND: No Contamination; Small Contamination; High Contamination; No Decision

Increasing SMT RF / Wash / Rinse Cycles →

Comp #	Total Sampl	NO rf /Wash Control	1 rf /Wash SN 05	2 RF/Wash SN 03	2 RF/Wash SN 04	3 RF/Wash SN 01	3 RF/Wash SN 02	VENT AREA (mm^2)	[illegible]
1	2	1	1					0.00	100%
2	1		1					0.00	100%
3	6	1	1	1	1	1	1	0.00	80%
4	5	1	1	1	1		1	0.00	100%
5	6	1	1	1	1	1	1	0.00	80%
6	6	1	1	1	1	1	1	0.00	100%
7	6	1	1	1	1	1	1	0.00	100%
8	5	1	1	1	1		1	0.00	0%
9	5	1	1	1	1		1	0.002	75%
10	6	1	1	1	1	1	1	0.002	80%
11	5	1	1	1	1		1	0.04	50%
12	3	1	1		1			0.10	100%
13	6	1	1	1	1	1	1	0.17	100%
14	6	1	1	1	1	1	1	0.27	0%
15	6	1	1	1	1	1	1	0.36	60%
16	6	1	1	1	1	1	1	0.60	40%
17	6	1	1	1	1	1	1	0.78	40%
18	1		1					1.13	0%
19	6	1	1	1	1	1	1	2.00	100%
20	6	1	1	1	1	1	1	2.21	80%
21	6	1	1	1	1	1	1	2.35	100%
22	3	1	1		1			3.46	100%
23	6	1	1	1	1	1	1	3.68	0%
24	6	1	1	1	1	1	1	4.21	0%
25	6	1	1	1	1	1	1	4.36	0%
26	6	1	1	1	1	1	1	6.82	40%
27	2	1	1					8.85	0%
28	2	1	1					25.28	0%
	136	26	28	21	23	17	21		
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		

Increasing Component Vent (Open) Area ↓

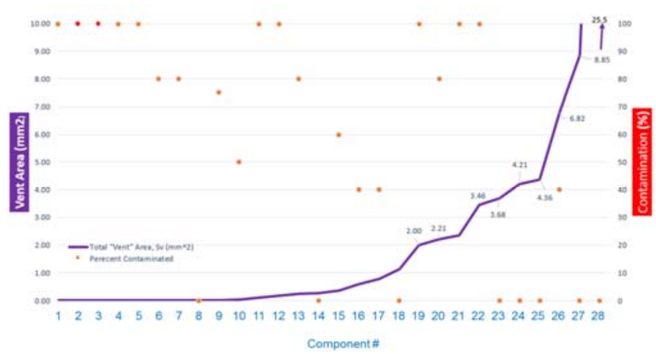


Figure 16. The 28 components arranged in order of increasing vent area (left y-axis, solid line) vs. their %

overall contamination (right y-axis, dots). A strong vent area to contamination correlation was observed.

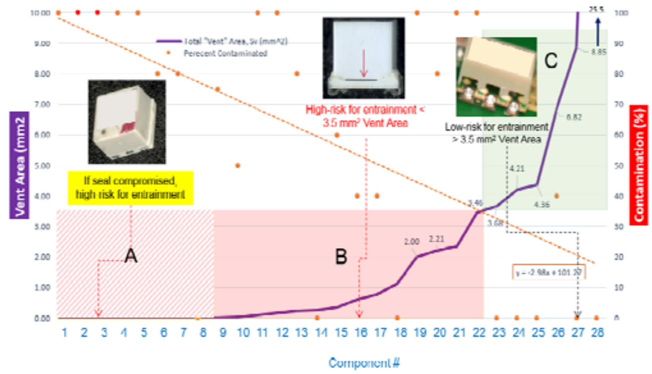


Figure 17. The component contamination risk vs rinse-ability are super-imposed with the three (3) major vent area zones defined as: (A) 0 mm^2, (B) 0 to < 3.5 mm^2 and (C) > 3.5 mm^2 vent areas, where contamination was least likely to occur.

Interestingly, Zone A where components appeared to have been well epoxied-bonded or ultrasonically sealed, appeared to be the most prone to entraining / entrapping cleaning solutions, Figure 17.

EFFECT OF THERMAL PROCESSING:

Although components may appear to be well-sealed, they may not be hermetically sealed and may be further compromised when subjected to thermal expansion effects due to entrapped cleaning solutions / moisture expanding during multiple SMT reflow cycles or other subsequent thermal processes. This may result in dis-bonding of the cover from the substrate, essentially creating a seam that enables cleaning agents to be entrained via capillary action, and remaining residues not readily rinsed-out, Figures 18-20.

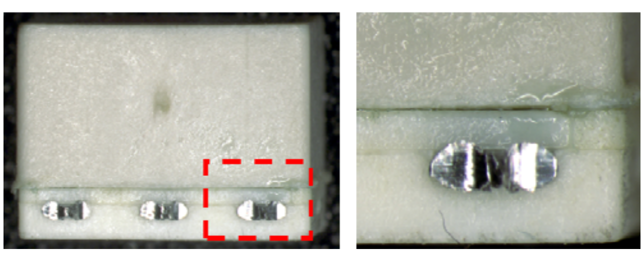


Figure 18. Ultrasonically welded component that exhibited viscous fluid leakage after SMT-RF and cleaning processes.

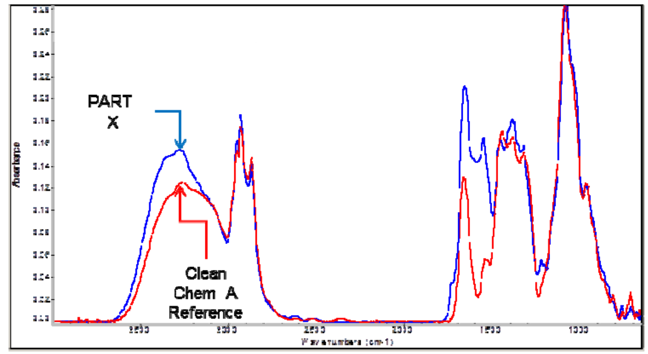


Figure 18. FTIR analysis showed that viscous fluid had similar constituents vs. the cleaning chemistry A, as taken from the SMT cleaning "bath."

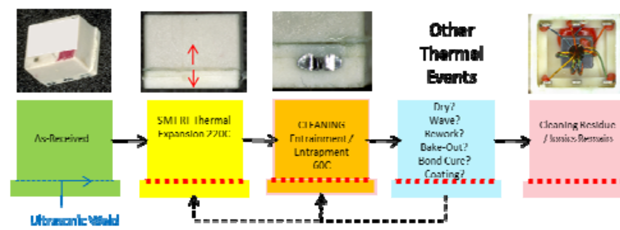


Figure 20. Thermal exposure events possible during SMT assembly, any of which, could cause dis-bonding of a well-sealed component cover resulting in a capillary condition for entraining contamination.

DfR- DESIGN for RINSE-ABILITY:

DfR focuses on the water rinsing, rather than the chemistry or washing process of the SMT cleaning process. Although, cleaning chemistries may be aggressive, if the waste by-products are removed quickly because the components have been designed to be rinse-able, then the component materials will have had limited exposure, and any long-term or latent degradation and / or corrosion effects would still be reduced, Figure 21.

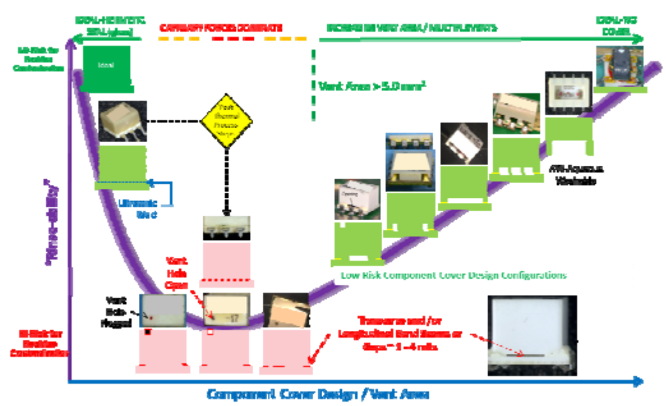


Figure 21. Shows component types with various cover designs with increasing vent areas vs. their relative "rinse-ability" or ability to remove entrained and entrapped cleaning solutions.

CONCLUSIONS

There are two (2) major chemical interactions reacting with SMT assembled electronic component materials in cleaning bath solutions that enter component housings via capillary forces, through seams / holes and / or insufficient vent openings for adequate rinsing, are listed as follows:

1) Cleaning agents; that primarily degrade polymers (wire insulation)

2). Ionics or halides from cleaning bath; primarily chlorine (catalyst) that primarily oxidize metals (contact pads).

Cleaning chemistries were reviewed with the current cleaning solution A considered more aggressive than cleaning solution B, in particular on materials, such as polyurethane used in Cu wire insulations.

The component housing construction / assembly design in terms of vent areas or openings is a major factor that determines if a component will readily entrain cleaning solutions and / or limit the ability of water rinsing to effectively remove cleaning residues.

The effect of component cover vent areas was clearly demonstrated from SMT RF / cleaning experiments that strongly correlated the effect of component vent areas on the occurrence of cleaning residue entrainment / entrapment with a minimum vent area required.

Thermal processing effects may compromise the bonding interface seals, creating conditions for capillary forces to come into play to entrain and entrap cleaning solutions within components, and at the same time, water is prevented from entering and rinsing-out contamination.

In summary, certain components have more “rinse-ability” than others. If the component is designed in such a manner that water can easily flow in and out of the component, then the component should be rinsed of any residual contamination, thus reducing the effect of any latent materials degradation on the components electrical performance and reliability.

RECOMMENDATIONS

Identify the materials used in components constructions in order to understand and reduce the risk to materials susceptible to cleaning chemistry and long-term exposure.

Select less aggressive cleaning solutions that may be available that better target the particular residue or contaminants to be removed and yet have a benign effect on the electronic materials being cleaned.

Evaluate component constructions for rinse-ability. Review product data sheets for AW-aqueous rinse-able designations, and if not noted, then further inquiry or evaluation of the component design is recommended.

Drive component designers and vendors to incorporate DfR principles based on the following vent area geometric characteristics or attributes in housing covers to improve rinse-ability, rather than design for what may not be a reliably sealed or “pseudo-hermetic” component.

- Vent Area Minimum > 5.0 mm^2
- Vent Area to Surface Area Ratio > 0.025
- Minimum Number of Vents- 2 (1 inlet / 1 outlet)
- Vent Locations- opposite of each other on bottom.

FUTURE WORK

Future work will include lifetime reliability testing on high-risk components by controlled introduction or “injection” of known SMT cleaning “bath” chemistries in representative amounts to determine the effect of entrapped cleaning residue on their electrical performance and if any risk to product currently deployed.

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