FLUID FLOW MECHANICS: KEY TO LOW STANDOFF CLEANING

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ABSTRACT:

In recent years, various studies have been issued on cleaning under low standoff components; most however, with incomplete information. It is essential to revisit and describe the latest challenges in the market, identifying obvious gaps in available information. Such information is crucial for potential and existing users to fully address the cleanliness levels under their respective components. With the emergence of lead-free soldering and even smaller components, new challenges have arisen including cleaning in gaps of less than 1-mil.

This study was initially designed to investigate the impact of mechanical vs. chemical energy contributions during the removal of contamination under 1-2 mil standoff components. To validate the results obtained, extensive studies were conducted, specifically prepared test-assemblies, iterative experimentation, as well as new mechanical innovations that might help users in the future. The latter include, but are not limited to, various flow pattern designs and industry-leading cleaning agents. As a result, the authors will also include experimental data to address fluid flow mechanics, temperature and solvent concentration-related effects.

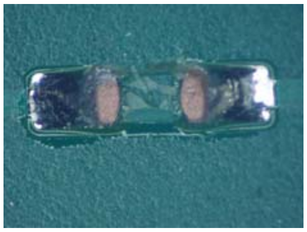
Initial results obtained indicate that cleanability of residues under low standoff components has become a non-trivial issue. Not only are residues becoming harder to remove, the penetration of the cleaning agent seems to be in direct relationship with the geometry and height of the components in question.

INTRODUCTION:

Is cleaning becoming more difficult, or is the performance level of today's electronics demanding cleaner boards? The answer is "both of the above." Signal propagation is the name of the game in high-speed circuits. Designers worry about "little" details like the length and width of the trace. Necking, or other discontinuities, in the traces can cause timing differences that can prevent the circuit from operating as designed. Changes in bulk flux residues can, and do, cause similar circuit problems[1]. These are not the same old green, corroded circuit reliability woes that caused many a quality assurance manager to prematurely gray. Electronic packages today are required to perform at higher temperatures, lower power consumption, faster clock speeds, and in smaller formats. All of these market-driven requirements demand cleaner and cleaner electronic assemblies to perform properly.

Cleaning challenges also are evolving. Circuit integration at the silicon level has changed the part count and the component demographics on newer designs. Current designs have fewer ICs and more discrete components like resistors and capacitors. Both are getting smaller. From a cleaning perspective, space under components is shrinking, and this smaller space is more likely to be completely filled by the flux residue. Looking at the evolutionary path, we have transitioned from flux being around the component (through-hole and SMT outline packs); to flux moving under the part (SMT arrays); to completely filling flux under tightly spaced components (0204s and flip chips) (Figure 1).

Flux around surface mount



Flux under cap

Figure 1: Flux residues around and under the component Changes in flux and soldering technology have created new cleaning challenges. Higher temperature profiles for lead-free solders routinely heat flux for longer times and at higher temperatures, making cleaning more difficult. The number of flux formulations has propagated demand for a cleaning system that can work with all types. As a result, cleaning systems must have the flexibility to adjust and not leave the user with obsolete equipment.

Fluid Flow Theory (un-filled gaps):

The basic tenets are straightforward. To get reasonable rates of cleaning in tight spaces, a suitable cleaning agent technology must be presented with sufficient force and agility to create fluid flow in these tight spaces. Exactly how much force depends on the application and the chemical ease of cleaning. In the easier cases, where open air gaps remain, capillary forces must be overcome to create flow. Depending on the surface tension and density of the cleaning agent, wetable gaps of 1 mil or less will require greater than 1 psi differential just to create flow once the space is filled. In tighter gaps, or in tight spaces with solvent-phobic surfaces, the required differential pressure may be 10 psi or greater. To create this kind of differential pressure on the surface of the circuit board, cleaning system designers have used pump manifold pressures of 40 to 100 psi, depending on the type of nozzle chosen.

Capillary force is significant in small gaps and can be calculated in equations 1 and 2 listed below. Data for pure water on glass surfaces is shown in Figure 1.

$$\boxed{\Delta p = 2\gamma \cos\theta \;/\; R}$$

Equation 1: Interfacial pressure differential (planar)[1]

Where

$\boldsymbol{\gamma}$ = surface tension

R = radius meniscus

$\boldsymbol{\theta}$ = contact angle of liquid at surface

$$\boxed{\Delta p = \gamma \cos\theta / R}$$

Equation 2: Interfacial pressure differential (cylinder)[1]

Note that if $\boldsymbol{\theta}$ is greater than 90°, as with water on waxy surface, the force becomes negative or repulsive.

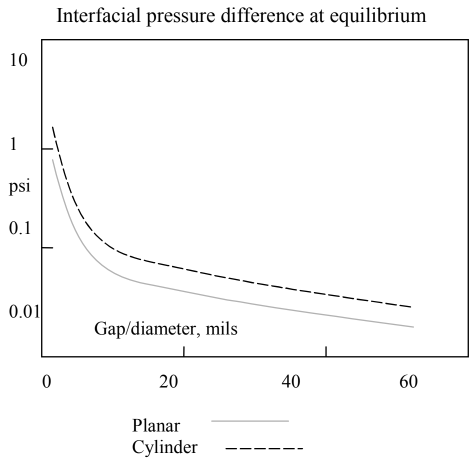


Figure 2: Relationship between gap size and capillary force for water on glass

Adding surface tension-reducing agents, commonly called “wetting agents,” lowers surface tension and reduces the resistance to flow The same effect can be achieved by using organic solvents with lower surface tension. It is essential to stress that gap size, cleaning agent, and the fluxed surfaces determine total flow in the gap.

Fluid Flow Theory (filled gaps):

If flux residue fills or partially blocks the fluid path, the residue must be softened to allow fluid flow channels to be forced in the flux matrix. Previous research[i] has suggested that most inline cleaners using nozzles at these pressures are not capable of completely removing fully-filled spaces of 4 mils or less at speeds of 1 fpm or greater. Recent experiments conducted with glass slides used to simulate flip chip configurations[ii] show a three step process is required to remove a fully blocked gap. First, there is a finite amount of time required to soften the outer shell (solvent depleted zone). This time varies from seconds to minutes depending on the flux and the solder reflow profile. Second, once the outer shell is sufficiently softened, a liquid jet with sufficient energy forms flow channels in the flux matrix, injecting cleaning chemistry and further softening the matrix. In the third and final phase, the bulk residue is eroded away by the ever-widening flow channels until complete removal is effected.

Mechanical steps required for rapid removal of flux filling component gaps:

1. Soften the outer solvent depleted shell and flux matrix
2. Fluid jets with sufficient energy create flow channels in matrix
3. Bulk flux residue is completely eroded away by flow channels

Fluid flow in the gap to be cleaned is the key to speeding the process. Establishing sufficient velocity to penetrate and erode the flux matrix mechanically requires impact pressure high enough to establish turbulent/interactive flow in the gap to be cleaned. Higher manifold pressures can be an indicator of a system's ability to clean tight spaces, but high pressure alone will not guarantee a positive result.

Video analysis of these interactions reveals them to be dynamic and complex[2]. The rate of change in flow in the flux-filled gap can be described by the Navier-Stokes equations. The turbulent nature of the flow can be predicted by the Reynolds equation.[ii] None of these equations is sophisticated enough to address all the variations we can see on the production line, so, one has to perform iterative testing protocols. The equations should simply provide starting points and a basic understanding of what is important.

It should be noted that batch cleaners further complicate this because issues like shadowing, part orientation, and spray distance make it very difficult to guarantee the required pressures on all surfaces. This can render batch cleaners problematic for cleaning flux-filled tight gaps unless these issues are addressed.

Inline Progressive Energy Dynamics Approach:

This research focuses on a new approach to designing the wash section sprays of an in-line cleaner. Dubbed "progressive energy dynamics," this involves a manifold design that is optimized to distribute the wash energy needed at each step of the cleaning process. This is contrasted with the current approach of using bigger pumps and adding more manifolds, which adds length to the cleaner and requires more power. A progressive energy design is a fluid delivery system that recognizes the three-step process required to clean flux-filled spaces, delivering only what is needed at each step. This does two things. First and most crucial, it guarantees that the appropriate amount of energy is available at each step of the process to effect complete flux removal. Secondarily, it avoids wasting energy by directing less energy in the beginning, and more at the final spray where flow channels are fully formed.

Figure 3: Picture of wash section equipped with progressive energy dynamics

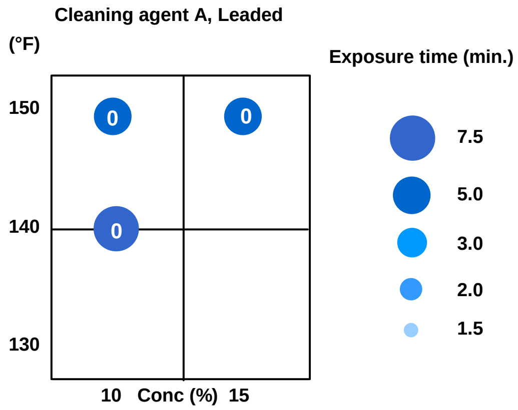
Testing Protocol:

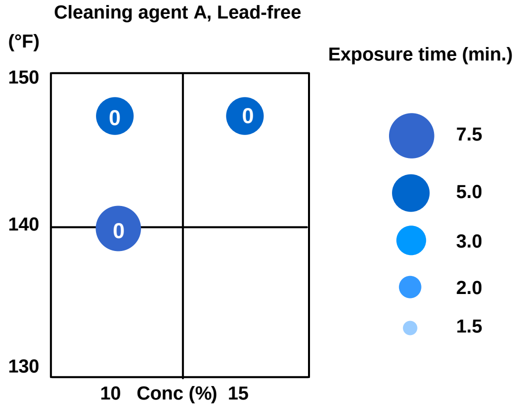
Test boards were populated with 0603 chip capacitors having an average standoff height of 1 mil. Each board was populated to its maximum component density (30 components per board). Three different phases of tests were conducted which were differentiated by the spray bar configuration/spray nozzle type. This subsequently gave different spray manifold pressures for each phase. A novel cleaning agent technology specifically designed for penetrating under low stand off components was used in conjunction with two solder paste formulations. Leaded and lead-free solder pastes were specifically chosen based on having the highest level of difficulty to clean. Soldering was performed in a 10-stage reflow oven under an air-atmosphere. Reflow under nitrogen had previously been demonstrated to provide significantly better cleaning results. The authors therefore opted for reflow with air to produce worst-case scenarios. During all experiments, only one parameter was changed at a time and the results recorded before the next experiment was conducted. The overall test plan is shown in Chart 1.

			Phase I	**Phase II**	**Phase III**
Fixed Parameters	Spray Configuration Design	1	✓		
		2		✓	
		3			✓
	0603 component density per board	30	✓	✓	✓
	Cleaning agent	A	✓	✓	✓
	Spray pressure (psi)	55	✓		
		49		✓	
		50			✓
Variable Parameters	Pastes	Lead-free	✓	✓	✓
		Leaded	✓	✓	✓
	Concentration (%)	10	✓	✓	✓
		15	✓	✓	✓
	Temperature (°F)	140	✓		✓
		150	✓	✓	
	Conveyor belt speed (ft/min) / Exposure time (min) / *Total wash section: 3ft.*	0.4 / 7.5	●		
		0.6 / 5.0	●	●	
		1.0 / 3.0		●	●
		1.5 / 2.0		•	•
		2.0 / 1.5			•

Chart 1: Overall experimental overview

Findings Phase 1:
In phase one, a standard (non-progressive) cleaning manifold design was tested to establish a base line. Results from Phase I tests (Chart 2) showed that even belt speeds as low as 0.4 fpm yielded minor residues underneath the components for both leaded and lead-free formulations. This is consistent with results reported in other inline machines cleaning no-clean and lead-free fluxes.





+: Clean 0: Partially cleaned -: Not clean

Chart 2: Cleaning agent A removing lead-free and leaded under low stand off – Phase 1

Fixed Parameters					
Equipment Specification				**Board Specification (0603 components)**	
Spray Pressure (psi)	**55**	Spray bars (top)	**5**	Component density	**30**

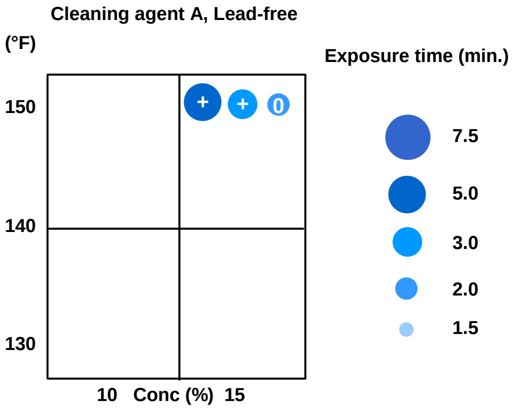
	Variable Parameters					
	Cleaning agent	Board #	Conc. (%)	Temperature (°F)	Conveyor belt speed (ft./min.) / Exposure time (min) *Total Wash Section: 3ft*	Cleaning Result
Lead-free	A	1	10	140	0.4 / 7.5	0
		3	10	150	0.6 / 5.0	0
		5	15	150	0.6 / 5.0	0
Leaded	A	2	10	140	0.4 / 7.5	0
		4	10	150	0.6 / 5.0	0
		6	15	150	0.6 / 5.0	0

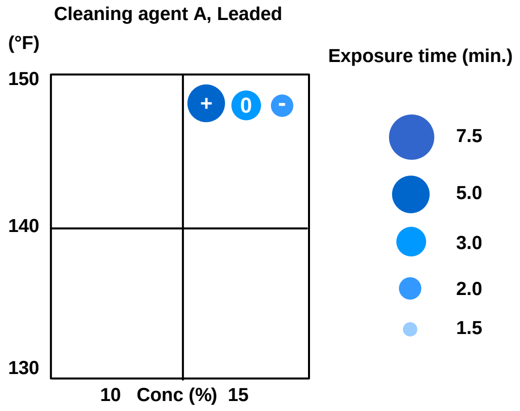
+: Clean 0: Partially cleaned -: Not clean

Chart 2: Phase 1 experimental results

Findings Phase 2:

In phase II testing, the same machine was modified by removing the wash spray manifolds and replacing them with manifolds designed to provide increasing flow as the board progresses through them. The results from Phase II tests (Chart 3) showed a major improvement in cleaning performance by changing the spray configuration to the progressive energy dynamics approach. Chemistry A was able to clean under the low standoff components effectively at belt speeds of 1 fpm (employing a 3 ft. long wash section), which corresponded to a 3-minute exposure time. A further increase in belt speed yielded only partially cleaned residues. It is important to mention that the results were significantly better than the authors were able to achieve in a previous study[iii] (employing a wash length section of 5 ft.) with the same chemistry and test substrates. These findings led the authors to conclude that spray configuration 2, utilizing progressive energy dynamics, enhanced and expedited cleaning under low standoff components.





+: Clean 0: Partially cleaned -: Not clean

Chart 3: Cleaning agent A removing lead-free and leaded under low stand off – Phase 2

Fixed Parameters					
Equipment Specification				**Board Specification (0603 components)**	
Spray Pressure (psi)	**49**	Spray bars (top)	**5**	Component density	**30**

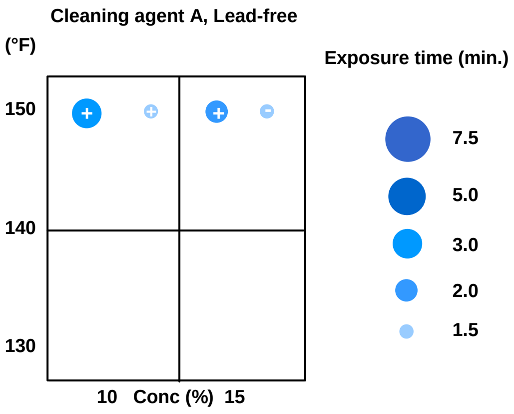
	Variable Parameters					
	Cleaning agent	Board #	Conc. (%)	Temperature (°F)	Conveyor belt speed (ft./min.) / Exposure time (min) *Total Wash Section: 3ft*	Cleaning Result
Lead-free	A	7	15	150	0.6 / 5.0	+
		9	15	150	1.0 / 3.0	0
		11	15	150	1.5 / 2.0	-
		13	15	150	1.5 / 2.0	-
Leaded	A	8	15	150	0.6 / 5.0	+
		10	15	150	1.0 / 3.0	+
		12	15	150	1.5 / 2.0	0
		14	15	150	1.5 / 2.0	0

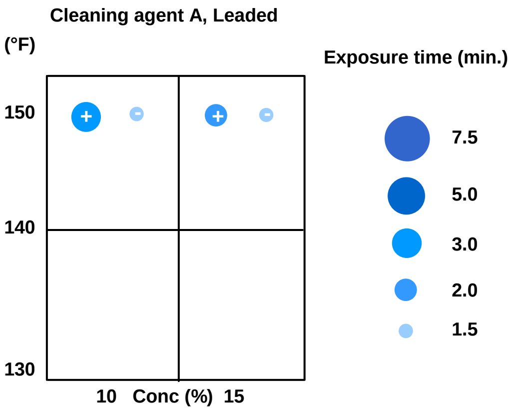
+: Clean 0: Partially cleaned -: Not clean

Chart 4: Phase 2 experimental results

Findings Phase 3:

A new machine was built for Phase III testing, incorporating the progressive energy dynamics concept with one additional feature. In this design, the energy progression was enhanced by adding a second pump. The wash tank was also expanded 6 inches to permit a larger sump volume and a longer wash length. The results from Phase III tests (Chart 4) showed an additional improvement in cleaning performance achieved by adding a second, higher-flow pump and changing to the spray configuration that uses the progressive energy dynamics approach. Chemistry A was able to clean under the low standoff components effectively at belt speeds of 1.7 fpm (employing a 3.5 ft. wash section), which corresponded to a 2.1 minute exposure time. The two-pump machine had an overall length of 18 feet, with a total cycle time for wash/rinse/dry of 10.6 minutes at 1.7 f/m.





+: Clean 0: Partially cleaned -: Not clean

Chart 5: Cleaning agent A removing lead-free and leaded under low stand off – Phase 3

Fixed Parameters					
Equipment Specification				**Board Specification (0603 components)**	
Spray Pressure (psi)	**50/50**	Spray bars (top)	**7**	Component density	**30**

	Variable Parameters					
	Cleaning agent	Board #	Conc. (%)	Temperature (°F)	Conveyor belt speed (ft./min.) / Exposure time (min) *Total Wash Section: 3.5ft*	Cleaning Result
Lead-free	A	21	10	150	1.2 / 2.9	+
		22	10	150	1.7 / 2.1	+
		23	10	150	2.2 / 1.6	-
		24	15	150	1.2 / 2.9	+
		25	15	150	1.7 / 2.1	+
		26	15	150	2.2 / 1.6	-
Leaded	A	27	10	150	1.2 / 2.9	+
		28	10	150	1.7 / 2.1	-
		29	10	150	2.2 / 1.6	-
		30	15	150	1.2 / 2.9	+
		31	15	150	1.7 / 2.1	+
		32	15	150	2.2 / 1.6	-

+: Clean 0: Partially cleaned -: Not clean

Chart 4: Phase 3 experimental results

Conclusion

It is safe to assume that components will continue to get smaller, board densities will increase, and assemblies will get tougher and tougher to clean. Given those challenging parameters, the "old" approach to cleaner design – adding bigger pumps and lengthening the machine while using surfactant based cleaning agents – is not the most efficient, effective route to pursue. With this approach, marginal cleaning was achieved at belt speeds not commensurate with the demands of a production environment. After thorough analysis of the interaction between chemical and mechanical energy in the cleaning process, a new approach was evaluated that optimizes pressure and flow by increasing impingement force of the cleaning agent as the board is conveyed through the system.

Progressive energy manifold design in conjunction with the latest cleaning agent innovation clearly improves overall performance. Cleaning performance achieved with this new design and product was the best seen to-date in similar types of tests conducted over a period of years. As with most studies, evaluation of cleaning performance will remain a work in progress and follow-on testing is planned, however, both throughput (belt speed) and quality (elimination of residues) were enhanced significantly with this new, progressive energy design.

REFERENCES

[i] "Effect of post-reflowed no-clean solder paste residue on electrical performance" Beikmohamadi, A., IEEE Transactions on Component packaging and Manufacturing Technology volume 16, issue 8, Dec. 1993 pages 799-801

[ii] "Optimizing cleaning energy in electronic assembly spray in air systems: Phase II". Stach, S., & Bixenman, M. (2005, Sep). SMTAI Technical Forum, Rosemont, IL, Donald Stephens Convention Center.

[iii] “A new definition of low stand off cleaning” Wack, H., Tosun, U., Ravindran, N., Becht, J., Schweigart, H., Ellis, D.