OPTIMIZING CLEANING ENERGY IN ELECTRONIC ASSEMBLY SPRAY IN AIR SYSTEMS: PHASE II

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ABSTRACT

At the SMTA 2004 tech forum, Stach & Bixenman (2004) presented research for optimizing cleaning energy in batch and inline cleaning systems. The research questions for the 2004 study asked: What equations define surface energy at board level? How does this energy affect the fluid delivery design in a cleaning system? How much impingement pressure is needed at the board level? Which is better, high pressure or high flow? Defining an optimized electronic assembly cleaning system requires an understanding of the balance between the static (potential) and dynamic (kinetic) energies to achieve maximized cleaning performance. Attributes or characteristics that influence cleaning performance center around surface energy, surface tension, capillary action, spray nozzle design, equipment design, time, temperature, and cleaning chemistry.

Phase II of this research test the process cleaning rate equation, which equals the static cleaning rate (chemical forces) plus the dynamic cleaning rate (mechanical forces) using spray-in-air cleaning equipment. The baseline for this experiment establishes the solubility rate of the cleaning solution, at static conditions, to determine the dissolution rate of flux residue, at a pre-determined cleaning chemistry concentration and temperature. Once the cleaning rate is known, how will it be improved by applying physical energy to the board surface? The designed experiment will test the effect of energy applied to the board surface by varying pressure at the board surface. The study's hypothesis infers that a known dissolution rate and a known surface energy configuration allows an equation to calculate cleaning time and distance. The response variables will be video imaging of the actual cleaning tests, and removal efficiency using ultraviolet detection of residue under low standoff test vehicles. Independent variables consist of substrate standoff heights, cleaning temperature, and cleaning time with various attributes. Constants include fixed amount of nozzles per square inch, predetermine maximum force that does not result in component marking damage, and chemistry concentration.

Key words: Process Cleaning Rate, Cleaning, Pb-free

BACKGROUND

The objective of spray-in-air batch and in-line cleaning systems is to reduce time by engineering fluid displacement that maximizes the physical energy delivered at the surface to be cleaned. An optimized cleaning system delivers the necessary chemistry and energy to clean the most difficult and sensitive areas, at a rate that will meet the process time requirements using minimal chemical energy and floor space consumption. Process savvy helps avoid common mistakes in controlling process parameter such as time, temperature and concentration, or operator variables related to racking and shadowing in dishwasher style cleaners. Understanding the balance between the static chemical and dynamic mechanical forces is fundamental in predicting and optimizing process performance at each step of the washing, rinsing and drying process.

The timing and sequence of events in a cleaning process are critical. Each section or step in the process requires careful thought and understanding. The pre-wash should thoroughly wet the parts with the wash solution chemistry and provide sufficient flow and contact time to bring the assembly to wash temperature. This facilitates the full static-cleaning rate while softening the residues. In the wash zone, the part should see several high impingement scourgings, punctuated by brief soak periods. This optimizes the static rate by maintaining fresh cleaning fluid and optimizes the dynamic rate by focusing the maximum physical energy at the part surfaces. The cleaning rates in in-line and planar racked batch cleaners can be significantly improved by engineering impingement systems that deliver the cleaning chemistry to the heart of the residue.

PROBLEM STATEMENT

Today, many high reliability electronic assemblies require removal of tenacious no-clean flux residue and other residual contaminants. This is compounded by the ongoing change to Pb-free flux formulations that have their own set of cleaning problems, many of which are just not being understood. Miniaturization and reliability concerns drive more customers to specify cleaning as a required step in the manufacturing process. The problem is that cleaning performance changes when processing Pb-free, different

flux types, dense substrates, and boards assembled with advanced packages. Chemical and mechanical forces must work in tandem to deliver totally cleaned assemblies on a wide range of residues, at higher reflowed temperatures, while lowering cost of ownership. This research uses a correlational quantitative design to measure mechanical fluid transfer efficiency for cleaning under low standoffs. The research supplements the findings using a predictive equation to calculate the rate at which flux is removed at various conditions.

PURPOSE STATEMENT

The initial study hypothesized an empirical process cleaning rate equation ($R_p=R_s+R_d$) where R_p represents the process cleaning rate, R_s represents the static cleaning rate, and R_d represents the dynamic cleaning rate. All cleaning systems are governed by two fundamental principles: 1.) The chemical driving forces that solubilize the residue at a known rate and 2.) The energy applied to the surface of the part to do the work. Nozzles are used in "spray in air" systems to create jets that carry energy to the surface of the part to be cleaned, rinsed, or dried. The design and layout of the nozzles becomes important if the cleaning system is to be truly optimized. The purpose of this designed experiment is to develop a test method that allows a visual based assessment of the effect on the cleaning rate as a function of energy applied to the board surface by varying pressure/mass flow rate at the board surface, and concentration and temperature of the cleaning fluid at 3, 4 and 5 mil planar gaps. A mathematical model will be developed to help explain our results. It is also our purpose to develop new tools to optimize cleaning of the new Pb-free fluxes.

RESEARCH METHODOLOGY

Quantitative methods discover themes and explore patterns, describe the problem, and predict an outcome. In this experiment, the research helps engineers understand the science of cleaning parts through the study of fluid dynamics, nozzle design, and energy applied to the surface being cleaned. The old premise that increasing the manifold pressure with a bigger pump is being challenged. Fluid mechanics suggests that the energy delivered to the surface is equal to the mass times the velocity squared. Designers of cleaning equipment have historically correlated cleaning efficiency with manifold pressure. Impingement pressure at the cleaning surface is very dependent on the nozzle type and distance from the nozzle manifolds to the surface to be cleaned. Prior measurements of different nozzle types have shown typical pressure drops of 50% for fan nozzles, 75% for conical nozzles, and 25% for coherent nozzles for each inch traveled.

This experiment video records, as shown in Figure 3, the cleaning process in action. The following variables influencing spray cleaning rate optimization will be used in study.

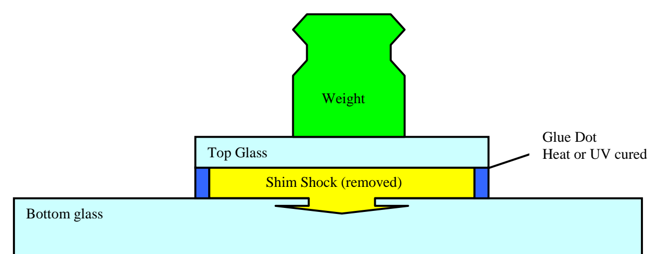
- Process Cleaning Rate (Dependent Variable)
- Nozzle Design (Independent Variable)
  - Coherent
- Material Variables (Fixed)
  - Flux type
    - Eutectic Sn/Pb (Indium SMQ 92J)
    - Pb-Free (Multicore LF-300)
  - Cleaning chemistry (Kyzen Aquanox A4630)
  - Chemistry concentration (10% & 15%)
- Process Variables (Fixed)
  - Reflow profile (eutectic peak of 218ºC and Pb-free of 240ºC)
  - Time between reflow & clean (0-4 hours)
  - Wash temperature (120ºF and 140º)
  - Spray impingement pressure at surface (0-10 psig)
  - Location of spray (within one impact diameter)
- Design Variables (Fixed)
  - Component dimensions (glass die was .875" x .875")
  - Stand-off height (3 mil, 4 mil, and 5 mil)
  - Surface materials (glass substrates with glass die)

TEST PROTOCOL

The test coupon was designed using a top and bottom glass to allow full visibility of the cleaning mechanisms and their rates of cleaning. The top plate was .875" X .875" square and 0.96mm thick. It is commercially available as a thicker than normal microscope slide cover. The bottom plate was 3" X 3" square and was .125" thick with ground edges. It was obtained at a local glass shop.

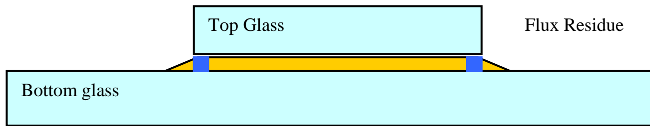
Four dots of chip bonding adhesive were dispensed on the corners of the smaller plate. The desired stand-off was achieved by placing the appropriate shim stock between the plates. The adhesive was then cured and the shim removed. Figure 1 illustrates the diagram of the construction process

Figure 1: Diagram of the Construction Process



The test coupon was then heated on a hot plate to 70$^{\pm}$10C where gel flux was added at the air gap interface until the gap is filled. The coupons were then transferred to a convection oven and brought to recommended peak temperatures for reflow profile. The coupons were then cooled to room temperature. The coupons are then aged for the appropriate time before running the cleaning test. A 0.078" coherent jet was chosen as is the standard jet used on the AAT HydroJet/MicroJet inline cleaners.

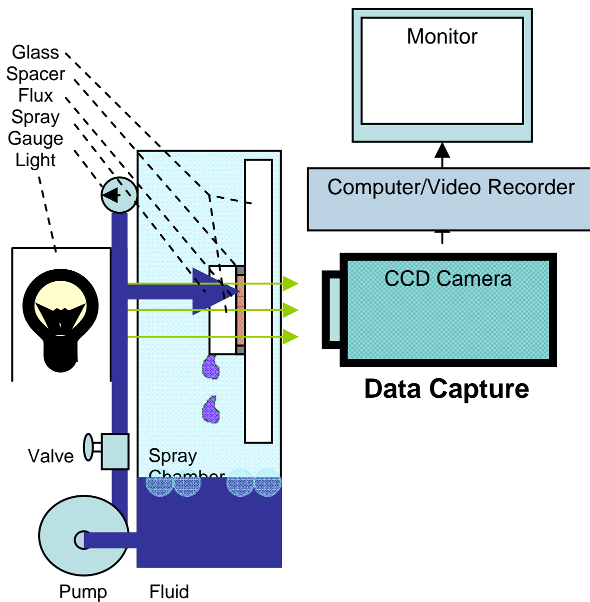
Figure 2: Completed Test Coupon Cross Section



TEST INSTRUMENT DESIGN

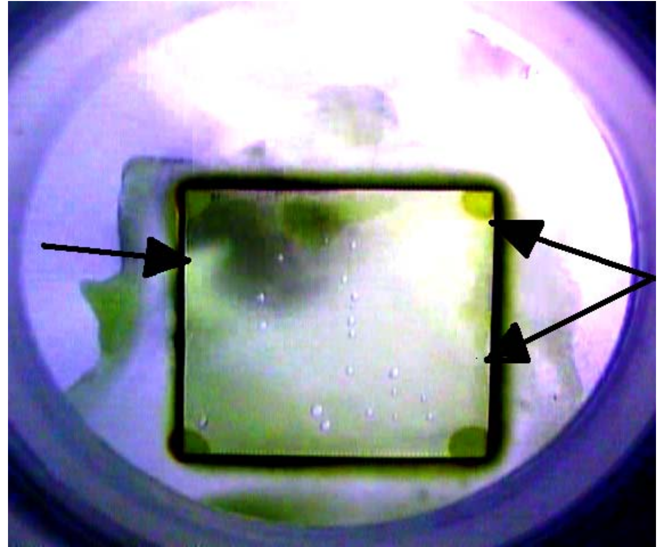
Figure 3 shows a system diagram of the test apparatus design we referred by the acronym "CARL" Cleaning Analysis Recording Laboratory. This system allows the filming and recording of real time cleaning on transparent assemblies/coupons. The capture rate of the video is 30 frames/second (33 milliseconds between captures).

Figure 3: Diagram of Cleaning Analyzer Recorder Lab (CARL)



A removable impact pressure sensor was inserted in the fluid jet to measure the impact pressure. Figure 4 shows a test slide mounted in the viewing window. A solvent rich zone in the center of the slide is visually detectable. The arrows indicate several out-gassing channel exit points in the flux mass. These out-gassing tracks remaining from the solder reflow heat cycle leave weak areas which allow cleaning fluid channels to initiate.

Figure 4: Completed test slide loaded into viewing position



DATA ANALYSIS

Analysis of the video data collected indicates that the physical process of cleaning the test coupons is a multi-step process governed by several critical parameters. Analysis of the test videos reveal an initial delay in penetrating under the flux filled test slide. Experiments showed that the time required to breakthrough and begin cleaning the flux under the slide (break-through time $\mathbf{T_{Br}}$) is dependent on the wait time between reflow and cleaning for the two flux types included in our matrix. Characterization of $\mathbf{T_{Br}}$ for the fluxes tested in this study is discussed later in the paper.

Cleaning Time Delay

The implications of this measurable delay in initiating the cleaning process can have profound effect on cleaning efficiency. In our initial paper we proposed that the total rate of cleaning ($\mathbf{R_p}$), was equal to the static rate ($\mathbf{R_s}$), plus the dynamic rate ($\mathbf{R_d}$).

Equation 1: Process cleaning rate equation: $\mathbf{R_p} = \mathbf{R_s} + \mathbf{R_d}$

Where;

Average process cleaning rate = $\mathbf{R_p}$

Static cleaning rate = $\mathbf{R_s}$

Dynamic cleaning rate = $\mathbf{R_d}$

It therefore follows that the total time to clean a solder joint is equal to the maximum thickness of the flux residue (D_{Fmax}), divided by the average process cleaning rate.

Equation 2: Time to clean = $D_{Fmax}/\mathbf{R_p} = D_{Fmax} /(\mathbf{R_s} + \mathbf{R_d})$

The introduction of an initial delay before any appreciable cleaning occurs changes equation 2 to equation 3 below.

Equation 3: Time to clean

$= \mathbf{T_{Br}} + (D_{Fmax} / (\mathbf{R_p})$

$= \mathbf{T_{Br}} + (D_{Fmax} / (\mathbf{R_s} + \mathbf{R_d}))$

Introduction of the $\mathbf{T_{Br}}$ factor helps explain the long standing observation that some fluxes get a lot harder to clean with the passage of time. $\mathbf{T_{Br}}$ can be measured for any

given flux type, cleaning chemistry, impingement pressure, cleaning temperature, and cleaning time delay using the apparatus described in this paper. Our experimentation suggests that all of these parameters have an effect on the time to begin active cleaning. This new metric would now allow today's process engineers to predict and avoid cleaning problems in production and rework cycles.

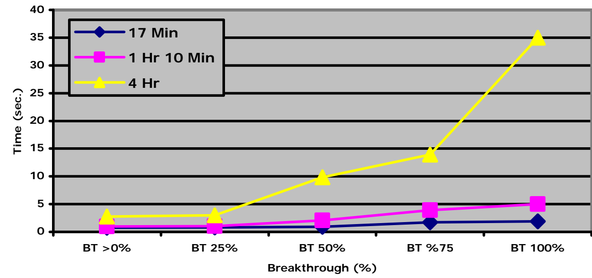
Cleaning Delay Theory

The hypothesis by the authors of this paper infers that this delay period where the high molecular weight resin molecules are being surrounded by smaller solvent molecules, which penetrate the matrix at different rates, are dependent on the nature of the non-volatile flux residue. If the flux mass is old or has been over-heated, it will contain few of its original solvent molecules added by the flux formulator.

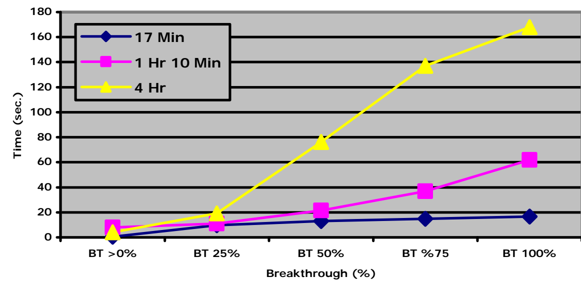
One big difference discovered in the testing was that the Pb-free flux reflow at 240ºC peak became much more difficult to clean very rapidly with passage of time following reflow. The no-clean eutectic tin-lead formula, which reflows at 210ºC peak, was less subject to the passage of time as correlated to cleaning break-through times indicated on Graph #1. Breakthrough rates for the Pb-free flux residue were greater than 10 times longer once the flux cured for 4 hours prior to cleaning as indicated on Graph #2.

Graph 1 and 2 show the deterioration of the cleaning times as a function of the delay following solder reflow heat cycle. Both the 63/37 eutectic and the Pb-free showed significantly longer cleaning cycles as the flux aged. Both fluxes tested show a 10X increase in the time required to fully penetrate the test slide at 4-hours versus cleaning directly following reflow. The higher temperature reflow Pb-free flux averaged nearly 300 seconds to penetrate an 875 mil distance from entry to exit after a 4-hour wait. The large delta change from 1 hour to 4 hours suggests that this trend would continue beyond 4 hours. The rapid deterioration in cleanability suggests Pb-free cleaning will be very sensitive to this parameter. This sensitivity will be much greater than existing 63/37 fluxes. The good news is that this data also suggest that exposed flux with thicknesses less than 5 mils should clean-up even after a 4 hour wait. Trapped flux residue could be a problem.

Graph #1: Cleaning rates for several reflow to cleaning wait times for no-clean eutectic tin-lead flux (210ºC peak)



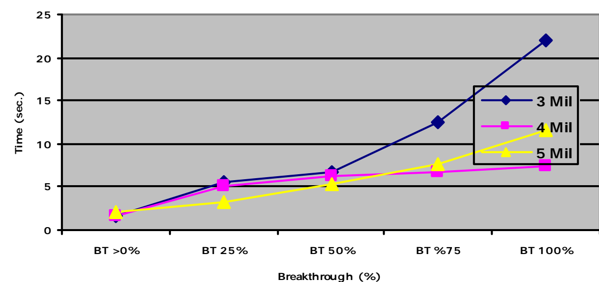
Graph #2: Cleaning rates for several reflow to cleaning wait times for Pb-free flux (240ºC peak)



Standoff Height

As the gap from the board surface to the bottom of the die decrease, experience tells us that cleaning becomes more difficult. Graph 3 illustrates the breakthrough time on freshly reflowed T-20 eutectic tin-lead reflowed substrates under 3, 4, & 5 mil standoffs. Breakthrough was 22 seconds for the 3 mil gap, 7 seconds for the 4 mil gap and 12 seconds for the 5 mil gap. The longer time to achieve breakthrough from the 3 mil gap is consistent with expectation. Breakthrough from the 5 mil gap took longer than for the 4 mil gap, which does not correlate with expectations. The flux buildup on the outside of the die may have contributed to this anomaly.

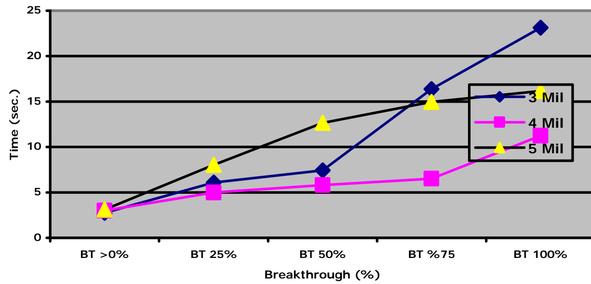
Graph 3: Breakthrough time for the T-20 eutectic tin-lead flux residue



Graph 4 illustrates the breakthrough time for the LF-300 on freshly reflowed LF-300 Pb-free reflowed substrates under

3, 4, & 5 mil standoffs. Breakthrough was 23 seconds for the 3 mil gap, 11.5 seconds for the 4 mil gap and 16 seconds for the 5 mil gap. The longer time to achieve breakthrough from the 3 mil gap is consistent with expectation. Breakthrough from the 5 mil gap took longer than for the 4 mil gap, which once again does not correlate with expectations.

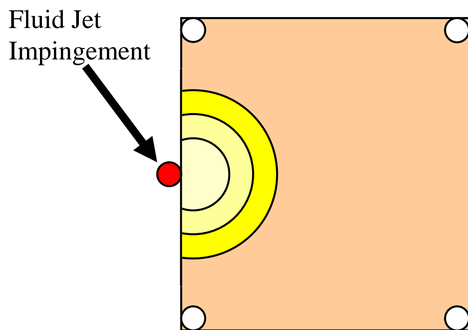
Graph 4: Breakthrough time for the LF-300 eutectic Pb-free flux residue



Observed Cleaning Mechanics

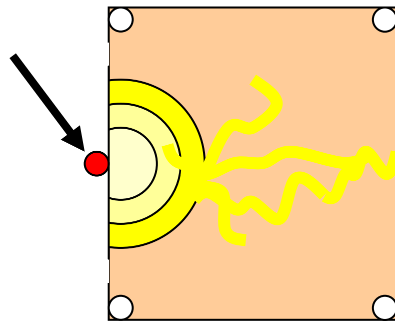
Once the cleaning fluid has broken through the outer “skin”, experiments reveal one of two possible mechanisms will predominate. The first and slower mechanism is based on the observed removal of flux residue in ever increasing diameters of material being cleaned primarily by dissolution to the flux in the cleaning solvent. Figure 5 illustrates the mechanism of “concentric” cleaning.

Figure 5: Concentric Cleaning



Concentric cleaning tended to be the observed mechanism on older samples ran at lower impingement pressures. Very little concentric cleaning was observed on samples cleaned less than one hour from reflow. Practically all samples tested eventually changed from concentric to channeling as the flux removal mechanism as illustrated in Figure #5. The rates measure for concentric dissolution cleaning averaged 10-50 mils/sec in heated 10% chemistry concentration at 10 psig impingement pressure for both fluxes tested in this study. Cleaning rates for channeling driven cleaning tend to be a least and order of magnitude higher than that of concentric driven flux removal.

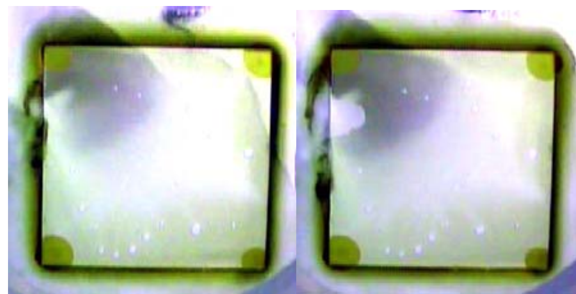
Figure 6: Concentric to Channeling



Cleaning by Channeling

A new and faster process referred to here after as “channeling” was also observed. Channeling is a process where cleaning fluid penetrates in rapidly developing channels inside the reflowed flux mass. These channels quickly interconnect and break through to the adjacent and opposite sides. Photo’s 1 through 6 shows the progression of a cleaning process dominated by channeling as illustrated in Figure #7.

Figure 7: Sequence of the Channeling Cleaning Process



#1 T= 1 Seconds #2 T = 2 Seconds

#3 T = 3 Seconds #4 T = 4 Seconds

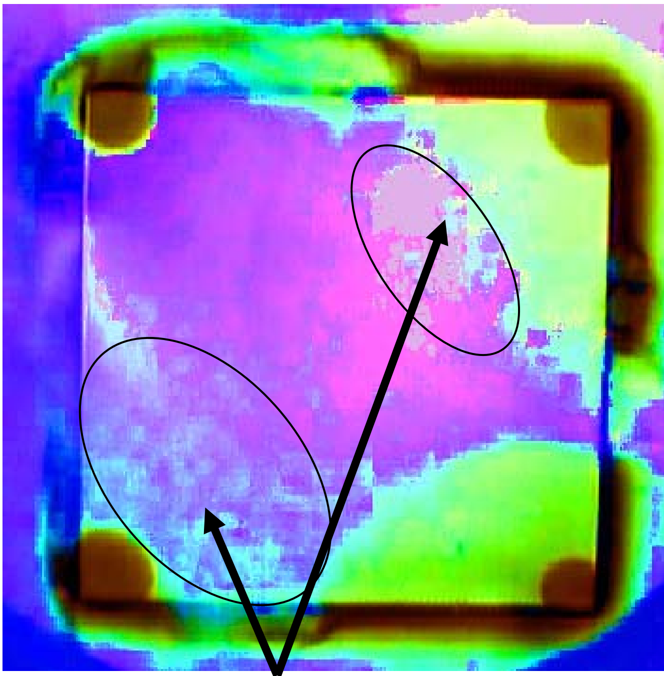
#5 T = 30 Seconds #6 T = 45 Seconds

These channels can form at relatively low impingement pressures if the flux matrix is soft, as can be the case with freshly reflowed flux residue. Test results indicate that both fluxes tested in this research paper required increased cleaning pressure to rapidly form these channels as the flux samples were aged a few hours.

In the one second photo the cleaning jet is beginning to remove the external flux in a concentric pattern of ever increasing diameters. In this photo the cleaning solvent has just began to penetrate under the slide. In the two second photo the concentric cleaning zone has expanded and there is evidence of rapid channeling beginning as the cleaning fluid reaches the softer interior region of the flux matrix. The three second photo shows the rapid expansion of the fluid channel as it follows the path of least resistance into the reflowed flux matrix.

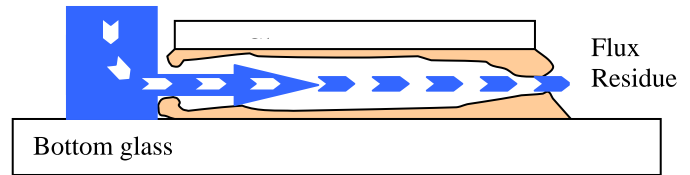
In the four second photo the cleaning fluid continues to expand and follow what appears to be a weak area created possibly by the flux solvent out gassing in the reflow heat cycle. This weaker path is apparent visually in first 3 slides. Slide #5 shows a fully developed flow pattern where the initial channels have interconnected and cleaning is occurring by dissolving the flux in the flow stream from the interior of the flux matrix to the glass surfaces bounding the flux. Figure 8 is a color enhanced version of photo #5 showing where the flux center is gone but flux remains on glass surfaces – actively being dissolved.

Figure 8: Color Enhanced Version of Photo from figure 7



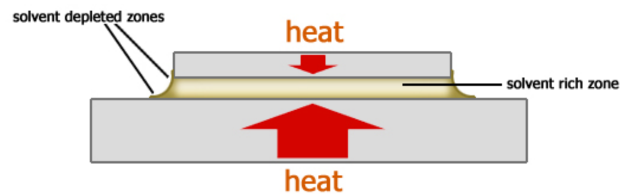
The drawing illustrated in Figure #9 is a cross section diagram of interim flux removal – note; center clears first, followed by glass surfaces. Flux residue remains around the perimeter of the die adjacent from the nozzle. Once breakthrough occurs, the cleaning solution dissolves the flux residue through the impinging forces pushing the fluids under and out of the cavity.

Figure 9: Cross-Section diagram of interim flux removal



The middle of the flux is softer and more easily breached by pressurized cleaning solvent because in the soldering process the heat drives the solvent molecules towards the center of the flux creating a solvent rich zone (Figure 10). This solvent rich zone is typically softer and more easily penetrated and dissolved. Conversely, a solvent depleted zone is created next to the heated and exposed surfaces. When a zone is solvent depleted it becomes harder and more crystalline and there by significantly more difficult for cleaning agents to soften or dissolve.

Figure 10: Creation of solvent rich/solvent depleted zones follow solder reflow heat cycle



Referring back to Figure #7, Photo #6 shows the flux nearing 100% removal. As expected, the last flux to be removed was the most distant from the impingement area. The rates measured for rapid channel dissolution cleaning averaged 150-250 mm/sec in heated 10% A4630 chemistry concentration at 10 psig impingement pressure.

Static Group Control Samples

To measure the static cleaning rate, the control assemblies were subjected to the cleaning process by flowing the A4630 cleaning solution over the die using low pressure. In the low pressure control groups, it was noted that the flux was not removed from underneath the glass surfaces (die) in the two minute time allocated, even though the visual data indicated full flow of cleaning fluid between the plates. The control groups are not included in the data tables since they did not clean completely in the ten minute cleaning test period allocated.

Visual inspection was conducted in both “white” light and in UV light. White light was used in the initial inspections. UV lighting was used to verify the presence of flux residue. Both fluxes fluoresced where as the A4630 cleaning solution and adhesive did not. Subsequent inspection of the glass surfaces under UV light revealed flux remaining on both surfaces. Figures 11 & 12 show areas where flux

remained on glass surfaces. This surface layer of flux was more rapidly cleaned in the high pressure runs.

Figure 11: UV inspection of low pressure coupon for remaining surface flux

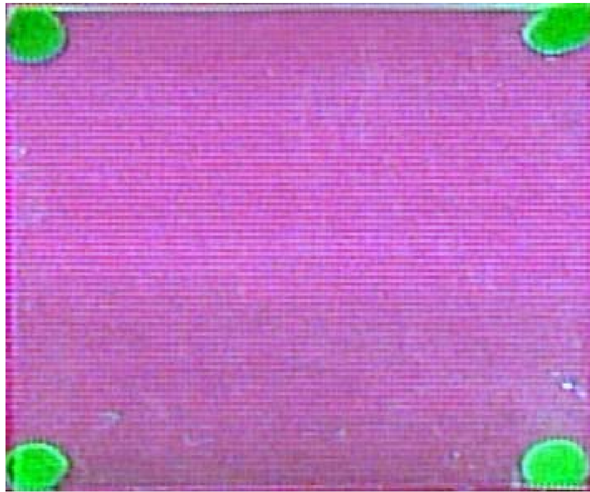
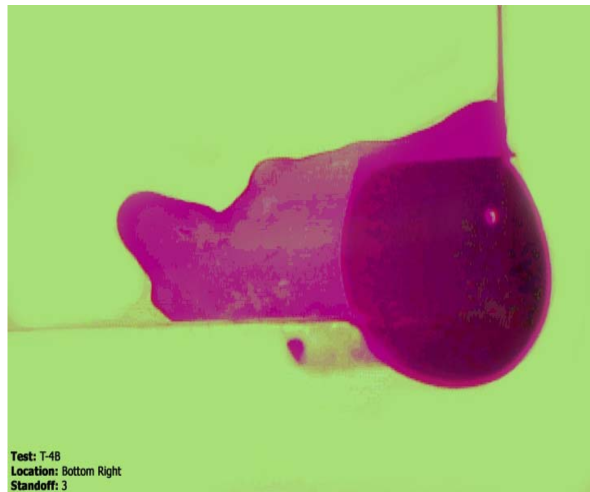


Figure 12: UV inspection of high pressure coupon for remaining surface flux



Observed Cleaning Rates

Cleaning rates varied significantly depending on the parameter being changed. The cleaning mechanisms change, and therefore the rates change depending on the nature of the flux residue. Theory and practical experience suggest the difficulty level increases as the gap gets smaller, the temperature of the cleaning solution goes down and time between solder reflow and cleaning increases. Test data in this study followed some expected and unexpected patterns.

Linear Propagation/Clean Rates

Linear cleaning propagation rates varied tremendously because the rapid and some what random direction of the channeling events. Measurements we made by determining the time it took for the first arrival of cleaning solvent to indicated quarter (see diagram 13)

Figure 13: Measurement of linear cleaning rate

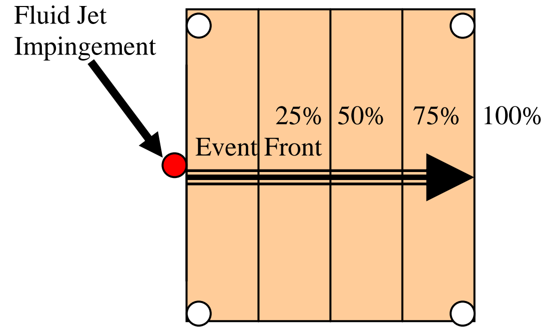


Table #1 Linear cleaning rates for T-20 no clean leaded flux (210 Cº peak) .875" X .875" area, 0.078"dia. coherent jet @ 15 psig impact, 10% concentration. Q1 equates to one hour from reflow, Q2 equates to 2 hours from reflow, Q3 equates to three hours from reflow and Q4 equates to fours hours from reflow.

Flux/profile temp	Gap mils	Wash Temp.	Clean rate mils/second*			
			Q1	Q2	Q3	Q4
T20/210ºC	3	120ºF	46	1877	180	922
	4	120ºF	71	230	246	216
	5	120ºF	158	2857	105	1132
	3	140ºF	91	154	42	43
	4	140ºF	65	168	4258	577
	5	140ºF	146	114	131	131
	3	120ºF	46	1877	180	922

*Higher number equates to a faster rate

Table #2 Linear cleaning rates for LF-300 lead free flux (240 Cº peak) .875" X .875" area @ 15 psig impact, 10% concentration.

Flux/profile temp	Gap mils	Wash Temp.	Clean rate mils/second*			
			Q1	Q2	Q3	Q4
LF300/240ºC	3	120ºF	252	2190	230	1288
	4	120ºF	5493	5525	5535	10956
	5	120ºF	126	1570	153	2765
	3	140ºF	55	148	1568	144
	4	140ºF	902	2296	2855	1602
	5	140ºF	419	544	5574	8340
	3	120ºF	252	2190	230	1288

Area Cleaning Rates

Another way to evaluate the cleaning rates is by area removed. Table 3 shows the time to remove 50% and 100% of the flux for the respective test coupon.

Table #3 Area cleaning rates for T-20 No-clean (210 Cº peak) and LF-300 lead free flux (240 Cº peak) to clean .875" X .875" area , 0.078"dia. coherent jet @ 15 psig impact, 10% concentration.

Flux/profile temp.	Gap	Wash	50% Clean	100% Clean
	mils	Temp.	Seconds	Seconds
T20/210ºC	3	120ºF	64	99
	4	120ºF	32	100
	5	120ºF	76	98
	3	140ºF	28	53
	4	140ºF	27	34
	5	140ºF	63	106
LF300/240 ºC	3	120ºF	48	115*
	4	120ºF	5	38
	5	120ºF	17	79*
	3	140ºF	43	117*
	4	140ºF	49	102
	5	140ºF	48	123*

*failed final inspection flux remains near corners

Area based rate measurements give a better "real world" look at the time one might expect if your component was similar to the test coupon.

Turn Up the Pressure?

Turing up the pressure does not necessarily help improve the cleaning rate. In fact, data in graph #3 indicates that there is an optimal impingement pressure for a given cleaning result. In this case, hardened, four hour old samples were cleaned at various pressures.

Results here indicate the higher pressure does not produce the best result. Reviewing the video record showed a possible reason the 5 psi jet yielded a better result. The 5 psi jet splashed much less than the 15 psi jet did. This resulted in a much more even spreading of the cleaning fluid on the glass surface. In the higher pressure jet the fluid tended to "bounce' off the surface.

The 3-dimentional aspects of a high pressure jet leaves less fluid mass on the board's surface spreading to clean areas adjacent to the impact area. Diagram 14 illustrates this point.

Graph #3: Illustrates the effects of jet bounce in Jets with too high pressure.

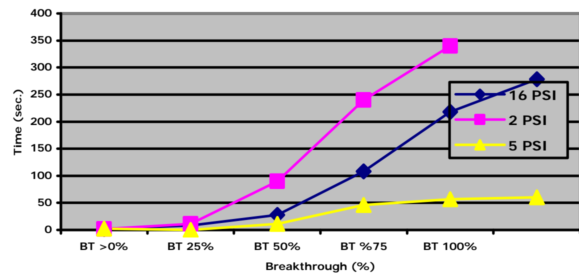
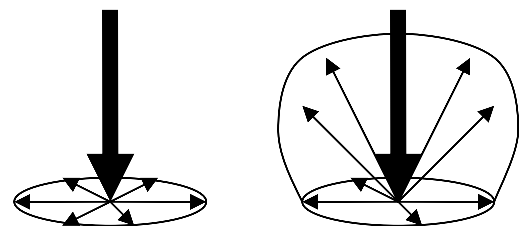


Figure 14: Observed effect of to high pressure jet spreading in 3-D pattern verses 2-D surface spread on lower pressure jet



Optimum pressure impact spreads 2-D

Too high a pressure impact spreads 3-D

Predicting Cleaning Rates

There are many variables to consider when attempting predicting the rate of cleaning. In addition to the process variables looked at in this study, many other factors such as material of construction, racking, adjacent components can influence the cleaning rate. Cleaning under a component inside a RF cage is different that cleaning that same component in an open area of the assembly.

Predicting the rate of cleaning really comes down to understanding how the material is being removed. The mechanism determines the rate. In this study we have observed 3 different and sometimes overlapping mechanisms. The rate of removal varies from static dissolving; the slowest representing a more moderate rate as contrasted with dynamic concentric cleaning representing a very active rate found with channeling.

Three Rates, Three Mechanisms

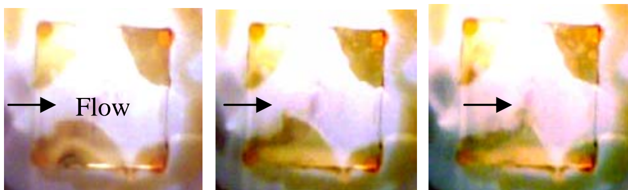
Static dissolution is the slowest of the observed mechanisms. Spot cleaning is the most often used type of cleaning by static dissolution found on the assembly line. This really works best on not too heated and thinly applied flux applications such as touchup or rework operations where flux residue remain soluble and therefore the rate

remains high. The removal of water soluble flux can also be largely solubility driven except in tight or dead end spaces.

Cleaning the test samples and fluxes described in this paper took days with no clear end point. This would correspond to a rate of only a few mils per hour.

Once spray energy is introduced, two new cleaning mechanisms with differing rates were found to exist. These mechanisms previously described as concentric cleaning and channeling cleaning are active processes where some flux is no doubt being dissolved, but the vast majority is being physically and chemically softened and being carried away by the cleaning agent. Figure 15 shows a relatively large mass of semi solid flux mass being swept away by the cleaning agent and the associated dynamic flow.

Figure 15: series showing semi solid flux being removed by cleaning agent flow dynamics



Smaller versions of this layer shedding occur in concentric cleaning where successive layers of flux are first softened and then stripped away. This resembled peeling an onion from the inside out, thus the origin of our pet name for this process "the reverse onion peel".

Figure 16: example concentric cleaning by progressive layer removal

Rapid large scale events such as those shown in fig. 15 peeling rates of 250 mils/second at 15 psig impingement pressure. Typical rates for concentric cleaning averaged 25 to 50 mils/second range (shown in Fig. 16).

Figure 17: This series show the rapid progression of channeling flow cleaning mechanism

Channeling yield the fastest cleaning rates. Brief rates of over 5000 mils per second were measured on some of the samples tested in this study. Channels formed in bursts which resembled small lighting bolts jumping across the sample. Once these smaller bursts break out, they quickly widen into flow channels that clear by concentric cleaning rate mentioned above.

In summary there are three rate mechanisms that govern the rate of flux dissolution.

1. Static dissolution
2. Concentric stripping
3. Channeling

Calculating Linear Cleaning Times

Going back to equation #3 we can now describe a new improved equation to include the two newly discovered cleaning mechanisms.

Equation 3:
Time to clean = $\mathbf{T_{Br}} + (D_{Fmax}/(\mathbf{R_s} + \mathbf{R_d}))$

Becomes

Equation 4:
Time to clean (using linear rate) = $\mathbf{T_L}$
$= \mathbf{T_{Br}} + (D_{Fmax}/(\mathbf{R_s} + (\mathbf{R_{ch}} * \% \mathbf{T_{ch}}) + \mathbf{R_{co}}))$

Where;
Time to clean the area = $\mathbf{T_A}$
Distance of flux to be cleaned = $\mathbf{D}_{Fmax}$
Time to breakthrough = $\mathbf{T_{Br}}$
Static cleaning rate = $\mathbf{R_s}$
Dynamic channeling cleaning rate = $\mathbf{R_{ch}}$
Dynamic concentric cleaning rate = $\mathbf{R_{co}}$
Fractional % of time were channeling occurs = $\mathbf{T_{ch}}$

The channeling component of the equation is attenuated by the decimal fraction of the time where channeling predominates divided by the total active time to clean. The active time to clean is the time in the process following but not including $\mathbf{T_{Br}}$. The $\mathbf{R_s}$ and $\mathbf{R_{co}}$ terms are not multiplied by this factor as these mechanisms occurs continuous throughout the active cleaning process.

Using the data obtained from a fresh rapidly cleaned sample, static rate=1mil/sec, concentric rate = 50mil/sec, and the momentary channeling of 1000 mil/sec for 10% of the active cleaning time, the calculation resulting from equation #4 would look like:

T=1s + (875mil/(1mil/s. +(1000mil/s.*0.1)+50mil/s)
=1s + (875mil/151mil/s)
=1s. + 5.8s
=6.8 seconds to clean .through 0.875" of solid flux residue in four mil gap

Harder to clean sample look like this,

Break through time ($\mathbf{T_{Br}}$) = 10sec
Static rate ($\mathbf{R_s}$) =1mil/sec
Concentric rate ($\mathbf{R_{co}}$) = 20mil/sec
Momentary channeling ($\mathbf{R_{ch}}$) of 500 mil/sec
Percentage of time where channeling dominates = 1%

TL=10s + (875mil/(1m/s+(500mil/s*0.01)+10mil/s
=10s + (875mil/16mil/s)
=10s + 54.7s
=64.8 seconds to clean to .875" deep in the flux matrix.

Calculating Area or Volume Cleaning Times

Area or volume cleaning rates can be estimated in a similar calculation by substituting the area cleaning rate information for the linear rates. This gives rise to equation #5 for an area calculation and equation 6 for a volume calculation.

Equation 5:
Time to clean area (using area cleaning rates) = $\mathbf{T_A}$
$=\mathbf{T_{Br}} + (\mathbf{A}_{Fmax} / (\mathbf{R_s} + (\mathbf{R_{ch}} * \%\mathbf{T_{ch}}) + \mathbf{R_{co}}))$

Equation 6:
Time to clean volume (using volumetric cleaning rates) = $\mathbf{T_v}$
$=\mathbf{T_{Br}} + (\mathbf{V}_{Fmax} / (\mathbf{R_s} + (\mathbf{R_{ch}} * \%\mathbf{T_{ch}}) + \mathbf{R_{co}}))$

Where;
Time to clean the area or volume = $\mathbf{T_A}$ or $\mathbf{T_v}$
Area or volume of flux to be cleaned = $\mathbf{A}_{Fmax}$ or $\mathbf{A_{Vmax}}$
Time to breakthrough = $\mathbf{T_{Br}}$
Area or volumetric static cleaning rate = $\mathbf{R_s}$
Area or volumetric dynamic channeling cleaning rate = $\mathbf{R_{ch}}$
Area or volumetric dynamic concentric cleaning rate = $\mathbf{R_{co}}$
Fractional % of time were channeling occurs = $\mathbf{T_{ch}}$

Using typical volumetric rate data taken in this study, a volumetric calculation would look like this using equation #6
Area to be cleaned $\mathbf{A}_{Fmax}$= 3,062,500 mil^3
Break through time($\mathbf{T_{Br}}$) = 3sec
Average static rate ($\mathbf{R_s}$) =2000mil^3/sec
Concentric rate ($\mathbf{R_{co}}$) = 50,000mil^3/sec
Momentary channeling ($\mathbf{R_{ch}}$)of 2,000,000 mil^3/sec
Percentage of time where channeling dominates = 1%

TL=3s + (3,062,500mil^3/ (2000mil^3/sec + (2,000,000 mil^3/sec *0.01)+ 50,000mil^3/sec)
=3s + (3,062,500mil^3/77,000mil^3/sec))
=3s + 42.5s
=45.5 seconds to clean to .875" X .875" X .004" gap of solid flux matrix.

These rate equations require empirical data to be taken for each flux type in normal to worst case process time/temperature ageing. Using data taken with the "CARL" unit described in this paper should provide a good basis to predict cleaning times in differing geometries.

New Process Tools for "Lead-Free"
The process information provided "CARL" unit provides useful information in screening lead-free materials and controlling the lead-free soldering/cleaning process.

Cleaning Difficulty Factor
Two potentially important parameters can the taken from this the methods described in this paper. The relative difficulty to clean the flux residue with any given process can be expressed as the average process cleaning rate ($\mathbf{R_p}$) over some standard time, say the first minute. Once the process has been identified, i.e. the machine pressures, the solvent system, temperature and concentration, different fluxes/cleaning parameters can easily be compared.

Equation #6
Flux Difficulty Factor (FDF) = $\mathbf{R_{p1st\ minute}} =$
$\mathbf{R_{s1st\ minute}} + (\mathbf{R_{ch1st\ minute}} * \%\mathbf{T_{ch1st\ minute}}) + \mathbf{R_{co1st\ minute}}$

Flux Aging Factor
The change in rate of cleaning as the flux ages between reflow and clean is an important process parameter. This indicates how much more difficult a given flux is to clean as time passes.

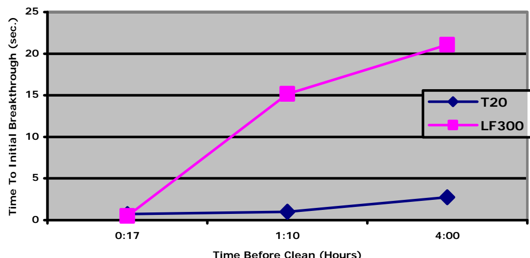
Flux ages by loosing original solvents added to allow processing, as previously covered in this paper. Re-solvation of the flux matrix to soften or dissolve the residue takes more time as the flux ages, especially the lead-free. If not allowed for in the process qualification and process controls, this can result in cleaning and/or product reliability problems.

A screening tool is required to understand and optimize the Flux Ageing Factor (FAF). A simple way to gauge the FAF would be to measure the process rate at one time (R_{T1}), and compare it to a measured rate (R_{T2}), at some future time. The ratio of rates would be the FAF as shown in equation #7.

Equation #7 **BOLD EQUATION**
Flux Aging Factor (FAF) = R_{T2}/ R_{T1}

Production aging factors should have rates measured at the extremes of the process time window, say initial rate and the four hour rate. Rework FAF's should be calculated with rates equal to the maximum rework time cycle. This could be an extremely long cycle when field rework/repairs are considered.

Graph #4 shows the difference between FAF's for the "leaded" and "lead free" fluxes tested in this study.



The ingredients in flux comprise resins, activators, solvents, and rheological additives. The alloys used for eutectic tin-lead and Pb-free 305 are identical for a wide range of products offered to industry. The differentiator amongst the products offered comprises the flux formulation. Depending on the flux formulation used for a specific solder paste, each will have its own unique aging factor. Understanding the aging characteristics of each flux (FAF) in a process is essential to controlling the output quality of any flux cleaning process.

CONCLUSIONS AND RECOMMENDATIONS

Analysis of the video imaging data indicates that the physical process of cleaning is a multi-step process governed by several critical parameters. Experiments showed that the time required to breakthrough and begin cleaning the flux is dependent on the wait time between reflow and cleaning. The implications of this measurable delay in initiating the cleaning process can have a profound effect on cleaning efficiency. This breakthrough observation helps explain the hypothesis that some fluxes get harder to clean with the passage of time.

Reflowed flux residue contains high molecular weight resin molecules surrounded by smaller solvent molecules. Areas of a circuit board that receive higher heat gradients drive off the solvent molecules, which results in residue that is harder to clean. The data suggests that the time from reflow to clean increases cleaning difficulty with the passage of time, due to degassing of the solvent molecules from the body of the flux residue. This explains why Pb-free, which is reflowed at 30-40ºC higher than eutectic tin-lead, rapidly increases in difficulty with the passage of time. Additionally, the data suggests that the middle of the flux is softer and more easily breached by pressurized cleaning.

The study revealed two possible cleaning mechanisms based on concentric and channeling. Concentric cleaning is a slower mechanism based on removal of flux residue in ever increasing diameters similar to peeling an onion. Concentric cleaning tended to be the observed mechanism on older samples ran at lower impingement pressures. Channeling is a process where cleaning fluid penetrates in rapidly developing channels inside the reflowed flux mass. These channels quickly interconnect and break through to the adjacent and opposite sides. Once breakthrough is achieved, cleaning occurs by dissolving the flux in the flow stream through impinging forces pushing the cleaning fluid under and out of the cavity.

Cleaning rates varied depending on the parameter being changed. Theory and practical experience suggest the difficulty level increases as the gap gets smaller, the temperature of the cleaning solution goes down, and time between solder reflow and cleaning increases. Test data in this study pointed to expected and unexpected patterns. Linear cleaning propagation varied due to the rapid and random direction of the channeling events. Turning up the pressure did not always improve the cleaning rate. Too high pressures tended to bounce off the surface whereas an optimized coherent jets pressure at the surface of the part resulted in more even spreading of the cleaning fluid under the component.

Predicting the rate cleaning comes down to understanding that the cleaning mechanism determines the rate. Static dissolution, the slowest of the observed mechanisms, is not effective for cleaning low standoff components. Harden flux residues points to the concentric mechanism that tunnels the flux out from under the component, which relies on time. When channeling occurs, there is a rapid propagation with a rapid lightening burst in very little time. The two newly discovered cleaning mechanisms allow the researchers to develop equations for determining the linear cleaning time, area of volume cleaning time, and flux difficulty factor.

Follow on Research

Due to the wide range of variables associated with cleaning, there is no shortage of researched needed in the area. The impingement source used for the studies, within this body of research, was the coherent nozzle technology. Follow on research of the nozzle design and manifold configuration is needed. This study suggests that too high spray pressures are just as bad as very low spray pressure. It would be interesting to know the correlation between fan, conical, and coherent nozzle design.

Practical experience supports the theory that pre-washing (soaking) the board with the wash solution raises the heat of the part and improves cleaning efficiency in the high pressure wash zones. Follow on study is needed to correlate the rate of cleaning when using a prewash prior to wash impingement.

This study evaluated an industry standard eutectic flux vehicle (Indium SMQ 92J) and Pb-free flux vehicle (Multicore LF-300). Test data suggests that flux formulations clean at different rates. This has to do with solvent degassing discussed in this paper and the materials of construction used to formulate the flux. Follow on study

is needed on a wider range of flux materials. The data from this research supports a new theory called Cleaning Delay Theory. Does this theory hold true for different flux types?

The cleaning chemistry (Aquanox A4630) used in the study exhibits a high static cleaning rate. Follow on study is needed on other industry standard cleaning materials to test the linear, area, and volume cleaning times.

The test vehicle used in this study had no solder bumps under the die. Follow on study is needed using test vehicles that are populated with solder bumps on both BGA and Flip Chip designs.

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