Optimizing cleaning energy with spray in air systems - pt 2 of 2

Part 2 of the article presented in *Global SMT & Packaging issue 5.10*. 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.

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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' and 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.

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.

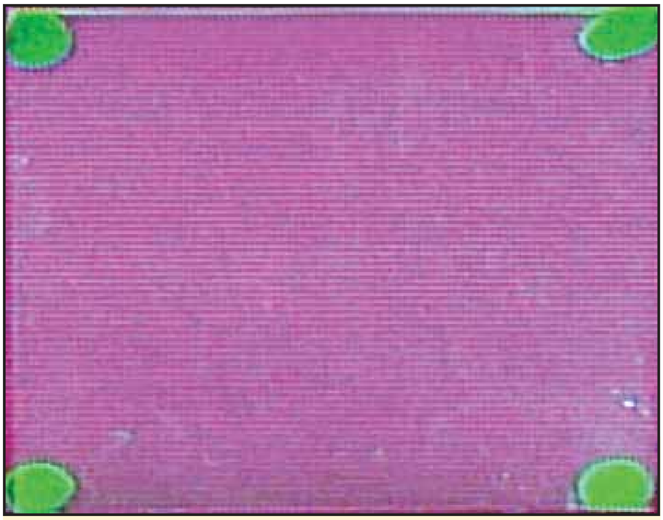


Figure 11. UV inspection of low pressure coupon for remaining surface flux.

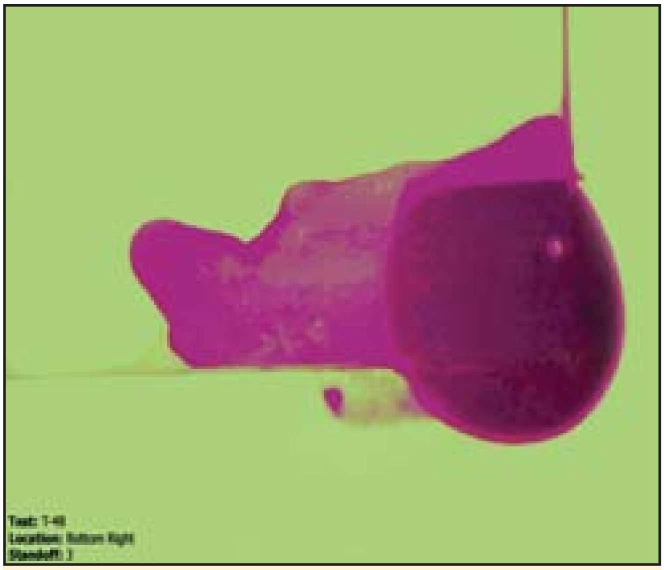


Figure 12. UV inspection of high pressure coupon for remaining surface flux.

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.

Table 1. Linear cleaning rates for T-20 no clean leaded flux (210 C° 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
T20/210°C	3	120°F	46	1877	180	922
	4	120°F	71	230	246	216
	5	120°F	158	2857	105	1132
	3	140°F	91	154	42	43
	4	140°F	65	168	4258	577
	5	140°F	146	114	131	131
	3	120°F	46	1877	180	922

*Higher number equates to a faster rate

Table 2. Linear cleaning rates for LF-300 lead free flux (240 C° 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
LF300/240°C	3	120°F	252	2190	230	1288
	4	120°F	5493	5525	5535	10956
	5	120°F	126	1570	153	2765
	3	140°F	55	148	1568	144
	4	140°F	902	2296	2855	1602
	5	140°F	419	544	5574	8340
	3	120°F	252	2190	230	1288

*Higher number equates to a faster rate

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

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

*failed final inspection flux remains near corners

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 Figure 13)*.

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.

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?

Turning up the pressure does not necessarily help improve the cleaning rate. In fact, data in *Graph 5* 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. *Figure 14* illustrates this point.

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 than 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 three 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

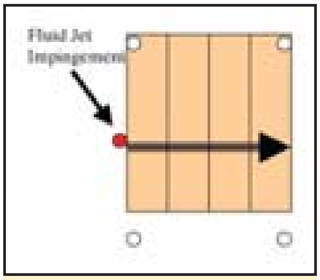


Figure 13. Measurement of linear cleaning rate.

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.

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'.

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

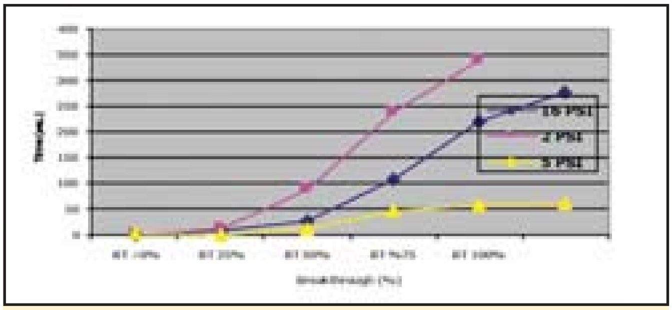
Channeling yield the fastest cleaning rates. Brief rates of over 5000 mils per second were measured on some of the samples tested in this study. Channels formed in bursts which resembled small lighting bolts jumping across the sample. Once these smaller bursts break out, they quickly widen into flow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



Graph 5. Illustrates the effects of jet bounce in Jets with too high pressure.

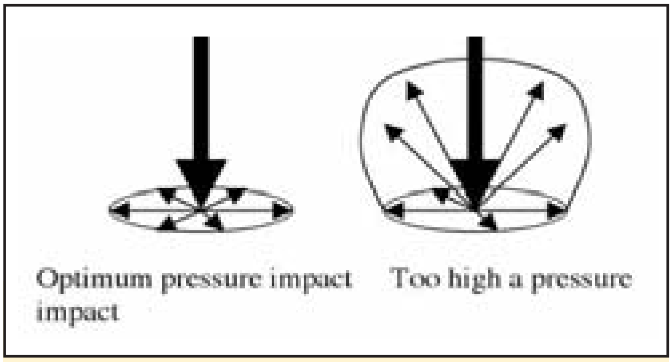


Figure 14. Observed effect of to high pressure jet spreading in 3-D pattern verses 2-D surface spread on lower pressure jet.

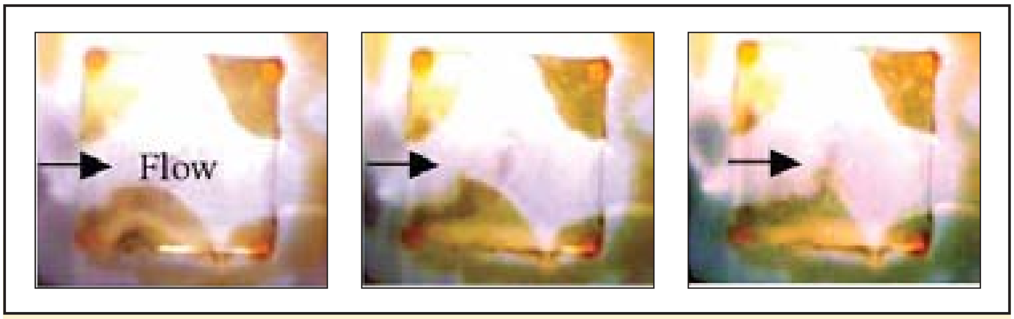


Figure 17. This series show the rapid progression of channeling flow cleaning mechanism

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

Becomes

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

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

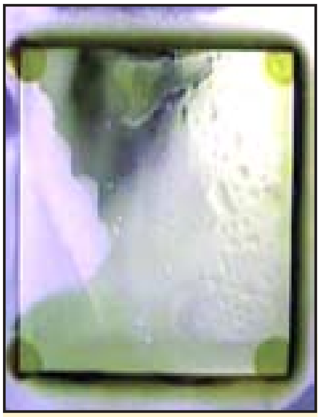


Figure 16. example concentric cleaning by progressive layer removal.

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

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 T_{Br}. The R_s and 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 looks like this,

Breakthrough time (T_{Br}) = 10sec
Static rate (R_s) =1mil/sec
Concentric rate (R_{co}) = 20mil/sec
Momentary channeling (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 0.875” 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.

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.

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

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

Where:
Time to clean the area or volume = T_A or T_v
Area or volume of flux to be cleaned = A_{Fmax} or A_{Vmax}
Time to breakthrough = T_{Br}
Area or volumetric static cleaning rate = R_s
Area or volumetric dynamic channeling cleaning rate = R_{ch}
Area or volumetric dynamic concentric cleaning rate = R_{co}
Fractional % of time were channeling occurs = 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 A_{Fmax}= 3,062,500 mil3
Break through time(T_{Br}) = 3sec
Average static rate (R_s) =2000mil3/sec
Concentric rate (R_{co}) = 50,000mil3/sec
Momentary channeling (R_{ch})of 2,000,000 mil3/sec
Percentage of time where channeling dominates = 1%

TL=3s + (3,062,500mil3/ (2000mil3/sec + (2,000,000 mil3/sec *0.01)+ 50,000mil3/sec)
=3s + (3,062,500mil3/77,000mil3/sec))
=3s + 42.5s
=45.5 seconds to clean to .875” X .875” X .004” gap of solid flux matrix.

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 (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) = $R_{p1st\ minute}$ =
$R_{s1st\ minute}$ + ($R_{ch1st\ minute}$ *%$T_{ch1st\ minute}$) + $R_{co1st\ minute}$

Flux aging factor

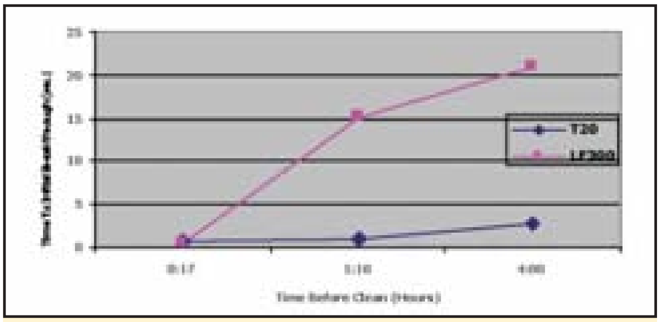
The change in rate of cleaning as the flux ages between reflow and clean is an important process parameter. This indicates how much more difficult a given flux is to clean as time passes.

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 (RT1), and compare it to a measured rate (RT2), at some future time. The ratio of rates would be the FAF as shown in *Equation 7*.

Equation 7:

$$\text{Flux Aging Factor (FAF)} = R_{T2}/R_{T1}$$



Graph 6. shows the difference between FAFs for the lead and lead-free fluxes tested in this study.

Production aging factors should have rates measured at the extremes of the process time window, say initial rate and the four hour rate. Rework FAFs 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.

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 jet 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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