# Cleaning for Reliability

**By Mike Bixenman, Kyzen Corporation and Michael Konrad, Aqueous Technologies**

**Mike Konrad**
**President / CEO**

The leading manufacturer of cleaning and cleanliness testing products.

## Cleaning for Reliability Post QFN Rework

*Mike Bixenman, Kyzen Corporation and Michael Konrad, Aqueous Technologies Corporation make an argument for removing flux residue under the quad flat pack no lead (QFN) post-rework, and present cleaning process options for meeting this cleaning challenge. The need for cleanliness under individual components increases as the spacing between connector leads decreases and power increases. The low stand-off height of QFNs traps flux between the ground pad and component leads. Flux trapped under the QFN is a reliability concern. The purpose of this research is to develop process knowledge for cleaning all flux residues from under the QFN device. The authors, representing cleaning material and equipment organizations, investigated process variables such as solder paste, cleaning agents, cleaning equipment, and wash process factors.*

While this article addresses the complexities of removing flux under QFN devices, the information presented may be applied to all post-reflow defluxing applications. There are rapidly growing quantities of surface mount components that are mounted very close to the printed circuit board (PCB). Most surface mount assemblies feature fine-pitch components. Board and component miniaturization challenge conventional defluxing equipment and chemistries. The same successful defluxing methods outlined in this article may be applied generally to all defluxing applications.

When reworking electronic assemblies, assemblers must have the assurance that the product will work for its designed life expectancy. Flux residue under QFN components can impact performance when conductive ions migrate within the electrical field.1 Moisture, in the form of humidity, creates an electrolyte where flux residue remaining under the QFN is propagated as conductive ions. The total current density entering and leaving the electrolyte causes metal ions to split and form dendrites. This spatial coupling depends on the distance between the conductors, with closer solder connections coupled more strongly. As the difference in potential across the conductors rises, the risk of failure increases.

QFNs are placed flush onto the printed circuit assembly. These components are difficult to clean due to size, spacing, and low standoff height.2 The standoff clearance under QFNs is defined by the solder paste print — typically less than 4 mils high. Compounding the problem, smaller components and organic solder protected (OSP) circuit boards use solder mask defined on bare copper, which further reduces the spacing under the QFN to less than 2 mils.

**Reworking QFN Components**

QFN rework is typically a low-volume operation with limited options for cleaning flux


**Aqueous Technologies**
9055 Rancho Park Court
Rancho Cucamonga, CA
91730

**Phone**
(909) 944-7771

**Fax**
(909) 944-7775

**E-mail**
sales@aqueoustech.com

**We're on the Web!**
*See us at:*
www.aqueoustech.com

residues post-soldering. The common cleaning equipment used for rework operations is the dishwasher-style aqueous spray-in-air machine. Engineered cleaning materials are needed to dissolve flux residues left from rework and repair. Process factors must be understood to successfully clean all flux residues under the QFN.

The conceptual framework for this research provides insight into the problem of cleaning flux residues post QFN rework. The quantitative paradigm inquires into the problem of cleaning all flux residues under the QFN component based on hypothesis testing composed of variables, measured visually, and analyzed to determine best cleaning practice. This research quantifies the relationship between flux type, cleaning time, and QFN standoff heights. The goal is to provide the rework technician with a process menu that is predictive, repeatable, and confirms cleaning efficacy.

The best practices discussion for designing the QFN cleaning process using the batch dishwasher-style cleaning machine includes an overview of the science of aqueous-engineered cleaning fluids used to remove a broad range of flux residue types used in QFN rework. The experiment illustrates the relationship between research hypotheses and the variables tested. A Practical Components rework test card was used to confirm the research findings.

**The Reliability Problem**

Highly dense and smaller component features increase rework complexity as termination pads and standoff heights decrease. Miniaturization imposes a great challenge on the chemistry of fluxes creating higher levels of flux oxides.3 Additionally, as QFNs decrease in size, the component and conductor spacing generate more heat during soldering, which increases the cleaning challenge.4

Notwithstanding flux changes, the QFN standoff height is considered to be the critical cleaning differentiator. To address this problem, technicians use shims, which can be placed onto the ground pad to elevate the QFN to a standoff height of 4–6 mils.2 Increasing standoff height significantly improves cleaning results. The problem with this method is the solder joint has to form a bridge between the distance of the QFN and the pad. Another method is to plate the QFN pads up another 4 or 5 mils to increase the standoff height, but this is not practical for rework operations.

The electronic assembly industry is facing numerous changes — RoHS, miniaturization — that create new soldering demands. The chemical changes in flux materials and soldering temperatures can complicate cleaning. For QFN rework, a flux that provides thermal stability and forms a soft residue that readily dissolves into the cleaning agent is critically important.

**Cleaning Agent**

Electronic assemblies are evolving, demanding innovations to satisfy these changing customer needs. PCB manufacturers continue to deal with density and miniaturization challenges. Electronic assembly cleaning agents must improve solubility for a wide range of flux compositions; wetting properties for penetrating low-standoff gaps; and materials compatibility to prevent damage to circuit board laminates, components, packages, and connectors.

Aqueous-engineered cleaning materials are keeping pace with this electronic assembly roadmap. The best aqueous cleaning agents are derived from the laws of thermodynamics. Engineered cleaning agent building blocks use a combination of dispersive, polarity, and hydrogen boding energies. The first design criterion is to engineer solvating blend combinations that show a high affinity for varied flux residue soils. A mix of polar materials with permanent dipole moments will rapidly interact with and soften rosin/resin structures. The unique combination of ingredients must form an electron exchange with water to bond molecules and ions into a cohesive and stable composition.

A combination of thermodynamic (chemical) and kinetic (energy) forces is needed to clean residues under the QFN component. Aqueous cleaning agents are designed to be diluted with water and operate at an optimal concentration range from 12 to 15%. Kinetic energy — heat, fluid flow, motion (spray impingement), and directional forces — delivers the cleaning agent to the electronic assembly. The thermodynamic energies require the right combination of ingredients working in unison to wet, dissolve, and bond flux residues, cleaning the circuit assembly. Optimizing the thermodynamic and kinetic energies requires specific cleaning agents designed to operate in specific cleaning equipment.

Materials compatibility is a critical factor that must not be overlooked. Electronic assemblies expose the cleaning agent to wide range of metal alloys, board laminates, plastics, polymers, and coatings (inks). Denser and more miniaturized electronic assemblies drive many cleaning agents to contain more reactive ingredients, attempting to improve cleaning efficacy. Highly reactive cleaning agents oxidize and reduce metal alloys; attack some board laminates; and attack plastics, polymers, and coatings. These highly interactive reactive cleaning agent properties can improve cleaning performance, but with material compatibility issues. Cleaning agents engineered with high Van der Waals dispersive and low reactive forces avoid these issues. When formulating with low reactive forces, minor ingredients are highly effective and work to protect the assembly from materials compatibility concerns. An added benefit is the ability to increase kinetic forces in the form of time and energy without damaging the assembly.

**Rework Cleaning Machine**

In past decades, vapor degreasers running CFC-based solvents such as Freon TMS or 111 Trichloroethene were the cleaning method of choice. The workload between solvent and machine was unevenly divided. The solvent fulfilled dual roles as a solublizing agent and as a delivery device. This was due to the fact that vapor degreasers utilized an immersion process.

The equipment was only responsible for containment, solvent distillation, and heat, the latter being the most critical of the equipment's process steps.

While solvent-based immersion defluxing systems still exist, they lack popularity due to cleanliness capabilities, environmental concerns, and other factors. Modern, effective cleaning processes use aqueous-based chemistries in aqueous defluxing equipment.

The technological differences between the vapor degreasers of yesterday and conventional aqueous defluxing systems are vast. While vapor degreasing equipment relied on the chemistry to do most of the work, the pendulum has swung the other way today. The best modern cleaning chemistries will produce vastly different cleanliness results when used in different equipment designs. A successful defluxing process requires a proper marriage between chemical and equipment. No longer is mere contact between the defluxing chemistry and the target the sole requirement of a successful defluxing process.

While modern defluxing chemistries require contact between the chemical and the target, there is much more to the process than that. There are fourteen fundamental elements across four specific design criteria to an effective defluxing machine (Table 1).

**Table 1**

| | Wash cycle (heat) | Rinse cycle | Dry | General equipment |
|---|---|---|---|---|
| **Design elements** | Contact, spray design, segregation of wash solution, chemical dosing. | Contact, spray design, ionic contamination (IC) detection. | CFM, convection heater power, radiant heater power. | Chemical compatibility, operator safety, environmental safety, process control. |

*Wash cycle (heat).* Effective aqueous chemistries require heat. If operated unheated, disastrous results, including poor cleanliness and extreme foaming, can occur. Most cleaning chemicals produce optimum results when operated at temperatures between 50° and 70°C. The defluxing machine must be capable of heating and maintaining the wash solution to these temperatures.

*Wash cycle (contact).* No defluxing chemistry can ever remove flux if it doesn't come into contact with the assembly. Modern surface mount assemblies feature complex geometries.

Large and small components may be mounted in close proximity to each other, allowing one component to shadow another.

In the industry's most popular cleaning equipment format (batch), shadowing is of particular concern, as assemblies are stacked much like dishes in a dishwasher. While batch defluxing machines use upper and lower rotating spay bars that produce thousands of possible angles of attack, shadowing is still potentially a problem. This can be mitigated with the implementation of an oscillating device that moves the assemblies in a forward/rearward motion simultaneous to the spray-arm rotation. The rack oscillating device increases contact by reducing the possibility of shadowing.

*Wash cycle (spray design).* There are two competing theories when it comes to fluid diffusion. All cleaning begins with contact: contact between the cleaning fluid and the cleaning target. Even though a defluxing machine may be equipped with rotating spray arms and even a rack oscillating device, at the core is the fluid delivery device. Some equipment designs utilize spray nozzles; others do not. The purpose of a spray nozzle is to bend the fluid to a shape that best fits the target, much like placing your thumb over the end of a hose to increase the fluid's diffusion pattern. This action forces fluid through a smaller hole, increasing its velocity and therefore its impact pressure while reducing the water drop size and associated surface tension.

Nozzle-less defluxing machines simply utilize a hole with a specified diameter to produce a coherent stream of fluid with no diffusion. The advantage of a coherent spray is that the flow can travel farther before losing velocity, since coherent fluid flows produce larger fluid drop sizes.

The debate between nozzle-based and coherent-based fluid delivery designs is based on indisputable factors. The more water is bent, the faster it loses its impact pressure. On the other hand, nozzles produce smaller droplet sizes, aiding in under-component penetration, or impingement, which is among the most critical elements in a successful defluxing process. Nozzles, by widening the fluid's trajectory, ensure full (and even overlapping) contact with the target assemblies.

Coherent fluid distribution maintains fluid velocity for a longer distance, but produces the largest fluid droplet size, impeding its ability to penetrate under low standoff components. In addition, coherent spray patterns do not overlap. Thorough assembly coverage is only possible if the fluid hitting the assembly ricocheted in a manner to allow thorough coverage. It should be noted that when the fluid changes direction (like with ricochets), it loses the majority of its velocity, and rapidly becomes ineffective.

*Wash cycle (segregation of wash solution).* Most modern defluxing chemicals are prepared as concentrates, then mixed with water (normally deionized water) to form wash solution. Common in-use percentages are 10–20% concentrated defluxing chemistry. Most modern defluxing chemistries provide a relatively wide process window. Commonly, ±5% concentration or dilution still produces acceptable cleanliness results. Due to increased environmental sensitivities and budgets, many defluxing equipments now incorporate wash solution recyclers. The same chemical/water mixture may be used dozens of times over the course of days or weeks. Because of this, it is vital that the defluxing machine have safeguards to prevent dilution of the wash solution with rinse water.

Design elements such as segregated spray and drain/transfer pumps reduce the chance of chemical dilution. Anti-dragout features such as programmable rest (drainage) times and self-purging wash pumps also help. A highly effective drying system will also prevent chemical dilution by eliminating any residual rinse water from mixing with the upcoming cycle's wash solution.

*Wash cycle (chemical dosing).* Many failures in a defluxing process are caused by inaccurate chemical mixing, usually by equipment operators. A well-designed automatic chemical dosing technology combined with periodic monitoring (via titration or refractometer) will provide consist and accurate chemical concentrations without the need for operator intervention. This reduces operator errors and ensures that the process stays within required guidelines.

*Rinse cycle (contact).* Like the wash cycle, contact between water (the rinsing agent) and the assemblies is required. Because most batch defluxing systems have one chamber for all cycles (wash, rinse, and dry), the spray technology used in the wash cycle will be used in the rinse cycle. All required design attributes associated with the wash section (contact and spray design) are identical.

*Rinse cycle (spray design).* While both contact and spray designs are identical between wash and rinse cycles, the most critical aspect of a successful defluxing process is the rinse cycle. While most attention goes to the wash cycle, cleanliness results would be catastrophically worse if the rinse cycle were not performed properly. While conventional aqueous defluxing chemicals perform substantially better than their obsolete solvent counterparts, they cannot be left on an assembly. Most modern defluxing chemistries maintain a pH level in excess of 11. While anti-corrosion (brightening) agents prevent dulling of the solder joints during the wash cycle, the defluxing chemical must be thoroughly removed.

After the wash cycle, assemblies are covered in wash solution, above and below the components. A thorough rinsing process should remove all traces of wash solution. Because the wash chemical reduces surface tension of the solution from 72 dynes (water) to 25 dynes, under-component penetration is more easily achieved in the wash cycle than in the rinse cycle. This is when the small water droplet attributes of spray nozzles come into play. The only way to effectively chase out 25-dyne fluid with 72-dyne fluid is to manipulate the water droplet size mechanically, using precision-cut spray nozzles and a large pump that provides the necessary pressure and velocity.

*Rinse cycle (ionic detection).* A successful defluxing process relies on flux being removed into the wash solution during the wash cycle and wash solution being removed during rinse.

Fortunately, all aqueous defluxing chemistries contain highly ionic properties. The incorporation of an ionic residue detection device (resistivity sensor) into the rinse plumbing is highly effective at detecting ionic contamination in the normally non-ionic DI rinse water. A defluxing machine equipped with this technology can automatically add or subtract rinse cycles until the rinse effluent's ionic properties reach a preset limit. This ensures complete, consistent removal of wash solution (and the flux it contains) batch after batch.

*Dry cycle (CFM).* Most batch format defluxing systems use a mechanical blower to provide air exchange within the process chamber. The larger the blower (CFM), the greater frequency of complete air exchange within the process chamber. For rapid and thorough drying, the objective is to exchange the moisture-saturated air with hot, dry (moisture-receptive) air. Depending on the defluxer's location, a particle filter may be required.

*Dry cycle (convection heat power).* Replacing hot, moisture-saturated air with hot, dry air requires convection heaters to heat the incoming air before it enters the process chamber. The degree of power (wattage) should be proportionate to the CFM of the blower.

*Dry cycle (radiant heat power).* A radiant heater will allow the assemblies to absorb heat, becoming mini-heaters that help water trapped below components (and between layers) to evaporate. A successful drying process will produce assemblies that measure a lower post-defluxing weight than pre-defluxing.

*General equipment guidelines (chemical compatibility).* The equipment must be compatible with the defluxing chemical. There are two levels of compatibility, material and process.

Material compatibility requires that all wetted surfaces of the equipment be compatible with the defluxing chemical, including seals (pumps, doors, covers, etc.). Materials such as rubber, Buna, Viton, etc. are not generally compatible with defluxing chemicals. Teflon, EPDM, EPR, and similar materials are widely compatible.

The defluxing machine must also meet the chemical's process requirements. If a chemical requires heat, so will the equipment. If the chemical requires mixing before use, the equipment must be equipped with a mixer. Other considerations such as ventilation, chemical re-use capabilities, dosing requirements, and foam control factor into a defluxing machine choice.

*General equipment guidelines (operator safety).* Operator safety is paramount. Modern aqueous defluxing chemicals, while maintaining their ability to remove all flux types, are non-flammable. The use of non-flammable chemicals has greatly increased the overall safety of cleaning equipment. Additional desired safety features include hands-free chemical dosing, overheat protection, and keyed maintenance functions.

*General equipment guidelines (environmental safety).* Today's defluxing chemicals and equipment are widely considered environmentally responsible. Many defluxing machines have evaporators to eliminate any effluent (wash or rinse solution) discharge into the drain. While most municipalities allow the discharge of effluent from modern defluxing systems, zero-discharge configurations are preferred, as they are proofed against future environmental regulations.

*General equipment guidelines (process control).* Who controls your process? Process control ensures a predictable and consistent result. The operator interface should be clear and intuitive. Closed-loop process feedback eliminates operator panic (Did I press start? Is the water turned on? Is there chemical in the machine?). Password-protected sections of the interface prevent unintentional and/or unauthorized process changes. Statistical process control (SPC) data logging allows cleanliness analysis and historical review of process trends.

**Research**

Hypothesis 1: The standoff height is directly correlated to removal of all flux residues under the QFN component.

Hypothesis 2: Flux compositions and soldering processes that form soft residues post-soldering are directly correlated to removal of all flux residues under the QFN component.

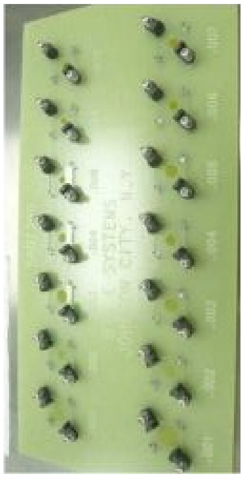


*Figure 1. Test vehicle.*

The designed experiment investigates removing all flux residues from under OFN components following the rework process. The research hypotheses were tested to determine predictive process variables. Our objective is to quantify the relationships between stand-off height and flux type. Does a relationship exist between standoff and flux types for cleaning under QFN components, and to what degree?

The test vehicle (Figure 1) was designed by B.A.E. Systems (patent pending). It is made of FR-4 laminate, with stainless steel pins placed at specific standoff heights and positioned to place 1 × 1″ glass slides 2 mils thick. Two pins were inserted to lock in two corners of the die and prefabricated tension holders locked in the remaining sides. The test vehicle provides ten standoff heights in 1 mil increments from 1 to 10 mil.

Eight paste fluxes used in commercial solder paste products were tested: three water-soluble technologies, two rosin technologies, and three no-clean technologies. Two milliliters of the flux was applied to each of the test sites, then slides were locked in. The test vehicle was reflowed using the standard eutectic tin/lead reflow profile (Figure 2).

*Figure 2. Test vehicle reflow.*

Following reflow, the test vehicle was placed in the batch dishwasher cleaning equipment (Figure 3).The equipment used has several of the desired equipment design characteristics discussed prior.

*Wash.* Two rotating spray bars (one above and one below the assemblies) were each equipped with ten stainless-steel spray nozzles. The nozzles produced a flat spray with a 15° diffusion angle. Fluid was pumped through the nozzles with a 3 horsepower stainless-steel dual impeller Gould (ITT Industries) pump, producing 65 PSI manifold pressure. The nozzles were mounted on the spray bars in an asymmetrical manner to produce overlapping nozzle pattern coverage while eliminating direct nozzle flow collisions. A stainless steel sump tank equipped with 10.5 kW stainless steel heaters provided the necessary power to heat the wash solution to the set point and maintain the temperature throughout the wash cycle.

*Figure 3. Position in batch cleaning equipment.*

The assemblies were presented to the spray systems vertically with a 15° off-vertical angle. The equipment used an oscillating device that transported the assemblies 19 mm forward then 19mm rearward during the wash and rinse cycles to reduce shadowing.

*Rinse.* The rinse cycle used the same spray bars and nozzles as the wash cycle. Each rinse used a unique 11 liter volume of de-ionized water. The spray pump was mounted in an inverse vertical manner, allowing the previous wash solution and each volume of rinse water to be completely purged from the pump. An on-board resistivity monitor detected ionic contamination levels within each rinse cycle, ensuring complete removal of wash solution (and the flux contained therein).

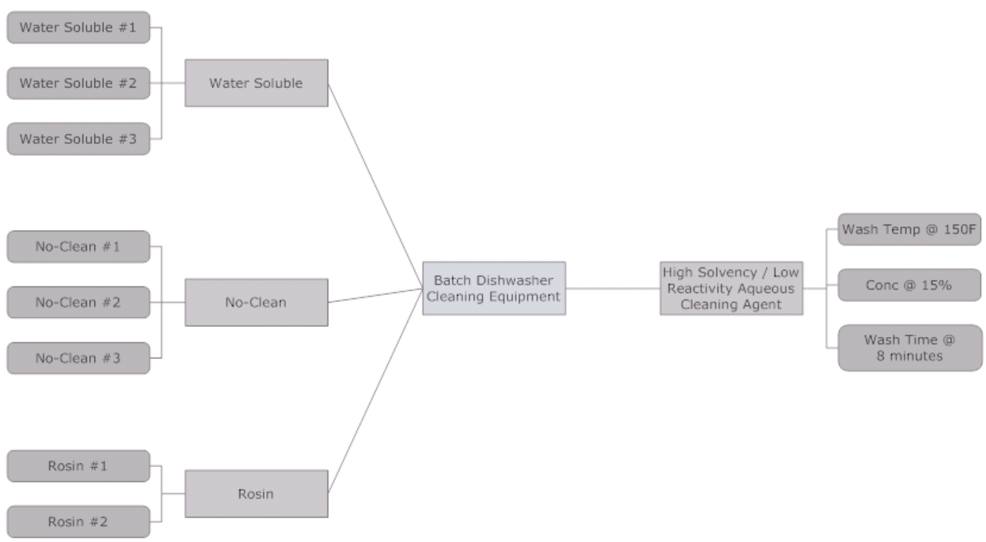
*Dry.* The equipment's drying technology comprised a 1,500 CFM blower, a convection heating system consisting of three 2kW stainless steel tubular finned air heaters (6 kW total), and a 5kW stainless-steel heater mounted in the process chamber acting as a radiant heater.

**The process recipe used to evaluate cleaning was:**

- Cleaning agent: high solvency/low reactivity
- Cleaning agent concentration: 15%
- Cleaning agent temperature: 150°F
- Wash time: 8 minutes
- Rinse cycles: 4
- Rinse temperature: 140°F
- Convection drying: 5 minutes

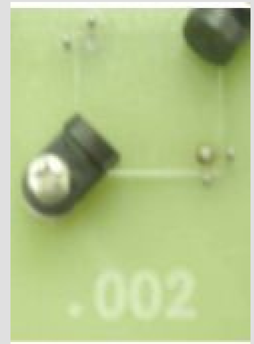
Figure 4 offers a visual overview of the designed experiment. Residue remained under 1 mil standoff die for no-clean soluble paste #1 but all die with larger than 1 mil gaps were clean.

**Figure 4 Designed Experiments**




The data findings accept the first hypothesis that stand off height is directly correlated to removal of all flux residues under the QFN component. Stand-off heights lower than 1 mil were not cleaned using the DOE research factors and levels. At stand off heights greater than 1 mil, most of the flux compositions were successfully cleaned.

**Table 2. No-clean solder paste findings. Photographs of all data findings (water soluble and rosin pastes) are available at www.aqueoustech.com.**

| No-clean paste 1 | 8 minute wash time after cleaning | 15 minute wash time after cleaning |
|---|---|---|
| 1 mil standoff<br><br>Flux residue remaining under both dies cleaned at 8 and 15 minutes |   |   |
| 2 mil standoff<br><br>No flux residue remaining under both dies cleaned at 8 and 15 minutes |   |   |
| 3 mil standoff<br><br>No flux residue remaining under both dies cleaned at 8 and 15 minutes |   |   |

The findings highlight the importance of some level of clearance needed to successfully remove flux residue under the Z axis. Successful results were achieved when QFNs were placed with stand-off heights of at least 2 mils. The research findings indicate that QFNs with standoffs at least 2 mils can be cleaned using the cleaning agent and cleaning equipment at the research process conditions.

The data findings accept the second hypothesis that flux residue types and reflow processing conditions directly correlate to removal of all flux residues under the QFN component. Leading- edge circuit designs are increasingly small and dense. As the space between conductors diminishes, removing flux residues becomes more important. Cleaning must be a consideration when designing for manufacturing.

Miniaturization imposes a great challenge on flux chemistries due to the increasing amount of oxides and requirements for no-clean lead-free applications.3 The decreased size of components and the conductor spacing generates more heat during operation.

*Figure 5A. QFN soldered with water-soluble paste.*

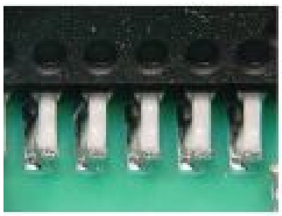


*Figure 5B. QFN soldered with rosin.*

*Figure 5C. QFN soldered with no-clean.*

Problems arise from boards with greater mounting density resulting in electrochemical reactions, metal migration, and reduction of surface resistance.5

Flux compositions designed for lead-free consist of multiple polymer species and property-modifying additives.3 These additives affect the system's mobility, solvent-retention properties, long- and short-term dielectric properties, and thermal behavior. Maintaining all desired product attributes, as well as maximizing top-side fillet performance, requires a thorough understanding of the interactions between these polymers and certain properties of the modifying additives.

Many factors go into solder paste selection. The data findings strongly correlate cleaning under low stand offs with residues that easily dissolve in the cleaning agent. Optimizing reflow to prevent oxidation and charring is also important.

Three Practical Component test boards were assembled using QFN components. The stand-off clearance under the component was between 3 and 4 mils. One board was soldered with water-soluble solder paste, one with rosin solder paste, and one with no-clean solder paste. The boards were processed using a cleaning agent and cleaning equipment with the best-in-class properties discussed in this article.

When the QFN components were removed from each test board, no visible flux residue was left from the three solder paste technologies evaluated. Figures 5A-C show the visual cleanliness under the QFN components.

**Conclusion**

A product making its designed life expectancy is an important parameter when reworking electronic assemblies. Flux residue under QFNs can impact performance when conductive ions migrate within the electrical field.1 Dishwasher-style aqueous spray-in-air cleaning equipment is commonly used for rework operations. Engineered cleaning materials are needed to dissolve flux residues commonly used in the rework operation. To successfully clean all flux residues under the QFN, process factors must be understood.

Cleaning under low-feature components requires an optimized process. Neither the cleaning agent nor equipment accomplishes successful flux removal on its own. Integrating the right cleaning agent with the right cleaning machine and other process factors is the key to cleaning leading-edge circuit assemblies.

When optimizing QFN rework, users should view cleaning as an integrated process. Cleaning agent and cleaning machine science has dramatically improved with time. Integrating best in class technologies provide proven performance that accomplishes this demanding cleaning need.

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Mike Bixenman, doctor of business administration (D.B.A.), chief technology officer (CTO), Kyzen Corporation, is responsible for R&D, analytical, application testing, tech service, and engineering groups at Kyzen.

Michael Konrad is an SMT Advisory Board member and president of Aqueous Technologies. Konrad also is an IPC SMEMA Council APEX Committee Member. He was a "High Performance Electronics Assembly Cleaning Symposium" panelist. Contact him at konrad@aqueoustech.com.

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