

# Wave Soldering Performance and Optimization of VOC-Free, No-Clean Fluxes

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## Abstract

Environmental regulations restricting the emissions of volatile organic carbons (VOCs) have prompted many printed circuit assemblers to evaluate alternatives to isopropanol-based flux chemistries. The soldering performance of several VOC-free, no-clean wave solder fluxes has been evaluated, through production testing and by standard wetting balance measurements, and compared to the performance of VOC-containing, no-clean wave solder fluxes. Both the wetting balance testing and the production trials were conducted in three separate soldering atmospheres (less than 10 ppm O<sub>2</sub>, 1% O<sub>2</sub>, and air). The results characterize VOC-free, no-clean fluxes as suitable alternatives to isopropanol-based, no-clean flux systems.

## Introduction

The Clean Air Act regulates the emission of chemicals that contribute to ozone generation. Volatile organic compounds (VOCs) are carbon-containing substances that vaporize at low temperature and result in harmful ozone generation when discharged into the environment. Ozone precursors, such as VOCs, when discharged near the ground, lead to smog and unhealthy air conditions in the lower atmosphere. Therefore, it is a matter of public health and well-being that VOC emissions be held to a minimum.<sup>1</sup> Until recently, wave soldering fluxes commonly contained organic solvents, such as alcohols, which act as a carrier of flux activators and vehicles to the surfaces being soldered.

## History

Local Air Quality Management Districts (AQMDs) are directed with the responsibility for regulating and controlling emissions of VOCs. Each AQMD has its own set of rules and regulations governing VOC emissions based upon the severity of the air quality conditions in the respective district. Both the South Coast Air Quality Management District (SCAQMD) based in the Los Angeles basin, and the Bay Area Air Quality Management District (BAAQMD) based in the San Francisco Bay Area have different rules governing the emissions of VOCs from wave soldering machines.

Until the spring of 1991, "flux applicators" associated with wave soldering were exempt from regulations governing VOC emissions in the BAAQMD. Since then, wave soldering machines in the BAAQMD are governed by the following:

Regulation 8: Organic Compounds

Rule 4, General Solvent and Surface Coating Operations, specifies emission limitations for operations involving heat, noncomplying solvents, and complying solvents in Sections 301 through 303.

In general, if any new or modified source results in VOC emissions of either more than 365 pounds per year or 5 pounds per day, then best available control technology (BACT) must be implemented. "New or modified" sources would be any wave soldering equipment brought into the facility or any equipment that is physically relocated from its current geographical position. Thus, if one wanted to reorganize a manufacturing line that has been in its present location since before the spring of 1991, and moves the wave soldering equipment to a new location within the facility, then permits and regulations for VOC control would be required.

Soletron, based in Milpitas, California, faced this situation when consolidating several manufacturing sites scattered across San Jose and Milpitas into its current campus facility in April of 1992. This led to the investigation of VOC-free wave soldering fluxes by the Soletron Advanced Technology Group. At the time only one known VOC-free flux existed: HF-1189 developed by Ray Turner at Hughes in Fullerton, CA. This was a water-based aqueous cleanable flux with activators uniquely derived from lemon juice. Shortly thereafter, Alpha Metals submitted a new no-clean, VOC-free flux 4942 (known as NR-300A2) for beta site testing. All other competing flux manufacturers then began development of VOC-free, aqueous cleanable and VOC-free, no-clean fluxes. This report will attempt to measure and document the performance of seven of these new no-clean, VOC-free fluxes versus three well-established VOC-containing, no-clean fluxes.

## Description of Fluxes

Flux components include activators, vehicles, solvents, and special additives. Activators for no-clean fluxes are typically organic acids classified as carboxylic and dicarboxylic acids. The vehicles for no-clean fluxes have been selected from rosins, chemically modified natural resins and synthetic resins. Traditionally, no-clean wave soldering fluxes have been formulated using volatile organic compounds such as methanol and isopropanol as their primary solvent carrier. The use of alcohols as the solvent aids in evaporation during preheating. When the assembly touches the wave, only activators and vehicles remain. Incomplete evaporation of the solvent can lead to spattering and tiny solder balls being transported through the holes of a board and deposited on its top side. For this reason, the water content has been kept to a minimum in traditional flux formulations. Alcohols have also acted as wetting agents in the traditional no-clean formulations. Special additives can include surfactants, stabilizers, inhibitors and dyes.

New VOC-free fluxes are water-based formulations utilizing low solids, halide-free activators. As with alcohol-based no-clean formulations, a similar class of organic carboxylic acids is used as activators. Surfactants are added to the formulation to reduce the surface tension of the water which enhances the wetting properties of the flux to the PCB. The BAAQMD classifies a flux as VOC-free only if it has less than 1% by weight VOCs as tested by EPA test methods. The seven VOC-free fluxes and three VOC-containing fluxes tested in this report are labeled A, B, C, D, E, F, H with a "-c" for VOC-containing and a "-f" for VOC-free. A-f, B-f, C-f corresponds to the

same manufacturer for A-c, B-c and C-c respectively. The fluxes tested contain between 1% to 3% solids.

## Wetting Balance Solderability Evaluations

### Wetting Balance Apparatus

The performance of seven VOC-free, no-clean wave soldering fluxes was evaluated using wetting balance techniques to characterize wetting force, wetting time, and wetting rate. Three VOC-containing, no-clean wave soldering fluxes were also tested so that the performance of the VOC-free fluxes could be compared to traditional solvent-based, no-clean flux systems.

Wetting balance measurements were obtained using a Multicore Universal Solderability Tester (M.U.S.T.). The system was modified to collect voltage output from the M.U.S.T. armature using a Rustrak Ranger II data acquisition system, which allowed wetting force data to be collected at a higher sampling frequency (62.5 millisecond intervals). This feature was useful to accurately characterize flux performance when wetting force changed rapidly as a function of time.

Wetting balance data was collected in soldering atmospheres that are representative of cryogenic, noncryogenic, and compressed air delivery systems. The wetting balance apparatus was placed inside a glove box to evaluate flux performance in controlled soldering atmosphere. The experimental setup has been described elsewhere.<sup>2</sup> A 1% oxygen in nitrogen soldering atmosphere, typical of gas streams produced by noncryogenic gas generators, was obtained by blending zero grade compressed air with nitrogen to achieve the desired oxygen content. Experiments were also conducted using a soldering atmosphere containing less than 10 ppm O<sub>2</sub>, which is typical of a wave soldering atmosphere produced using cryogenic nitrogen storage and delivery systems. The oxygen content of the controlled soldering atmospheres was measured using a Thermox TM-1A analyzer. Wetting balance results were also obtained in ambient air.

### Wetting Balance Principles

In the wetting balance test method, the cleaned and fluxed specimen is suspended from a sensitive balance and immersed edgewise, at a controlled rate and to a consistent depth, into a bath of molten solder at a controlled temperature. The specimen is subjected to time-variant vertical forces of the downward surface tension

force ( $F_\gamma$ ) and the upward buoyancy force ( $F_b$ ), which can be represented as:<sup>3</sup>

$$\begin{aligned} F_{\text{wet}} &= F_\gamma - F_b \\ &= \gamma_{l-g} P \cos\theta - \rho g V \end{aligned} \quad (1)$$

where  $F$  is dependent on the surface tension of the molten solder  $\gamma_{l-g}$ , the perimeter of the specimen  $P$ , and the contact angle  $\theta$ . The buoyancy force is expressed by the density of the solder  $\rho$ , the acceleration due to gravity  $g$ , and the immersion volume  $V$ . The contact angle,  $\theta$ , is determined by Young's equation:<sup>4</sup>

$$\cos\theta = \frac{\gamma_{s-g} - \gamma_{l-s}}{\gamma_{l-g}} \quad (2)$$

where for this study,  $\gamma_{s-g}$  is the surface tension of a copper test coupon and  $\gamma_{l-s}$  is the interfacial tension between copper and molten Sn-Pb solder. In equation (1) the buoyancy force  $F_b$  and the perimeter  $P$  can be regarded as constants if the size is uniform for all of the test coupons. Therefore, the total wetting force  $F_{\text{wet}}$  varies as a function of  $F_\gamma$ . By combining equations (1) and (2), the surface tension force can also be expressed as:

$$F_\gamma = P(\gamma_{s-g} - \gamma_{l-s}) \quad (3)$$

From equation (3) the surface tension force is predicted to vary as a function of the oxygen concentration within the soldering environment due to the variation of the copper surface tension  $\gamma_{s-g}$  and the copper/solder interfacial tension  $\gamma_{l-s}$ .

As the oxygen concentration increases within the soldering environment, the solid copper surface and the molten solder alloy are subject to oxidation so that both  $\gamma_{s-g}$  and  $\gamma_{l-g}$  decrease.<sup>5</sup> The presence of an oxide layer on both the copper and solder surface prevents the direct contact and interaction between copper and solder upon immersion of the coupon into the solder, and therefore wetting is delayed and the interfacial surface tension,  $\gamma_{l-s}$ , is increased.<sup>6</sup> From equation (3) it can be concluded that the surface tension force,  $F_\gamma$ , generally decreases with increasing oxygen concentration of a soldering environment. From equation (1), a decrease in the surface tension force will result in a decrease in the total wetting force,  $F_{\text{wet}}$ .

It is important to note that discussions related to the surface tensions described by Young are often based upon assumptions that wetting parameters are in equilibrium such that the surface tension values are constant. However, wave soldering is a non-equilibrium process and therefore  $\gamma_{s-g}$ ,  $\gamma_{l-s}$ , and  $\gamma_{l-g}$  are changing as the substrate, solder, flux, and atmosphere interact with respect to time and temperature.<sup>7</sup>

### Sample Preparation

The test samples were 15 mm x 15 mm x 0.25 mm, 99.999% pure copper foil coupons. The samples were degreased with 1,1,1-trichloroethane in an ultrasonic cleaner for ten minutes at 80°C, and then triple rinsed with deionized water.

The as-received and post-cleaned copper foil coupons were analyzed in a UHV surface science analytical tool equipped X-ray photoelectron and Auger electron spectroscopy (XPS and AES respectively). This analysis was performed to determine the soldering quality of the raw material and to ensure that the cleaning process did not contaminate the coupons. The XPS utilized a double pass cylindrical mirror analyzer and a nonmonochromatized Mg K<sub>α</sub> source. Data was collected before and after sputtering with a 4 KeV Ar beam for 10 seconds to remove adventitious carbon. The sample surface was analyzed as a thin layer of copper (I) oxide with an underlying base of copper metal. Other surface contaminants, such as halide residues from the cleaning procedure, were not detected.

The sample preparation provided a mild cleaning of the copper, which removed gross carbon contamination and did not compromise the surface chemistry of the sample. The native oxide was not removed prior to wetting balance testing. Removal of copper oxides with aggressive sample preparation methods that utilize strong acids or etchants can affect the surface microroughness, which in turn can affect the solderability of the substrate.<sup>7</sup> Therefore the test coupon finish evaluated in this study is assumed to be representative of copper substrate materials used in printed circuit board assembly. The effect of coatings that are designed to preserve the solderability of copper substrates on solder wetting performance was not investigated in this study.

### Test Procedure

The copper coupons were fluxed by uniformly dipping the coupon into the liquid flux. Several other fluxing methods were evaluated, including dipping followed by decanting excess flux, dipping followed by blotting excess flux using an adsorbent material, and application of the flux by spraying the coupons. Each of these methods proved to yield inconsistent results as determined by wetting balance analysis. Although flux application by dipping may have resulted in a liberal flux coating on the coupon, it proved to be the most reproducible method. After fluxing, the coupon was positioned vertically in the sample armature thirty seconds prior to immersion into the solder pot. The solder used for the experiments was a 60/40 tin-lead near eutectic alloy at a temperature of 235°C. The solder pot was skimmed fifteen seconds prior to each trial to remove solder dross and expose a pristine alloy surface. The foil samples were immersed in the solder pot to a depth of 5.0 mm at an immersion rate of 20 mm/sec. Data was collected over an immersion time of 10 seconds. Twenty coupons per condition were tested to acquire statistically relevant data.

### Wetting Balance Results and Discussion

The figures 1a, 1b, and 1c represent the wetting balance curves obtained for flux A-f (a VOC-free flux) acquired in a nitrogen, 1% oxygen, and air soldering atmosphere. The vertical bars on the curves show the standard deviation of the wetting force measurement at a given time for each of twenty trials performed under the same test conditions. Figure 1d illustrates the average wetting balance curves obtained for flux A-f in each of the three soldering atmospheres. The wetting balance data was analyzed in this manner for each of the fluxes tested. The wetting performance of the ten fluxes was characterized by the wetting force, wetting time, and wetting rate to compare flux performance and the effects of oxygen within the soldering atmosphere on solder wetting.

Figure 1a

Wetting Balance Curve for Flux A-f Processed in a Nitrogen Soldering Atmosphere

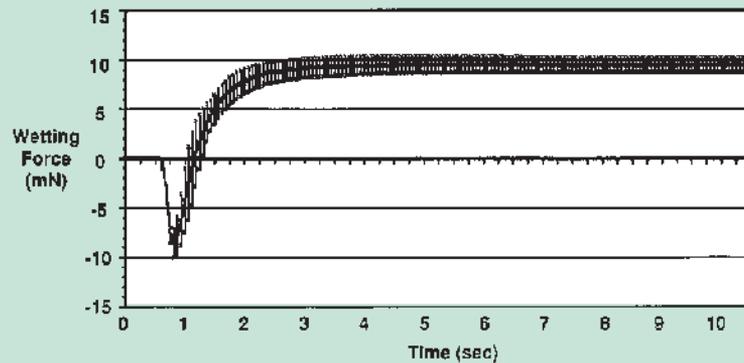


Figure 1b

Wetting Balance Curve for Flux A-f Processed in a 1% Oxygen in Nitrogen Soldering Atmosphere

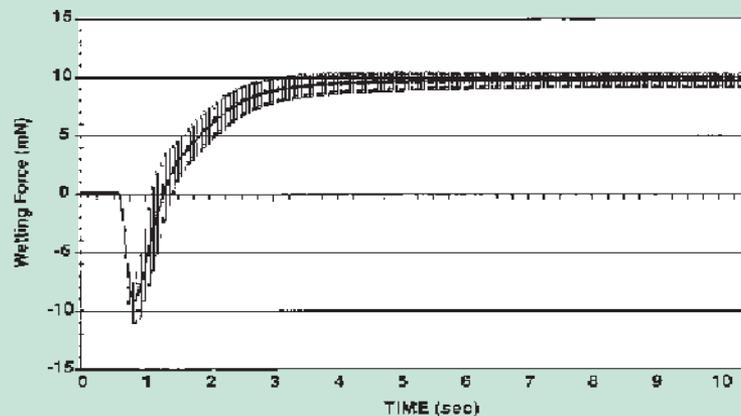


Figure 1c

Wetting Balance Curve for Flux A-f Processed in an Air Soldering Atmosphere

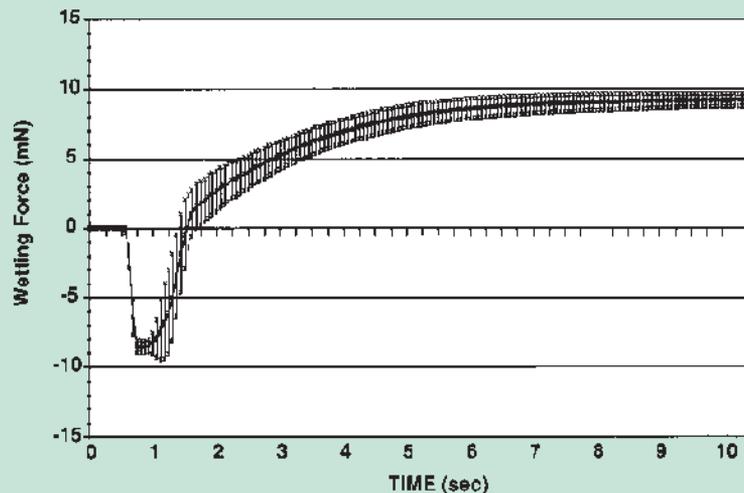


Table 1, located after References, summarizes the average wetting performance of each of the ten fluxes evaluated in three different soldering atmospheres. The table provides wetting force data (in millinewtons) determined at three points on the wetting balance curve:  $F_{2\text{sec}}$ ,  $\frac{2}{3} F_{\text{max}}$ , and the maximum force,  $F_{\text{max}}$ . Wetting time data (in seconds) is given for  $F_{\text{zero}}$  and  $\frac{2}{3} F_{\text{max}}$ . Wetting rate data (in mN/sec) is provided at  $\frac{2}{3} F_{\text{max}}$ . The standard deviation of the wetting force at  $\frac{2}{3} F_{\text{max}}$  and  $F_{\text{max}}$  is also given.

Theoretically, the maximum wetting force can be obtained from equation (1)<sup>3</sup> as the contact angle  $\theta$  reaches zero degrees by assuming the surface tension of the liquid solder,  $\gamma_{l-g} = 0.4 \text{ N/m}$ , the density of the solder,  $\rho = 8000 \text{ kg/m}^3$ , and the acceleration due to gravity,  $g = 9.81 \text{ m/s}^2$  for a near eutectic tin-lead alloy at  $235^\circ\text{C}$ . The theoretical maximum wetting force  $F_{\text{th}}$  on the coupon was calculated to be  $10.75 \text{ mN}$ .  $F_{\text{th}}$  was not obtained during the wetting tests and therefore perfect wetting ( $\theta = 0$ ) was not achieved; however, for each atmosphere condition, the largest maximum wetting force was obtained with fluxes A-c, C-f, and B-c, while the lowest maximum wetting force was observed using flux E-f. The significant differences in the wetting performance observed among the ten fluxes are believed to be due primarily to the fluxing and wetting properties of the formulations and also due to the variability of the testing method as shown by the standard deviation of force as a function of time.

Each of the fluxes is a low residue, low solids content (between 1% and 3%), no-clean formulation with halide-free activators. However, differences in flux chemistries likely had an effect on the wetting balance results. For example, differences in flux activity or activator strength, percent solids or activator concentration, or the wetting (and evaporation) properties of the liquid flux can all affect the ability of a flux to promote solder wetting. The wetting of liquid fluxes to substrates has been shown to be dependent on the substrate material and the proper selection of process parameters. This interaction between flux and substrate was shown to affect soldering results.<sup>8</sup> In this study, the wetting properties of the fluxes on copper were observed to be dissimilar during the testing, which likely impacted the wetting balance results. Sessile drop experiments are currently being conducted to investigate the flux wetting properties on copper and several solder mask materials to quantify this observation.

In the wave soldering process, the printed circuit board remains in contact with the solder wave

Figure 1d

Wetting Balance Curve for Flux A-f as a Function of Soldering Atmosphere

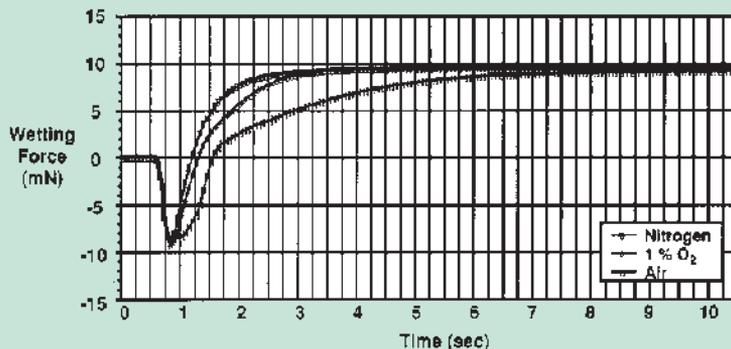
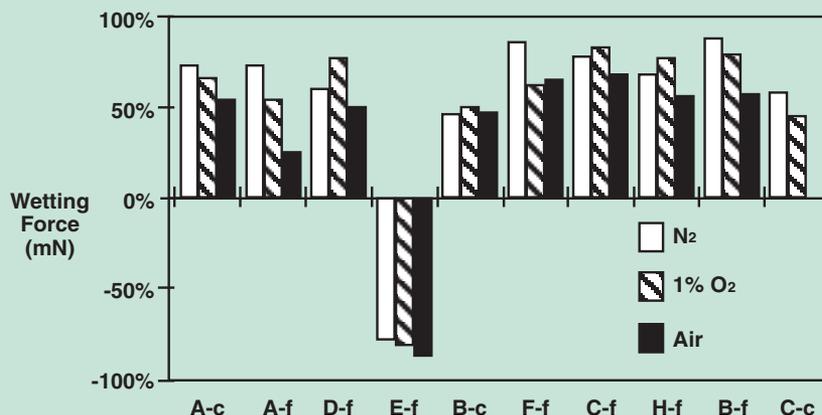


Figure 2

Wetting Balance Results—Wetting Force at 2 Seconds as a Percentage of the Theoretical Wetting Force



for approximately two seconds, based upon typical board immersion depths and conveyor speeds. Therefore the wetting force obtained at 2 seconds was calculated, plotted as a percentage of the maximum theoretical wetting force, and used to evaluate flux performance.<sup>9</sup> As shown on Figure 2, the percentage of theoretical wetting at two seconds is generally greater when soldering was performed in an inert atmosphere versus that in air.

Wetting time data was evaluated from the wetting balance curves at  $F_{(t)} = 0$  ( $F_{zero}$ ) and at  $F_{(t)} = \frac{2}{3} F_{max}$ . The time at  $F_{zero}$  is of interest because it represents the time for a positive wetting force to be recorded which is a measure of flux performance within the time domain of wave soldering. The practice of evaluating wetting time at  $\frac{2}{3}$  maximum wetting force originates from the relationship between  $F_{(t)}$  and  $F_{max}$ . Wetting curves, from  $F_{min}$  to  $F_{max}$ , can be represented by the following equation<sup>10</sup>:

$$F_{(t)} = F_{max} (1 - e^{-t/k}) \quad (5)$$

where  $t$  is wetting time at  $F_{(t)}$  and  $k$  is a time dependent constant which is characteristic of the wetting curve for a given set of test conditions. As wetting time  $t$  approaches  $k$ , the corresponding wetting force  $F_{(t)}$  approaches  $\frac{2}{3} F_{max}$ . Therefore, wetting time at  $\frac{2}{3} F_{max}$  serves as an indicator of the wetting kinetics since  $t = k$ . From equation (5) it follows that shorter wetting times at  $\frac{2}{3} F_{max}$  (smaller values of  $k$ ) represent an increase in wettability. Figure 3 summarizes wetting time at  $\frac{2}{3} F_{max}$  for each flux. It shows that for some fluxes, inert atmospheres can significantly decrease wetting time, such as for fluxes A-c and C-c. However, for fluxes B-c and D-f, the wetting time was not affected by oxygen within the soldering atmosphere, while flux E-f showed poor wettability.

Wetting rate, or the change in wetting force as a function of time, characterizes the advancing solder meniscus<sup>11</sup> which provides wetting kinetics for solder fillet formation. A wetting rate (corresponding to a specific wetting force or wetting time) can be calculated from the slope of the wetting curves. Figure 4 shows the average wetting rate (mN/sec) observed at  $\frac{2}{3} F_{max}$  in three soldering atmospheres for each of the ten fluxes. It indicates that flux B-f has significantly higher wetting rate, and the wetting rate for all fluxes is improved when testing is conducted in an inert gas atmosphere.

Comparison of the wetting performance of the fluxes, as characterized in Figures 2, 3, and 4, shows that wetting force, wetting time and wetting rate data do not necessarily indicate the same trends in terms of flux performance. Therefore the analysis of several wetting parameters is suggested to accurately characterize flux wetting performance.

As shown in Figure 1d, the wetting performance of flux A-f was dependent upon the soldering

Figure 4

Wetting Balance Results—Wetting Time at  $\frac{2}{3} F_{max}$

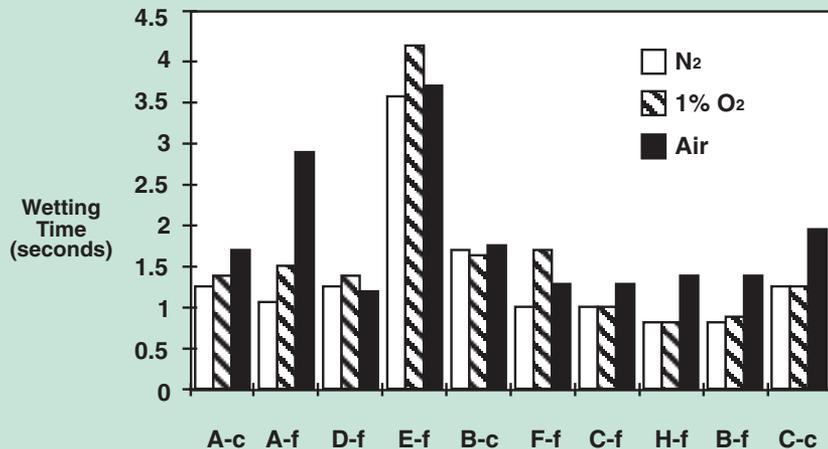


Figure 4

Wetting Balance Results—Wetting Rate at  $\frac{2}{3} F_{max}$

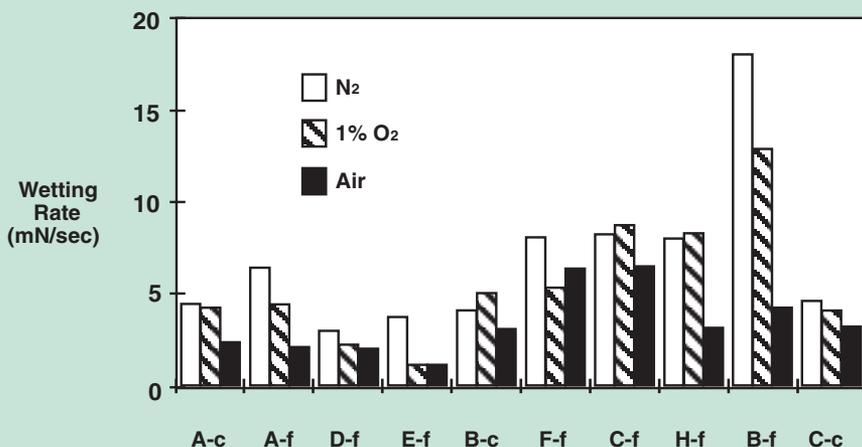
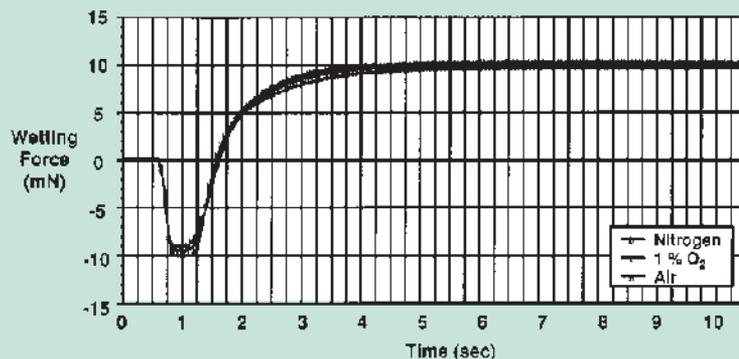


Figure 5

Wetting Balance Curves for Flux C-f as a Function of Soldering



atmosphere. The wetting force, wetting time, and wetting rate were improved when testing was conducted in a 1% O<sub>2</sub>-containing soldering atmosphere versus air. Further improvement in wetting performance was observed when testing was conducted in a low O<sub>2</sub>-containing atmosphere. In contrast, the wetting performance of C-f (a different VOC-free flux formulation), as shown in Figure 5, was invariant to oxygen within the soldering atmosphere.

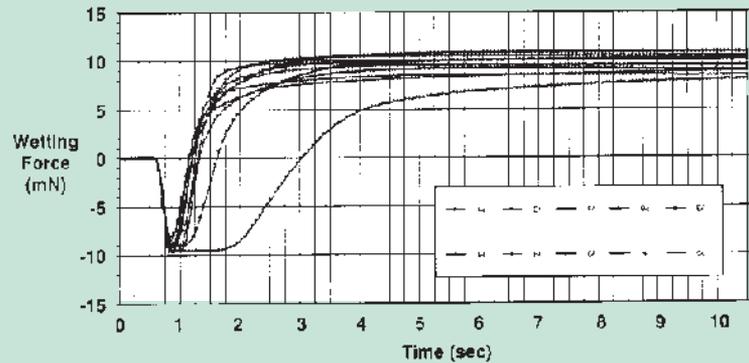
Figures 6, 7, and 8 are composites of the average wetting balance curves for all fluxes obtained in nitrogen, 1% oxygen in nitrogen, and air soldering atmospheres, respectively. Comparing these three figures gives an indication of the relative flux performance within each soldering atmosphere. Figure 6 shows a consistent level of wetting performance for nine of ten fluxes tested. Figures 7 and 8 show that as the oxygen content of the soldering atmosphere increases, variation in the consistency of the wetting performances of the group of fluxes is observed. Comparison of wetting performance of VOC-free versus VOC-containing fluxes showed that the water-based, VOC-free formulations performed similarly to isopropanol, VOC-containing flux formulations.

The effect of soldering atmosphere on the consistency of flux performance is especially evident as solder wetting progresses between one and three seconds. Over this interval, the wetting rate and wetting force vary significantly for the air soldering case and vary moderately for the 1% oxygen in nitrogen case; however, these wetting parameters are relatively uniform for the test conducted in nitrogen. This observation indicates that inert gas atmospheres can expand the process window by providing consistent soldering performance irrespective of dissimilarities in flux chemistry.

The average wetting curves of the ten fluxes in each atmosphere were combined to obtain a comparison of general flux performance as a function of soldering atmosphere purity. The results, illustrated in Figure 9, show that as the oxygen concentration decreases from 21% O<sub>2</sub> to less than 10 ppm O<sub>2</sub>, the wetting force at two seconds as a percentage of the theoretical force increases by 49%, the wetting time at  $\frac{2}{3} F_{max}$  decreases by 25% and the wetting rate at  $\frac{2}{3} F_{max}$  increases by 100%.

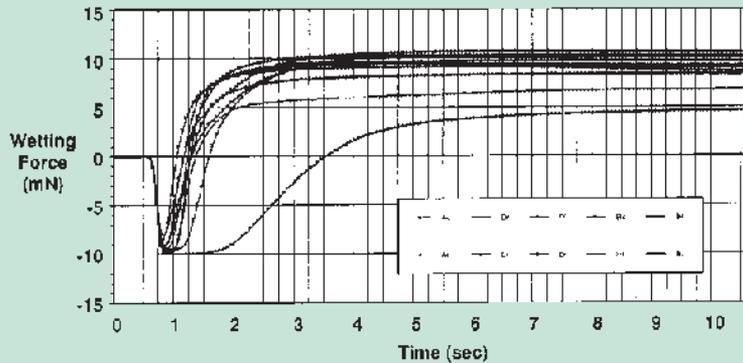
**Figure 6**

**Wetting Balance Curves for All Fluxes Tested in a Nitrogen Soldering Atmosphere**



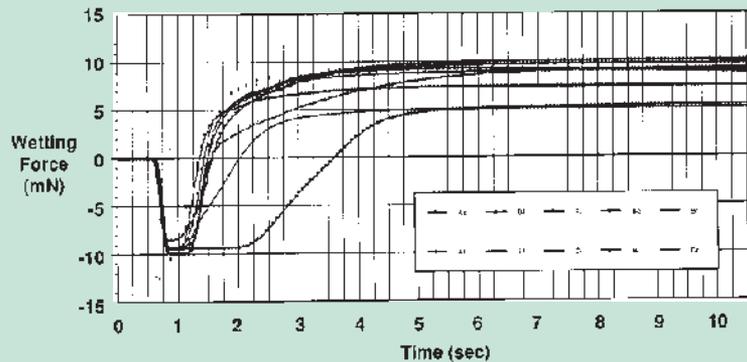
**Figure 7**

**Wetting Balance Curves for All Fluxes Tested in a 1% Oxygen in Nitrogen Soldering Atmosphere**



**Figure 8**

**Wetting Balance Curves for All Fluxes Tested in an Air Soldering Atmosphere**



These results indicate that soldering performance achieved with no-clean fluxes is dependent on the oxygen content within the process atmosphere, and that the soldering parameters of force, time, and rate maximize when no-clean wave soldering is performed in an inert environment.

## Production Evaluations

### Test Procedure for Wave Soldering

Production trials evaluated the performance of the ten fluxes in cryogenic nitrogen, 1% O<sub>2</sub>, and air soldering atmospheres. The production testing consisted of two separate evaluations. In each evaluation, flux is uniformly sprayed onto the bottom side of the printed circuit boards, wave soldered, and visually inspected for the following defects: bridging, icicles, solder balls, topside wetting, solder joint appearance, and amount of residue. In each trial the run order and choice of flux was randomized. The two evaluations differed in the wave soldering machines selected for use and in the printed circuit board used as a test vehicle.

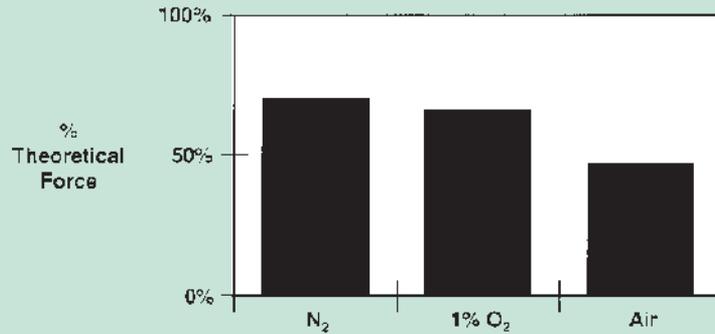
In trial #1, a Sensbey wave solder machine with a full-length nitrogen hood retrofit was utilized for soldering medium density HASL boards. The atmosphere was measured and controlled at the smooth wave. Five boards for each flux and atmosphere condition were used. Each PCB contained 1276 solder joints. The connectors and PTH components made up 436 joints; surface mount SOICs, 164 joints; with surface mount capacitors and resistors totaling 676 joints. The solder mask on this board was a smooth, glossy liquid photoimageable resist.

The most critical parameters when using VOC-free, no-clean fluxes are: 1) the ability to apply flux without entrapping excess flux within the board or the carrying fixture and 2) the ability of the equipment to completely dry the boards. The temperature profile was set for a conveyor speed of 6.0 ft/minute. Three bottom side preheaters were utilized and were adjusted to thoroughly dry the assembly before contact with the wave. The boards were supported with a wave soldering fixture. Solder splashing and solder balling due to wet flux conditions were non-existent with the profile used. Critical care must be taken in order not to overheat the assembly when passing over the molten solder. The profile was not optimized for any given flux and was held constant throughout the test. Performance would be compared at a location in the process window which may or may not be close to the optimum of any given flux. The desire of process

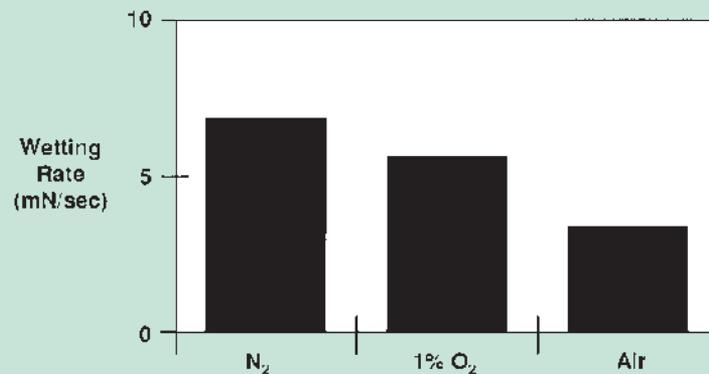
Figure 9

### Wetting Balance Results

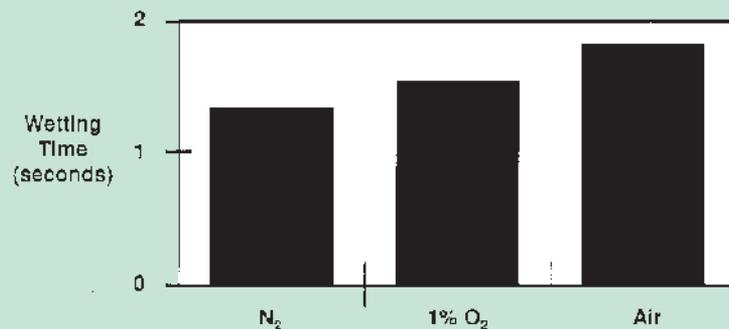
#### Wetting Force at 2 Seconds as a Percentage of the Theoretical Wetting Force



#### Wetting Rate at $\frac{2}{3} F_{max}$



#### Wetting Time at $\frac{2}{3} F_{max}$



The average values for all fluxes tested are given for the percent theoretical force at two seconds, the wetting time at  $\frac{2}{3} F_{max}$ , and the wetting rate at  $\frac{2}{3} F_{max}$ .

engineers and this test is to identify a flux with broad performance capabilities.

Visual inspection was performed using a 3X magnifying lens. Solder balls were inspected and counted in three locations on evenly spaced connectors. All solder balls which could be identified of any size were counted. Topside wetting, solder joint appearance, and amount of residue were ranked on a 1–5 scale. Excellent residue

that would be similar in quality to an aqueous cleaned board would rank 1, moderate residue would rank 3, and gross residue would rank 5. In trial #1, topside wetting and solder joint appearance for all fluxes tested ranked 1; therefore, these inspection criteria were judged to be unaffected by the test matrix.

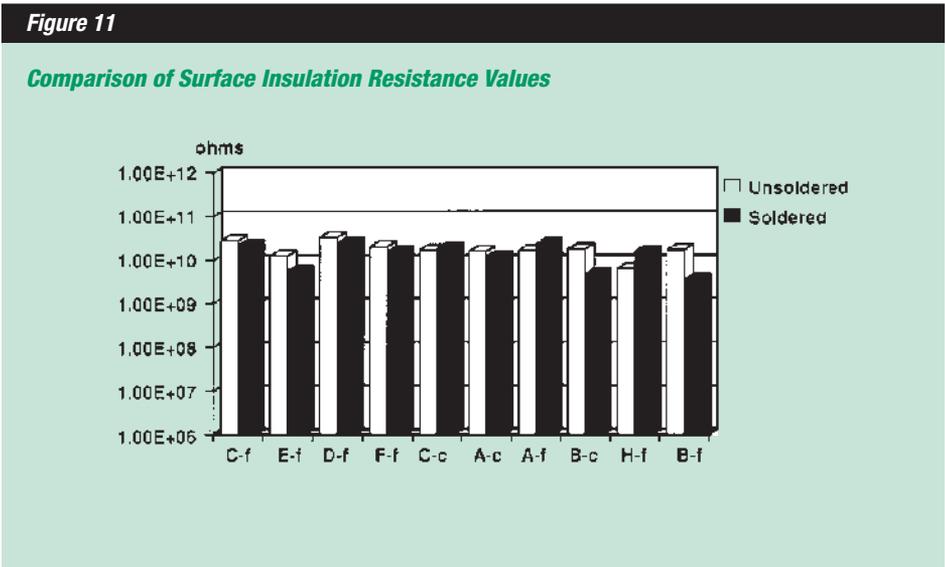
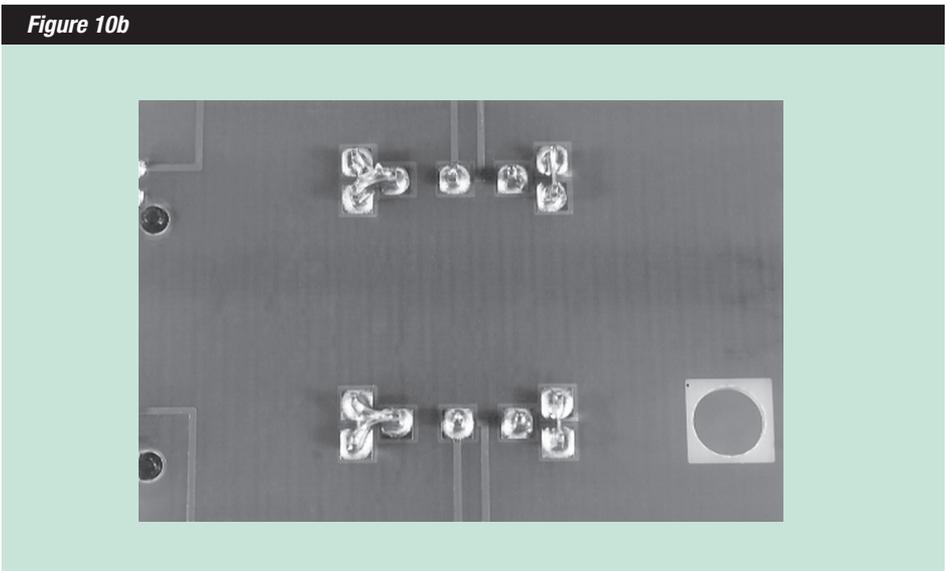
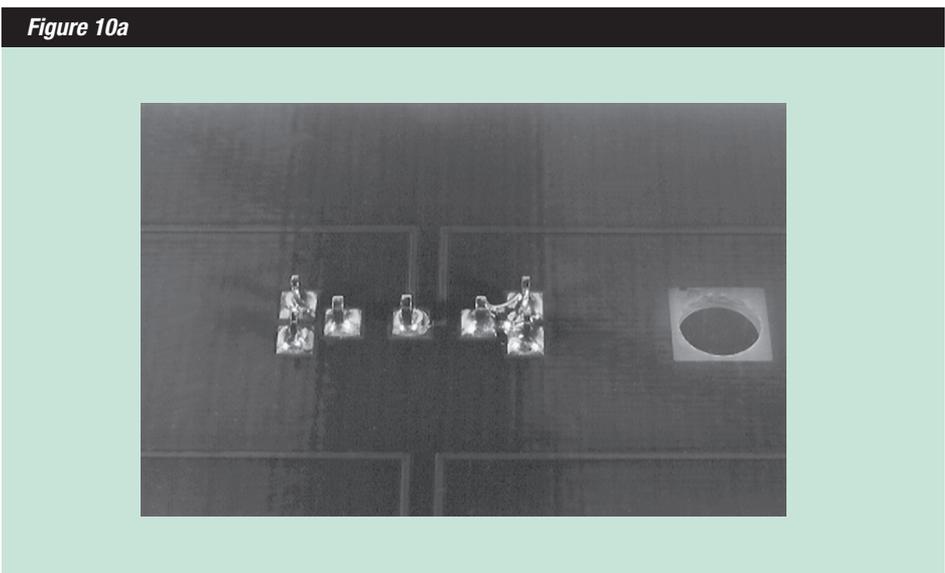
In trial #2, an Electrovert Econopak I equipped with a CoN<sub>2</sub> four nitrogen system was used

for soldering low density HASL boards. Three boards for each flux and atmosphere condition were used. The purity of the cryogenic nitrogen (3 ppm O<sub>2</sub>), 1% O<sub>2</sub>, and air soldering atmospheres was measured in the incoming gas to the CoN<sub>2</sub>tour nozzles. The atmosphere was not measured at the wave or exit region of the board. The pcb contained 148 PTH joints which consist of a 40-pin connector, twelve 7-pin switches and 24 PTH joints. The solder mask on this board was a smooth, glossy liquid photoimageable resist.

In trial #2, two bottom side preheaters were utilized. Due to the short preheat zone, a conveyor speed of 3.0 ft/minute was used. The preheat profile was adjusted for absolute drying of the board before entrance into the solder bath. This assembly represents a worst-case condition for bridging between pins. A 3-pin bridge shown in Figures 10A and 10B was identified as a “node”. From previous production experience, bridging can only be totally eliminated on this assembly by using a very active organic acid flux. Therefore this assembly is an excellent candidate for measuring the performance of no-clean fluxes. Solder balls were inspected using a 3X magnifying lens and counted in the area of the 40-pin connector. PTH wetting and flux residues were ranked on a scale from 1–5 as in trial #1.

**SIR Test Procedure and Results**

The surface insulation resistance test used bare copper IPC-B-25 test boards patterns B and E. The boards were washed twice in an in-line aqueous cleaner, zeroed in an Omegameter 600 SMD for one hour, and subsequently recleaned in the Omegameter until the solution registered clean. Flux was applied to both sides of the board and wave soldered (one side only) using a standard profile. The boards were tested at 85°C and 85% relative humidity for 7 days. The bias voltage and test voltage was 100 V DC. All fluxes, both VOC-free and VOC-containing, responded well above the IPC pass/fail criteria of 1.00 X 10<sup>8</sup> ohms. Figure 11 shows the plot of the average final SIR values. All fluxes tested nearly the same, and no significant difference could be noted between the unsoldered (topside) and soldered (bottomside) condition. In terms of SIR response, there is no cause for alarm in switching to a VOC-free flux.



### Wave Soldering Results

The results of bridging for trial #1 are shown in Figure 12. From Figure 12 the general trend for bridging is lower for atmospheres of less than 10 ppm O<sub>2</sub>, and a general rise in bridging in the presence of air. The manufacturer is the same for both flux C-c and C-f; their flux results in the lowest average bridging defects per board. Several VOC-free fluxes are comparable to the VOC-containing fluxes in terms of soldering performance.

Figure 13 shows the response for solder balls. The solder balls which were detected typically ranged in size of 3–5 mils in diameter, with many being less than 3 mils in diameter. Two VOC-containing fluxes indicated no response for solder balls in any atmosphere, while many of the VOC-free fluxes produced some response. There appears to be no discernible trend in solder ball formation for the various atmospheres in trial #1. Solder balls are generated by metallic geometries of the pads and leads coupled with the dynamic flow properties of solder at the point of exit from the solder bath. The appearance of solder balls relates to the issue of whether solder balls stick or adhere to the surface of the solder mask or board. Therefore, “The morphology and the chemistry of the resist surface greatly affect the frequency of solder balls.”<sup>8</sup> Thus this data will simply report the phenomena with the tested fluxes against the condition of the PCB used, the solder mask material, the prior thermal condition and manufacturing exposure. It appears that flux D-f and H-f may have a higher solder balling tendency than the rest of the field. Bottom side solder ball formation remains a very complex issue and the ultimate solution has not been well established in the industry.

Figure 14 shows the flux residue rating of the 10 fluxes. None were rated poorly at a 5 level. It appears that the VOC-containing fluxes may leave more visually perceptible residues than the VOC-free fluxes. A general trend is noticed with residue ratings improving in the presence of cryogenic nitrogen versus air at this operating condition. Flux A-f, B-f and H-f have the lowest residue rating, with A-f having a better bridging performance. From inspection of the boards, it appeared that the fluxes with the consistently best residue rating exhibited poorer soldering performance. For the data in trial #1, the overall best VOC-free flux would be flux C-f. The data indicates no performance lost between VOC-free and VOC-containing fluxes.

Trial #2 is a more rigorous test of raw soldering performance of the fluxes tested due to the

Figure 12

### Wave Soldering Results—Bridging: Full Nitrogen Hood System

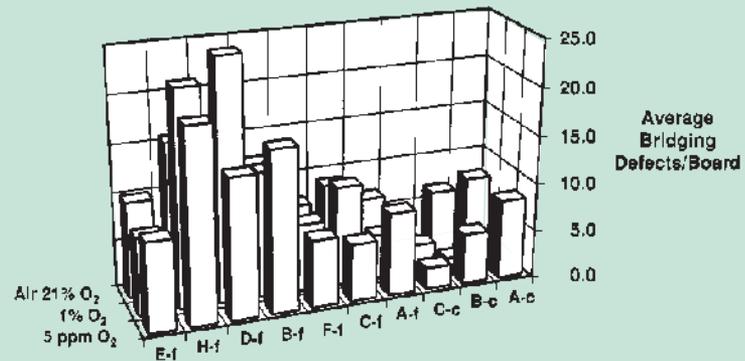


Figure 13

### Wave Soldering Results—Solder Balls: Full Nitrogen Hood System

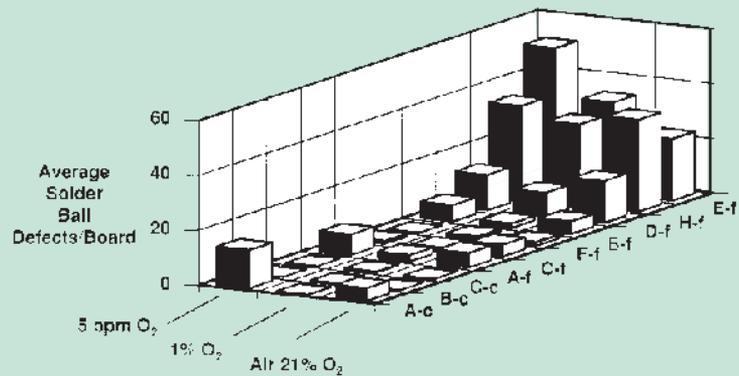
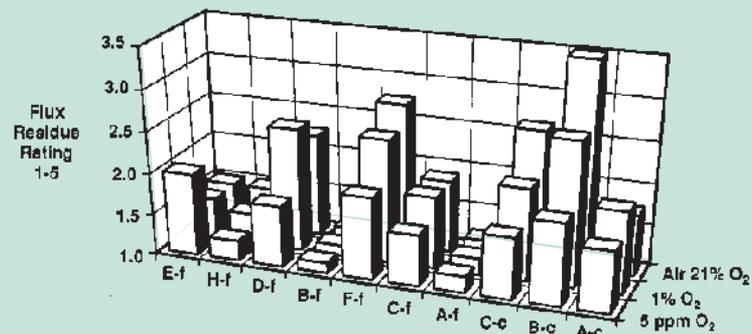


Figure 14

### Wave Soldering Results—Residue: Full Nitrogen Hood System



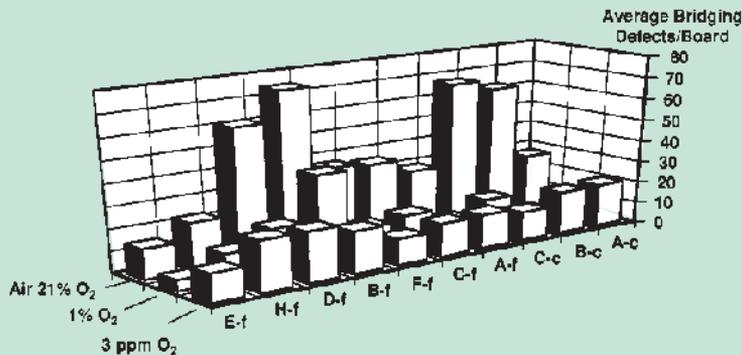
unique layout and bridging problems of this assembly. Figures 10A and 10B show what is defined as bridging “nodes”, where a bridge forms between three leads. In Figures 10A and 10B, notice the icicles which have formed. Icicling is a direct indication of flux performance when comparing fluxes, given all other soldering factors remain the same. Figure 15 shows the results for bridging. From inspection of the figure, one will observe a general increase in bridging from cryogenic nitrogen to air. The VOC-free fluxes performed equally as well as, if not better than, the VOC-containing fluxes. Of the VOC-free fluxes, A-f, C-f, F-f, and E-f performed the best for low bridging defects. It is clear that four fluxes performed meagerly in air: B-c, C-c, B-f, and D-f. For an optimum condition, the use of cryogenic nitrogen is required. Figure 16 shows the results of node bridging. These parallel the response of bridges from Figure 15, which again shows the general trend that bridging is reduced by controlling the oxygen in the process. The most important figure which best evaluates the raw performance of the various fluxes is Figure 17.

Figure 17 shows the response of icicles. No icicles were recorded when using cryogenic nitrogen. Several icicles were created using a 1% O<sub>2</sub> blend with fluxes B-c, C-c, F-f, and B-f. None of the fluxes resulted in defect-free boards when using air. The worst performing fluxes were B-c, C-c, C-f, and B-f. The high rate of icicles may indicate that the flux had been depleted during the slow travel through the solder wave. The use of cryogenic nitrogen in this case is extremely important in reducing icicles.

Figure 18 displays the pin through hole wetting rating. A rating of 1 is excellent, 3 is moderate and 5 is poor. All of the fluxes performed at least moderately well. The best performance once again was in cryogenic nitrogen. The best performers were fluxes A-c, A-f, C-f, and F-f. It has been reported that VOC-free fluxes may perform better for through hole wetting. This data indicates that several VOC-free fluxes outperformed their VOC-containing counterparts for PTH wetting when in the presence of cryogenic nitrogen.

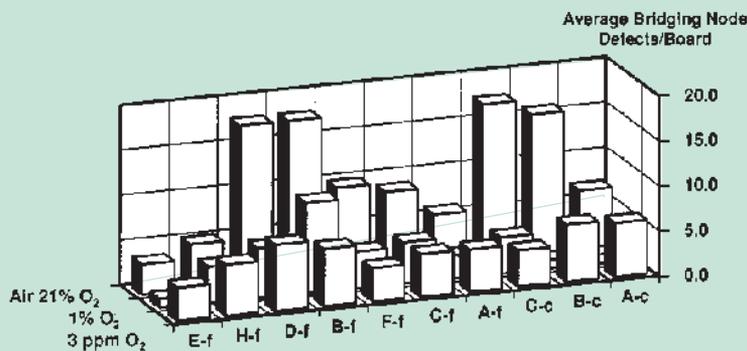
**Figure 15**

**Wave Soldering Results—Bridging: CoN<sub>2</sub>tour Nitrogen System**



**Figure 16**

**Wave Soldering Results—Node Bridging: CoN<sub>2</sub>tour Nitrogen System**



**Figure 17**

**Wave Soldering Results—Icicles: CoN<sub>2</sub>tour Nitrogen System**

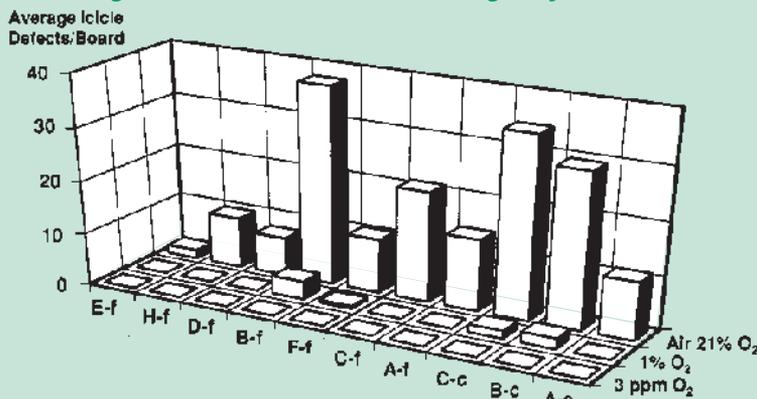
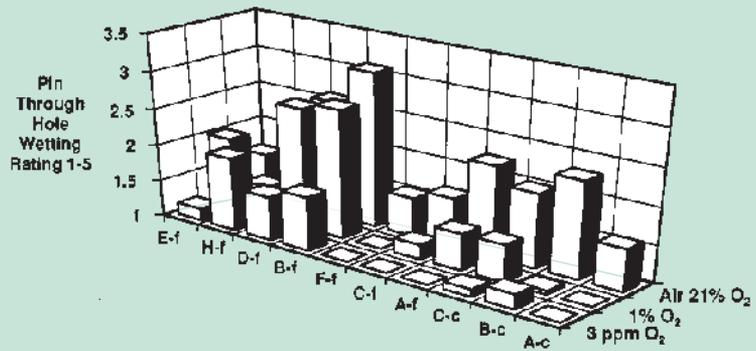


Figure 19 displays the solder ball defects per board. It appears that a trend towards fewer solder balls results when using air versus nitrogen. This agrees with the statement that: "The process is apparently more sensitive to solder ball formation and will under many conditions have more solder balls than a similar process performed at ambient conditions, all other parameters being equal."<sup>8</sup> It remains, however, that the solder balling phenomenon is a very complex problem and the adhesion of the solder balls to the resist is most likely not a function of the flux, but primarily a strong function of the solder mask and its properties: the hot air solder leveling flux, its cleanliness, prior thermal exposure and resist cure history.

Figure 20 reveals the flux residue ratings for trial #2. A trend is observed in that the residue appearance is improved in the presence of nitrogen and tends to increase when exposed to air. This correlates with the data from trial #1. The VOC-free fluxes have outperformed the VOC-containing fluxes, where the best fluxes for residues are A-f, C-f, and B-f. The results indicate that VOC-free fluxes will perform as well or better than VOC-containing fluxes.

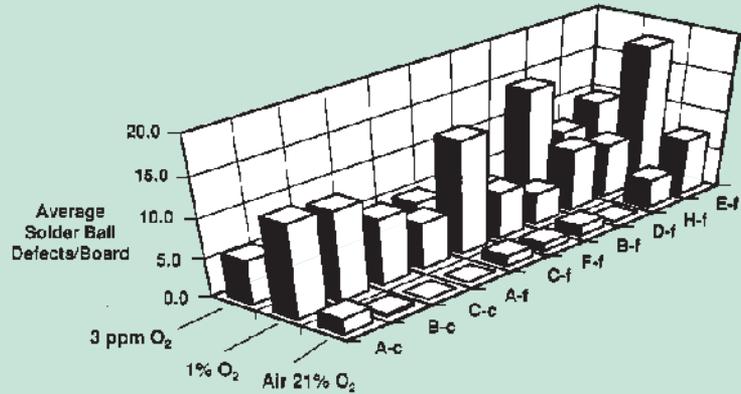
**Figure 18**

**Wave Soldering Results—PTH Wetting: CoN<sub>2</sub>tour Nitrogen System**



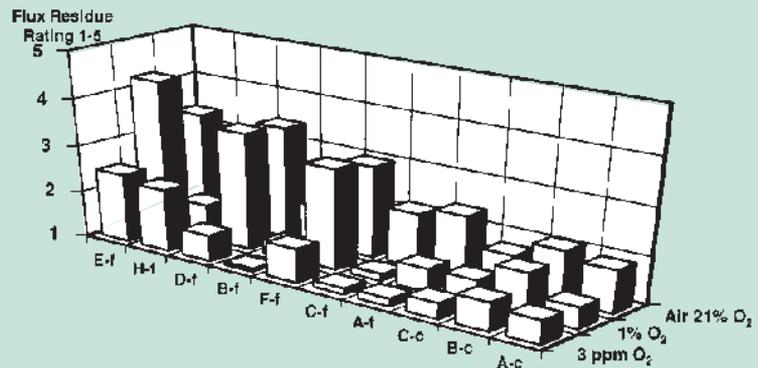
**Figure 19**

**Wave Soldering Results—Solder Balls: CoN<sub>2</sub>tour Nitrogen System**



**Figure 20**

**Wave Soldering Results—Flux Residue: CoN<sub>2</sub>tour Nitrogen System**



## Conclusions

The use of water-based VOC-free, no-clean fluxes removes the expensive requirement for BACT, gains compliance with air quality regulations, creates good working relations between the manufacturer and the AQMDs, mitigates fire hazards associated with flammable solvent-based flux systems, reduces flux loss due to evaporation, and lowers soldering defect levels. The use of VOC-free fluxes also minimizes the quantity of spent flux materials that must be disposed of as hazardous waste.

The raw soldering performance of VOC-free, no-clean fluxes challenges and surpasses the performance of VOC-containing fluxes. Based upon the production trials, any of the water-based fluxes tested would be suitable for use in wave soldering assembly operations. The performance of each flux is anticipated to improve after the process is optimized for its specific properties. However, the ultimate optimization occurs with the use of cryogenic nitrogen.

The use of wetting balance techniques can be a useful tool to evaluate the wetting performance characteristics of fluxes; however, as the data indicates, wetting balance results may not always be an accurate indicator for predicting the production performance of fluxes.

A comparison of the wetting balance performance data for water-based VOC-free fluxes and isopropanol-based VOC-containing fluxes shows that both classes of fluxes exhibit similar characteristics. Based on the results, VOC-free fluxes are suitable alternatives to VOC-containing flux formulations. Evaluation of several wetting parameters is recommended when comparing the wetting performance of fluxes. In this study, wetting force ( $F_{2\text{sec}}/F_{\text{th}}$ ), wetting time and wetting rate at  $\frac{2}{3} F_{\text{max}}$  were found to best characterize flux performance.

Many fluxes exhibit an improvement in the measured wetting parameters in controlled soldering atmospheres; however, the wetting performance of some fluxes is invariant to the oxygen content within the atmosphere.

In general, the consistency of the wetting balance performance data for the set of fluxes evaluated is improved by the use of low oxygen-containing soldering atmospheres.

As the oxygen concentration is decreased from 21% to less than 10 ppm  $O_2$ , the average performance of the ten fluxes is significantly improved. For example, the wetting force at two seconds as a percentage of the theoretical force increases by 49%, the wetting time at  $\frac{2}{3} F_{\text{max}}$  decreases by 26%, and the wetting rate at  $\frac{2}{3} F_{\text{max}}$  increases by 100%.

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**Table 1**

**Rosin vs. Resin Wetting Performance as a Function of Soldering Atmosphere**

Flux Type	Soldering Atmosphere	Wetting Force (mN)			Standard Deviation (mN)		Wetting Time (sec)		Wetting Rate (mN/sec)
		at 2sec	at $\frac{2}{3}$ Fmax	at Fmax	at $\frac{2}{3}$ Fmax	at Fmax	at Fzero	at $\frac{2}{3}$ Fmax	at $\frac{2}{3}$ Fmax
A-c	N <sub>2</sub>	7.86	6.34	9.51	1.45	0.79	0.50	1.06	6.42
	1% O <sub>2</sub>	7.05	6.50	9.75	1.37	0.53	0.63	1.50	4.45
	Air	5.77	6.16	9.23	0.93	0.43	0.88	2.88	2.10
A-f	N <sub>2</sub>	7.84	7.23	10.65	1.23	0.28	0.50	1.25	4.49
	1% O <sub>2</sub>	5.82	7.13	10.48	1.43	0.49	0.50	1.38	4.29
	Air	2.67	6.72	10.08	0.85	0.15	0.69	1.69	2.37
B-c	N <sub>2</sub>	4.99	6.77	10.12	1.05	0.51	0.94	1.69	4.11
	1% O <sub>2</sub>	5.31	6.85	10.27	1.47	0.32	0.94	1.63	5.06
	Air	5.01	6.47	9.71	0.66	0.28	0.88	1.75	3.18
B-f	N <sub>2</sub>	9.41	6.52	9.78	1.46	0.50	0.63	0.81	18.11
	1% O <sub>2</sub>	8.43	6.38	9.56	1.70	0.43	0.63	0.88	12.95
	Air	6.17	6.17	9.26	1.15	0.35	0.81	1.38	4.29
C-c	N <sub>2</sub>	6.26	5.91	8.86	2.27	0.71	0.69	1.25	4.64
	1% O <sub>2</sub>	4.85	4.52	6.79	1.43	1.29	0.75	1.25	4.09
	Air	0.03	3.40	5.10	1.67	1.28	1.38	1.94	3.23
C-f	N <sub>2</sub>	8.36	6.78	10.17	1.46	0.29	0.63	1.00	8.25
	1% O <sub>2</sub>	8.87	6.87	10.31	1.92	0.27	0.56	1.00	8.75
	Air	7.29	6.34	9.52	1.33	0.24	1.20	1.70	6.53
D-f	N <sub>2</sub>	6.40	6.14	9.21	1.27	0.59	0.50	1.25	3.00
	1% O <sub>2</sub>	8.24	6.29	9.43	1.18	0.50	0.44	1.38	2.26
	Air	5.35	4.91	7.36	1.46	0.65	0.75	1.19	2.03
E-f	N <sub>2</sub>	-8.37	5.35	8.02	1.52	1.46	2.38	3.56	3.76
	1% O <sub>2</sub>	-8.75	3.06	4.59	2.66	2.87	3.50	4.18	1.15
	Air	-9.32	3.59	5.39	1.90	1.97	2.94	3.69	1.15
F-f	N <sub>2</sub>	9.21	6.99	10.48	1.54	0.20	0.56	1.00	8.11
	1% O <sub>2</sub>	6.69	5.54	8.30	1.69	1.28	1.25	1.69	5.35
	Air	6.95	6.12	9.18	1.49	0.50	0.78	1.70	6.39
H-f	N <sub>2</sub>	7.29	5.72	8.58	1.11	0.81	0.56	0.81	8.04
	1% O <sub>2</sub>	8.22	6.07	9.11	1.45	0.87	0.50	0.81	8.33
	Air	6.00	6.04	9.06	0.75	4.99	0.81	1.38	3.17

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