QUALIFICATION OF NO-CLEAN MATERIALS AND PROCESSES FOR CLEANING OF PRINTED CIRCUIT BOARD ASSEMBLIES

The evaluation of a no-clean process involves both materials qualification and process qualification. Materials qualification includes not only testing the flux or paste for adequacy but considering numerous other factors, including solder joint quality, reliability, interaction with solder mask, long-term corrosion, cosmetics, and solder balling. Process qualification involves analyzing the board after soldering. Numerous factors can affect the quality and reliability of a solder joint, including material compatibility, component cleanliness, and soldering process variables. This section describes both the major considerations in qualifying no-clean fluxes and solder pastes and the recommended test methods and results required for qualifying a no-clean process. The flux testing results obtained by one telecommunications manufacturer are presented in Appendix D.

Material Screening

The qualification of a no-clean wave or reflow soldering process begins with a thorough screening of the materials (flux or paste). An preliminary screening is performed to determine whether or not the flux or paste will solder the components in question. This simple preliminary screening ensures that poor candidates are eliminated as early in the qualification process as possible, thereby eliminating unnecessary testing.

After the preliminary screening is completed, the manufacturer should be left with a small, manageable number of candidates. The next step in the materials screening process is to perform a variety of standard tests which have been designed to evaluate the effect of fluxes, pastes, and their residues on PCBs.

A large number of standard tests can be performed in order to screen out unacceptable materials. The recommended tests and required results differ depending on the application and the quality standards which apply. However, the following five tests are usually considered sufficient for qualifying most materials:

- Copper Mirror
- Silver Chromate
- Corrosion
- Surface Insulation Resistance (SIR)
- Electromigration.

There are two generally accepted sources for these test procedures. The first is the IPC-TM-650 test methods manual, published by the Institute for Interconnecting and Packaging Electronic Circuits (IPC). The second is Issue 3 (December 1991) of the Bellcore specification TR-NWT-000078.

To achieve the highest possible reliability, a flux or paste should achieve satisfactory results in each of these tests.

Copper Mirror Test. The copper mirror test is recommended as a test for the short-term corrosivity of a flux. Specifically, it is used to determine the level of copper removal caused by a flux. The test should be performed according to the methods described in IPC-TM-650, test method 2.3.32.

After the test is completed, the uncoated glass panel is visually inspected to determine the extent to which the flux induced corrosion of the copper. If there is any instance of complete copper removal on the test panels, the flux has failed the test.

Silver Chromate. The silver chromate test is the recommended test for determining the presence of halides (chlorides and bromides) in a flux. This test for halide content should be performed according to the procedures outlined in IPC-TM-650, test method 2.3.33. Test results are evaluated by visually inspecting the test paper to determine if any color change has occurred. If halides are present, the color of the test paper will change to off-white or yellow-white.

Corrosion Test. The flux corrosion test is recommended in order to determine the corrosive properties of flux residues which remain on the PCB after the soldering operation. While the copper mirror and silver chromate tests are chemical tests of the flux itself, the corrosion test evaluates the effect of the flux residue remaining after soldering. This test, which should be carried out in accordance with the procedures outlined in IPC-TM-650, test method 2.6.15, is especially useful for evaluating the corrosivity of flux residues under extreme environmental (temperature and humidity) conditions. In order to analyze the test results, the test specimens are examined under 20X magnification. The presence of a green-blue discoloration indicates corrosion. Other changes in color, however, do not necessarily indicate corrosion.

Surface Insulation Resistance (SIR) Test. The SIR test should be performed as part of the flux or paste qualification process to determine its long-term electronic reliability. SIR testing involves exposing standard test boards to temperature, humidity, and an electrical bias in order to determine board resistance. The test should be carried out in accordance with the procedure outlined in IPC-TM-650, number 2.6.3.3, or according to paragraph 13.1.4 of Bellcore specification TR-NWT-000078. To evaluate the acceptability of the results, they are compared to a standard value. Too low an SIR value indicates that long-term operation may cause circuit failure due to shorts.

As shown in Exhibit 9, the primary differences between the IPC and Bellcore SIR tests are the temperature settings and the length of time after which readings are taken. In the IPC test, measurements of the insulation resistance are taken after 1, 4, and 7 days at conditions of 85°C and 85 percent relative humidity. The test results are evaluated using the 4- and 7-day measurements. In the Bellcore test, measurements are taken after 1 and 4 days at 35°C and 90 percent relative humidity, with the 4-day result being used to classify the flux or paste.

While the IPC test does not specify exact minimum SIR values as pass/fail criteria, the Bellcore specification does. In the case of a test pattern with 0.050 inch spacing, a minimum resistance of 1×10^5 megohms is required to qualify the flux or paste. If the IPC-B-25 board is used (spacing of 0.0125 inches), a minimum resistance value of 2×10^4 megohms must be achieved.

Electromigration. The electromigration test should be carried out as described in the Bellcore document TR-NWT-00078, Issue 3. After the test is completed, the test samples are examined visually using back-lighting and 10X magnification. The product is said to pass the test if there is no evidence of electromigration that reduces conductor spacings by more than 20 percent. The test is considered a failure if heavy corrosion occurs, although minor discoloration is considered acceptable.

Process Qualification

The qualification of a no-clean wave soldering process depends on a wide variety of factors, including:

- Solderability
- Quality
- Cosmetics
- Testability
- Repeatability.

Since it is highly unlikely that a single flux will be superior in all of these categories, tradeoffs must be made selecting the correct flux for a given process.

Solderability. Solderability is the ability of a flux to aid in the formation of a solder joint. Solderability is not usually a significant problem when substituting a no-clean flux or paste for a traditional flux or paste, provided that soldering process parameters are correctly adjusted and adequately monitored.

Just as important as the flux and paste is the solderability of the components which are being soldered to the board. In order to maintain board cleanliness and overall solderability, all

Exhibit 9

Comparison of IPC and Bellcore SIR Testing Procedures

Parameter	IPC-SF-818	Bellcore TR-NWT-000078 (Issue 3)
Test Pattern	IPC-B-25, B comb	IPC-B-25, B comb (0.0125 inch spacing), or 0.050 inch spaced board
Temperature	85°C ± 2°C[1]/50°C[2]	35°C ± 2°C
Humidity	85 percent[1]/90 percent[2]	90 percent
Testing intervals	24, 96, and 168 hours	24 and 96 hours
Passing results	$1x10^2$ megohms	IPC-B-25: $2x10^4$ megohms 0.050 in: $1x10^5$ megohms

[1] Class III only.
[2] Classes I and II.

components and the board itself must be clean. Due to the reduced solids content of the flux used in a no-clean process, pre-solder cleanliness of components becomes a major factor in maintaining the solderability of the board. You must ensure that your suppliers provide you with sufficiently clean and solderable components since they will not be cleaned later in the assembly process.

Quality. The quality of a soldered board is a measure of the defect rate and is obviously the most important consideration in qualifying a no-clean wave or reflow soldering process. Bridges, skips, webbing, and other defects should be closely monitored in qualifying a process and in normal operations.

Cosmetics. The overall visual appearance of a board after soldering is an important consideration in qualifying a no-clean flux. Cosmetic appearance does not affect the reliability or quality of a soldered board.

However, cosmetics are the primary reason for some manufacturer's choice not to switch to a no-clean flux. In the case of high-solids no-clean fluxes, cosmetics are the major factor contributing to their lack of large-scale penetration into the American manufacturing market. Conversely, these fluxes have gained widespread acceptance in Europe. While the use of no-clean fluxes may leave a visible residue on the board, the residues are most often benign and, given good flux selection, do not affect board performance or reliability. Controlling the amount of flux applied to the board impacts the amount of final residue. Thus, proper application can minimize the amount of residue.

Testability. Testability is a measure of the ability to accurately test the electrical performance characteristics of the board after assembly and soldering. Testability often depends on clean solder connections if pin-test fixturing is used.

Repeatability. The term repeatability refers to the ability to produce the same quality of board regularly with few modifications to process parameters. Repeatability is essential in maintaining efficiency in the soldering process. A soldering process which varies regularly will require that production be stopped frequently to adjust the appropriate parameters and re-test the operation.

Repeatability will often be more difficult to obtain with a no-clean process than with a traditional soldering process because of two factors. These include:

- the small process window within which the no-clean process is carried out
- the frequent monitoring and process auditing required because of the components' sensitivity to change.

These audits, however, ensure that all applicable parameters are at optimal levels to carry out the soldering operation.

ECONOMICS OF NO-CLEAN PROCESSES

Each of the no-clean processes described in this manual has associated costs (both fixed and variable) and offsetting benefits. This section describes, for each no-clean process, the average cost of implementing the process as well as any benefits which might result from its use.

Regardless of the no-clean process which is utilized, the largest benefits realized occur from the complete elimination of the cleaning process. Thus, facilities which switch to a no-clean soldering process save both the capital cost of cleaning equipment and floor space, and the material and operating costs associated with the use of the cleaner, including the elimination of solvent disposal.

No-Clean Wave Soldering

Each of the options for instituting a no-clean wave soldering operation (eliminate cleaning, change flux, change flux application method) at the least eliminates entirely the post-solder cleaning step, resulting in savings in equipment expenditures, solvent purchases, and solvent disposal costs. This section describes the costs associated with each of the no-clean wave soldering options presented earlier in the Process Details section of this manual.

No-Clean Wave Soldering in Air

No-clean fluxes (low- or high-solids formulations) can sometimes be substituted directly for traditional fluxes with no additional process changes. In this case, an overall savings usually results since both the solvent and cleaning equipment costs are eliminated.

In instances where a manufacturer wishes to retrofit existing wave soldering equipment for use with a spray fluxer, there is a cost associated with the purchase of this new equipment. Spray fluxers are produced as stand-alone units by several manufacturers and costs range from approximately $4,500 to $20,000. There are additional benefits associated with the use of a spray fluxer because, due to the controlled nature in which a spray fluxer applies flux to a board, a smaller quantity of flux is consumed over any given period of time. One manufacturer, for instance, has seen a flux savings of 68 percent by switching to a spray fluxer. In addition, many spray fluxers eliminate the use of flux thinners.

Retrofitting Equipment for Controlled Atmosphere Soldering

No-Clean wave soldering in a controlled atmosphere may be accomplished by retrofitting existing equipment with a device such as a hood or other innovative technique which permits nitrogen inerting.

Depending on the type of hood chosen, the capital cost of retrofitting existing equipment typically totals between $10,000 and $30,000 for the addition of a nitrogen hood. The lower cost is associated with a nitrogen hood that covers the solder pot area only, while a hood which covers the preheat and solder areas brings the cost to the higher end of the range. Additional costs arise in the installation of piping to carry the nitrogen to the soldering machine. Installed piping costs an average of $30 per foot, but can range from $15 to $50 per foot. The total cost of piping depends on the distance which the nitrogen is piped.

Purchasing nitrogen is another cost which primarily depends on the size of the area to be controlled as well as the amount of time during which the machine is operational. The amount of nitrogen required in these machines is usually in the range of 1500 to 2000 cubic feet per hour (cfh) and the cost of industrial grade nitrogen purchased in bulk ranges from approximately $0.12 to $0.50 per 100 cubic feet (note that this cost varies with the grade purchased and the country in question). In some newly designed retrofit packages, the amount of nitrogen required has been as low as 300-600 cfh.

Economic benefits from retrofitting existing equipment for no-clean wave soldering in a controlled atmosphere include the elimination of the cleaning process as well as the potential for substantial savings in flux and solder usage. The experience of several manufacturers has shown that flux and thinner savings in the range of 50 to 70 percent are possible with the addition of a spray fluxer and soldering in a controlled atmosphere. In addition, a 50 percent reduction in the amount of solder used is also feasible since solder dross is often greatly reduced. A breakdown of traditional soldering costs by component is shown in Exhibit 10.

New Equipment Options

The purchase of new equipment which is specially designed for controlled atmosphere wave soldering will be significantly more costly than retrofitting existing equipment. As mentioned earlier, two
types of equipment are available -- open-tunnel and sealed-tunnel machines. A typical open-tunnel wave solder machine has a capital cost of $80,000 to $300,000. The range in cost is due to the large number of options available, including spray fluxing modules, extra preheaters, computer controls, oxygen analyzers, and bar code scanners. Nitrogen usage in open-tunnel machines is generally between 700 and 2400 cfh.

A sealed-tunnel wave solder machine will often be more expensive than an open-tunnel machine. Unlike open-tunnel machines, there are very few manufacturers of fully enclosed soldering equipment. A typical model, which costs in the neighborhood of $300,000, consists of a spray fluxing module, preheaters, a solder module, and entrance and exit vacuum chambers. Additional options for these machines such as oxygen analyzers and bar code scanners can add approximately $30,000 to the capital cost. Nitrogen usage in a sealed-tunnel machine ranges from 100 to 700 cfh.

The benefits which can be achieved from conducting soldering operations in a controlled atmosphere include the costs associated with the cleaning process which would have otherwise been required as well as flux and solder savings. In the case of both the open-tunnel and sealed-tunnel machines, flux savings can be as high as 70 percent (depending on the flux application method used), and solder savings can be as high as 50 percent.

No-Clean Reflow Soldering

The most cost effective method for converting a traditional reflow soldering operation to a no-clean operation is to use traditional pastes without post-solder cleaning. In this case, there are no additional costs incurred, and the expenses associated with the purchase and operation of cleaning equipment are saved. If this change does not produce acceptable results, the implementation of a low-residue paste may affect the process cost. The cost of a low-residue paste may be higher than that of conventional pastes because it is produced in smaller quantities. In addition, new stencils may be required for use with low-residue pastes.

Retrofitting Equipment for Controlled Atmosphere Soldering

A controlled atmosphere can often be employed in existing reflow ovens by performing retrofits to ensure that nitrogen is adequately confined to the soldering area within the oven. This retrofit involves ensuring that the equipment is leak-free as well as installing nitrogen supply pipes from a tank to the soldering machine. Depending on the size of the oven, the cost of such a retrofit can range from $20,000 to $100,000.

In general, it takes approximately one week to retrofit an oven so that it can accommodate a controlled atmosphere. An oven which has been retrofitted typically consumes approximately 2400 cfh of nitrogen and can achieve an oxygen level of

Exhibit 10

less than 500 ppm, although actual nitrogen consumption and oxygen levels will depend on the degree to which the tunnel has been successfully sealed as well as the flux or paste being used. The work atmosphere must maintain a sufficiently high level of oxygen to ensure worker safety.

New Equipment Options

In cases where it is not possible to retrofit existing ovens to adequately seal nitrogen within the tunnel, a nitrogen-dedicated oven can be purchased. These ovens are specially designed for use with a controlled atmosphere and therefore consume less nitrogen while achieving lower levels of oxygen. The cost of a new oven with nitrogen capabilities can range from approximately $75,000 to $175,000. These ovens consume approximately 2000 cfh of nitrogen and can limit oxygen levels to less than 20 ppm.

ENVIRONMENTAL, HEALTH, AND SAFETY ISSUES

Several issues relating to the environment, human health, and safety must be considered when evaluating the various no-clean soldering processes available. These are:

- Volatile organic compound (VOC) emissions
- Waste disposal
- Worker comfort and safety

Regardless of the process used, the primary environmental benefit realized is the elimination of CFC-113 and methyl chloroform (MCF). Not only will the reduced use of CFC-113 and MCF have a significant effect on ozone layer depletion, but, since these compounds are greenhouse gases, their elimination will help to mitigate potential global warming problems. Other environmental, health, and safety issues depend on the soldering process chosen.

Environmental Issues

In addition to the effects of eliminating the impacts of CFC-113 and MCF on ozone depletion and global warming, there are additional environmental issues to consider including emissions of volatile organic compounds and waste disposal.

Volatile Organic Compounds (VOCs)

VOCs are gases released into the atmosphere at normal use temperatures during the soldering process. VOCs contribute to the formation of ground-level ozone (smog). When compared with a traditional soldering and solvent cleaning operation, a no-clean soldering process results in an overall reduction in VOC emissions. VOC emissions are increased from the use of low-solids fluxes which contain 0.5 to 5 percent solids as opposed to nearly 40 percent solids in traditional fluxes. The remainder of the low-solids formulation is approximately 1 percent activator and the balance is comprised of alcohol (usually isopropyl alcohol). Therefore, depending on the alcohol used in a given flux formulation, VOC emissions from low-solids no-clean fluxes may be higher than those from traditional flux. However, the elimination of the CFC-113 and MCF solvent cleaning process will result in an overall reduction of VOC emissions from board assembly processes since both have traditionally been combined with an alcohol. In addition, the use of a spray fluxer and/or a controlled atmosphere may decrease flux usage by approximately 50 percent, thereby reducing VOC emissions. The net reduction in VOC emissions will depend on the solids content of the flux and the cleaning process being eliminated.

Waste Disposal

The U.S. Environmental Protection Agency (EPA) classifies solder dross as a hazardous waste under the Resource Conservation and Recovery Act (RCRA). When compared with conventional wave soldering operations, using no-clean fluxes results in little change in the amount of solder dross produced. In the case of controlled atmosphere soldering, however, the reduced concentration of oxygen present during the soldering operation results in the formation of substantially less solder dross, thereby reducing the amount of hazardous waste produced.

In addition to a reduction in solder dross waste, the elimination of the post-solder cleaning processes will further reduce waste disposal needs for assembly plants by eliminating disposal of spent solvents or wastewater.

Health and Safety

There are several issues associated with no-clean soldering processes which may affect the health and safety of workers. These include formic acid usage in some controlled atmosphere processes, prolonged exposure to high-alcohol content fluxes, and reduced oxygen atmospheres.

Formic Acid

Formic acid is currently used as a reducing agent in a small number of controlled atmosphere soldering processes, often those where strict soldering standards exist. Formic acid can have potentially serious health effects for workers. Therefore, the U.S. Occupational Health and Safety Administration (OSHA) has set a mandatory Permissible Exposure Limit (PEL) of 5 ppm for formic acid. The careful handling of formic acid is critical. Spills may result in the need to evacuate the manufacturing facility, resulting in a work stoppage that may last for several hours. Besides the hazard of formic acid itself, metal formates are produced as a by-product of the use of formic acid in soldering processes. These waste products require that workers clean the soldering equipment regularly, thereby increasing their exposure to lead and requiring that all work be stopped during the cleaning process. While the cleaning of equipment is more frequent when formic acid is used than when it is not, the frequency of cleaning when formic acid is used is still over 50 percent less than in machines used to solder in air atmospheres. In any processes where formic acid is handled or used, safety showers, eye wash stations, and respiratory protection must be available.

Flux Exposure Issues

In facilities where production lines are modified for the use of spray fluxers, precautions must be taken to ensure that any overspray of flux is contained under an exhaust hood. The fumes from excess flux, if not properly recovered, can cause heart irritation and lung damage as well as headaches and upset stomachs. Spray fluxers are generally equipped with a timer and sensor which switch the spray on when a board arrives, and turn the spray off as the board leaves the fluxing zone. This mechanism helps to minimize overspray and reduces the hazards posed by flux exposure. In addition, because of their high alcohol content, liquid fluxes are often extremely irritating to the eyes and skin with repeated or prolonged contact. In order to protect against these hazards, the use of protective gloves and safety goggles is recommended.

Regardless of the flux application method employed, workers on production lines which utilize no-clean flux formulations may experience discomfort due to odor. The high alcohol content of no-clean fluxes contributes to this strong odor. Adequate workplace ventilation is required to ensure worker safety and comfort.

Reduced Oxygen Atmosphere

Another worker safety issue results from the use of controlled atmosphere soldering equipment. If not properly controlled, the presence of nitrogen results in a deficiency of oxygen, thereby posing potential danger to workers near the machine. Workers must be sure that they do not place their heads inside machinery where a nitrogen atmosphere is being maintained. Doing so could result in the worker receiving insufficient oxygen and blacking out. Potential users of controlled atmosphere soldering should consult with the nitrogen supplier as well as the equipment manufacturer concerning the possible hazards associated with the handling and use of nitrogen. In addition, facilities must ensure that adequate ventilation is present in the area in which the nitrogen atmosphere is to be used.

MANUAL SUMMARY

This manual provides a structured program to evaluate the feasibility of a change to a no-clean soldering process. It also provides a methodology for evaluating a variety of no-clean soldering options. This information includes:

- An overview of the currently available no-clean technologies
- Major characteristics of the various types of no-clean soldering processes
- Detailed information on procedures to determine the applicability of a no-clean option in a specific manufacturing process
- Data on the cost of implementing the various no-clean options
- Information on environmental, health, and safety issues associated with no-clean processes.

The next section builds on this basic understanding of no-clean soldering processes and presents detailed case studies of these applications as they are implemented in industry.

CASE STUDIES OF INDUSTRIAL PRACTICES

The following section presents actual industrial experiences with some of the alternative technologies discussed earlier in this manual.

Mention of any company or product in this document is for informational purposes only and does not constitute a recommendation of any such company or product, either expressed or implied by EPA, ICOLP, ICOLP committee members, and the companies that employ the ICOLP committee members.

Case Study #1:	No-Clean Wave Soldering in a Controlled Atmosphere Environment
Case Study #2:	An Alternative Testing Method To Qualify No-Clean Processes
Case Study #3:	Evaluation of No-Clean Processes at AT&T
Case Study #4:	Flux Selection Criteria
Case Study #5:	Spray Fluxing for Today's Soldering Processes
Case Study #6:	Choice of a No-Clean Process at NCR.

CASE STUDY #1: "NO-CLEAN" WAVE SOLDERING IN A CONTROLLED ATMOSPHERE ENVIRONMENT

Motorola (Government Electronics Group) joined in a Cooperative Research and Development Agreement with Sandia National Laboratories and Los Alamos National Laboratory to evaluate a no-clean solder materials system for military applications. The study evaluated the physical, chemical, electrical, and long term aging effects of the no-clean system under varying environmental conditions and using various materials and concentrations. After evaluating systems, the research group proposed using low-solids adipic acid and gaseous formic acid materials as an alternative for the rosin flux process which required cleaning after wave soldering.

The adipic and formic acid materials system has been used successfully as a no-clean application in many commercial installations. Although Motorola has six machine/material installations similar to the one described here, none of the installations has been evaluated for use in military applications.

In this study, tests to evaluate ionic cleanliness, chemical residues, and surface insulation resistance (SIR) were performed on three different printed wiring board (PWB) designs. These designs also included a group of electronically functional boards that were subjected to an accelerated aging test to simulate 20-year long-term storage conditions.

The IPC B-24 comb pattern circuit board served as the SIR test vehicle; a general purpose Motorola Test Board (MTB) designed for through-hole assembly served as a vehicle for ionic cleanliness as well as chemical and physical testing; and a high-volume production FMU-139 bomb fuse board served as the functional vehicle for long-term storage testing.

A series of designed experiments subjected the test boards to a broad array of process variables, including normal process conditions and concentrations of adipic and formic acids.

Evaluation of the Effects of Wave Solder Machine Parameters

The wave soldering machine used during this program has several key features, including three independent conveyors (flux, preheat, and solder), a dual wave (turbulent chip and laminar), and an ultrasonic spray head for the adipic acid flux. The extent to which the various tests could be controlled allowed the research group to methodically evaluate the machine parameter effects. The soldering process has many different controllable parameters that influence the visual solder quality and ionic cleanliness of the PWB. All of these parameters were evaluated with the designed experiments. The parameters include:

- Flux conveyor speed
- Preheat conveyor speed
- Solder conveyor speed
- Solder pot temperature
- Wave angle
- Turbulent wave on/off
- Adipic acid percentage
- Formic-nitrogen flow.

Experiments

The effects of machine parameters were evaluated to determine their contribution to PWB cleanliness and electrical performance. Because of the complexities of the PWB design, no single setting for machine parameters will provide uniformly high visual quality for all products. To evaluate as broad a group of settings as possible, the experiments were designed to use a realistic range of levels for machine parameters. The levels evaluated represented the extreme levels that would potentially be used in processing PWBs.

The effect of each of the designed experiments were analyzed, and the subsequent experimental design was based upon this analysis. With the exception of the initial screening experiment, two PWBs per cell were used in all of the tests. This format not only allowed the research group to evaluate a broad range of machine parameters, but also yielded a significant amount of information on the process and material effects.

The study assessed three different PWB designs. The factors and extreme levels for all of the parameters evaluated in the experiments are presented in the following table:

Factors	Low	High
Flux conveyer speed	0.8	1.4 meter/minute
Preheat temperature	80	130 degrees C
Time in solder pot	1	4 seconds
Adipic acid concentration	1	2 percent
Nitrogen flow in formic acid	None	7 liter/min. nitrogen
Wave angle	5	9 degrees
Solder pot temperature	245	260 degrees C

The low and high levels of the factors shown above are composites of all the levels evaluated. An RMA flux was used as a control for this series of experiments.

Specific test objectives were to demonstrate that the process could produce hardware that:

- meets the military specification limits for ionic cleanliness and SIR
- does not degrade during typical environmental conditioning
- does not degrade with long-term storage.

Experiment Designs

The initial experiment consisted of a half fraction 2^5 screening experiment to evaluate the impact of process parameters on solder joint quality and ionic cleanliness. The FMU-139 bomb fuse PWBs, which were used to run this initial test are double-sided, 0.092 inch thick boards for solder joint quality and had their contamination levels measured in a Model 500R ionograph. The results from the initial screening were analyzed and provided inputs for additional work evaluating long-term storage characteristics.

The data from the first experiment provided direction to form the basis for setting the levels for the Long-Term Storage (LTS) test conditions. This experiment used machine parameters that produced low (3 to 5 micrograms sodium ion equivalent), medium (5 to 7 micrograms sodium equivalent), and high (20 to 30 micrograms sodium equivalent) ionic contamination on FMU-139 bomb fuse boards.

The FMU-139 bomb fuse boards were electrically functional and used to evaluate the effects of cleanliness on degradation of electrical performance in LTS conditions. In this portion of the evaluation, three different machine parameters were used to run the boards over the wave. Control boards for the long-term storage test used an RMA flux as a control. The boards from this experiment were subjected to an environmental stress test to simulate 20 years in storage -- 80°C at 40 percent humidity for 2,522 hours.

The second experiment used the MTB as the test vehicle. The MTB is a double-sided, 0.062 inch thick PWB, designed for through-hole components such as axial, DIP, TO-99 components, and connectors. The MTB has dry film solder mask on both sides and was specifically designed to support wave soldering process development. A 2^5 full factorial experiment, which gave a 64 cell experiment with two boards per cell, was used during this portion of the testing.

After running through the cells in the experiment, the MTB boards were subjected to ionograph testing and visual examination. After environmental conditioning, the components on the MTB were tested electrically and mechanically.

The third experiment evaluated the effects of machine settings on two PWB designs used in this series of testing -- MTB and IPC-B-24 boards. In this experiment, the boards were subjected to ionic cleanliness testing, visual inspection, chemical surface analysis via high pressure liquid chromatography (HPLC), electron microprobe analysis (EMPA), scanning Auger microscopy (SAM), secondary ion mass spectroscopy (SIMS), and Fourier transform infrared spectroscopy (FTIR).

Results

The results from the testing show that the no-clean soldering process is capable of producing reliable hardware whose visual quality is equivalent to that achieved with the existing rosin-based flux followed by cleaning.

The results from these tests were obtained from experiments designed to incorporate a wide range of machine control parameter settings. The levels evaluated represent the extreme limits of those that could potentially be used in processing PWBs.

The data from each of the experiments support these conclusions with very few anomalies. The results from the testing were reproducible and predictable. Level settings for factors were adjusted based upon statistical evaluations of test data with the subsequent PWBs having levels as clean as those obtained using rosin-based flux processes.

SIR

The standard SIR test as described in the IPC Test Method 650 Number 2.6.3.3 was used for this evaluation.

A total of 95 IPC B-24 boards from eight cells were subjected to SIR testing, with only six boards having low SIR values after 4 to 7 days of testing. Two temperature/humidity profiles were run in the SIR testing on separate groups of boards (85°C/85 percent relative humidity and 50°C/90 percent relative humidity for 21 days each). Exhibit 11 shows SIR data from day seven of the SIR test.

Exhibit 11

SIR Values of Boards from DOE Cells

The results from the SIR testing indicate that there is a sensitivity to machine parameters and that the boards soldered and not cleaned using adipic and formic acid materials provide SIR results as good as or better than PWBs soldered with an RMA flux and cleaned with methyl chloroform. A MTB was run using the same soldering conditions as each IPC B-24 board. This "witness" MTB provided the relative ionic cleanliness for the B-24 boards run in each DOE experiment cell. Thus, the research group was able to link the SIR test data with ionic cleanliness data for each of the cells.

Ionic Conductivity

The MTB tests provided data for ionic conductivity by acting as a common vehicle to assess ionic cleanliness in all experiments. The MTB provided a common reference point for review of data from experiment to experiment and cell to cell. Additional ionic conductivity verification testing was performed by the Navy EMPF facility in Indianapolis, IN. The results from this testing indicate that the conditions under which the wave soldering machine operates can radically affect the resultant cleanliness of a PWB. The testing conducted by the EMPF for the ionic conductivity readings verified the results obtained by Motorola. The results observed in this portion of the test indicated that ionic cleanliness varied from an average of near 3 micrograms equivalent sodium ion to a high of near 25. The results were both predictable and reproducible. This data is shown in Exhibit 12.

Exhibit 12

Ionic Cleanliness

Chemical Surface Contamination Analysis

The IPC Honeywell 355 HPLC procedure was modified to analyze the surfaces of the PWBs for traces of adipic and formic acid residues or their salts. The modified test was sensitive to as low as approximately 40 micrograms per square centimeter of adipic acid or its salts. Barely detectable trace amounts of adipate salts were found on the board. Subsequent FTIR and SIMS analysis also confirmed very low levels of residue. The Naval Weapons Center at China Lake, CA ran independent FTIR testing on samples and concluded that there appeared to be no significant residues present on the boards.

Temperature-Humidity and Temperature-Conditioning Test Results

No corrosion was observed when the boards were subjected to visual inspection under 10X magnification. Solder joints were evaluated for corrosion or cracking by four point Kelvin measurement. No significant shifts in the resistance values of the solder joints were observed.

Long-Term Storage Electrical Function

Forty of the FMU-139 bomb fuse boards were subjected to the long-term storage testing (30 from the adipic/formic acid process and 10 from the control group -- rosin flux process). The boards were placed in an environment of 80°C and 40 percent relative humidity for a total of 2,522 hours. These conditions simulate a 20-year long-term storage of these boards. The boards were pulled from the test chamber for verification of electrical function at discrete intervals of 126, 1,260, 1,639, and 2,522 hours. All boards tested functionally operable up to the 1,639 hour point (equivalent life of 13.3 years in storage). Some time after the 1,639 hour samples were pulled and tested, the environmental chamber control failed and the humidity in the chamber went to 100 percent. This caused water to drip down into the chamber on several of the boards at a continuous rate. It is estimated that, at this point, the life stress testing exceeded well over 100 years of storage. This overstress resulted in three boards from the adipic acid group failing the final electrical test and two rosin fluxed boards showing substantial visual corrosion damage. All of the boards that failed during the last portion of the test had water stains, attesting to the fact that they were directly under the leak in the chamber. The cause of the failure in these boards could be traced to the same mechanism: a specific single ceramic-bodied diode whose leads corroded and whose lead seal failed and allowed moisture into the diode cavity in the package. No other components failed or showed evidence of any problems. Even with the significant environmental overstress, the test results, based on the results obtained from the remaining boards that were not directly under the leaking reservoir, provided valuable positive information regarding the benign nature of the adipic/formic acid process.

Conclusion

The results from this series of tests are clear: adipic and formic acids are materials that are safe and beneficial to the wave soldering process and do not require cleaning after solder assembly. The products soldered with the adipic and formic acid materials exceeded the product design criteria by more than a 30 percent margin. The use of a controlled nitrogen atmosphere provides an environment where adipic acid can successfully and safely serve as a no-clean flux. This conclusion is supported by all of the data from the ionic conductivity test results to the SIR and long-term storage test results. The solder joints obtained with the adipic/formic acids have the same high quality visual appearance of solder joints formed with RMA fluxes. In addition, the adipic/formic materials do not degrade circuit performance and the residues do not require cleaning.

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CASE STUDY #2: AN ALTERNATIVE TESTING METHOD TO QUALIFY NO-CLEAN PROCESSES

In late 1991, Northern Telecom announced that it had eliminated the use of ozone-depleting solvents from its manufacturing facilities worldwide. This case study describes a unique testing method developed at one of Northern Telecom's facilities and its use as an audit tool for a specific no-clean process.

The Problem

In an effort to eliminate the use of ozone-depleting substances (ODSs) in solvent cleaning applications, the research team at Northern Telecom's Research Triangle Park (RTP), NC facility elected to implement a no-clean soldering process. In converting to the no-clean process, engineers at RTP were faced with the task of choosing an appropriate low-solids flux to be used in place of their conventional flux. The identification of an acceptable flux involved two stages -- the flux selection and flux testing/qualification.

While flux selection criteria assured that the flux used was totally safe, problems with the Final Inspection Quality Group (FIQC) often developed. The most frequent problem identified by the FIQC involved the amount of residue left on the wave soldered boards after using the low-solids flux. The amount of residue was significant enough to leave an easily perceivable tack. Different engineers, using different process parameters and taking samples at different times, achieved varying results when performing post-solder quality testing. These differing results proved to be very disruptive to the production process.

The Solution

In an effort to design a test for board tack which would produce reliably repeatable results, John Peterson, the senior chemist at the RTP facility, constructed a patented "dust box machine." It was decided that the most accurate way to measure the tack of a board is to determine the amount of powder that would stick to a sample board after wave soldering with a given quantity of flux.

The dust box, shown in Exhibit 13, is a device which applies a fine spray of powder to the surface of a printed circuit board. The device is comprised of several parts: an enclosed test chamber, a mechanism to introduce the powder into the chamber, and a fan to disperse the powder.

Selecting an appropriate powder was a unique challenge in and of itself -- weight, safety, and adhesion to board surfaces all posed problems. Calcium carbonate was eventually chosen. Pass-fail criteria were determined by a general consensus of manufacturing and quality engineers after they were presented with a wide variety of test samples.

The Test Process

A test coupon made of normal production board material with solder mask applied is precleaned, run through the normal manufacturing process (including fluxing, preheating, and wave soldering), and weighed. The weight is recorded and the test coupon is placed in the dust box machine for exactly two minutes, during which time the fan blows the calcium carbonate dust onto the test coupon at a constant rate. The test coupon is then removed from the chamber and re-weighed to determine whether the amount of powder that has stuck to the board is acceptable. The exact test procedure is as follows:

exhibit 13

Dust Box Test Procedure

1. Clean an IPC-B-25 test coupon with solder mask with an alcohol rinse
2. Run the clean coupon through the current production process with the solder mask side down
3. Weigh the coupon after processing
4. Record the weight (W1)
5. Place the coupon into the dust box with the flux side facing the fan
6. Close the dust box door and turn on the switch
7. Run the fan for two minutes
8. Remove the coupon from the dust box and record its weight (W2)
9. Calculate percentage weight gain as: {[(W2-W1)/W1] x 100}.

In order to determine the acceptable amount of flux residue which could be allowed to remain on the boards after soldering, the boards were run using differing degree of flux concentration. Results must be related to a flux type and specific quality criteria. The Northern Telecom levels for one flux are as follows:

Percent Weight Gain	Classification
0.0% - 0.5%	Pass
0.51% - 0.8%	Marginal Pass
0.81% - higher	Fail

Acceptability criteria such as these were determined for each manufacturing line depending on the product and quality control requirements of the line.

The total cost of the dust box testing is approximately $3,500 ($1,000 for the dust box and $2,500 for a laboratory scale). Both are one-time capital costs.

Results and Benefits

Several benefits were realized by using the dust box as a tool to measure board tack. First, the tests yielded quantitative, repeatable results when compared with the previous subjective evaluations. Second, by achieving an accurate measure of board tack, the wave solder parameters could be accurately adjusted to result in fewer flux-related soldering problems. Finally, for the specific flux tested, Northern Telecom found that traditional SIR test results correlated well with the tack results produced by the dust box.

The correlation of dust box test results with results from SIR tests may be of particular interest to small manufacturers, many of whom cannot afford the expensive equipment necessary to perform tests such as SIR. Throughout the implementation of the no-clean processes at the RTP facility, seven production lines were monitored for several months, and the correlation between board tack, SIR, ionic contamination, and flux deposition rate was analyzed. Any one of the tests could be used as a stand-alone method to audit process control while using no-clean fluxes. Because of the relatively low cost of the equipment used in two of the tests, overlapping tests were run to increase the confidence of the results.

Deposit rate testing, which is no more than calculating the weight difference in flux solids left on a mylar sheet, correlated well with solvent extract testing. Flux deposit testing can easily be done by production staff, with a laboratory scale costing less than $3,000. Mylar sheets are inexpensive, and a test can be completed in less than five minutes.

Using the dust box, SIR testing can be correlated to a specific flux type and to a board tackiness. SIR tests require expensive environmental chambers, time, and specially trained staff. The dust box test method, whose equipment can be purchased for under $3,500, can be run in under 15 minutes by machine operators or lab technicians.

Conclusions

In the process of converting from soldering with solvent cleaning to a no-clean soldering process, Northern Telecom designed two inexpensive but effective audit methods to predict board quality. The dust box is a product quality audit tool and the flux deposit testing is a process audit tool. Once correlated to a given flux, both devices quickly and easily predict production quality. The simplicity of the tests allows them to be conducted as often as needed at little cost. Although not a replacement for typically used SIR tests, they have proven to be very predictable for specific fluxes.

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CASE STUDY #3: EVALUATION OF NO-CLEAN PROCESSES AT AT&T

At AT&T, materials used in soldering processes are carefully evaluated to ensure product reliability and compatibility with manufacturing processes. AT&T tests fluxes, pastes, and their residues to determine their ability to corrode copper mirrors or plates and their halide content, pH level, and conductivity. In addition, AT&T evaluates liquid fluxes and solder pastes for soldering performance and also tests solder pastes for rheology, printability, and slump resistance.

No-Clean Solder Paste and Reflow

In 1988, AT&T started to evaluate low-residue solder pastes in controlled reflow atmospheres. While the physical and rheological properties of these early materials were far from ideal, AT&T could reflow them in atmospheres with various reactive additives to produce good solder joints and small amounts of residue. Results from reliability tests showed that these residues were noncorrosive and nonconductive. AT&T obtained a patent that covers this reactive-atmosphere soldering method.

For general applications, a controlled atmosphere is greatly preferred to one that incorporates reactive species. Thus, our focus turned to the evaluation of paste materials that would reflow in nitrogen and were compatible with AT&T's reliability and process requirements. The physical, rheological, thermal, electrical, and chemical properties of more than 25 materials from 10 vendors were evaluated. By the end of 1990, AT&T had identified several materials that met its requirements.

As a parallel effort to evaluation of pastes, AT&T evaluated nitrogen-capable reflow ovens for their thermal profile and the oxygen content of the reflow environment. AT&T obtained thermal profiles on assembled printed wiring boards, typical of those soldered in production, and performed oxygen mapping under loaded production conditions.

Several commercially available ovens met the thermal requirements. The best ovens were those that incorporated forced convection to promote temperature uniformity. Nearly all the ovens from major vendors could maintain less than 100 parts per million (ppm) of oxygen (O_2) and the most gas-tight systems could maintain less than 10 ppm throughout their length.

Next, to determine oxygen window or range of oxygen concentrations that gave favorable results, a metered air leak (about 20-percent oxygen) was introduced into the nitrogen source line that fed the heated zones of the oven. Low-residue solder pastes were evaluated in atmospheres that had up to 10, 100, 500, 800, 1000, and 1500 ppm of oxygen. The results suggested that up to 500 ppm, compared to less than 10 ppm of oxygen, neither decreased the visible quality of the solder joint nor increased the visible paste residue left on the board after reflow.

In some instances, a level of 800 ppm of oxygen did not cause severe problems with joint quality, but tended to cause more solder balls to form and unprotected copper to oxidize. Therefore, the maximum oxygen level that can be tolerated was determined, not by the oxygen sensitivity of the solder paste, but rather by the need to minimize oxidation to preserve solderability for later operations.

In early 1991, AT&T conducted a factory trial at AT&T's Shreveport Works in Louisiana. Reflow soldering was conducted in nitrogen with less than 100 ppm of oxygen. The soldering results were good, with solder defects of less than 15 ppm. As a result, in September, 1991, the process was implemented at AT&T's Columbus Works in Ohio. Since then, most AT&T surface-mount assembly factories have purchased nitrogen-capable reflow equipment.

No-Clean Flux and Wave Soldering

Post-solder cleaning can be eliminated only if the flux residues that remain on the board do not affect performance, testability, or reliability. Flux manufacturers have formulated low-solids fluxes to completely eliminate cleaning operations. However, accelerated aging tests of circuit boards uncovered long-term corrosion problems. When these aging tests were repeated with new boards exposed to less low-solids flux (LSF), there were no failures. Experiments showed that the surface insulation resistance (SIR) decreased as the amount of flux applied was increased, suggesting that excessive flux residues may compromise the circuit's integrity. Most of the SIR testing was done at extreme performance conditions (i.e., 35° C and 90 percent relative humidity). Pollutants in the air, higher temperatures, and relative humidities could exacerbate an electrical integrity problem.

To date, over 60 formulations of LSF have been received from 14 different vendors. The dependence of SIR on flux quantity has been demonstrated for most of the formulations that passed the prescreening tests (i.e., pH, halide, and copper mirror).

The discovery of the inverse relationship between flux quantity and SIR revealed the need to apply the flux in a carefully controlled way, so that only the amount required to ensure a good solder connection was applied to the board. It is also important to insure that the flux is applied uniformly and the process can be consistently repeated.

In addition, AT&T found that partially heated flux residue which did not come into contact with the solder wave caused more damage than the fully heated residue that came into contact with the wave. Thus, flux residue that remains on the top side of a circuit board (i.e., the component side) was potentially more detrimental to circuit-board reliability than the residue on the bottom side (i.e., the circuit side). This means that application methods that deposited excessive amounts of flux on the top side of the board were not desirable.

Because of the extremely low solids content of these fluxes, traditional flux-monitoring techniques are not accurate enough. Typical application methods require monitoring because they use open reservoirs which allow the main constituent of a flux (i.e., alcohol) to evaporate and absorb water. Accordingly, a closed flux reservoir and delivery system are beneficial because they prevent compositional changes and negate the need for monitoring.

Moreover, significant savings in time and expense are realized with a closed system. For example, when the cost to dispose of 5 gallons of spent flux each day is included, the closed system of AT&T's patented spray fluxer (the LSF-2000), when compared to an open system, can save $20,000 per year in costs for monitoring, additional flux and alcohol, and disposal.

Development of a Low-Solids Spray Fluxer

Because of the characteristics of LSFs, the following application properties are considered preferable:

- Uniform, controlled flux application
- Minimal flux residue on the top side of a circuit board
- Closed system (to avoid evaporation and water absorption).

To address these needs, AT&T in 1988 developed a low-solids spray fluxer. This spray fluxer used an ultrasonic atomization system to deposit flux on circuit boards. AT&T was granted patents that cover both the methods and the apparatus.

The first generation spray fluxer helped to successfully eliminate the need for post-solder cleaning. But after extended field experience with it, users demanded more efficient performance and a wider range of features, including better uniformity in flux disposition, wider spray capability, and decreased maintenance.

In 1990, the second generation low-solids spray fluxer was developed. It uses a pressure-assisted, airless spray system that is mounted on a traversing mechanism. A spray nozzle passes back and forth beneath the circuit boards on the conveyor and releases four overlapping coats of flux material, which results in a highly controlled and uniform layer of flux. With specially designed board sensors, exhaust system, and self-cleaning nozzle, the system ensures high solder quality and efficient use of flux material.

During the summer of 1990, a prototype of the LSF-2000 was tested successfully at AT&T's facility in Mesquite, TX and at the Columbus Works. A production model was installed in Columbus in September 1990. The LSF-2000 system has now been deployed in many AT&T factories and has also been made available to industry in general.

Conclusions

The most promising alternatives for no-clean soldering are modified processes, not simple substitutions of material. Controlled atmosphere reflow processes that use low-residue solder pastes have been shown to produce minute amounts of benign residue. With the improved solder pastes now available, this process can provide the reflow capability needed for total no-clean, surface mount assembly.

AT&T has defined a production process that can be implemented with equipment that is commercially available. Further optimization will be done as AT&T gains experience with the system in its factories and as improved materials become available.

Before fluxes are used in production, proper evaluation is imperative. AT&T found that some LSFs are better than others. For all LSFs, SIR testing confirmed the theory that arose from accelerated aging studies. That is, large quantities of post-solder LSF residues can be detrimental to the circuit. This work points out the need for the appropriate qualification of materials and the use of proper application equipment.

The equipment developed and used by AT&T maintains the original flux composition and controls the quantity of flux applied. This system has been successfully deployed at AT&T manufacturing locations. By using low-residue solder paste materials and processes and by using low-solids fluxes with the appropriate process, AT&T has eliminated the need for cleaning and is making progress toward its environmental goals.

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CASE STUDY #4: FLUX SELECTION CRITERIA

When Northern Telecom, Ltd. decided to phase out its use of CFC-113 and methyl chloroform ahead of the mandated phaseout schedule, engineers made the decision to replace conventional soldering operations with no-clean processes. In order to implement the no-clean wave soldering process, it was necessary to extensively test candidate fluxes to determine their applicability to no-clean applications.

Initially, there was no significant doubt that no-clean fluxes could solder, but the long-term resultant quality was questioned within Northern Telecom as well as by influential customers. The initial task in converting to a no-clean soldering process was a three-step program to evaluate candidate fluxes. The three steps were:

- Evaluate the long-term reliability of components after they have been exposed to the flux

- Determine whether flux residues were active or inactive

- Evaluate the processed PCB for reliability after extended environmental stressing.

It was decided that a flux and all components must pass all of these tests before any of the materials could be run in production. Production was the fourth step in the process change-over.

Virtually all tests were based on stressing the product by three to five times the severity commonly seen in a production cell. This was done to provide a high confidence level even if irregularities in the process took place.

Test #1 - Component Reliability

The first test in choosing a flux for use in the no-clean wave soldering process was designed to evaluate the long-term reliability of components after they had been exposed to the flux. A single comprehensive screening test was designed and implemented to facilitate this evaluation. By immersing a component in flux and subsequently aging the part in an environmental chamber under conditions of 85°C and 85 percent relative humidity for 10 days, five potential problems could be discovered:

- Breakdown of seals
- Deterioration of plastics
- Deterioration of markings
- Corrosion
- Changes in performance.

In order to ensure that a wide variety of components was tested while not performing excessive testing, several hundred discrete components were categorized into 13 general component families. Testing was reduced by using a few parts from a given family and designating them as being representative of the group.

Parts, as received in a normal fashion, were electrically tested to the facility's incoming inspection standard for the part, visually inspected, and weighed. The part was then immersed for 15 minutes in a room temperature beaker of the no-clean flux. At the end of the 15 minutes, the part was removed, air-dried, re-weighed, re-tested, and visually re-inspected. The part was then place in the environmental chamber for 10 days, at which time all of the tests were repeated. The significant failure noted during this test was copper corrosion, with few failures in the other four potential problem categories.

Test #2 - Flux Residue Activity

The second test used by Northern Telecom in the evaluation of no-clean fluxes was designed to determine if a flux candidate contained active residues. The presence of these active residues might adversely affect the performance of a product several years after delivery of the products to a customer.

The standard IPC-B-25 comb pattern test panel was the primary tool used in this test, although for a part of the test a plain copper pattern was used. In the second part of the test, a striped solder mask pattern was imposed on the combs. A bias voltage was used in both tests. This modification tested any interaction between flux, mask, and substrate as well as the potential of the flux to cause circuit changes after years of use. The surface insulation resistance and electromigration tests were used to determine reliability with one significant change from the standard procedures used for these tests. The key difference in the Northern Telecom test was that the comb pattern was fluxed, air dried, and tested in a comb-up position. Approximately 90 percent of all flux candidates failed this test, even though many had passed similar tests as presented in the Bellcore TSY-000078 specification.

Test #3 - PCB Reliability

The third test used by Northern Telecom in evaluating candidate no-clean fluxes was designed to determine the long-term reliability of the assembled no-clean PCB under extreme environmental conditions. This test involved taking a printed circuit assembly which had been processed in a no-clean manner and stressing that unit for an extended length of time in an environmental chamber.

Chamber parameters were 35°C and 90 percent relative humidity, and the test was extended to approximately 1,000 hours. The logic in this test plan was that discrete components were carefully screened for use in the process, as were the flux, board substrate, and solder mask. The interactions of the common denominator had been tested, and any product, having passed this environmental stress test, could be used with predictable long-term performance.

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CASE STUDY #5: SPRAY FLUXING FOR TODAY'S SOLDERING PROCESSES

Spray fluxing technology is currently receiving a considerable amount of attention by some progressive electronic manufacturers. Using a spray application method to coat the bottom of a printed circuit board with flux is not a new process for printed circuit assembly operations. What is new are the vast improvements in spray fluxing equipment that can improve quality, increase efficiency, and lower manufacturing costs for companies using low solids "no clean" fluxes in their soldering processes.

These improvements have been substantiated through practical application at the UDS subsidiary of Motorola located in Huntsville, AL. This case study describes the need, acceptance criteria and benefits realized by implementing a spray fluxing system in an operational printed circuit assembly soldering process. If companies are to successfully pursue defect reduction programs, Just-In-Time manufacturing, and CFC elimination, it is essential that they continuously improve the soldering process. One of the more critical elements in a wave soldering process is the flux formulation that is used, especially for operations using low solids fluxes. The impact of a flux formulation on the solder defect rate for printed circuit assemblies can be significant.

Some of the soldering fluxes available on today's market considerably reduce solder defects, but can emit offensive vapors into the work environment. Keeping the assembly line operators' well-being in mind makes it more difficult to select defect-reducing fluxes. For this reason, an enclosed spray fluxing system is very advantageous. If the proper system is implemented, the vapors will be restricted to and contained within the area of the actual fluxing operation. This allows the use of any low solids flux without fear of operator irritation.

Advanced technology spray fluxing systems not only improve the quality of the soldering process, but can also eliminate the need for some process control requirements. The traditional fluxing systems such as foam, wave, and conventional spray fluxers require titration and/or specific gravity measurements to properly control the chemical balance of the flux. When using these types of fluxing systems, it is necessary to regularly compensate for evaporation of the flux solvent by manual and/or automatic methods.

Recent advancements in spray fluxing equipment by some equipment manufacturers, however, have eliminated the need for these process controls. The liquid flux is totally enclosed in a pressurized vessel, eliminating concerns about solvent evaporation and water absorption from the atmosphere. Titration, specific gravity, and solvent compensation are no longer important aspects of the wave soldering operation.

Substantial material savings will be realized with the implementation of this new equipment technology. In the case of the UDS subsidiary of Motorola, a 68 percent reduction in flux and 100 percent elimination of solvent usage were noted. These savings were accomplished by the intermittent operation of the spray fluxer. The flux spray is activated only when a printed circuit board enters the area of the fluxing operation. In most conventional operations, the flux is pumped in a continuous flow, creating enormous waste.

There are several spray fluxing units currently on the market. UDS/Motorola analyzed four different units from four different equipment manufacturers for a single soldering operation at UDS. The equipment was evaluated according to seven general categories:

1. Uniformity and consistency of flux deposition

2. Ventilation and safety

3. Maintenance

4. Ease of operation

5. Equipment reliability

6. Equipment compatibility with a high product mix and low volume operation

7. Enclosed flux reservoir.

As a result of these considerations, the field of possible candidates narrowed quickly to two equipment manufacturers, because of noncompliance of the other systems with the above criteria. Further evaluation and testing of the remaining two spray fluxing units was then performed using the same criteria.

After careful evaluation of the results, it was obvious that the low-solids spray fluxer manufactured by AT&T (LSF-2000) was the best choice for the type of soldering operation that was required. The matrix shows a comparison between the AT&T unit and the competitive unit, which is labeled unit "B."

This information was collected by observing both units in operation. The consistency of flux deposition was measured by processing test printed circuit board samples through each separate fluxing unit. The test samples were weighed before the application of flux, processed through each fluxing unit, allowed to dry, and then weighed again to determine the amount and consistency of flux applied to each sample.

This test concluded that process variation with the AT&T unit could be expected to vary with ± 10 percent and unit "B" was within the range of ± 50 percent. With fine tuned adjustments, however, the AT&T unit during actual production showed variation of only ± 5 percent.

The AT&T unit's dual ventilation system, with amplifiers to exhaust the vapors of the flux spray quickly and restrict the fumes to the immediate processing area, satisfies the UDS ventilation and safety concerns. The unit includes a flame detector system that senses a fire up to 35 feet away. If a flame is detected, the entire system shuts down instantly and automatically.

With the proper equipment options, the unit self-adjusts the width of the flux spray for the width sizes of various printed circuit boards. This eliminates the need for special set-up considerations for the unit during multiple product line changeovers. None of the other low-solids spray fluxers analyzed and evaluated offered all of these special operating features.

Recent improvements in low solids spray fluxing technology offer a viable means for electronics assemblers to enhance soldering processes, improve quality levels, and lower manufacturing costs. With the enclosed reservoir and improved ventilation systems, a wider selection of defect-reducing fluxes are available for use. Reductions in total chemical usage of as much as 85 percent can be realized by implementing spray fluxing technology. Spray fluxing technology for low-solids no-clean applications works extremely well in any wave soldering environment.

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CASE STUDY #6: CHOICE OF A NO-CLEAN PROCESS AT NCR

Previous Process

NCR, Workstation Products Division (WPD) Clemson designs and assembles medium to high-end computer workstations. In 1987 the Clemson plant installed an SMT circuit board assembly line to enhance the plant's high volume production capability. The process flow of this initial SMT line is: STENCIL PRINT - SMT PLACEMENT -REFLOW - HAND ASSEMBLY - WAVE SOLDER - INLINE CLEAN - POST SOLDER INSPECTION - TEST. Up to the present phaseout of CFCs, Clemson SMT Operations used rosin chemistry solder paste, convection reflow, SA flux wave solder and in-line CFC-113 clean.

Alternatives Considered

In February 1991, WPD Clemson received corporate approval to install a second SMT production line to meet the increased production demands that resulted from new products and increased orders. An equipment selection team, made up of manufacturing engineers, was formed to evaluate state-of-the-art SMT soldering technology and to determine the layout and strategy of the new line.

In May 1990, NCR formed a corporate-wide Ozone Depleting Substances (ODS) phaseout team to establish the NCR corporate schedule for ODS elimination. At its first meeting, the ODS team set the end of 1992 as the deadline for all NCR plants to eliminate CFCs in circuit board cleaning operations for bareboard and board assembly operations.

In light of the corporate CFC phaseout deadline, the equipment selection team was forced to face the CFC issue head-on and select equipment and process strategies accordingly. Whatever decision was made for the new SMT line would also be implemented on the existing line.

The options considered were:

1. Convert from CFC-113 to an HCFC solvent

2. Convert from CFC-113 cleaning to aqueous-saponifier cleaning and continue with rosin flux chemistry

3. Convert from CFC-113 cleaning to water-only cleaning and use OA flux chemistry

4. Convert from CFC-113 cleaning to semi-aqueous-aqueous cleaning, i.e., terpene, and continue with rosin chemistry

5. Eliminate the need for cleaning by converting to a no-clean process.

The following actions were undertaken after preliminary evaluation of each of these options.

Option #1. Immediately dropped because of the price of HCFC solvents, incompatibility with existing in-line cleaning machine, and fear of a future ozone-related ban.

Option #2. Initially seen as attractive because it would allow NCR to continue using rosin solder pastes and wave solder flux and avoid the pains of weaning from rosin chemistry. Also, aqueous cleaning with saponifier is an old and proven process in through-hole assembly. NCR decided against this option for several reasons:

- The uncertainty of ability to clean under the tight spacings found in SMT
- The requirement of major facilities work to install floor drains and water treatment system
- Saponifier concentration/foaming issues and odors.
- Uncertainty as to future EPA legislation on water and water emissions.

Option #3. Considered very seriously because of the relative simplicity of the cleaning process. Several site visits were made to evaluate various equipment. Also, OA flux would enhance solderability and lower solder DPM. However, this option was dropped because:

- NCR did not want the reliability risk of OA flux being left on boards
- Major work on facilities would be required to install floor drains and water treatment system
- Uncertainty as to future EPA legislation on water and water emissions.

- Unavailability then of a water soluble solder paste that met NCR processing requirements for printability and reflow.

Option #4. Much has been written about semi-aqueous terpene cleaning and the ability of the terpene process to exceed the cleanliness of CFC-113 cleaning. This option was attractive. However, NCR looked at terpene equipment at several trade shows and decided that the equipment was too expensive and complex. NCR also did not want to have to pacify angry operators who might be irritated by orange/citrus-odors.

Option #5. In light of the dissatisfaction with options 1-4, NCR decided that the best long-term strategy was to eliminate the need for cleaning altogether. There are definite challenges to implementing a no-clean process, but it poses the least threat to the environment and involves the lowest volume of chemicals and effluents.

Evaluation of the No-Clean Option

In February 1991, the NCR Clemson equipment selection team attended the NEPCON West trade show to evaluate SMT equipment for the second line. At the time, both the no-clean and water-only cleaning options were very serious contenders. Prior to the NEPCON show, the team held many discussions as to the particular no-clean strategy which should adopted, should no-clean be the final choice. In these discussions, the team realized that there were three hurdles to overcome in attaining no-clean status:

- Stencil Print/Reflow
- Wave Solder
- Touchup and Repair

Stencil Print

With regard to stencil printing, the primary decision is what paste to use -- no-clean/low solids paste or continued use of the RMA paste. The concern here was that the stencil printing process had been set up using RMA paste. Initial testing of no-clean and low solids solder pastes was discouraging because the pastes lacked the same printability and tackiness characteristics as the RMA paste. The team did not want to sacrifice its low printing DPM level nor the reliability of an RMA paste. One engineer on the equipment team was assigned to focus on solder pastes at the NEPCON show.

Reflow

NCR had been successfully reflowing RMA solder paste with an SPT convection reflow oven. To implement no-clean soldering, the team was not sure if it would have to purchase controlled atmosphere reflow equipment. One engineer on the team focused on reflow equipment at the show.

Wave Solder

Up to this point, NCR had been using an Electrovert Century 2000 wave solder machine with a foam fluxer, using an SA flux. The team realized that there were several paths to achieving no-clean wave soldering. One was to simply put a 2-5 percent solids no-clean flux in the fluxer and foam it onto the board. This requires modifying the wave soldering parameters (no-clean fluxes generally require a higher topside board preheat temperature). Also, the no-clean flux requires acid titration rather than specific gravity to maintain the proper flux-to-solids percentage.

Another path was to use the same wave solder equipment but add on a more controlled method of applying the no-clean flux -- namely a spray fluxer. This is accomplished by either upgrading the fluxer in the machine itself or by purchasing a stand-alone spray fluxer module.

The third path was the controlled atmosphere option. This is accomplished by either retrofitting an existing wave solder machine with a hood (long hood enclosing preheat and solder pot; short hood enclosing the solder pot only) or purchasing a new nitrogen wave solder machine. One engineer on the equipment selection team focused on wave soldering equipment selection.

Touch-Up and Repair

Touch-up and repair initially did not come up in the team's discussions, but no-clean hand soldering and repair may pose the greatest challenge. The other processes involve equipment which can be controlled to accomplish no-clean soldering. Hand soldering involves people; specifically, people trained to solder with RMA flux. This is raised as an issue because RMA flux, unlike no-clean fluxes, is actually very forgiving and allows for deviation in the hand soldering process with regard to tip temperature and tip contact time. Operators with marginal soldering skills usually can mask their deficiencies with RMA flux.

The team had already obtained no-clean flux samples, and as an experiment gave various samples to hand solderers in place of RMA flux at the bench. The results were obvious. The no-clean fluxes are primarily alcohol and evaporate almost immediately upon solder tip contact. Tip temperature has to be controlled, time on the connection has to be minimal, and initial component solderability is critical. Instead of a 5 second wetting window as with RMA flux, the operator using no-clean flux now has only a 1-2 second window. In addition, the no-clean samples tested left some residue after hand soldering. When operators are accustomed to a CFC-113 cleaning culture where any residue can and should be washed off, the appearance of residue is difficult to accept. Thus, an entire change in attitude towards residues is necessary. The NCR team used the NEPCON show to meet with flux vendors and attend technical sessions in the hope of learning from the experience of others in this area.

The Selection Process

The 1991 NEPCON West show proved an excellent catalyst for a decision by the equipment selection team. The team was so favorably impressed with no-clean technology (particularly controlled atmosphere technology) that the water clean option was dropped and the focus was shifted totally on no-clean soldering.

The NCR team's selection of a specific no-clean process and its evaluation of each of the available technologies is discussed in detail below.

Stencil Print/Reflow

The team decided to pursue controlled atmosphere reflow and was impressed with most vendors at the show. The engineer focusing on reflow prepared a comparison matrix and, based on cost and design of equipment, narrowed the selection down to five key vendors. Evaluation trips were then taken and, based on reflow performance and cost, the decision was made to purchase a Watkins Johnson controlled atmosphere convection oven. Though NCR has achieved satisfactory reflow results in its conventional reflow oven, the inerted oven gives cosmetically smoother and shinier joints with better classical wetting traits -- using the same RMA paste. Based on information gathered at NEPCON technical sessions and experience gathered during vendor evaluations, the team decided that the controlled atmosphere during reflow would at least enhance the process, especially the reflow of no-clean pastes. The controlled atmosphere reflow oven has been in operation on the second SMT line since January 1992. NCR continues to run RMA solder paste in production but has been seriously testing no-clean pastes, and with good results. While the team completes its no-clean paste testing, NCR continues to use an in-line CFC-113 cleaner even though earlier tests by various NCR plants have shown that RMA paste residues can be safely left on. WPD changed to a no-clean solder paste in Summer 1992.

Wave Solder

The team left the NEPCON West show having tentatively decided on controlled atmosphere wave soldering, though not clear on whether to pursue a machine with a "retrofit" hood or a new-design nitrogen machine. Prior to NEPCON, the team had already conducted tests with no-clean fluxes in the Century 2000 machine, utilizing a foam fluxer. The results were discouraging, for several reasons:

- Amount of flux applied with a foam fluxer could not be controlled
- Residues could not be totally eliminated. Though benign, they interfered with incircuit bed-of-nails testing and resulted in many Quality Assurance battles
- Flux balance could not be adequately controlled with specific gravity or titration methods
- Wave soldering yields were inconsistent due to battles with solder balls, shorts, and webbing.

The team had not yet totally discounted this option, though with the above results in mind, it decided to aggressively evaluate controlled atmosphere equipment. At the time of the 1991 NEPCON West show, there were three primary suppliers of controlled atmosphere wave solder equipment -- SEHO (a German-based company was first to market), Soltec (based in Holland), and Electrovert. Electrovert had already introduced and implemented a "retrofit" hood for its Econopak line, had a proposed design for a hood for the Ultrapak line, and was showing the prototype new-design ATMOS machine. The team was impressed with all three for various reasons. Team members were further encouraged to pursue controlled atmosphere wave soldering because the sister NCR WPD plant in Augsburg, West Germany had been using a SEHO machine for over a year with very good results. Two members of the equipment selection team traveled to Oosterhout, Holland (Soltec), NCR Germany, Kreuzwertheim, Germany (SEHO) and Montreal, Canada (Electrovert) to test solder boards on each system.

The results of the trip were encouraging for controlled atmosphere wave soldering on the whole. Each vendor's machine performed equally well with regard to soldering and no-clean results on the NCR production boards used for the testing. With the controlled atmosphere technology, a 1 percent adipic acid "preparation fluid" is often used in lieu of a traditional flux. Since it was recommended by each manufacturer during the testing, it was used for each test. It should be noted that at the Electrovert facility both the new ATMOS controlled atmosphere machine and an existing model Electrovert machine retrofitted with a full-length hood were evaluated.

The SEHO and Soltec machines are designed as nitrogen machines (not retrofits). The Electrovert and SEHO machines are "open tunnel" designs in that each end of the tunnel is open and metal doors or curtains are placed throughout the tunnel to baffle air flow. The Soltec machine is the only "closed tunnel" design, utilizing vacuum lock chambers at the entrance and exit of the tunnel to completely seal the tunnel. The SEHO and Electrovert machines use an ultrasonic spray fluxer. The Soltec machine uses a drum spray fluxer. Electrovert also offers a drum spray fluxer. Since all three machines soldered the test boards equally, other criteria were used to make a final selection. The criteria used were:

- Soldering performance
- Absence or presence of visible residues
- Nitrogen consumption
- Maximum conveyor width
- Production rate
- Local US. support

Soldering Performance

Each machine soldered equally well, and solder wetting under nitrogen was better than could be achieved in air. Two negatives, however, were encountered with each system. Each machine produced solder shorts only on specific through-hole connectors. This was determined to be due to a change in the surface tension of solder under nitrogen. The shorts occurred consistently, regardless of machine or soldering parameters (including flux). As demonstrated at NCR Germany with over a year's experience with nitrogen wave soldering, eliminating the shorts requires redesign of the particular problem areas to change the spacing of the leads and/or the length of the leads. The other problem encountered consistently was solder balls clinging to the bottom side solder resist. The balls in all cases could be easily brushed off. This seems to be an effect of the nitrogen atmosphere and the no-clean flux.

Visible Residues

The team was very impressed that with each system, boards were clean and dry upon exiting the machine. Each vendor's fluxer performed adequately in depositing consistent and controlled amounts of flux. The team could create visible residues with the 1 percent adipic acid solutions by applying heavy amounts, but excellent soldering occurred using only a light mist. One benefit of the controlled atmosphere is that small amounts of very low-solids fluxes can be used.

Nitrogen Consumption

Each machine was evaluated as to the nitrogen flow rate in cubic feet per hour (cfh) required to maintain 10 ppm oxygen over the solder pot. The Soltec and SEHO machines consumed the least nitrogen -- about 700 cfh. The Soltec accomplishes this by completely sealing off the tunnel with the vacuum locks. The SEHO minimizes nitrogen consumption by effective use of flap doors through the tunnel. The Electrovert ATMOS machine consumed around 1,500 cfh of nitrogen. This is primarily because it has a larger 20" width tunnel and minimally baffles air flow with rubber curtains. The Electrovert retrofit hood consumed the most nitrogen -- 2,000 cfh or higher, mainly because of its design. The "nitrogen" machines are designed to hold the nitrogen blanket by "humpbacking" the tunnel in the solder pot section. The retrofit hoods are straight with the high point being the exit end. There is little to hold the nitrogen in.

Maximum Conveyor Width

NCR produces boards ranging in widths from 4.8 inches to 15 inches. The larger boards are run in 18-inch wide picture frame pallets. Team members wanted to be able to run existing pallets in whatever machine was purchased. At the time of evaluation, the Soltec machine could not handle the 18 inch width. New pallets for bigger boards would need to be purchased, clip stiffeners would be needed, or boards would have to be run without pallets. The SEHO machine available at the time required the use of special SEHO pallets which greatly added to the cost of the system. The Electrovert machines utilized traditional finger type conveyors at widths up to 20 inches.

Production Rate

Production rate requirements vary in real life production. The Clemson wave solder machines are fed by a hand assembly conveyor, with the rate depending on the size of the board and the number of through-hole components that have to be hand placed. Quite a few smaller plug-in boards with very few through-hole parts are also run. Hand assembly feeds them as fast as the wave solder machine will accept them. The team did not want to have to limit speed if at all possible. The Soltec machine could only take a board every 20-30 seconds because of the processing time of the vacuum locks. The SEHO machine was limited because of the timing of the pallets through the flap doors. The Electrovert machines had no limitation because there are no chambers or flap doors.

Local U.S. Support

The team wanted evidence from each vendor that it could adequately support this equipment in the U.S. (NCR Clemson does not stock large inventories of spares and relies on overnight shipments and quick response field service). At the time of initial evaluation, Soltec and SEHO had very limited resources in the U.S. Electrovert maintains two facilities in the U.S. and a factory in Canada.

The initial recommendation after the evaluation trip was to purchase an Electrovert Ultrapak machine with a full-length nitrogen hood. Electrovert had not yet produced an Ultrapak with a hood, but it was a proven machine in the field and would handle Clemson width and production requirements. This recommendation was based on successful results with an Econopak with a hood at the Electrovert factory (the Econopak would not handle the NCR width requirement). The overall cost of an Ultrapak with a hood and all of the necessary options was around US$150,000. Because of the relatively low system cost, and with the cost of nitrogen at about $0.20 per 100 cubic feet, the Ultrapak option was very attractive despite the anticipated nitrogen consumption rate of 2,000 cfh. However, after further discussion and cost analysis, it was decided that the 2,000 cfh consumption rate was too high and the Ultrapack style machine did not fit the streamlined, state-of-the-art image the team wished to portray with its new line. Next in line was the new Electrovert ATMOS. Though it was a new model, the team felt comfortable in its rugged design, the use of existing solder pot and software control packages, and the conveyor width of 20 inches. An ATMOS with all the options is twice the cost of the Ultrapak system -- around US$300,000. This was still cheaper than a Soltec or SEHO with equivalent options and its nitrogen consumption rate of 1,500 cfh was considered reasonable. Also, the low-profile streamlined design of the ATMOS was very well received by NCR managers attending the 1992 Nepcon West show. Based on the above discussion, the team chose the Electrovert ATMOS controlled atmosphere wave solder machine. NCR Clemson has purchased one machine for its new SMT line and one to replace its old Century 2000 on the existing SMT line. Both systems have been in full production use since January 1992.

Hand Soldering/Repair

This area poses the most challenge in NCR-Clemson's operation. From Nepcon technical sessions and conversations with other NCR plants and other companies, it was learned that no-clean hand soldering techniques are available and do work. What the team currently faces is final material selection and the learning curve. SMT manufacturing associates are all required to go through an initial in-house 40-hour solder training program and receive yearly certification after that. Current activity is to modify the training curriculum to reflect the use of no-clean flux and core solder and to teach stricter techniques -- namely the need for lower tip temperatures and very strict adherence to a 2 second soldering window. Part of the challenge is that it is often very frustrating for the hand soldering operator when he or she cannot make picture perfect solder joints within 2 seconds using no-clean flux. Another part of the challenge is accepting, both internally and externally, visible residues from the no-clean flux. SIR and analytical chemical testing are being done at NCR's Manufacturing Technology Research Center to support safely leaving the residues on the board.

Conclusions

NCR eliminated CFC usage in the U.S. for PCB assembly in early 1993. To date, Clemson has fully achieved no-clean status in the wave solder process by implementing controlled atmosphere no-clean technology. Problems encountered as a result of implementing this technology are solder shorts and solder balls. Board design is being changed where appropriate and when possible to eliminate the shorting issue. Engineers are also working with Electrovert on some developments to the equipment, as well as with bareboard vendors on changes to the solder mask to try to eliminate the solder balls. On the positive side, NCR Clemson has realized the following benefits:

1. Greatly enhanced solder wetting
2. 75 percent reduction in solder dross
3. 50 percent reduction in flux consumption
4. Reduced chemical inventory
5. Savings of $2,300/barrel of CFC-113 solvent.

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LIST OF VENDORS FOR NO-CLEAN PROCESS EQUIPMENT AND MATERIALS TO REPLACE CFC-113 AND METHYL CHLOROFORM

Controlled Atmosphere Soldering Equipment

Dover Soltec
7 Perimeter Road
Manchester, NH 03103
Tel: (603) 647-6005
Fax: (603) 647-6501

Electrovert Limited (International Sales)
1305 Industrial Blvd.
LaPrairie, Quebec J5R 2E4
Canada
Tel: (514) 659-8901
Fax: (514) 659-2759

SMT-Automation, Inc.
325-L Hill Carter Parkway
Ashland, VA 23005
Tel: (804) 798-6000
Fax: (804) 798-5933

Electrovert USA Corp. (North American Sales)
805 W.N. Carrier Pkwy.
Suite 200
Grand Prairie, TX 75050
Tel: (214) 606-1900
Fax: (214) 606-1700

Hollis Automation, Inc.
15-T Charron Avenue
Nashua, NH 03063
Tel: (603) 889-1121
Fax: (603) 880-0939

No-Clean Fluxes and Pastes

AIM Products Inc.
9-T Rocky Hill Road
Smithfield, RI 02917
Tel: (401) 232-2772
Fax: (401) 232-2802

Alpha Metals
600 Route 440
Jersey City, NJ 07304
Tel: (201) 434-0098
Fax: (201) 434-2529

Cramco
80 Sinnott Rd.
Scarborough, Ontario M1L 4M7
Canada
Tel: (416) 757-3667
Fax: (416) 757-5530

Hi-Grade Alloy Corp.
17425-T S. Laflin Avenue
P.O. Box 155
East Hazel Crest, IL 60429
Tel: (708) 798-8300
Fax: (708) 798-8924

Indium Corporation of America
1676 Lincoln Avenue
Utica, NY 13502
Tel: (315) 768-6400
Fax: (315) 768-6362

Kester Solder
515 East Touhy Ave.
Des Plaines, IL 60018-2675
Tel: (708) 297-1600
Fax: (708) 390-9338

London Chemical Co., Inc.
240 Foster Avenue
Bensenville, IL 60106
Tel: (312) 766-5902
Fax: (312) 860-1218

Multicore Solders, Inc.
1751 Jay Ell Dr.
Richardson, TX 75081
Tel: (214) 238-1224
Fax: (214) 644-9309

Senju Pastes
Christopher Associates
2601 S. Oak Street
Santa Ana, CA 92707
Tel: (714) 979-7500

Spray Fluxing Equipment

AT&T
P.O. Box 900
569 Carter Road
Princeton, NJ 08542-0900
Tel: (609) 639-2232
Fax: (609) 639-2818

Electrovert USA Corp. (North American Sales)
805 W.N. Carrier Pkwy.
Suite 200
Grand Prairie, TX 75050
Tel: (214) 606-1900
Fax: (214) 606-1700

Electrovert Limited (International Sales)
1305 Industrial Blvd.
LaPrairie, Quebec J5R 2E4
Canada
Tel: (514) 659-8901
Fax: (514) 659-2759

Precision Dispensing Equipment, Inc. (microjets)
P.O. Box 40370
Bay Village, OH 44140-0370
Tel: (216) 899-9911

Process Control Technologies, Inc.
9100 West Plainfield Road #12
Brookfield, IL 60513-2422
Tel: (708) 387-0906
Fax: (708) 387-0937

SEHO
SMT-Automation, Inc.
325-L Hill Carter Parkway
Ashland, VA 23005
Tel: (804) 798-6000
Fax: (804) 798-5933

Sonatech, Inc.
702 Botello Road
Goleta, CA 93017
Tel: (805) 967-0437

Wenesco, Inc.
6423-T N. Ravenswood Avenue
Chicago, IL 60626
Tel: (312) 973-4430 ext 65
Fax: (312) 973-5104

Industrial Grade Nitrogen

AGA Gas, Inc.
6225 Oaktree Boulevard
Cleveland, Ohio 44131
Tel: (216) 642-6600
Fax: (216) 642-6746

Air Products & Chemicals, Inc.
7201 Hamilton Blvd.
Allentown, PA 18195
Tel: (215) 481-4911
Fax: (215) 481-5900

Airco Gases
575 Mountain Avenue
Murray Hill, NJ 07974
Tel: (201) 464-8100
Fax: (201) 464-3379

MG Industries
2460A Boulevard of the Generals
P.O. Box 945
Valley Forge, PA 19482
Tel: (215) 630-5400
Fax: (215) 630-5600

Liquid Air Corp.
2121-T N. California Blvd.
Walnut Creek, CA 94596
Tel: (415) 977-6500
Fax: (415) 977-6840

Union Carbide Industrial Gases Inc.
Linde Division
39 Old Ridgebury Rd.
Danbury, CT 06817-0001
Tel: (800) 521-1737

GLOSSARY

CFC -- An abbreviation for chlorofluorocarbon.

CFC-113 -- A common name for the most popular CFC solvent -- 1,1,2-trichloro-1,2,2-trifluoroethane -- with an ODP of approximately 0.8.

Chlorofluorocarbon -- An organic chemical composed of chlorine, fluorine and carbon atoms, usually characterized by high stability contributing to a high ODP.

Conformal coating -- A protective material applied in a thin, uniform layer to all surfaces of a printed wiring assembly including components.

Controlled atmosphere soldering -- A soldering process done in a relatively oxygen-free atmosphere. The process greatly reduces oxidation of the solder, contributing to better solder joint metallurgy and less dross formation.

Defluxing -- The removal of flux residues after a soldering operation. Defluxing is a part of most high-reliability electronics production.

Flux -- An essential chemical employed in the soldering process to facilitate the production of a solder joint. It is usually a liquid material, frequently based on rosin (colophony).

Formic acid -- A substance which is sometimes used in conjunction with no-clean wave soldering to reduce the level of oxygen present in the soldering chamber. Formic acid can cause human health threats and has an exposure limit of 5 ppm.

Greenhouse effect -- A thermodynamic effect whereby energy absorbed at the earth's surface, which normally radiates back out to space in the form of long-wave infrared radiation, is retained by gases in the atmosphere, causing a rise in temperature. The gases in question are partially natural, but manmade pollution is thought to increasingly contribute to the effect. The same CFCs that cause ozone depletion are known to be "greenhouse gases," with a single CFC molecule having the same estimated effect as 10,000 carbon dioxide molecules.

High-solids no-clean flux -- A flux which contains more solid matter than traditional fluxes.

Low-residue solder paste -- A solder paste containing less solids than a traditional paste. The decreased solids content allows for the elimination of post-solder solvent cleaning.

Low-solids no-clean flux -- A flux which contains little solid matter, thereby leaving less post-solder residue and usually eliminating the need for cleaning. See no-clean flux.

Methyl chloroform (MCF) -- A designation for a popular solvent called 1,1,1-trichloroethane. Methyl chloroform has an ODP of 0.12.

No-clean flux -- A flux whose residues do not have to be removed from an electronics assembly; therefore, no cleaning is necessary. This type of flux is usually characterized by low quantities of residues. It may be a low- or high-solids formulation.

ODP -- An abbreviation for ozone-depletion potential.

Ozone -- A gas formed when oxygen is ionized by, for example, the action of ultraviolet light or a strong electric field. It has the property of blocking the passage of dangerous wavelengths of ultraviolet light. Although it is a desirable gas in the stratosphere, it is toxic to living organisms at ground level (see volatile organic compound).

Ozone depletion -- Accelerated chemical destruction of the stratospheric ozone layer by the presence of substances produced, for the most part, by human activities. The most depleting species for the ozone layer are the chlorine and bromine free radicals generated from relatively stable chlorinated, fluorinated, and brominated products by ultraviolet radiation.

Ozone-depletion potential -- A relative index indicating the extent to which a chemical product may cause ozone depletion. The reference level of 1 is the potential of CFC-11 and CFC-12 to cause ozone depletion. If a product has an ozone-depletion potential of 0.5, a given weight of the product in the atmosphere will, in time, deplete half the ozone that the same weight of CFC-11 will deplete. The ozone-depletion potentials are calculated from mathematical models which take into account factors such as the stability of the product, the rate of diffusion, the quantity of depleting atoms per molecule, and the effect of ultraviolet light and other radiation on the molecules.

Ozone layer -- A layer in the stratosphere, at an altitude of approximately 10-50 km, where a relatively strong concentration of ozone shields the earth from excessive ultraviolet radiation.

PCB -- An abbreviation for printed circuit board.

Printed circuit -- A printed circuit is an electronic component designed for interconnecting the other components. It usually consists of a metallic conductor pattern on an insulating substrate. After fabrication, it is known as a printed circuit board (PCB); after assembly where components are added, it is known as a printed wiring assembly (PWA).

Process Window -- A term used to describe the range of settings for various soldering parameters at which satisfactory soldering results will occur. Process parameters include preheat temperature, conveyor speed, and solder wave height. A small process window implies that strict control needs to be maintained over the process parameters.

PWA -- An abbreviation for printed wiring assembly.

Reflow soldering -- A method of electronics soldering commonly used with surface mount technology, in which a paste formed of solder powder and flux suspended in an organic vehicle is melted by the application of external heat.

Rosin -- A solid resin obtained from pine trees which, in a pure form and usually with additives, is frequently used as a flux.

Rosin flux -- A flux whose main nonvolatile constituent is rosin. There are several categories of rosin flux, often designated by the codes R (pure rosin), RMA (rosin, mild activation), RA (rosin, activated usually with free chloride ions), RSA (rosin, super activated), SA (synthetic resin, activated).

Solvent -- Although not a strictly correct definition, in this context a product (aqueous or organic) designed to clean a component or assembly by dissolving the contaminants present on its surface.

Surface mount technology (SMT) -- A technique of assembling surface mount devices or surface mount components on the surface of PCBs and PWAs, as opposed to wiring them through holes. Surface mount technology offers a number of important advantages such as miniaturization, but also some disadvantages such as difficulty in defluxing under certain types of SMD.

Surface mount component (device) -- A component capable of being attached to (device) a PCB by surface mount technology. The device may be either leaded or leadless.

Vesication -- A blistering defect which may occur on boards with conformal coatings when excessive residues are present

Volatile organic compound (VOC) -- These are constituents that will evaporate at their temperature of use and which, by a photochemical reaction, will cause atmospheric oxygen to be converted into potential smog-promoting tropospheric (ground-level) ozone under favorable climatic conditions.

Wave soldering -- Also known as flow soldering, a method of mass soldering electronics assemblies by passing them, after fluxing and pre-heating, through a wave of molten solder.

APPENDIX A

International Cooperative FOR OZONE LAYER PROTECTION

The International Cooperative for Ozone Layer Protection (ICOLP) was formed by a group of industries to protect the ozone layer. The primary role of ICOLP is to coordinate the exchange of nonproprietary information on alternative technologies, substances, and processes to eliminate ozone-depleting solvents. By working closely with solvent users, suppliers, and other interested organizations worldwide, ICOLP seeks the widest and most effective dissemination of information harnessed through its member companies and other sources.

ICOLP corporate, affiliate, and associate members include:

- AT&T
- British Aerospace
- Compaq Computer Corporation
- Digital Equipment Corporation
- Ford Motor Company
- Hitachi Limited
- Honeywell
- IBM
- Matsushita Electric Industrial
- Mitsubishi Electric Corporation
- Motorola
- Northern Telecom
- Texas Instruments
- Toshiba Corporation

In addition, ICOLP has a number of industry association and government organization affiliates. Industry association affiliates include American Electronics Association (AEA), Association Pour la Research et Development des Methodes et Processus Industriels, Electronic Industries Association, Halogenated Solvents Industry Alliance, Japan Electrical Manufacturers Association, and Korea Specialty Chemical Industry Association. Government organization affiliates include the City of Irvine (California), the Russian Institute of Applied Chemistry, the Swedish Environmental Protection Agency, the U.S. Air Force, and the U.S. Environmental Protection Agency (EPA). Other organization affiliates are the Center for Global Change (University of Maryland), Industrial Technology Research Institute of Taiwan, Korea Anti-Pollution Movement Association, National Academy of Engineering, and Research Triangle Institute. The American Electronics Association, the Electronic Industries Association, the Japan Electrical Manufacturers Association, the Swedish National Environmental Protection Agency, the U.S. EPA, the U.S. Air Force, and the U.S.S.R. State Institute of Applied Chemistry have signed formal Memorandums of Understanding with ICOLP. ICOLP will work with the U.S. EPA to disseminate information on technically feasible, cost effective, and environmentally sound alternatives for ozone-depleting solvents.

ICOLP is also working with the National Academy of Engineering to hold a series of workshops to identify promising research directions and to make most efficient use of research funding.

The goals of ICOLP are to:

- Encourage the prompt adoption of safe, environmentally acceptable, nonproprietary alternative substances, processes, and technologies to replace current ozone-depleting solvents
- Act as an international clearinghouse for information on alternatives
- Work with existing private, national, and international trade groups, organizations, and government bodies to

develop the most efficient means of creating, gathering, and distributing information on alternatives.

One example of ICOLP's activities is the development and support of an alternative technologies electronic database "OZONET." OZONET is accessible worldwide through the United Nations Environment Program (UNEP) database "OZONACTION," and has relevant information on the alternatives to ozone-depleting solvents. OZONET not only contains technical publications, conference papers, and reports on the most recent developments of alternatives to the current uses of ozone-depleting solvents, but it also contains:

- Information on the health, safety, and environmental effects of alternative chemicals and processes
- Information supplied by companies developing alternative chemicals and technologies
- Names, addresses, and telephone numbers for technical experts, government contacts, institutions and associations, and other key contributors to the selection of alternatives
- Dates and places of forthcoming conferences, seminars, and workshops
- Legislation that has been enacted or is in place internationally, nationally, and locally.

Information about ICOLP can be obtained from:

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APPENDIX B

THE IPC PHASE III TESTING PROGRAM

Introduction

The Institute for Interconnecting and Packaging Electronics Circuits (IPC) Phase III Controlled Atmosphere Soldering (CAS) program was initiated to evaluate the effects of nitrogen as an inerting atmosphere for a wave solder process utilizing low residue fluxes in a no-clean application. The use of inert atmosphere soldering had been introduced and used by many different companies as an early alternate to cleaning circuits after wave soldering. The IPC CAS study examined two independent variables -- atmosphere and flux materials -- as they relate to wave solder processing to determine if there are any significant problems which arise when using either the fluxes or the inerting process. The results of this study provide data on the effect of an inert atmosphere in wave soldering, as well as on no-clean alternatives to standard wave soldering using rosin based fluxes and post-solder solvent cleaning.

Structure of Study

The study used surface insulation resistance (SIR) testing as a primary indicator of flux/cleanliness effects. The study was further supported with ionic cleanliness testing and surface chemical analysis to provide additional data for assessing the relative effects of the materials and processes used in the test. The Phase III CAS program used IPC B-24 SIR test boards for the study, which have served in several other previous IPC studies gathering similar data. Five B-24 boards were used in each test cell.

The control materials for this study were rosin based RA and RMA flux formulations whose characteristics had been evaluated in previous IPC testing. The test fluxes evaluated were a 2 percent solution of adipic acid in isopropyl alcohol, and a commercially available low-solids flux formulation. These materials were subjected to a series of tests. These tests examined the materials in an array of process configurations involving different fluxes, board placement, and cleaning options.

The series of tests included the following combinations:

- Blank
- Control
- Adipic/Up/NC
- Adipic/Down/NC
- LSF/Up/NC
- LSF/Down/NC
- Adipic/Up/C
- Adipic/Down/C
- LSF/Up/C
- LSF/Down/C
- RA
- RMA

Where the test legend is as follows:

Adipic	2 percent adipic acid in anhydrous isopropyl alcohol
LSF	Commercially available low solids flux.
Down	B-24 test board run circuit side down in wave solder
Up	B-24 test board run circuit side up in wave solder -- no solder of test contacts
NC	Not cleaned
C	Cleaned in a batch non-saponified deionized water cleaner
RA	Control flux-solvent cleaned (methyl chloroform)
RMA	Control flux-solvent cleaned (methyl chloroform)

The tests evaluated the B-24 board in both face up (circuit side up) and face down (circuit side down) formats. This provided a direct comparison to assess the effects of normal processing in comparison to a worst case scenario with flux deposition on the top side of the board where the flux would not be subjected to the full effects of molten solder. Low residue fluxes were applied using an ultrasonic spray fluxer for those circuits that were processed in the face down position. For circuits that required face up processing, the low residue fluxes were applied to those boards with manual spray application using pump-spray bottles until the board was saturated with flux. The rosin-based RA and RMA control fluxes were applied using standard foam fluxing techniques. A new foam stone was used with each material to prevent cross contamination of flux materials.

During the soldering process the average oxygen content in the wave section ranged between 5 and 14 ppm of O_2, with an average of about 10 ppm. The control samples using RA and RMA fluxes were run in an ambient atmosphere. All other test fluxes and conditions were run using the inert atmosphere.

The Phase III CAS program evaluated these processes for use in both military and commercial electronic assemblies with the primary concern being cleanliness of the boards after wave soldering. Two different types of Ionic Cleanliness checking machines were used in the CAS program -- an Ionograph 500 and two Omegameter 600 SMD machines. Prior to initiation of the testing, all of the boards were visually examined, serialized, electrically checked, cleaned in the Omegameter 600 SMD machines to a baseline reading, dried in nitrogen and sealed in individual Kaypak bags. Process travelers accompanied each board through the production process to track the board and its process flow.

After the boards were passed through the wave soldering machine, they were inspected for visual defects, sealed again in individual Kaypak bags, and routed to other testing procedures. The additional testing procedures included ionic cleanliness, SIR testing (using two different profiles -- Standard Navy - Condensing Atmosphere Profile and the Modified Navy Profile - Noncondensing Atmosphere Profile), and evaluation by high-pressure liquid chromatography (HPLC) and ionic chromotography (IC) to determine ionic contamination levels. During the processing all boards were handled with clean white gloves to help minimize extraneous contamination.

The results from the ionic cleanliness testing are presented in Exhibit 14. The results of the condensing atmosphere SIR testing are presented in Exhibit 15. The results of the noncondensing atmosphere SIR testing are presented in Exhibit 16.

Conclusions

Based upon the results obtained from the ionic cleanliness and SIR testing, the low-solids fluxes provided results equal to or better than the solvent cleaned rosin-based controls.

HPLC and IC test results indicate a similar level of organic and inorganic residue present on the surface of the boards. These test results are consistent with values observed in other IPC tests as well as those observed in industry. The test results indicate that low-solids fluxes can be effectively used in controlled atmosphere soldering applications when used with appropriate materials, proper handling, and proper operating procedures.

No negative effects were observed that could be attributed to the reduction of oxygen in the solder wave area. In addition, no solderability issues were observed in running the boards across the wave solder machine and nothing was found in the cleanliness or SIR testing. It should be noted that components were not soldered to these test boards. The effect of the reduced oxygen levels in the wave soldering zone can be observed in the visual inspection of through-hole solder joints. However, facilities using nitrogen inerted wave soldering in conjunction with low-solids fluxes routinely report low defect levels (less than 200 ppm) for processes that are running under proper control. Therefore, considering all of the information gathered in this study, it has been demonstrated that the combination of low-solids fluxes with a controlled atmosphere offers an effective alternative to cleaning after wave soldering and can significantly reduce waste streams in manufacturing.

Exhibit 14

AVERAGE IONIC CLEANLINESS OF TEST SAMPLES

Key:
- AA = Adipic Acid
- LSF = Low-solids flux
- U = Board face up
- D = Board face down
- NC = Board not cleaned
- C = Board cleaned in nonsaponified deionized water cleaner
- RA = Activated rosin control flux cleaned in methyl chloroform
- RMA = Rosin mildly activated control flux cleaned in methyl chloroform

Exhibit 15

AVERAGE SIR DATA FROM CONDENSING ATMOSPHERE TESTS

Key: AA = Adipic Acid
LSF = Low-solids flux
U = Board face up
D = Board face down
NC = Board not cleaned
C = Board cleaned in nonsaponified deionized water cleaner
RA = Activated rosin control flux cleaned in methyl chloroform
RMA = Rosin mildly activated control flux cleaned in methyl chloroform

Exhibit 16

AVERAGE SIR DATA FROM NONCONDENSING ATMOSPHERE TESTS

Key: AA = Adipic Acid
LSF = Low-solids flux
U = Board face up
D = Board face down
NC = Board not cleaned
C = Board cleaned in nonsaponified deionized water cleaner
RA = Activated rosin control flux cleaned in methyl chloroform
RMA = Rosin mildly activated control flux cleaned in methyl chloroform

APPENDIX C

PATENTS RELEVANT TO CONTROLLED ATMOSPHERE SOLDERING

APPENDIX D

SOLDER FLUXES AND PASTES EVALUATED BY NORTHERN TELECOM