

# No-Clean Soldering Processes

Leslie A. Guth  
John R. Morris

AT&T is committed to a scheduled phase-out of emissions of chlorofluorocarbons and other solvents from its manufacturing operations. The proper use of low-residue solder pastes and low-solids fluxes obviates the need for post-reflow and post-wave solder cleaning in circuit-pack assembly and, therefore, contributes significantly toward achieving these corporate goals. For proper solder joints to be formed with low-residue solder pastes, we found that the reflow atmosphere must be controlled. The appropriate thermal and atmospheric control capabilities have been identified. Factory implementation is underway and, by the end of 1991, a minimum of 13 lines capable of using low-residue solder pastes will have been installed. For the low-solids fluxes used for wave soldering, test results showed we need to control the quantity of flux applied. This control was realized with the development of a spray fluxer. The unit has been successfully deployed at many AT&T manufacturing locations.

## Introduction

Assembly procedures routinely involved several cleaning steps to remove the residue from various soldering operations. These steps required the use of chlorinated solvents, including chlorofluorocarbons (CFCs), that are detrimental to our environment. AT&T is committed to reducing emissions of these chemicals. One way to do this is to use *no-clean* materials, such as low-residue solder pastes (LRSPs) and low-solids fluxes (LSFs), that leave little residue after soldering and, thus, eliminate the need for cleaning. However, their use should neither adversely affect the product's reliability nor complicate the manufacturing process, which would increase the product's cost.

To evaluate how commercially available low-residue solder pastes and low-solids fluxes affect product reliability and soldering processes, we have tested these pastes and fluxes against industry specifications and internal requirements. Our studies have found that the use of these no-clean LRSPs and LSFs becomes feasible when the surface-mount and wave-soldering processes are suitably altered. For example, nitrogen gas (N<sub>2</sub>)

is now used in the reflow ovens for good reflow of LRSPs, and the LSF must be precisely controlled during application. These material and process changes allow us to eliminate the cleaning steps, thus decreasing manufacturing costs and environmental impact.

In the next section, we provide background information about the circuit-pack assembly process, fluxes, solder pastes, and no-clean soldering. Other sections summarize our studies to characterize low-residue and low-solids materials, stencil printing, reflow processes, flux application, and wave soldering. (Panel 1 defines acronyms and terms used in this paper.)

## Background

In this section, we describe the circuit-pack assembly process, give the reasons for using fluxes and solder pastes and discuss their compositions, and identify the benefits of no-clean soldering.

**The Assembly Process.** Circuit-pack assembly consists of reflow soldering of surface-mounted components or wave soldering of surface-mounted or through-hole components to a printed-wiring board. Typically,

**Panel 1. Abbreviations, Acronyms, and Terms**

CFC	— chlorofluorocarbon
liquidus temperature	— the temperature above which the alloy is a liquid
LRSP	— low-residue solder paste
LSF	— low-solids flux
LSF-2000	— AT&T's low solids fluxer
N <sub>2</sub>	— nitrogen gas
O <sub>2</sub>	— oxygen gas
pH	— hydrogen power, a measure of a solution's acidity or alkalinity
SIR	— surface insulation resistance, a measure of a circuit's electrical integrity
SMD	— surface-mount device
Sn-Pb	— tin-lead

eutectic tin/lead solder (63/37 weight-percent) is used in the paste and the solder wave. (The melting point of eutectic solder is 183°C.) Figure 1 illustrates a typical assembly sequence for a "mixed technology" circuit board; i.e., the board has both surface-mounted and through-hole devices. The sequence incorporates both processes, i.e., reflow soldering and wave soldering.

For *reflow soldering*, solder paste is printed on the circuit board using a stencil, and the surface-mount devices (SMDs) are placed on the board by machine (e.g., a robot). Next, the assembly is heated in an oven to a temperature above the liquidus temperature of the solder, which ensures that the tin/lead alloy is in a liquid state. The solder melts to form the metallurgical connections between the component leads and the bond pads on the board.

For *wave soldering*, adhesive dots are placed on the circuit board. A machine places the surface-mount components on these dots, which are then cured. Next, the through-hole components are inserted, and flux is applied to the assembly. Then, the assembly is preheated and is passed over flowing molten solder, i.e., a solder wave. The solder wets the leads and bond pads, forming a solder fillet.

Traditionally, cleaning operations have been required after reflow soldering and wave soldering. But by using the no-clean soldering processes described later, we can eliminate both cleaning operations.

**Fluxes and Solder Pastes.** If a good metallurgical bond is to be formed between a component lead and the metal pad or through-hole on a printed-wiring board, the metal surfaces must be free from oxides and wettable by solder. The liquid fluxes used in the wave-soldering process and the flux constituent in solder pastes create these wettable surfaces.

From a simplistic viewpoint, liquid fluxes are made of three ingredients: a solvent, a vehicle, and an activator. Solder pastes have more complicated formulations because they must also have:

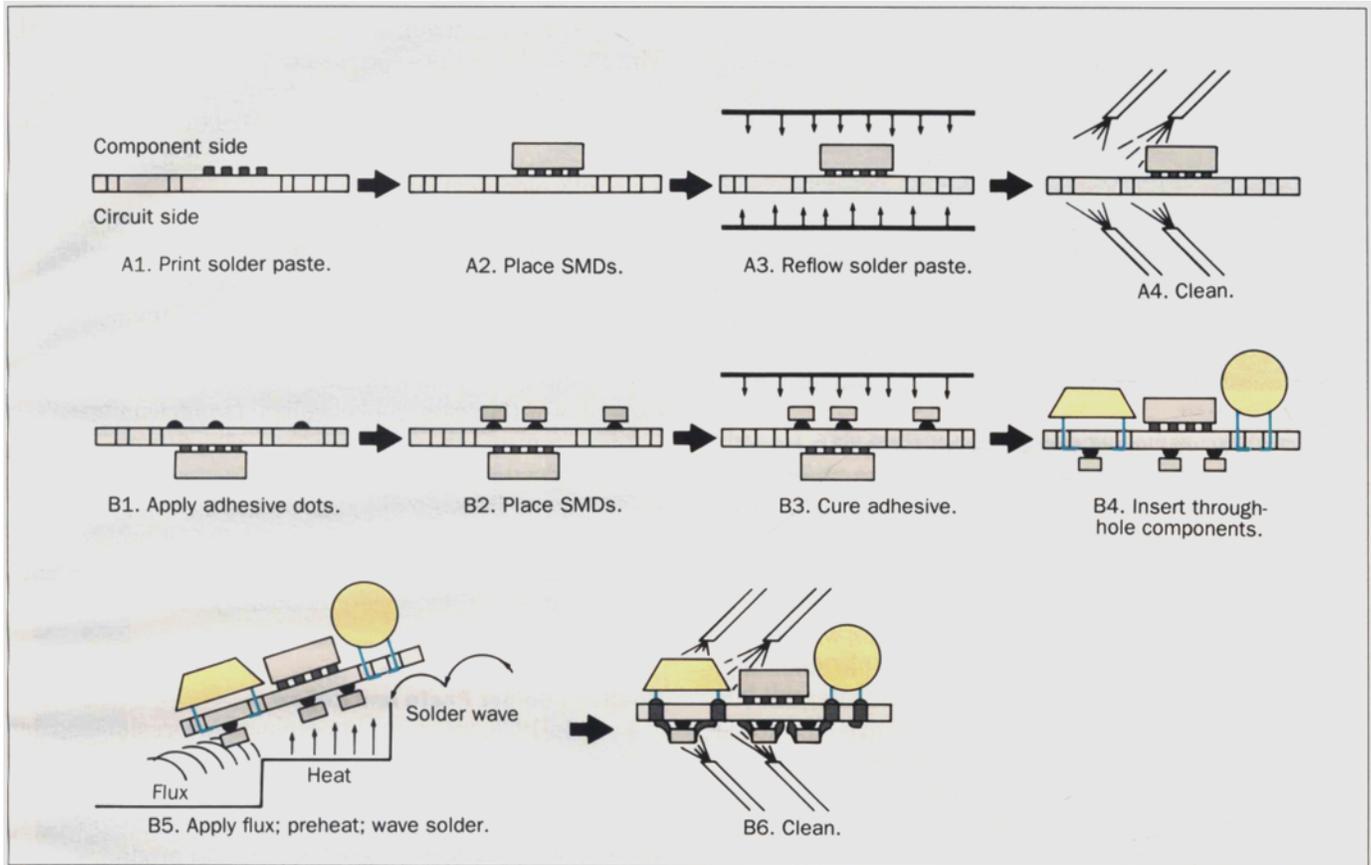
- The desired rheological properties for stencil printing. (*Rheology* refers to the form and flow of matter; specifically, a material's elasticity, viscosity, and plasticity—its ability to flow or be formed or to retain shape.)
- Adequate tackiness to hold components in place.
- Resistance to slumping (i.e., the deposit of paste holds its shape and does not spread out).

Fluxes and pastes can be categorized in terms of either their composition or their activity. Traditionally, they have been classified by their chemical makeup. When using this classification, one can choose from four categories of fluxes and pastes: rosin (R), water-soluble (WS) fluxes, synthetic-activated (SA), and low-solids (LS).

Depending on the composition of the flux or paste, the flux activity can vary from low to high, and the flux residue can vary from benign to corrosive and from tack-free to tacky. The choice of cleaning material and process is predicated on the characteristics of the flux or paste residue. Cleaning materials include chlorinated solvents, chlorofluorocarbons, nonchlorinated solvents (e.g., alcohols, terpenes), saponifiers, and water. (A *saponifier* reacts with flux residues to form water-soluble soaps that are then removed by rinsing.)

Solder pastes combine solder alloy and flux in a printable paste. Generally, the paste consists of a solder alloy powder that is dispersed in a vehicle of fluxing agents, rheology modifiers, and a suitable solvent.

As Figure 2 shows, conventional rosin-based solder pastes leave a sticky residue on the printed-wiring board after soldering. Low-residue solder pastes are formulated with a minimum amount of organic solids and use materials that are volatile at soldering temperatures. Both factors greatly reduce the amount of residue left on the product. If these low-residue solder pastes are to be used, an inert (i.e., nonoxidizing) atmosphere such as nitrogen is needed in the reflow oven.



**Figure 1. Typical assembly process for a circuit board that incorporates surface-mounted and through-hole components. The cleaning steps that follow (a) reflow soldering and (b) wave soldering can be eliminated.**

**Benefits of No-Clean Processes.** If one can eliminate post-reflow and post-wave solder cleaning, one also eliminates the cost of the cleaning machines and their maintenance and reduces materials and operating costs. Along with these cost reductions, one also saves floor space because the cleaning machines are no longer required. In addition, the processing interval is reduced and the process simplified because fewer processing steps are required.

Because these cleaning steps are no longer required, the need for post-solder assembly steps is eliminated for those components that are incompatible with the cleaning process. Previously, such components had to be inserted and soldered manually.

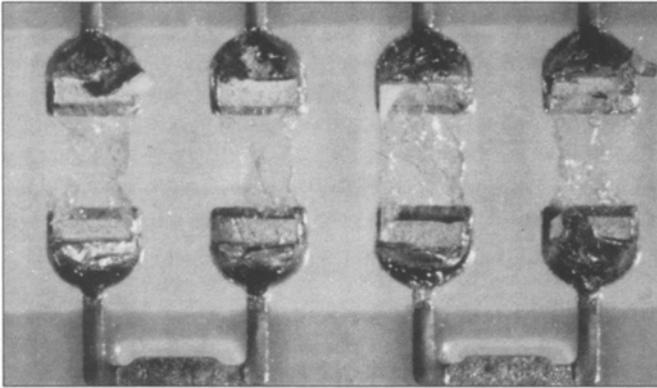
In addition, by eliminating the cleaning processes, we respond to concerns about local, state, and national environmental regulations; component qualification; and waste disposal. Now, more than ever, the environmental issues are important because of the

persuasive evidence that links CFCs and chlorinated solvents to the depletion of stratospheric ozone and the impending phase-out of CFCs and other chlorinated solvents. Disposal requirements for industrial waste are being tightened based on the composition of the effluent and its heavy metals content.

Besides the elimination of cleaning, the no-clean, wave-soldering process that we developed and discuss later provides these additional benefits:

- It reduces the use of flux materials.
- It improves soldering yields, compared to the yields associated with commonly used rosin fluxes.

Because test probes now can make better contact, the testability of the boards is also enhanced compared to



**Figure 2. Close-up view of surface-mount lands on a circuit pack that has been reflow soldered using conventional, rosin-based solder paste. Components have been removed to show the sticky paste residue.**

boards with rosin residues. Depending on the circuit-board design and the manufacturing location, we have observed as much as a tenfold improvement in soldering yields. Soldering yields have even improved after the change from water-soluble flux (a more active flux) to LSF, owing to the elimination of post-solder hand assembly.

For good reflow of LRSPs, an inert atmosphere is needed. Nitrogen gas or other inert gases are acceptable. (Conventional pastes do not need special atmospheres.) Additional advantages for using a no-clean solder paste in an inert atmosphere include:

- Less oxidation of surfaces to be soldered in later operations
- Improved yields and reduced solder-ball formation during reflow soldering
- The ability to use inexpensive, organic solderability coatings rather than tin-lead (Sn-Pb) coatings over bare copper.

#### **Test Methods and Specifications**

In AT&T, the materials used in soldering processes are extensively evaluated to ensure that the materials do not degrade the product's reliability and will be compatible with our manufacturing processes. We test fluxes, pastes, and their residues after heating to determine their ability to corrode copper mirrors or plates and their halide content, pH level, and conductivity as measured by surface-insulation resistance. [*Halide* is a

compound of a halogen and another element or a radical. The *pH* level identifies the material's acidity or alkalinity. Halide content and pH level are further indicators of the corrosivity (i.e., ability to corrode) or activity of flux residues. *Surface-insulation resistance* or SIR is a measure of a circuit's electrical integrity.]

In addition, we evaluate liquid fluxes and solder pastes for soldering performance and also test solder pastes for rheology, printability, and slump resistance.

Recent papers<sup>1,2</sup> describe some of the tests currently used in AT&T and throughout the electronics industry to qualify soldering materials. These papers also explain how the tests can be applied to no-clean processes.

Figure 3 shows three SIR comb patterns that were exposed to the same temperature and humidity environment, but with different preconditioning. The images show the oxidation of copper during processing and the potential corrosivity of the flux residue. For test details, the interested reader should consult the appropriate specifications.<sup>3-6</sup>

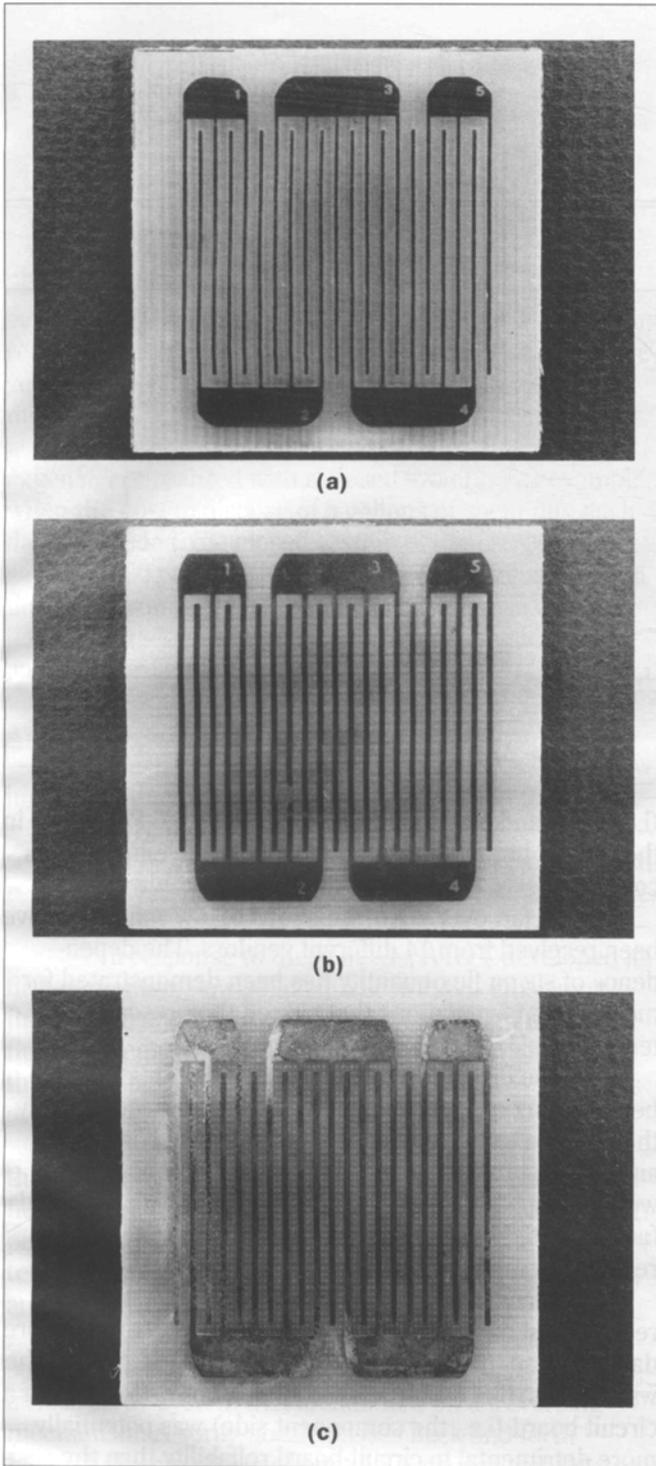
#### **No-Clean Solder Paste and Reflow**

In 1988, we 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, we could reflow them in atmospheres with various reactive additives to produce good solder joints and small amounts of residue.<sup>7</sup> Results from reliability tests showed that these residues were noncorrosive and nonconductive. AT&T obtained a patent that covers this reactive-atmosphere soldering method.<sup>8</sup>

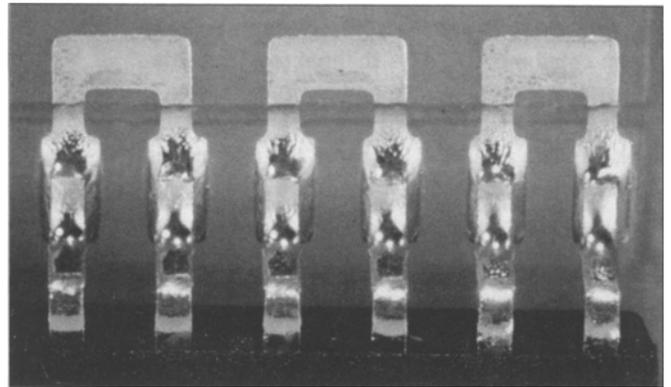
For general applications, an inert atmosphere is greatly preferred to one that incorporates reactive species. Thus, our focus turned to the evaluation of paste materials that would reflow in nitrogen and were compatible with AT&T's reliability and process requirements.

The physical, rheological, thermal, electrical, and chemical properties of more than 25 materials from 10 vendors were evaluated.<sup>9,10</sup> By the end of 1990, we had identified several materials that met AT&T's requirements. Figure 4 shows the well-formed solder fillets and minimal residues obtained using one of these pastes.

As a parallel effort to paste characterization, we evaluated nitrogen-capable reflow ovens for their thermal profile and the oxygen content of the reflow environment. We obtained thermal profiles on assembled



**Figure 3. Three SIR comb patterns that have been exposed to a test condition of 35°C and 90-percent relative humidity. (a) Bare copper not exposed to flux. (b) Oxidized copper not exposed to flux, but exposed to reflow temperatures in air. (c) Corroded copper exposed to a concentrated quantity of flux and heated. These images show the oxidation of copper during processing and the potential corrosivity of the flux residue.**



**Figure 4. This surface-mounted package has well-formed solder fillets and minimal residues. It was reflow soldered in nitrogen using a low-residue solder paste, one of several materials that met AT&T's requirements.**

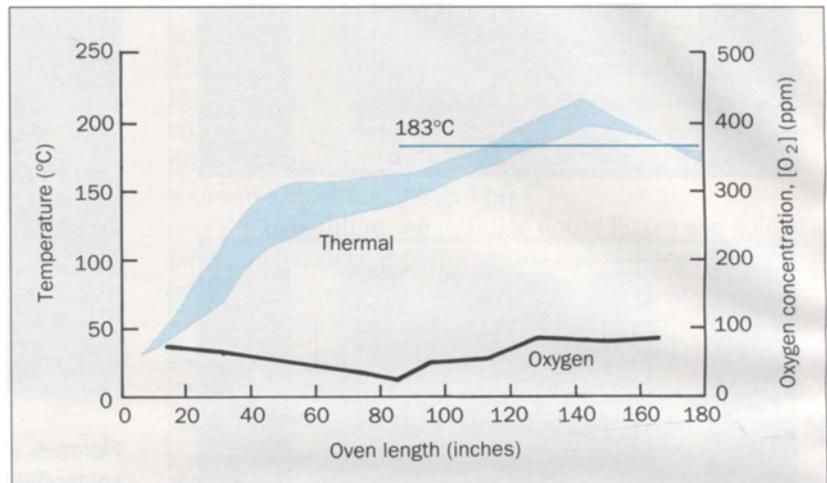
printed-wiring boards that were typical of those soldered in production and did oxygen mapping under loaded, production conditions. A description of our procedures and the results have been published.<sup>11</sup>

Several commercially available ovens could meet the thermal requirements. The best ovens were those that incorporate 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<sub>2</sub>) and the most gas-tight systems could maintain less than 10 ppm throughout their length. Figure 5 shows the thermal profile and oxygen map for an oven used in the trials.

Next, to determine the *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 feeds 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 suggest that up to 500 ppm of oxygen will neither decrease the visible quality of the solder joint nor increase the visible paste residue left on the board after reflow, compared to less than 10 ppm of oxygen.

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

**Figure 5. Several commercially available reflow ovens could meet AT&T's thermal requirements. This is the thermal profile and oxygen map for one oven that was used in a no-clean reflow trial. The line at 183°C indicates the melting point of eutectic solder.**



oxygen level that can be tolerated will be determined by the need to minimize oxidation to preserve solderability for later operations, and not by the oxygen sensitivity of the solder paste.

In early 1991, we conducted a factory trial at AT&T's Shreveport Works in Louisiana. Reflow soldering was done in nitrogen with less than 100 ppm of oxygen. The soldering results were good, with solder defects of less than 15 ppm.

In September 1991, AT&T's Columbus Works in Ohio implemented the process. Since then, most AT&T surface-mount assembly factories have purchased nitrogen-capable reflow equipment. By the end of 1991, at least 13 lines will have been equipped to use inert atmosphere, no-clean reflow soldering.

#### **No-Clean Flux and Wave Soldering**

Post-solder cleaning can be eliminated only if the flux residues that remain do not affect the circuit pack's performance, testability, or reliability.

Flux manufacturers have formulated low-solids fluxes to eliminate the cleaning operations. However, accelerated aging tests of circuit boards uncovered long-term corrosion problems. When the test was repeated with new circuit packs that were exposed to less low-solids flux, there were no failures. Experiments showed that the SIR decreased as we increased the amount of flux applied. These results suggest 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 and higher temperatures and relative humidities could exacerbate an electrical integrity problem.

So far, over 60 formulations of low-solid flux 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 this 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 would be applied to the board. Consistent with the need for application control are application uniformity and repeatability.

In addition, we found the partially heated flux residue that did not contact the solder wave caused more damage than the fully heated residue that did contact 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 meant 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 LSFs, traditional flux-monitoring techniques are not accurate enough. Typical application methods need monitoring because they use open reservoirs. These reservoirs allow the main constituent of a flux (i.e., alcohol) to

---

evaporate and to absorb water. Accordingly, a closed flux reservoir and delivery system is a benefit, because it prevents compositional changes and negates 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 the LSF-2000 can save \$20,000 per year in costs for monitoring, additional flux and alcohol, and disposal compared to an open system. (The LSF-2000 is AT&T's newest low-solids fluxer, and is described in the next section.)

#### **AT&T's Low-Solids 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 alcohol evaporation and water absorption).

In response to these needs, AT&T developed its first-generation, low-solids fluxer in 1988. This spray fluxer used an ultrasonic atomization system to deposit flux on circuit boards. AT&T has been granted patents that cover both the methods and apparatus.<sup>12,13</sup> Details of this fluxer have been published.<sup>2</sup>

The first-generation spray fluxer did 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 deposition, wider spray capability, and decreased maintenance.

In 1990, the second-generation, LSF-2000 low-solids 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 its 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, Texas, 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 is available to the industry, offering them an economically and environmentally sound flux-application method.

#### **Summary**

The most promising alternatives for no-clean soldering are modified *processes*, not simple substitutions of *material*. Inert-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.

We have defined a production process that can be implemented with equipment that is commercially available. Further optimization will be done as we gain experience with the system in our factories and as improved materials become available.

Before fluxes are used in production, proper evaluation is imperative. We found that some LSFs were better than others. For all LSFs, SIR testing confirmed the theory that arose from our 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 that AT&T developed 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 using low-solids fluxes with the appropriate process, AT&T has eliminated the need for cleaning and is making progress toward its environmental goals.

#### **Acknowledgments**

We gratefully acknowledge the help from our colleagues. At AT&T in Princeton, New Jersey, Linda Fletcher did the liquid-flux evaluation tests; Jim Conway did the solder-paste evaluations; and our supervisors, John Fisher and Gordon Roberts, supported our work.

We also collaborated with Mark Hahn from AT&T in Indianapolis, Indiana, who did the early accelerated aging tests on low-solids fluxes. Joe Kaczorek, Dave Hollesen, Russ Schuss, and Margit Elo-Genthner from

---

AT&T in Princeton were responsible for the development of the second-generation, low-solids fluxer. Also, we greatly appreciate input from AT&T's manufacturing engineers.

#### References

1. J. R. Morris, "No-clean Reflow Alternatives," *SMART VI 1990 Proceedings, Surface Mounting and Advanced Related Technologies Conference*, January 15-18, 1990, Lake Buena Vista, Florida, Electronic Industries Association, Washington, D.C., 1990, pp. 97-106.
2. L. A. Guth, "Low Solids Flux Technology for Solder Assembly of Circuit Packs," *1989 Proceedings, 39th Electronics Components Conference*, sponsored by the IEEE Components, Hybrids, and Manufacturing Technology Society and the Electronic Industries Association, May 22-24, 1989, Houston, Texas, IEEE 89CH2736-7, IEEE, New York, New York, 1989, pp. 748-753.
3. Institute for Interconnecting and Packaging Electronic Circuits, "General Requirements for Electronic Grade Soldering Fluxes," IPC Standard IPC-SP-818, Institute for Interconnecting and Packaging Electronic Circuits, Lincolnwood, Illinois, 1987.
4. Institute for Interconnecting and Packaging Electronic Circuits, "General Requirements for Electronic Grade Solder Paste," IPC Standard IPC-SP-819, Institute for Interconnecting and Packaging Electronic Circuits, Lincolnwood, Illinois, October 1988.
5. Bell Communications Research, "Generic Physical Design Requirements for Telecommunications Products and Equipment," Technical Reference TR-TSY-000078, Issue 2, Bell Communications Research, Morristown, New Jersey, 1988.
6. Japanese Standards Association, "Testing Method for Resin Type Soldering Flux," Japanese Industrial Standards JIS-Z-3197, Japanese Standards Association, Tokyo, Japan, October 1986.
7. J. R. Morris and N. Bandyopadhyay, "No-clean Reflow Processes," *Printed Circuit Assembly*, Vol. 4, No. 2, February 1990, pp. 26-31.
8. J. R. Morris, "Method of Soldering Articles," U.S. Patent 5,096,658, issued September 10, 1991.
9. J. R. Morris, J. H. Conway, and S. Chowdhury, "Characterizing Solder-Pastes for the 1990s," *The Second International Flux Technology Conference*, September 5-7, 1990, Pittsburgh, Pennsylvania, IPC-TP-901, Institute for Interconnecting and Packaging Electronic Circuits, Lincolnwood, Illinois, 1990.
10. J. R. Morris and J. H. Conway, "No-Clean Reflow Process Implementation—Part 1," *Circuits Assembly*, Vol. 2, No. 7, July 1991, pp. 38-42.
11. J. R. Morris and J. H. Conway, "No-Clean Reflow Process Implementation—Part 2," *Circuits Assembly*, Vol. 2, No. 8, August 1991, pp. 28-35.
12. J. Fisher, L. Guth, and J. Mahler, "Method for Applying Flux to a Substrate," U.S. Patent 4,821,948, issued April 18, 1989.
13. J. Fisher, L. Guth, and J. Mahler, "Apparatus for Applying Flux to a Substrate," U.S. Patent 4,871,105, issued October 3, 1989.

(Manuscript received October 1, 1991)

**Leslie A. Guth** is a distinguished member of technical staff in the Environmental Materials and Processes Department with AT&T Bell Laboratories at the Engineering Research Center in Princeton, New Jersey. She is responsible for the implementation of no-clean low-solids fluxes and optimization of the wave-soldering process. Ms. Guth joined the company in 1984 with a B.A. in physics from the University of North Carolina at Chapel Hill, and a Ph.D. in materials science and engineering from the University of Pennsylvania (Philadelphia). **John R. Morris** is a member of technical staff in the Assembly Technology Department with AT&T Bell Laboratories at the Engineering Research Center in Princeton, New Jersey. He is responsible for the implementation of no-clean reflow processes and the development of fine-pitch, surface-mount assembly technology. Mr. Morris joined the company in 1986 and earned a B.S. in ceramic engineering from Rutgers University (New Brunswick, New Jersey), an M.S. in materials science from Drexel University (Philadelphia, Pennsylvania), and a Ph.D. in ceramic science from Rutgers University.