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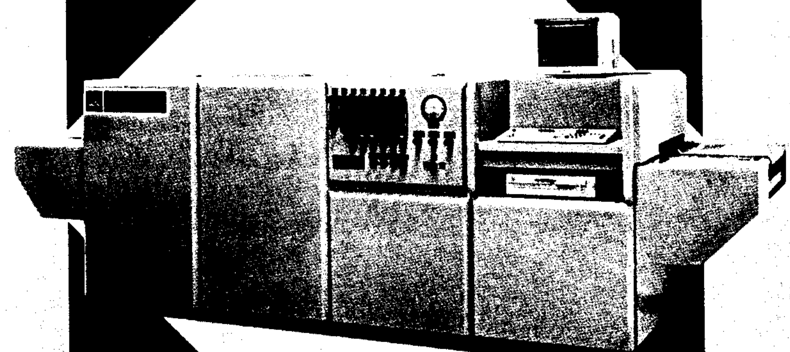
The Watkins-Johnson *Tech-notes* is a bi-monthly periodical circulated to educational institutions, engineers, managers of companies or government agencies, and technicians. Individuals may receive issues of *Tech-notes* by sending their subscription request on company letterhead, stating position and nature of business to the Editor, *Tech-notes*, at Watkins-Johnson's Palo Alto, California address. Permission to reprint articles may also be obtained by writing the Editor.

Printed in U.S.A.

VOL. 18 NO. 1 JANUARY/FEBRUARY 1991

WATKINS-JOHNSON COMPANY Tech-notes



Surface-Mount Devices Reflow Soldering

New Topics for *Tech-notes*

While the production of high-quality defense-electronics equipment and systems is synonymous with the name Watkins-Johnson, the company is also a leader in the manufacture of commercial equipment for semiconductor fabrication, thick-film firing, solder reflow, package sealing and thin-film coating.

To better acquaint readers with the latest developments in Watkins-Johnson's entire product range, the company's commercial equipment will be periodically featured in *Tech-notes*. The issues featuring articles written by members of the Commercial Group will be symbolized by a cover color other than the standard *Tech-notes* blue. The January/February 1991 issue carries the first of these articles, which features production furnaces for high-volume reflow soldering of printed-circuit boards.

Jose C. de León
Editor, Watkins-Johnson Company *Tech-notes*

Integrating the numerous components into a circuit is normally done at the printed-wiring-board level. Printed-wiring or printed-circuit boards (PWBs and PCBs, respectively) unite the components to form a subsystem of the finished product.

In general, the PWB industry can be seen as tracking the silicon chip industry on a larger scale. Just as it has become necessary to pack more circuitry on a silicon chip, PWBs have also had to be made more dense to provide higher operating speeds, space reduction, and improved efficiency.

Reduction in board size also creates problems in such areas as heat dissipation, placement of components at high speed and volume, and soldering and component design. Regardless of these obstacles, the trend to higher density continues at an accelerating pace, the logical conclusion possibly being wafer-scale integration.

It is this trend towards smaller size that drives the capital equipment industry and the component design industry. The upgrading of manufacturing facilities world-wide, generates sales that fuel the equipment manufacturing industry.

Along with the shrinking of circuits and the subsequent increase in density, the industry is seen moving to new substrate materials adaptable to very conformal package requirements, heat dissipation problems, and the continual striving to reduce costs.

The PWB Substrates

The most common medium used today for PWB substrates is fiberglass. This green-colored synthetic material handles heat relatively well, is very inexpensive and, due to the material's ability to resist chemicals, is easy to laminate with copper and etch back all but the desired conductive traces joining the component locations. These copper traces may then be plated with nickel, gold or silver.

Fiberglass circuit boards can be manufactured as single-layer, single-sided circuits or sandwiched to fifty-five or more layers, with conductors in the sandwich connecting the various layers electrically. Multilayer boards, as they are called, are more generally two-to-four layers in thickness.

Another medium for the PWB is mylar®. This material can literally come off of a roll, is laminated with copper conductors, and can be made to wrap around circumferences (eg., missile bodies) or conform to other non-rectangular chassis. Mylar was invented by DuPont and has seen its most popular use in military applications. Other materials have also been used for PWBs, but fiberglass will most likely continue to be the most common.

Circuits known as "hybrids" are in common use; the primary uses being military, high-end computer and automotive applications. Depending on the application, these hybrid circuits are enclosed in hermetic or nearly hermetic packages.

Generally, the chips are bonded to a ceramic substrate that can be encapsulated as a hermetically sealed package. This package is then soldered to the PWB for electrical contact. The conductors on the ceramic substrate are printed or vacuum-deposited on the substrate.

Advantages to hybrid technology include high-frequency capability, durability, and heat dissipation. Also, hermetic hybrids, being protected from the environment, provide high reliability, an attribute essential in missile and aircraft applications. However, hermetic hybrids are expensive, sometimes costing many times the price of conventional PWB's.

Definition of SMT

Surface-Mount Technology (SMT) is the mounting of electronic devices onto the surface of circuit boards or substrates, as opposed to the traditional through-hole mounting in which a wire lead penetrates through the board and is soldered on the back side.

Evolution of SMT

Originally, the hybrid industry evolved to reduce weight and volume in airborne equipment applications. SMT has provided similar benefits to commercial and consumer PCBs by reducing the size of all components, as well as the amount of required circuit-board area.

Much of this reduction can be attributed to new SMT device designs and the closer proximity in which the devices can be mounted next to each other.

The cost of SMT may be less expensive than conventional through-hole PCBs, but for SMT to be cost effective, moderate to very high production volume is necessary. While the components themselves are inexpensive, the high level of automation required to place, solder, and test the devices is relatively expensive.

Typically, SMT active components have been reduced to occupying one-half to one-third of the space on a PCB than in their former through-hole design. The passive components occupy even less space. This reduction of space is principally a function of lead pitch, which is the distance between the centers of adjacent leads. The typical DIP (dual in-line package) has a lead pitch of 100 mils (thousandths of an inch). The SMT equivalent has a lead pitch of 50 mils, and "fine pitch" SMT packages will feature 33, 25 or 20 mil pitches.

The savings in space can be further enhanced by the use of double-sided component placement. It should be noted that some of the space savings will be lost if mixed technology (a combination of through-hole and surface-mount components) is used on the same board.

Because of the totally automated nature of its manufacture, SMT is considered to be more reliable in terms of yield and performance. The high level of automation ensures better placement, orientation, and testing (electrical and mechanical).

In addition to smaller size, surface-mount technology devices offer less mass for high acceleration/deceleration, and the parasitic circuit factors are far superior due to the electrical configuring that can be realized.

In addition to excellent overall reliability, repairs, when necessary, are easier to accomplish and less likely to cause surrounding circuit damage. This attribute has been a significant factor in enhancing PCB up-time.

Advantages/Disadvantages of SMT

When selecting conventional or SMT designs, it is important to consider practicality over technology. SMT should be considered in those applications where performance, weight, function, and space requirements cannot be met by conventional through-hole fabrication. Many components are not available in surface-mount packages. These include some VLSI devices, sockets, connectors, delay lines, crystals, and oscillators. Consequently, use of these devices may eliminate some of the advantages SMT can offer.

Generally, SMT boards cost more to design and build because of such factors as higher component density and buried vias. Rule-of-thumb suggests that if multiple through-hole boards can be replaced by a single or fewer SMT boards, then a cost advantage will be realized by using the later technology. If performance is more important than cost, the choice is usually SMT.

The disadvantages of SMT come from the extensive capital and personnel requirements necessary. Many levels of technology are required and the work is engineering-intensive. SMT manufacturing is more complex, requiring more kinds of operations. CAD and CAM tools are almost mandatory. Solder-joint design, thermal management, and interconnects are all more complex for SMT.

The cost of capital equipment is so great for SMT, most companies are subcontracting this work out to vendors, who must then deal with the costs of buying and maintaining the manufacturing equipment. Costs may be even more significant than meet the eye due to the on-going rapid change within the industry. If surface-mount designs are being considered, several vendors will have to be evaluated for capabilities and design options.

Future Trends

There are many rapidly unfolding and very positive trends developing in the SMT industry. Standardization is rapidly evolving and will accelerate, as well as facilitate, the development and acceptance of this industry. This development is being managed and communicated by the EIA (Electronics Industries Association), IPC (Institute for Interconnecting and Packaging Electronic Circuits), and large companies with in-house development capabilities.

Component costs and availability are rapidly matching those of the through-hole design. This will allow the industry to go to a higher percentage of surface-mounted devices, thus enabling the designer to enjoy the full benefit of the surface-mount concept.

The actual PCB manufacturers are rapidly changing over and making the investment in new capital equipment to capture a larger share of the market, including the overseas market. American manufacturers are offering rapid turn-around, exceptional quality with state-of-the-art designs, and are relieving the system manufacturer of the cost and training of in-house circuit-board manufacturing. This will greatly facilitate U.S. companies' adoption of the SMT approach to PCB design.

Chip-on-board (COB) technology (the attachment of a bare integrated circuit to any substrate) is having a major impact on the design and manufacture of SMT. Since the die is much smaller than for packages having a lead pitch, the savings in space is very significant. This technology is being heavily used in consumer products such as smart cards, watches, calculators, cameras, etc. The COB technology is customarily divided into three categories: a) tape automated bonding (TAB), b) chip-and-wire and c) flip-chip.

Manufacturing Processes

The most common type of PCB is a multilayer through-hole and surface-mount assembly (TYPE II or TYPE III) utilizing a fiberglass substrate with copper conductors and, often, gold-plated connectors. Because of the large number of devices and the very high level of accuracy with which they must be located on the board, circuit-board manufacturing has become highly automated.

The circuit boards are normally designed and manufactured at a location separate from the final assembly. Upon arriving at the assembly facility, they are cleaned and checked. Solder paste is then applied to the appropriate locations for the surface-mount components. Application of solder paste is done by machine, quite rapidly, by screen-printing the traces across the entire board in one pass. The paste not only will provide the solder, but it will act as a temporary glue to hold the devices in place while the board moves through a belt-type soldering furnace. Once the PCBs have had the paste applied, they are ready to have the components located.

Components come in batch form (loose) or on tape. Either way, they are picked up, electrically and mechanically oriented, removed from the tape carrier, when applicable, and accurately positioned on the board to within a couple thousandths of an inch. The machine that performs this operation is appropriately referred to as a "pick-and-place" machine. This machine does its job so quickly that in most cases it is hard to follow with the human eye. For example, four hundred (400) components can be selected, properly oriented, and placed on a "12x12" board in less than two minutes. The software, complexity and cost of these pick-and-place machines is very high, often more than one million dollars, and usually represents the most costly piece of capital equipment in the manufacturing line.

From the pick-and-place process, the PWBs proceed to a belt-type furnace for soldering. This furnace can normally solder all the devices on both sides of the board simultaneously. It will solder surface-mount and through-hole boards at the same time as well.

After the soldering is completed, the boards are recleaned to remove excess solder flux and any beads of solder. Many fluxes are now water soluble, so that toxic solvents are not involved. In addition, no-residue or low-residue fluxes that require no cleaning are available for many applications.

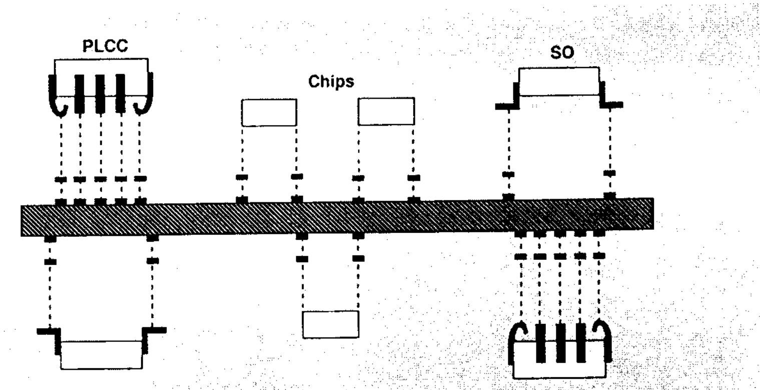
Electrical testing is the next stage prior to packaging and shipment. Electrical and mechanical testing checks are made for cold solder joints, device orientations, etc. This test equipment can be very elaborate and software-intensive or may be accomplished by highly skilled technicians.

SMT board design types have been divided into three categories for ease of reference by the industry.

Type I classification describes substrates containing only surface-mounted components, active and passive (see Figure 1). The substrates are most often double-sided boards, but may be single-sided and still fall into this category. Type I may be considered the high end of the technology, using the least amount of space and weight, with the highest performance and intermediate cost.

Type II is the most common classification manufactured. It incorporates through-hole and surface-mount components in active and passive form (see Figure 2). The design of these boards can be single or double-sided. If the design is double-sided, the passive components are often located on the bottom side with the PLCCs (plastic leaded chip carrier) and SOICs (small outline integrated circuit) on the top side. This type of assembly represents the transition between full SMT and through-hole technology, and represents the highest cost of manufacturing, as it requires all the process steps of TYPE I and TYPE III to fabricate and test.

Type III is similar to Type II, with through-hole and surface-mounted components (see Figure 3). However, the difference is that PLCCs or SOICs are not commonly used, but rather DIPs and only discrete surface-mount components (resistors, capacitors, transistors) are mounted on the bottom side of the board. This is a less expensive assembly to design and build, with corresponding performance.



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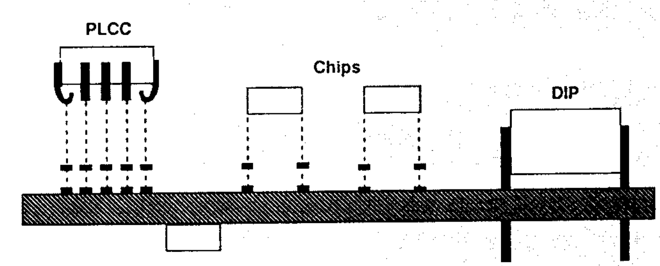

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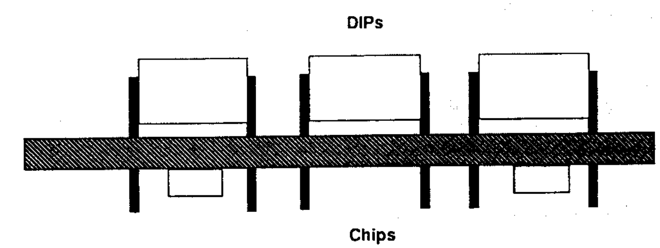

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SMD Furnace

The Watkins-Johnson production furnace line has evolved over many years in parallel with the evolution of the circuit-board industry. The SMD (Surface-Mount Device) furnace is the newest product to be introduced to meet the ever-more stringent requirements of the industry.

A short overview of the furnace soldering processes that have led to the development of the controlled-convection SMD furnace is necessary to understand the evolution.

Hot-Plate Soldering

This furnace soldering approach is perhaps the oldest and is still used with low-volume production. The hand-assembly application of this technology involves having a heated plate (approximately 200°C) of any size on which the boards are placed and brought up to a temperature just below the melting point of solder. The technician then brings the solder up to a reflow temperature using a hot-air gun, thus completing the soldering process. The PCBs are then removed and the next batch put in place to repeat the cycle.

The higher volume, automated hot-plate soldering uses a similar approach. This is a very direct approach in that the assemblies are passed over heated plates which ramp-up the temperature of the circuit board to drive off the fluxes and then melt the solder. Different temperature ranges, achieved by having separate heating zones within the length of the belt furnace, compensate for the thermal mass of the heating plates to obtain appropriate ramp-up or ramp-down temperature.

Vapor Phase Soldering (VPS)

The primary heating vapor in this furnace process is a perfluorocarbon with a boiling point of 215°C (419°F). This vapor is then covered with a lower-density, lower-temperature vapor of lower cost. This vapor serves two functions: it reduces loss of the primary vapor to the atmosphere and provides a slower temperature change as the products are inserted and removed. The assemblies are allowed to remain in this environment for a period of 30 to 60 seconds, depending on the thermal mass of the product. They are then processed out of the furnace for cleaning.

VPS furnaces are designed in a batch-type configuration in which the assemblies are introduced from the top down. Another furnace design is the in-line configuration, where the circuit boards are introduced at one end on a conveyor belt of steel mesh and transported through the vapor and out the other end for final work.

The heat transfer mechanism for VPS is:

$$Q = hA(T_v - T_s).$$

Where,

Q = heat trans. rate from vapor to part (Btu/hr)

h = heat transfer coefficient (Btu/hr x ft^2 x °F)

A = product surface area (ft^2)

T_v = saturated vapor temp. (°F)

T_s = part surface temp. (°F)

I.R. Lamp (near IR)

In this furnace process, heating from convection accounts for less than 5%, with the balance being directly radiated. The near-IR spectrum is in the short wavelength of .7 to 2.8 microns. The source of infrared is generated from lamps which heat the boards from the top and/or the bottom as desired. The board is gradually heated as it travels through the furnace. This gradual heating vaporizes the solvents and fluxes, which are immediately vented out of the system, leaving a clean surface for soldering. The final temperature rise is quite swift and goes just above the melting point of the solder and lowered again immediately to prevent leaching of the component terminations into the solder. This fast "spike" also reduces intermetallic formation and enhances the crystal structure of the solder joint.

At the time the soldering process is completed, the assemblies are cooled down with forced-air cooling and exited out of the system for cleaning and testing.

The heat transfer mechanism for radiated heat transfer between two bodies at different temperatures is:

$$Q = F_e F_v A K_B (T_e^4 - T_p^4)$$

This equation applies to heat transfer between two black bodies (two energy-absorbing bodies).

Q = radiation heat transfer rate (Btu/hr)

F_e = emissivity factor for emitter and product

F_v = geometric view factor (IR energy on component)

A = emitter area (ft^2)

K_B = Boltzmann's constant (0.1714×10^{-8} Btu/hr$-$ft^2$-$R^4) (R: Rankin)

T_e = emitter temp. (°R)

T_p = product temp. (°R)

The wavelength of the radiation is determined by the temperature of the emitter as defined in Wien's Law:

$$(W_p = K_w / T_e)$$

I.R. Panel (convection/infrared)

In this furnace system, the I.R. panel source of energy emits from heating panels in the 2.8 to 8 micron wavelength. The majority of the heating is done with convected hot air within the furnace. The smaller part of the heating is from the directly radiative source (heating panels).

Like the other belt-type furnaces, this system ramps up the heat to vaporize solder fluxes, exhausts it immediately and then creates a short heat spike in one chamber to melt the solder prior to bringing it back down to room temperature.

Convection

The idea of using forced convection of hot gases to heat the circuit assembly for solder reflow came into being as a means of heating the circuit board and its components as evenly as possible. This concept essentially was developed to overcome the shortcomings of the previously mentioned processes, which include cost, waste, and uneven heating.

Convection furnaces are now becoming the standard for the industry. They are the belt-type design that takes products in one end, with the components in place, and delivers them at the exit as finished assemblies ready for cleaning and testing. Convection furnaces are becoming more accepted for future technology.

WJ-SMD Production Furnace

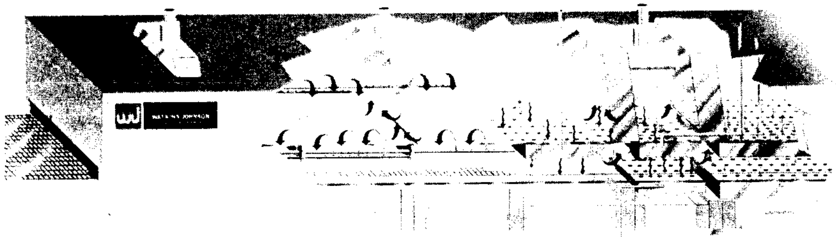
Watkins-Johnson Company has addressed the issues related to the convection approach to solder reflow and has produced a furnace that appears to have matched the requirements of the SMT industry well into the future.

The SMD production furnace was designed for the solder reflow process in the manufacturing of TYPE I, II and III printed-circuit boards. Specifically, it is focused on the emerging SMT industry and its very demanding solder reflow requirements.

The furnace uses a forced-convection approach to heating the assemblies for the solder reflow (see Figure 4). However, some very unique engineering has overcome the obstacles of previous designs.

minutes, with impurity levels below 10 ppm. Another problem that has been overcome is the heat-up time from a cold start. The new furnace will come up to operating temperature within 35 minutes.

Computer-controlled forced convection is directed down to the top of the board and/or up to generated and maintained via plenums with in-line and panel heaters. The vertical flow now allows cross-belt temperature gradients to be held to ±2°C, regardless of the belt loading. The cooling process is, likewise, very fast, due to the uniform exposure across the circuit board by the vertical flow of cooling atmosphere. The cooling gas may be inert or outside atmosphere.



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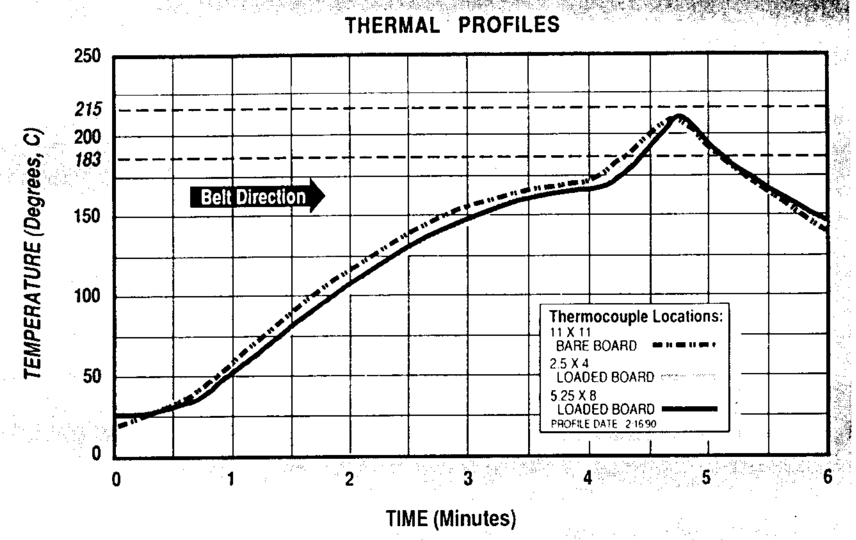
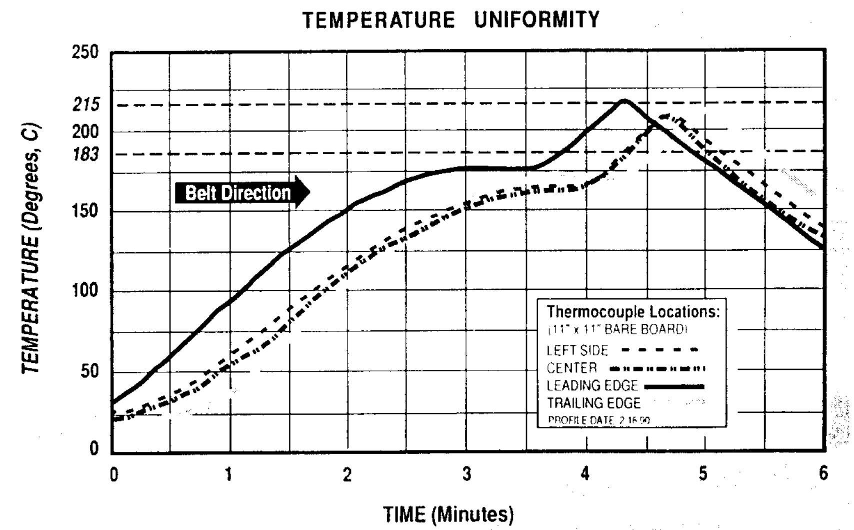
The process chamber, in which the belt carries the circuit boards through, is a low-mass, metal muffle which provides the most efficient way to maintain atmosphere integrity. The muffle acts as a tunnel that encloses the conveyor belt and product in a completely controlled atmosphere from the entry to the exit of the furnace. The "low-mass muffle" allows very fast ramp-up and down times as well as multiple atmosphere capability. The system can process circuit boards up to 63.5 cm (25 in.) in width in air or inert atmospheres. The atmosphere changeover time can be 4 to 5

The WJ-989 Controller allows all processes to be repeated by allowing the operator to store the "recipe" on the hard disk or floppy. This assures a degree of repeatability which was often difficult to achieve in the past. The temperature profiles for four commonly used printed-circuit boards are shown in Figure 5.





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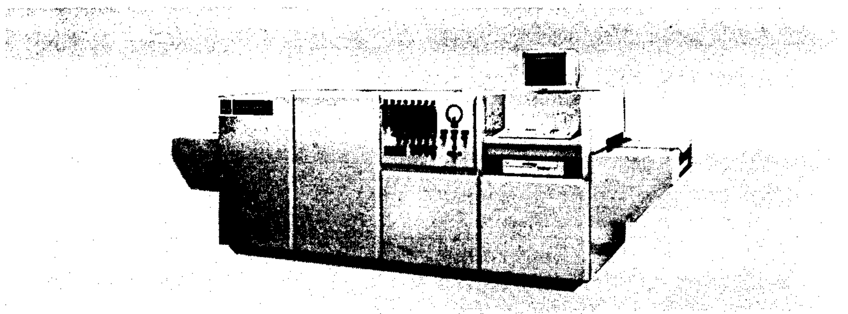
The exhaust system is also controlled such that it offers the operator the ability to match flow rates to control the airflow over the board surface (see Figure 6).

Because the temperature is so well controlled, single-sided and double-sided boards with a high diversity of thermal mass can be reflowed very successfully. An in-line ultraviolet curing system is also available for the bonding agents, if needed.



Conclusion

The printed-circuit board and silicon-chip industries continually strive to reduce the size of their products.

The benefits are direct and indirect. The direct benefits are faster circuitry, utilizing less power and less space. With the new manufacturing techniques, the completed product will also be less expensive, relative to performance.

The indirect benefits come as a result of the industry being in a very dynamic state. This provides manufacturers of production equipment to continually grow as they produce new and more efficient equipment to handle the shrinking devices and denser loading of the PCBs.

Ultimately, we may see the entire primary circuit on a wafer. However, until then, the printed circuit, in all of its configurations, will be the medium the components use to interface with each other.

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