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ELECTRONIC FABRICATION AND ASSEMBLY IN THE STEVEN MULLER CENTER FOR ADVANCED TECHNOLOGY

The relocation of the Electronic Fabrication Group to the Steven Muller Center for Advanced Technology resulted in many improvements in the fabrication of printed wiring boards (PWB's) and the assembly of components onto them. The plating and etching facilities are upgraded and fully operational, creating a well-controlled and safe environment for PWB fabrication. Furthermore, several new machines have been added that allow for the fabrication of multilayer PWB's. The assembly area is fully integrated with the wiring and harness fabrication areas, the encapsulation laboratory, and the inspection area, thereby creating smoother work flows. Technologically, the area is well-suited to fabricating more reliable assemblies because the new facility provides an atmosphere that virtually eliminates the discharge of static electricity and reduces the presence of airborne contamination to low, acceptable levels. Several new tools also have been added that will increase the reliability of the final assemblies and improve productivity.

INTRODUCTION

Engineering closely allies the process of hardware design with the process of hardware fabrication to provide customers with material that meets their performance, schedule, and cost expectations. This alliance is especially necessary in an environment where the designs are constantly in flux and each day brings wholly new challenges. The co-location of fabrication and design groups in the new Steven Muller Center for Advanced Technology (SMCAT) facilitates the concurrent engineering process and makes simple the maximum use of computer-aided design (CAD)/computer-aided manufacturing interfaces. Formerly, the facilities of the Electronic Fabrication Group were spread among several buildings at the Laboratory, making it difficult to coordinate the group's operations and establish state-of-the-art fabrication and assembly methodologies and tools. That arrangement also complicated the information interchange needed for the smooth construction of hardware. Now, with the entire group in the new location, its tools and techniques represent the most appropriate technologies for the hardware-producing segments of APL.

A very important part of the group's fabrication efforts is the new facility for producing printed wiring boards (PWB's) of many different materials and with more than the traditional two sides. We now have boards made of Teflon and boards composed of ten layers. The assembly of new style components onto these boards presents challenges for the group. The density and complexity of the components are greater than ever before, and our ability to work with smaller components with more and finer leads (or none at all) is growing. Many existing technologies are still appropriate, however, and are retained and improved. The group has also embarked on process control improvements that will serve the entire Laboratory well by improving the efficiency of fabrication and the reliability of the fabricated product. This article is a tour of the Electronic Fabrication Group's facilities in the SMCAT.

PRINTED WIRING BOARD FABRICATION

Process Planning

Today's PWB designs at APL are created with CAD or computer-aided engineering (CAE) workstations instead of older manual design methods. Artworks are no longer carried from the designers to the fabricators; designs now proceed from data to fabrication via floppy disk or local area computer networks. Figure 1 shows a listing of the Gerber-style data file that transfers the design details. This change to data transfer has prompted the fabrication group to implement computerized procedures for approving designs for fabrication and creating the necessary fabrication tools. The computer procedure allows the operator to "build" the design in the computer, where it can be viewed, verified, and revised to ensure that the finished PWB will meet its design requirements.

A high-speed workstation is used for this function. Small designs can be repeated on a panel (panelization) to increase fabrication efficiency. The computer can also add other features required for manufacturing and calculate the areas to be plated later in fabrication. This activity produces the final Gerber-formatted plotting file needed to generate the master films for PWB fabrication. Figure 2 shows a design being reviewed and edited on the workstation before manufacture.

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********************************
*Plotter File                  *
*Circuit Board xxxx-yyyy        *
*Layer 1                       *
*Aperture File: xxxxyyyy.aps    *
*Board Size: 4.000" x 4.000"    *
*Format 1.3                    *
********************************
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Figure 1. Information describing printed wiring board design, which was generated by computer-aided design. Data for the photoplotter are formatted in a language originally derived for mechanical pen plotters. Each command, contained between the asterisks, identifies a particular plotter action (e.g., select an aperture [shape to draw]; put the pen down, [draw a line]; and move from the previously specified location to the next location specified in *x–y* coordinates.

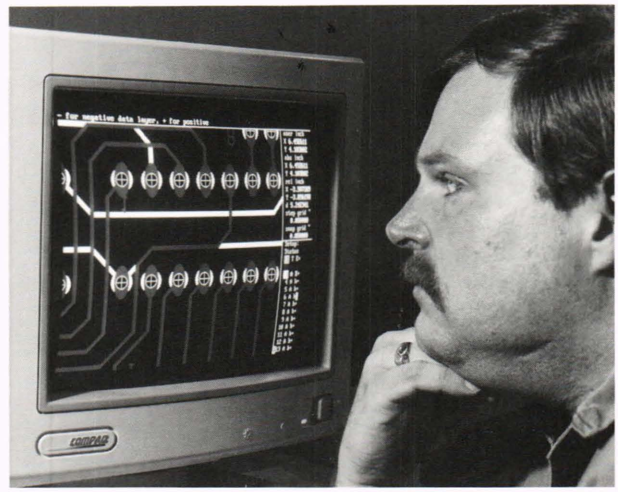

Figure 2. A plating and etching technician performs a manufacture review of a computer-aided design on a computer-aided manufacturing station.

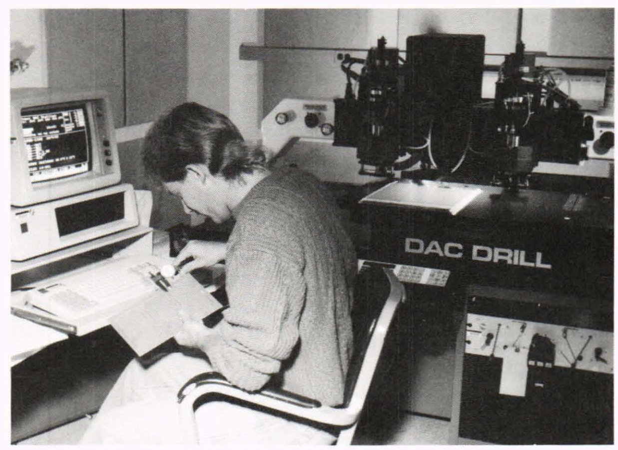

Figure 3. An operator of a computer numerically controlled drill/router examines the drilling instruction file received from a computer-aided design tool.

Processing

Computer-aided designs provide a listing of hole locations to facilitate the accurate and rapid drilling of PWB's. Without this coordinate listing, a design would need to be digitized, a less accurate and slower method of optically placing hole locations. With either method, the drill/router shown in Figure 3 (a computer numerically controlled machine tool) can then consistently drill each hole within 0.001 in. of its true location on each axis. This tool also routs the outline of the PWB by using instructions derived by the CAE/CAD tool or the built-in computer-integrated manufacturing software, which allows the programmer/operator to describe graphically the pattern to be routed. The tool's software also provides optimization routines that make drilling more efficient by minimizing machine motion. The drill/router also supplies information important for process control, such as the number of holes drilled by each tool.

When required in the processing cycle, the drilled holes are electroplated with copper to provide the electrical connection between layers. For electroplating to occur, however, the surfaces to be plated must be conductive. The first step, therefore, is to deposit a very thin layer of copper on the exposed resin in the holes and, in fact, on all surfaces. An electroless copper process is used. After activating the resin surfaces with a palladium catalyst, the board is immersed in a bath in which copper ions are reduced to metallic copper in the presence of the catalyst. Once the reaction begins, it becomes autocatalytic, and copper deposition continues. After a layer 0.50 to 0.75 μm thick is formed, a thin copper electroplate is applied to increase strength and chemical resistance.

Next, the board is imaged. Photolithography, the process of transferring the image from the film masters to the PWB panel, is accomplished in a class 100,000 clean room (a room having less than 100,000 particles 0.5 μm or greater per cubic foot of air). Photoresist (photosensitive material) is laminated to the panel with heat and pressure. After lamination, the film masters are aligned to the panel by using tooling holes to register accurately the front and back films. An exposure system of controlled, high-intensity ultraviolet sources exposes both sides simultaneously while keeping the films near the panel with a vacuum frame. The image is developed in a conveyorized developing system to provide consistent results. After plating, the photoresist is removed with a conveyorized stripping system. This entire system of photoresist lamination, developing, and stripping uses environmentally safe, nontoxic, aqueous-based solutions.

The circuit pattern and the inside surface of the holes are then electroplated in an acidic copper sulfate bath, increasing the thickness of the copper layer by about 25 μm. Next, a coating of 60% tin/40% lead is electroplated over the copper circuit pattern with an acidic fluoborate bath. The PWB plating line in the SMCAT, shown in Figure 4, is designed to process boards up to 18 in. × 18 in. and has thirty-two tanks to handle all cleaning, preparation, plating, and rinsing steps involved.

After removing the photoresist, the copper panel has the finished circuit defined in tin/lead. The copper not protected by the tin/lead is removed in an ammoniacal alkaline etchant system, and the circuit is completely formed. The final step is to fuse the tin/lead to yield a durable solder coating in the hot-air leveling equipment. Nickel and gold plating facilities are available for plating connector tabs and circuitry requiring the unique properties of gold.

Designs often include such features as solder masks and legend marking. Solder masks are applied with a semiautomatic screen printer. Some new solder masks that can be photoimaged are being evaluated for possible use. Legend marking is also screen printed with the same tool. A marking ink is selected, on the basis of hardware constraints, from several types: epoxy-based (both room and elevated temperature cured); ultraviolet cured; or solvent-based air-dried. After printing, the board is ready to be machined to its final dimensions.

Figure 4. Process tanks used to plate copper, tin, lead, nickel, and gold on printed wiring board substrates.

Multilayer Printed Wiring Board Fabrication

We use multilayer boards with increasing frequency as the needs arise for higher interconnection density. The fabrication of these boards presents greater problems and introduces additional constraints when compared with two-sided PWB's. Close alignment of layers becomes critical, the bonding of layers requires special surface treatments, and epoxy resin smears in the holes (resulting from the high temperatures induced by drilling) must be removed.

Layer alignment is achieved by accurately punching the films and laminates for each layer with an identical tooling hole pattern. Each film layer is aligned to a master by using 10× magnification in the precision film punch. Inner-layer circuitry is now accurately positioned relative to the tooling hole pattern for further processing.

The inner layers are processed first. The circuitry is not plated but formed with a print and etch technique. The copper surfaces are then coated with a very thin layer of tin, which enhances the bond to the laminate resin and prevents delamination of the finished board.[1] The layers are pinned together in the proper sequence with sheets of semicured laminate between them to form a laminating package. The package, sandwiched between very flat steel plates, is placed in the vacuum hydraulic press shown in Figure 5. Lamination occurs in a vacuum to eliminate air between the layers at temperatures around 350°F and pressures of about 200 psi. The exact temperature–pressure–time cycle depends on the material.

Figure 5. A computer-controlled 100-ton hydraulic press with a vacuum chamber for laminating multilayer boards.

The laminated board is then drilled. After drilling, the epoxy resin that was smeared onto the inner layer of copper must be removed to ensure a complete bond between the inner layer and the plating in the holes. A mixture of oxygen and tetrafluoromethane gases is passed through an intense electromagnetic field, creating a reactive gas plasma that will remove resin in the holes, thereby cleaning and exposing the inner layer of copper.[2]

Laminates made from different resins are available, depending on board requirements. Standard constructions use epoxies, either difunctional or tetrafunctional. (Difunctional epoxy resin contains two epoxy groups per molecule; tetrafunctional contains four. The tetrafunctional resin thus yields a higher cross-linking density and correspondingly higher strength.) Difunctional resins are less expensive and more readily available, but the tetrafunctional resins have superior performance. When the finished board is to be exposed to temperatures at which even tetrafunctional epoxy is affected, it may be advisable to use polyimide, which is superior because of its higher temperature resistance and lower thermal coefficients of expansion. For microwave circuits, where the laminate serves the dual function of circuit substrate and electronic component, Teflon is the optimum choice. Each substrate material mandates different process parameters; machining (drilling and routing) parameters may also vary.

Heat Sink Attachment

Many designs require that a heat sink be attached over part or all of the board's surface. Heat sink materials are typically aluminum or copper, and board material also varies. The elastic modulus of the adhesive becomes critical because of the different thermal expansion characteristics between the board and the heat sink.

Thermabond is a silicone rubber sheet adhesive designed specifically for this application.[3] It has good flexibility, thermal conductivity, consistent bond integrity, and easy adaptability to many different heat sink configurations. This adhesive is applied to the primed heat sink (patterned either manually with a sharp tool or automatically with a laser cutter),[4] placed on the PWB, and cured in a vacuum bag. Outgassing characteristics meet the NASA specification.[5]

OTHER SUBSTRATE FABRICATION PROCESSES

Wire Wrapping

The Gardner Denver 14-YA/YN system is a combination wire preparation and terminal locator. By using a database prepared from the CAD system, this numerically controlled machine, shown in Figure 6, will cut, strip, and give the operator a wire for wrapping on a terminal that has been automatically located and identified by the tool position. The operator then completes the wrap by using a hand-held, pneumatically driven wrapping tool. After wrapping the wire, the operator indexes the machine, causing it to move to the second terminal for wrapping the other end of the wire. When the machine is again indexed, it will supply another wire and move on to the next terminal. The machine can be directed to any point on a 24 in. × 36 in. area to within ±0.001 in. of the desired location. The numeric input can be read from punched paper tape, an 8-in. floppy disk, or an RS-232 serial data line.

Figure 6. A numerically controlled wire wrap tool positions terminals and provides properly cut and stripped wire by using instructions from computer-aided design/computer-aided engineering tools.

Figure 7 shows the typical work flow followed in generating a circuit design by using a CAE workstation and leading to the creation of wire wrap boards, PWB's, or stitch-welded boards. All fabrication steps maximize the use of computer or computer-aided tools and electronic rather than paper information transfer. This machine use and data interchange in turn maximize efficiency and minimize human error. The use of data generated on Mentor, Daisy, Valid, Computervision, P-CAD, and other CAE or CAD systems is also possible. A schematic can be electronically transferred to a CAD system, and most layout and routing of wiring interconnections can be done electronically. Operators in the wire wrap facility can also develop inputs for wiring boards from paper schematics or logic diagrams, a useful path when a circuit design has not been entered on a CAD or CAE system.

Welding

The welding facility employs resistance welding technology by using a storage battery power supply, an electronically switched square-wave current controller, and pressure-regulated pincer or parallel-gap electrodes.[6] The current-switching circuit permits selection of current pulses of 18.75 to 1481.25 Å in increments of 18.75 Å. The pulse duration is controlled by a timing circuit that can be set from 2 to 20 ms, and the force on the weld heads can be set from 0 to 10 lb. Each pin and wire combination requires a different selection of welding pressure, time, and current. The proper selection, called the schedule, is developed through a series of off-line tests and measurements.

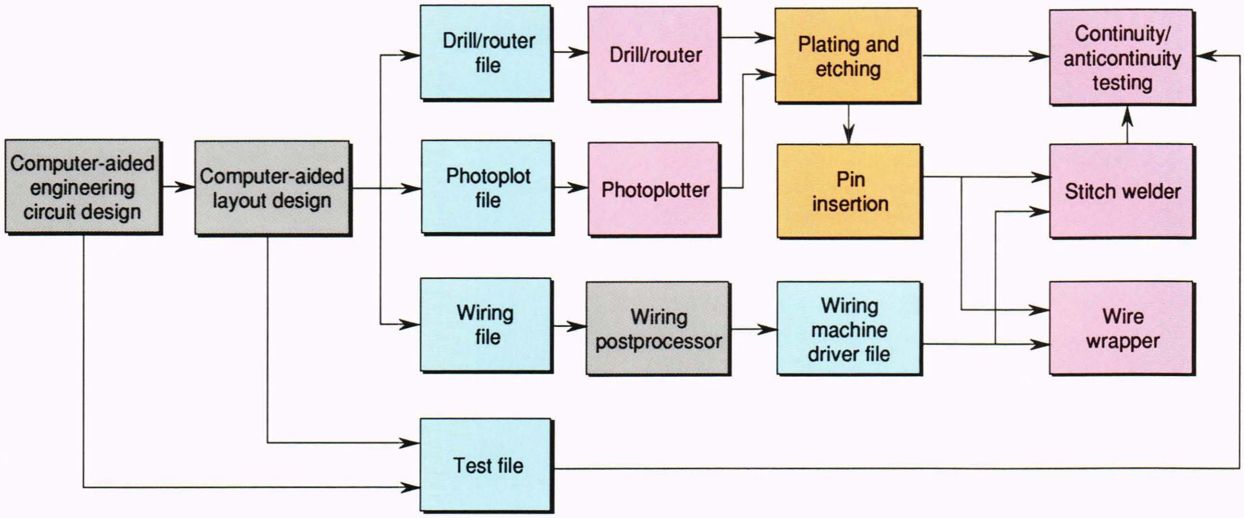

Figure 7. A flowchart showing the computer-integrated manufacturing information used in electronic fabrication. (Computer tools are gray; electronically stored information, blue; computer-aided manufacturing tools, red; and manual operations, orange.)

The point-to-point welding method connects a circuit by welding a single wire from one point to another from beginning to end. Welding is accomplished by pressing through the insulation with a scheduled pressure and by applying a current pulse through the metals to be joined to make the weld. The wire used is 99.9% pure nickel insulated by a 2.5-mil-thick covering of Teflon resin covered with 0.4 mil of polyimide resin to prevent cold-flow–induced breakdowns of the Teflon coating.

The welding electrodes have two forms. Pincer electrodes, shown in Figure 8, are dual electrodes mounted in the weld head at a 45° angle. Pressure is applied perpendicular to the plane of the electrode tips. These electrodes are used to attach wires to the sides of pins located in a circuit board. Parallel-gap electrodes are mounted in the weld head to be co-planar with an air gap insulation between them. The current path is down one electrode, through the metals to be joined, and back up the other electrode. This arrangement is used, for example, for attaching compliant leads to leadless ceramic integrated circuits to create an assembly with greater reliability or for attaching flat-pack, gull-wing interconnection leads to button pins (see Fig. 9).

Stitch welding is another method of making point-to-point welded connections by using a numerically or computer numerically controlled machine for locating and controlling the process. We have two machines, one of each type, in the facility. The stitch weld machines use a capacitor discharge power supply, a dual-stage pressure controller, a timing circuit, and terminal locating devices. The programming data are supplied by punched paper tape, 5 1/4-in. floppy disk, or RS-232 interface. The data are processed by the controller, which locates the pin to be welded. The operator must make the energy and pressure settings dictated by the wire and pin to be welded and then activate the foot switch, which starts the weld program. The program applies an insulation breaking pressure, then backs off to the weld pressure, applies the weld energy (maintaining the pressure during the weld cooling time), and finally releases the electrodes. Using the other foot switch, the operator indexes the machine to the next weld position. At the completion of each network, the machine gives an indication. The operator then cuts the wire and indexes the machine to the

Figure 8. Pincer welding electrodes attach wires to posts for circuit interconnections. A magnified view of the electrode area is shown above the technician making the weld.

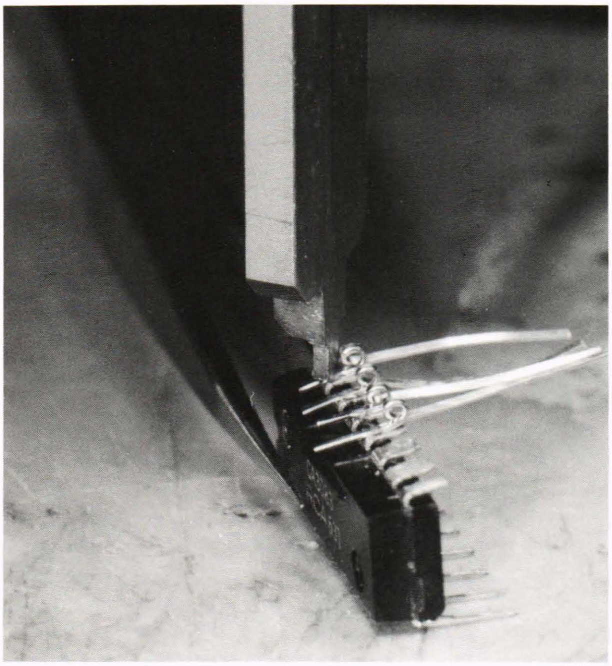

Figure 9. Parallel-gap welding electrodes attach component leads to posts, put leads onto leadless components, and put compliant leads onto components when required.

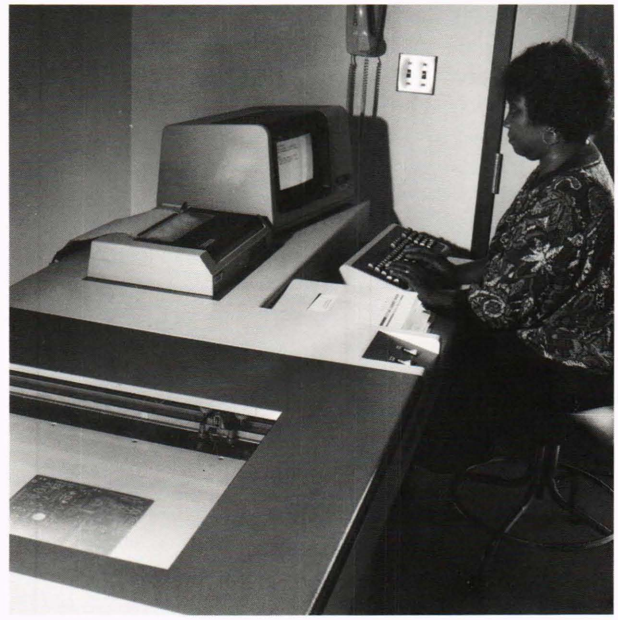

Figure 10. A technician programs a computer to test a circuit board for undesired open and short circuits by using test files generated by computer-aided design.

first weld of the next circuit. Wiring densities of up to 106 interconnections per square inch have been achieved with the stitch welding technique.

Bare Board Testing

The Kollmorgen Integri-Test 4500 shown in Figure 10 is a computer numerically controlled moving probe board tester that can test adjacent points as close as 0.020 in. apart. The probes are placed by the control system within 0.001 in. of the selected location. Continuity tests can be performed for open-circuit faults (indicated by a resistance of greater than a user-selected 1 to 127 Ω) and for short-circuit faults (indicated by a resistance of less than a user-selected 100 kΩ to 20 MΩ). The tester, controlled by its DEC PDP-11/23 minicomputer, can test up to 32,000 points anywhere on a 21 in. × 24 in. surface.

Connection and geometry data are produced by the CAD system that generated the schematic shown in Figure 7. Downloading from this level ensures that the final circuit board is verified against the original design information. Therefore, any errors introduced during the board design or fabrication phases will be revealed.

When testing one-of-a-kind designs (the typical situation at APL), N, the number of tests required, is given by

$$N = \frac{(n^2 - n)}{2} ,$$

where n is the number of circuit networks. Thus, for 1000 nets, 499,500 independent tests are required. The machine can test for open and short circuits at a rate of 54,000 points per hour. Typically, small PWB's might have 300 to 1000 nets each. A board with 1000 nets will require about nine hours to test each net for continuity and the absence of shorts to all other nets. In comparison, a technician with an ohmmeter working at the very rapid rate of two points per second would take seventy working hours to complete the same test. A set of four boards for a subsystem will require about forty hours for the Integri-Test process, which can run unattended. The PWB's for the subsystem will be tested in less than two days. A technician would require 280 working hours, or seven weeks, to complete the same task.

CIRCUIT BOARD ASSEMBLY

Soldering

Hand soldering remains the predominant process for attaching components to printed wiring assemblies. This venerable process is well understood and well controlled. The hand soldering tool has a control loop that stabilizes the temperature of the tip where soldering occurs to within ±10°F of the set point. The set point is variable to suit the job. Thick leads being attached to multilayer PWB's require a higher initial temperature than small surface-mounted component terminations attached to small lands (metallizations provided on the PWB for lead attachments). Of course, the tips themselves are also selected to match the geometry of the part and pad. In addition, APL uses several solder technician training and certification programs to emphasize quality and enhance reliability in the fabrication of hardware. These programs consist of hand soldering to NASA NHB 5300.4 (3A-1)[7] and MIL-STD-2000 specifications.[8]

When the quantity of similar assemblies or the number of solder joints on an assembly is large, machine soldering is warranted. A computer-controlled, dual-wave soldering machine designed to wave-solder both through-hole and surface-mounted components is located in the SMCAT. The machine, shown in Figure 11, has a 16-in.-wide, variable-speed pallet conveyor that can be controlled from 0 to 14 ft/min.

The first section of the machine is a foam fluxer that applies solder flux to the bottom surface of the board. The flux also foams up through the component lead holes to simultaneously apply flux to the top surface. The fluxer section is followed by an air knife that strips off excess flux before the electronic assembly enters the preheater section. This section consists of three independently controlled infrared heating panels 5 ft in length that slowly raise the temperature of the board, thereby avoiding thermal shock when the board reaches the solder waves.

Two pumped waves of molten solder are available. The first is a turbulent wave whose primary purpose is to attach surface-mounted components. The turbulent flow ensures that the solder reaches into the very small spaces allowed for attachment of these components to the PWB. The second is a laminar flow wave used to heat, solder, and drain excess solder from the board. Wave heights are independently adjustable. When the board leaves the second wave, a hot-air knife is energized. The narrow sheet of hot air strips off excess solder and removes any solder bridges between leads.

Process Control

The Future 1 wave soldering machine is equipped with a built-in IBM-AT–type computer used for process control and data logging. Flux activity is controlled by carefully adjusting the density by monitoring the specific gravity and automatically adding flux or thinner. The temperature of the top of the board is measured with a built-in infrared sensor and is recorded on the data logger as the board passes over the wave. Additional process monitoring is accomplished by periodically measuring solder temperature, conveyor speed, solder pump speed, and hot-air knife temperature and by recording these measurements on the data logger.

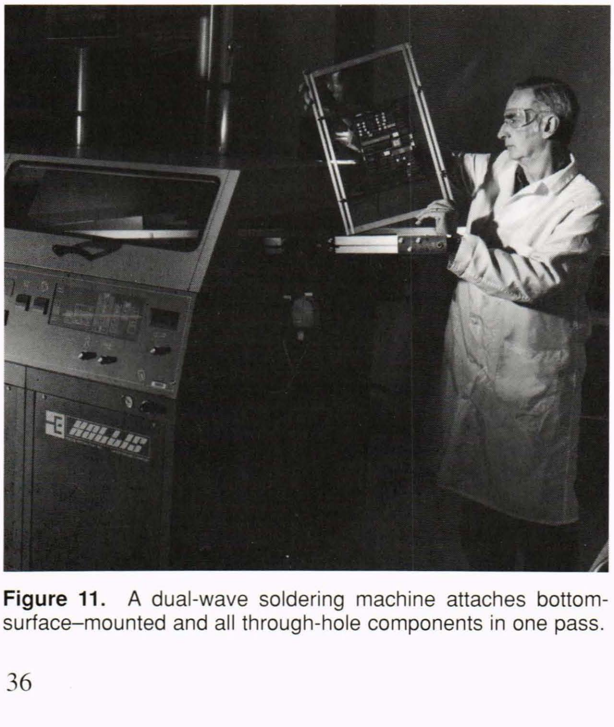

Figure 11. A dual-wave soldering machine attaches bottom-surface–mounted and all through-hole components in one pass.

An understanding of the process of machine or hand soldering is not enough to ensure that the resulting solder joints will be reliable or that the process will be efficient. The quality of the product must be monitored constantly, and changes in quality must be compared with process parameters to feed back information for maintaining and improving quality. By using internally developed logging and problem solving techniques coupled with statistical process control methods,[9] the rework rate for wave soldered joints was reduced from an acceptable 1% to a more efficient and reliable 0.02%.[10]

An insidious cause for defects in assembled electronic hardware is the discharge of electrostatic charges into many active components, which can destroy them or cause them to fail prematurely. Some components are so sensitive that a static charge producing 30 V of potential difference will create serious problems. The new facility is designed with this problem in mind, and many steps have been taken to eliminate the accumulation of static charges and to discharge them harmlessly if they should be formed. The primary element in the elimination of electrostatic discharge is maintaining the relative humidity in the area at a level high enough to discharge any accumulations of charge while avoiding the negative effects of high humidity (e.g., personal discomfort, formation of mold and mildew). The SMCAT fabrication area has conductive flooring that is connected to earth ground; all chairs and workbenches have conductive surfaces tied to earth ground; and the operators, who have all been certified through the APL Electrostatic Discharge Training Program, wear conductive shop coats and conductive wrist straps that are grounded through a resistor to earth ground. All grounds are monitored to detect any disruption in the grounding circuit. This collection of grounds of the workplace and personnel safely discharges all static charge buildups before they reach levels high enough to cause damage to sensitive components. The picture of the assembly area, Figure 12, shows technicians properly garbed and grounded at workstations that rapidly dissipate static charge accumulations.

Another hidden cause for failures of electronic hardware is trapped contaminants, generally deposited on the work by the normal settling of airborne particulates. To prevent such contamination problems, we maintain 7000 ft^2 of class 100,000 clean space in the SMCAT. The clean space contains multilayer lamination, pattern transfer, encapsulation, flight harnessing, flight systems assembly, and surface-mounted component attachment. This controlled environment contributes to product quality and reliability. The commitment to the clean areas extends to the personnel assigned to work in them; all personnel receive an extensive clean room instruction course and pass an examination to certify them to occupy and function in the clean areas.

Encapsulation and Marking

The Electronic Fabrication Group maintains a complete laboratory to provide services for encapsulation,

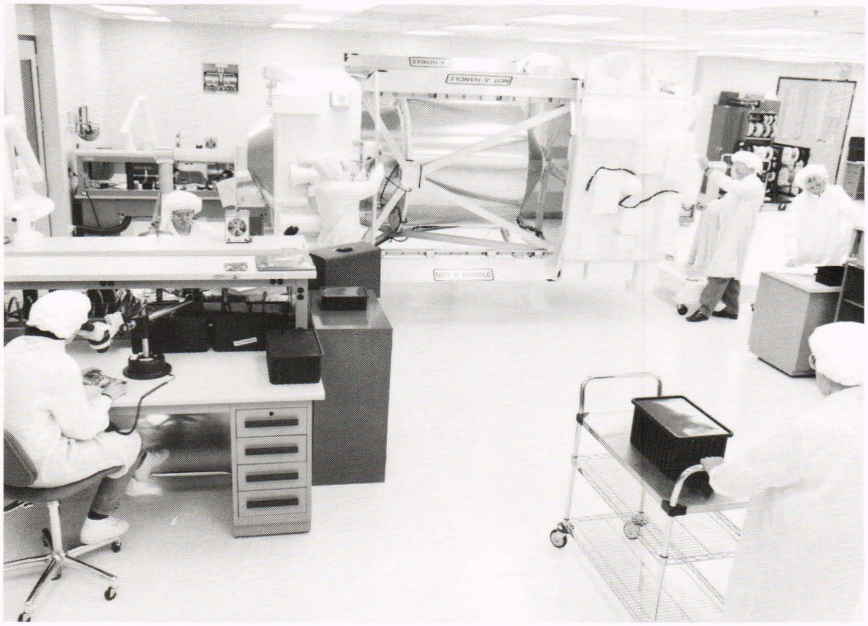

Figure 12. The electronic assembly area is a class 100,000 clean room with electrostatic discharge protection, requiring proper attire and static-reducing attachments.

casting, potting, and marking. Materials used are mainly epoxies, urethanes, acrylics, and solvent-based compounds. Chemical fume hoods are provided to maintain personnel safety and to exhaust volatiles before they can contaminate the class 100,000 clean room atmosphere of the encapsulation laboratory.

We use hardware marking inks made from several materials not normally applied for this purpose; colorants are added as appropriate. Most materials are thermally cured at constant temperature for specified times, and several ovens are available to accomplish this task. Other materials require a thermal vacuum chamber for low-pressure curing. Newly developed acrylics use the rapid-start, conveyorized source of extremely intense ultraviolet light for rapid (<30 s) cure.

CONCLUSION

The new SMCAT provides a very good environment for fabricating the electronic circuits and assemblies that APL delivers to its sponsors and those assemblies that allow staff members to test their scientific hypotheses. The clean room and the precise temperature and humidity controls in the building, as well as the protection from electrostatic discharge, undoubtedly improve the reliability of our products. The computer integration among circuit design, electromechanical design, and fabrication creates efficiencies and improves the quality of the hardware while minimizing the costs. To all of this, the Electronic Fabrication Group has added process controls where applicable to move toward very low defect levels that clearly improve quality, reliability, cost, and schedule simultaneously.

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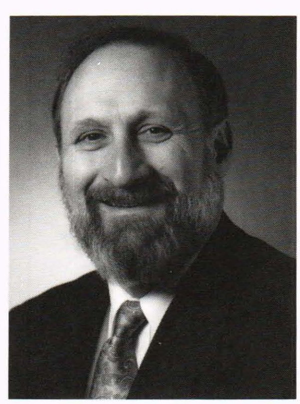
THE AUTHORS



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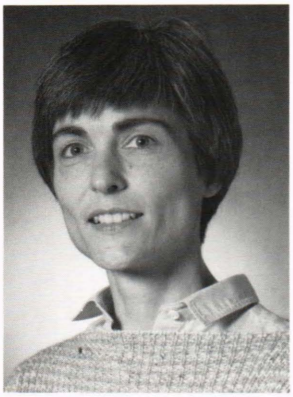

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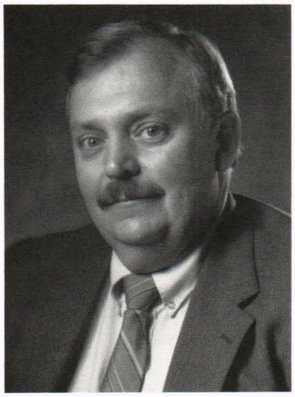

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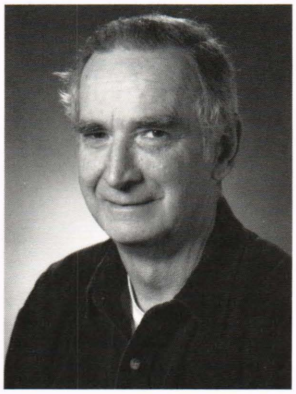

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