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THE ENGINEERING DESIGN, FABRICATION, TESTING, AND QUALIFICATION PROCESS WITHIN THE STEVEN MULLER CENTER FOR ADVANCED TECHNOLOGY

The Engineering and Fabrication Branch provides a wide range of engineering design and fabrication services for the Applied Physics Laboratory. The new Steven Muller Center for Advanced Technology has allowed the branch to consolidate all its electronic design and fabrication services in a single modern laboratory and office complex. The Center, with its built-in flexibility and modern equipment, will enable the branch to deliver advanced services and hardware well into the next century.

INTRODUCTION

The Engineering and Fabrication Branch (TEO) of the Technical Services Department is an integrated resource for the development, design, fabrication, testing, and qualification of prototype and advanced electronic, electromechanical, and mechanical hardware. The branch comprises six working groups—Design Automation, Design and Packaging, Electronic Fabrication, Mechanical Fabrication, Microelectronics, and Quality Engineering and Materials (formerly Quality Assurance)—plus a small staff for fiscal administration and overall work flow control. The groups are functionally aligned with a minimum of overlap or duplication of services. An outline of the major group functions is presented in the boxed insert. A full listing and details of TEO's services (more than 100) and contacts for each may be found in Ref. 1.

Support of a given Laboratory program begins when a program member (customer) identifies a need or service requirement and reports it to someone in TEO. Our staff members (more than 250) are trained or briefed in all our service areas (see the boxed insert) and can direct the customer to the appropriate group or person for further assistance. We also offer the customer a preliminary assessment of task complexity, initial cost, and schedule estimates. When the requests exceed TEO's capacity to respond, our personnel can facilitate the service through the use of off-site blanket contracts (for board layout, printed wiring board fabrication, machining, and so on) or direct the customer to other experts or sources of supply. By charter, TEO maintains a working knowledge of modern industrial engineering design, fabrication, and testing methods to serve as an in-house source of manufactured hardware and to provide resident expertise for most of the Laboratory's design and manufacturing requirements. This expertise has facilitated the production by commercial firms of such notable Laboratory developments as Transit and Aegis, as well as several biomedical devices.

To initiate work, the customer completes a TEO Work Request Form,[1,2] which asks for a description of the work to be performed and certain financial and administrative information. We then provide a formal estimate for the described work. When mutual agreement is reached (between the customer and TEO) on the estimated costs and schedule, TEO issues a charge-back job order number. The branch operates on a charge-back system that bills the customer at an effective hourly rate for each labor hour worked on that job. Materials and supplies charged directly to the customer's account are billed at cost. (Further details of the charge-back system are contained in Refs. 1 and 2.) By using this charge-back process, TEO has supplied hundreds of thousands of hours of service a year for more than two decades. Our job orders range from simple repair or part assembly involving a few hours to major projects involving tens of thousands of hours. A distribution of TEO job orders by size (number of hours) is shown in Figure 1A. Figure 1B shows the breakdown of total hours for 1990 by APL department. (The Space Department's soon-to-be-delivered TOPEX [Topography Experiment] spacecraft required more than 100,000 hours of TEO service; the upcoming MSX [Mid-course Space Experiment] project will exceed the TOPEX numbers by 50% to 100%.)

Except for extremely small projects, which are usually focused within a particular TEO group or involve only a few people, projects ordinarily call for multiple TEO resources that transcend group boundaries and use a full gamut of the branch's services. A typical project will comprise the following key elements of TEO service: engineering design and analysis support, package engineering and design drafting, electrical and mechanical fabrication, electronic and physical testing, and inspection and quality assurance (including equipment calibration and configuration control). In what follows, each of these service elements is described by using examples from current and past TEO projects. Emphasis will be

MATRIX OF SERVICES PROVIDED BY THE ENGINEERING AND FABRICATION BRANCH OF THE APPLIED PHYSICS LABORATORY

Designation	Mission	Primary service areas
Engineering and Fabrication Branch (TEO)	Provide quality electronic and mechanical engineering, design, fabrication, testing, and qualification services	Assistance in the development and fabrication of advanced prototypes, one-of-a-kind speciality items, and limited-production hardware products Application of tools of hardware design and fabrication to support APL experiments and other scientific activities Maintenance of technical awareness in all areas of fabrication technology for electronic, electromechanical, and mechanical hardware
Design Automation Group (TEA)	Provide computer-aided engineering and network support for TEO and the Laboratory	Computer-aided engineering network support, including configuration control, maintenance, and repair Computer-aided engineering library part (database) creation and standardization Engineering design application development in support of the Laboratory's engineering activities
Design and Packaging Group (TED)	Provide electronic, electromechanical, and mechanical design and packaging engineering services	Electronic, electromechanical, and mechanical packaging design Printed wiring board and card cage layouts Mechanical chassis and support structure design Mechanical and thermal modeling Finite-element analysis Composite design Cable and hardness design
Electronic Fabrication Group (TEE)	Provide electronic fabrication services	Printed wiring board fabrication Precision solder assembly Wave and condensation soldering Overcoating, encapsulation, and soldermask services Connector, cable, and harness assembly Rack and panel assembly
Mechanical Fabrication Group (TEF)	Provide mechanical fabrication services	Computer numerically controlled machining (e.g., milling, turning) Numerically controlled programming Electrical discharge machining Surface finishing and plating Sheet metal fabrication Riveting, welding, other metal joining processes
Microelectronics Group (TEM)	Provide microelectronic design, fabrication, and testing services	Design and fabrication of precision hybrids and surface-mounted assemblies Integrated circuit design, simulation, and testing Laser machining Precision photolithography and macrophotography Plasma etching and other forms of dry processing Thin and thick film materials deposition
Quality Engineering and Materials Group (TEQ)	Provide quality assurance and materials analysis services	Materials analysis using scanning electron microscopy, energy dispersive X-rays, and metallography Mechanical stress and hardness testing Configuration management services Inspection and quality assurance support Electronic equipment calibration and repair Instrument loan services

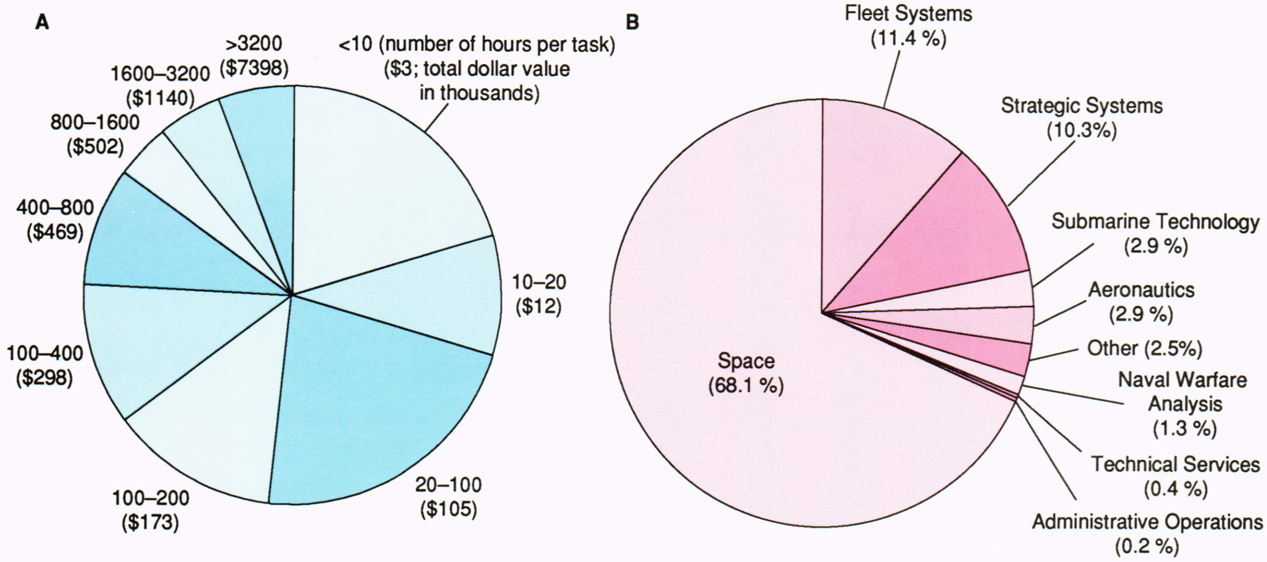

Figure 1. Customer workload demographics for the Engineering and Fabrication Branch in 1990. **A.** Breakdown of orders by size (number of hours) for a total of 184 programs. Total dollars in each range are shown in parentheses. (Amounts are in thousands of dollars.) **B.** Breakdown by customer's department (224,000 total hours).

placed not only on the products and services provided, but also on the project planning and work flow tracking available in TEO, along with the improvements made possible by the consolidation of services within the Steven Muller Center for Advanced Technology (SMCAT).

ENGINEERING DESIGN AND ANALYSIS SUPPORT

The Engineering and Fabrication Branch offers a full range of electronic, thermal, and mechanical design services. Our electrical engineers have participated in all major Laboratory electronic system development projects, including analog, digital, and microwave electronics. A current example of TEO's electrical engineering expertise, shown in Figure 2, is a direct digital synthesizer (DDS) circuit that operates at a system clock of 600 MHz, the fastest APL digital circuit to date. The unit uses gallium–arsenide integrated circuit technology combined with an advanced, low-temperature, multilayer, co-fired ceramic substrate. This substrate technology uses a newly developed low-temperature co-firing ceramic product from Du Pont Electronics with an APL-developed laser hole-patterning process to produce the substrates for the high-performance DDS. The synthesizer is undergoing extensive reliability qualification studies before its use on the MSX spacecraft.

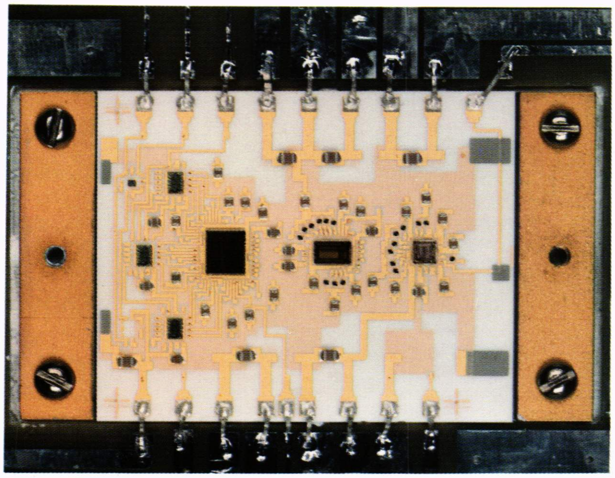

Figure 2. Direct digital synthesizer using gallium–arsenide hybrid technology. The substrate is a ten-layer, low-temperature, co-fired ceramic. The actual circuit measures 50.8 mm (length) × 31.8 mm (width) × 1.08 mm (thickness).

Our engineers have supported several APL biomedical activities, including the rechargeable pacemaker,[3] the implantable programmable infusion pump,[4] and the recently commercialized ingestible temperature monitoring system.[5] Other engineering activities are supporting the development of advanced circuit boards by using direct-imaging polyimide. In a recent article by Clatterbaugh and Charles,[6] the basic properties of direct-imaging polyimide were presented. Figure 3 shows some engineering modeling and analysis results that enable the use of this material in the fabrication of multichip modules (see, e.g., Ref. 7). Multichip modules are multilevel, thin-film hybrid structures needed to provide the high-speed performance and input/output densities for very large scale integrated circuits. The modeling has allowed the proper thickness of dielectric layer to be chosen while still maintaining high reliability and control of important electronic parameters.

Thermal and mechanical modeling skills have been applied by TEO engineers to develop advanced circuit board and heat sink systems to handle power-hungry integrated circuit chips in APL's stringent applications environments, including the vacuum of space. Figure 4 shows a finite-element analysis of an electronic package–joint system. This analysis allows the fabrication of low-stress joints and ensures greater reliability of the electronic system. Mechanical stress analysis has furnished the design and fabrication guidelines needed to

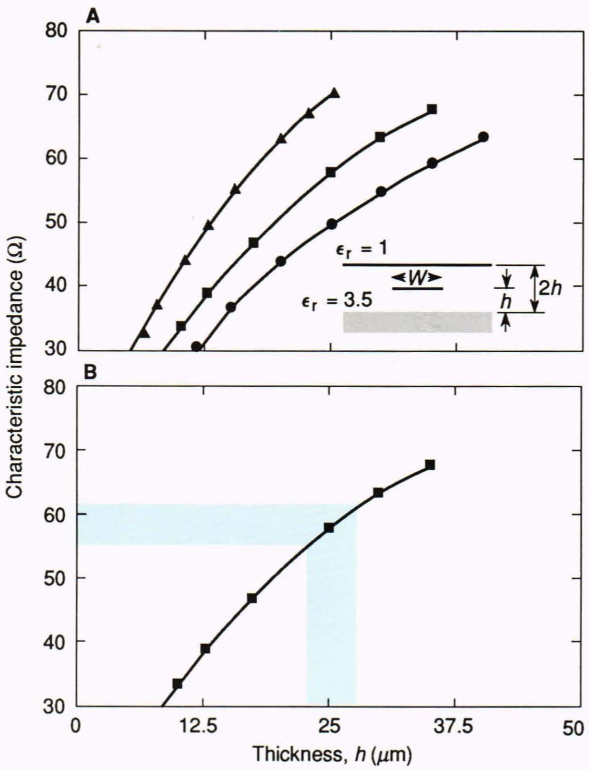

Figure 3. Design implications for a covered microstrip. **A.** Characteristic impedance of covered microstrip lines for three line widths (W) and various dielectric thicknesses (h) of polyimide interlevel dielectric (ε_r = 3.5). **B.** Impedance variations produced by thickness changes in polyimide layer of ±10% (blue area). (W = 25, 37.5, and 50 μm for diamonds, squares, and circles, respectively.) With increased W and h, circuits can operate at higher speeds. By selecting a narrower W and reduced h, circuits of greater density can be achieved.

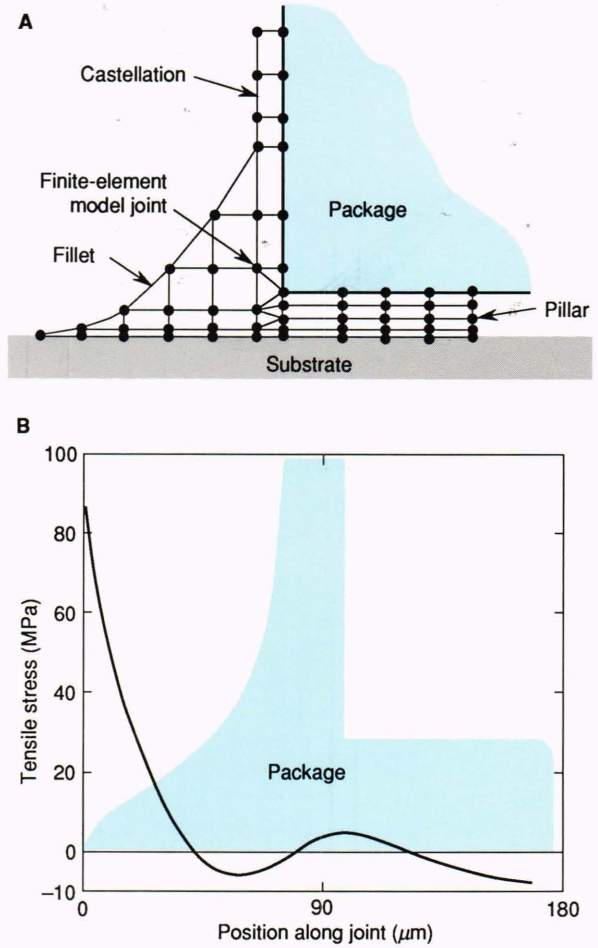

Figure 4. Finite-element analysis of a surface-mounted solder joint. **A.** Nodal-type finite-element model of solder joint. Pillar under the package determines the height. **B.** Model results of stress along solder board bonding pad interface.

fabricate a large, extremely lightweight antenna support out of carbon-reinforced graphite epoxy composite for use on an upcoming weight-critical spaceflight program. This antenna mount, weighting only 66 g, is shown in Figure 5 (a more conventional metal mount could weigh up to 200 g).

PACKAGE ENGINEERING AND DESIGN DRAFTING

The Engineering and Fabrication Branch has a long history of providing innovative package design and detailed design drafting support to Laboratory programs. The SMCAT has given TEO packaging engineers and designers modern work space, advanced computer-aided tools, an ergonomic environment conducive to advanced engineering work, and the versatility and flexibility to address future needs. A typical engineering work area arrayed with a modern engineering workstation is shown in Figure 6. Each work area contains storage space for reference material, table space to spread drawings and other reference material, and room to hold consultations with customer engineers and system developers. Individual area lighting and special overhead room lights supply the proper illumination for use with computer display terminals. Packaging engineers and layout designers use three forms of engineering workstation: (1) com-

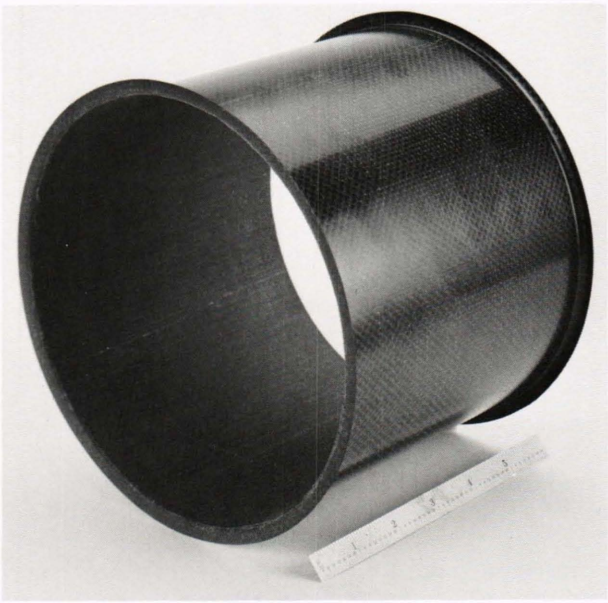

Figure 5. Advanced spacecraft antenna mount made of lightweight composite materials (graphite fabric and epoxy resin).

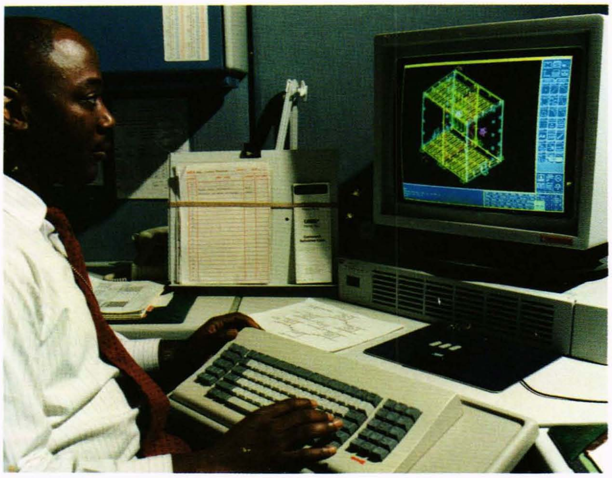

Figure 6. Computer-aided design workstation area featuring storage space for reference materials, a layout table, and appropriate sound conditioning.

puters with analytical software, (2) terminals running various forms of two- and three-dimensional mechanical design software, and (3) personal computers with printed wiring board layout software.

Figure 7 shows a finite-element package analysis model for the stresses contained within a ceramic substrate hard-mounted to a Kovar (iron–nickel–cobalt alloy with a coefficient of thermal expansion that matches that of the ceramic) carrier used in the C-band microwave power amplifier of the TOPEX program. The model, performed using PATRAN–NASTRAN software (see, e.g., Ref. 8), indicates that the maximum stresses are focused in the hard-mounted regions of the ceramic. This analysis caused some changes to be recommended, which, upon implementation, added to the productivity and reliability of the delivered product.

In addition to engineering analysis and modeling, TEO offers a full range of drawing and documentation services. Figure 8 is an example of a documentation package prepared by our design drafting activity. Such documentation has allowed the fabrication of fully described and reproducible hardware for many Laboratory programs. The SMCAT, with its prewired computer network, has given the designers rapid access to modern plotters and document reproduction facilities, which aid in the creation of drawings and text for documentation requirements. As Figure 8 illustrates, the paperwork associated with the fabrication of hardware in the traditional mode is significant. We are developing techniques through pilot initiatives by using three electronic engineering information transfer languages—CALS[9] (computer-aided acquisition and logistic support), IGES (initial graphic exchange specification), and the evolving PDES (product data exchange specification)—to reduce the amount of drawings and paperwork associated with the fabrication of electronic, electromechanical, and mechanical hardware. Other types of documentation and manufacturing information support (e.g., drafting standards, process standards) are part of TEO's complete suite of services.[1] In fact, TEO supports four levels of documentation and three distinct hardware types (see the boxed insert).[2]

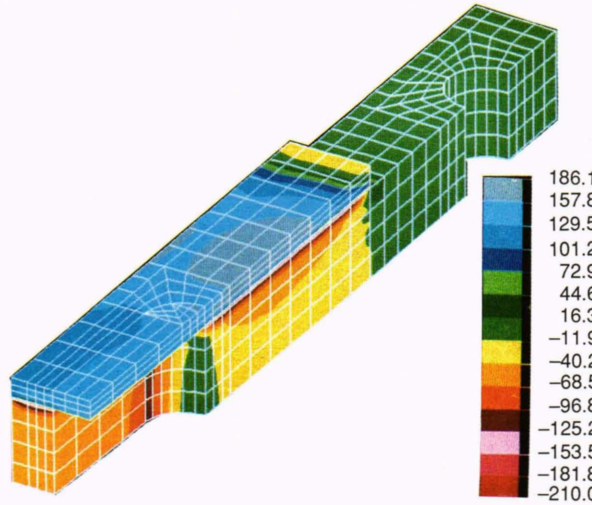

Figure 7. Finite-element analysis of a ceramic circuit board solder mounted to a Kovar carrier and then bolted onto a main chassis. The light-blue regions indicate the high stress points (tension). (Scale on right is in hundreds of psi. Positive values = tensile stress; negative values = compressive stress.)

Figure 8. Example of the documentation package necessary to create flight electronics hardware such as the 5-MHz ultrastable oscillator shown here.

This flexibility gives the Laboratory a key advantage in tailoring documentation and certification requirements to customer needs.

ELECTRICAL AND MECHANICAL FABRICATION

With the move to the SMCAT, all of TEO's electronic and electrical fabrication facilities are centrally located. Facilities range from our recently assembled and certified printed wiring board fabrication line[10] to a completely new and ultramodern microelectronics facility. Figure 9 shows a large, six-layer, printed wiring board fabricated in the Center. The DDS shown in Figure 2 is a recent example of our microelectronics activity.

In addition to advanced performance circuits and boards for high-reliability spaceflight use, the electronic fabrication facilities create a large volume of more con-

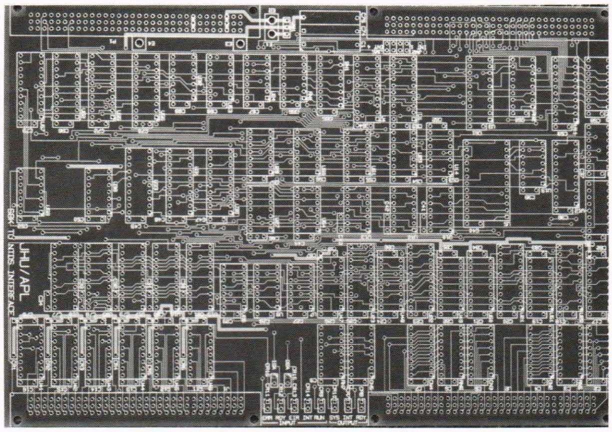

Figure 9. Example of a multilayer epoxy-glass printed wiring board fabricated in TEO's recently certified[10] Printed Wiring Board Facility.

DOCUMENTATION LEVELS AND HARDWARE TYPES[2]

Documentation levels

1 Informal documentation (development, breadboard, no configuration control support)

2a Formal documentation (deliverable, control print, change control, limited configuration support)

2 Formal documentation (deliverable, document change notice [DCN] change control, full configuration control support)

3 Formal documentation (DCN change control, full configuration control support, manufacture outside the Laboratory)

Hardware types

A Deliverable (fully qualified or "production") outside the Laboratory

B Deliverable (prototype) outside the Laboratory

C Deliverable for Laboratory use only

ventional electronics for ground and shipboard use and support the myriad of one-of-a-kind experiments conducted by our scientists and engineers. Figure 10 shows a complex electrical signal-processing system design for shipboard use.

Mechanical fabrication is performed with advanced machine tool equipment in Building 14. This equipment includes computer numerically controlled (CNC) lathes, mills, and sheet metal punches. Two CNC electrical discharge machine tools plus the carbon dioxide laser (located in the SMCAT) form the hub of TEO's advanced contactless machining activity. Other aspects of the Building 14 equipment and its application to advanced mechanical hardware have been described previously.[11] Building 14 also houses TEO's organic composite fabrication activities.[12]

Fabrication involves more than just the manufacture of advanced electrical and mechanical parts and systems. It also involves the application of the tools associated with the hardware fabrication to support other aspects of the Laboratory's scientific and engineering activities. For example, TEO photolithographic resources have been used to pattern gratings for optical experiments, sensors for biomedical and ocean physics applications, and films for basic research. Our carbon dioxide laser machine tool[13] has been employed in material ablation studies, has been used for novel pattern generation in unconventional materials, and has served as a heat source for material alloying. Such use of standard production tools, necessary for APL's and TEO's mainstream hardware production, gives APL a flexible resource base to augment its research equipment in other parts of the Laboratory.

Fabrication of hardware is a key element that distinguishes the Laboratory from many other research and development centers in the country. This hands-on hardware development resource forms the core of APL's internationally known systems engineering capability.

ELECTRONIC AND PHYSICAL TESTING

The Engineering and Fabrication Branch also offers many electronic and physical testing services. Our electronic test equipment can perform exacting electrical tests for analog, digital, and microwave circuits. A high-

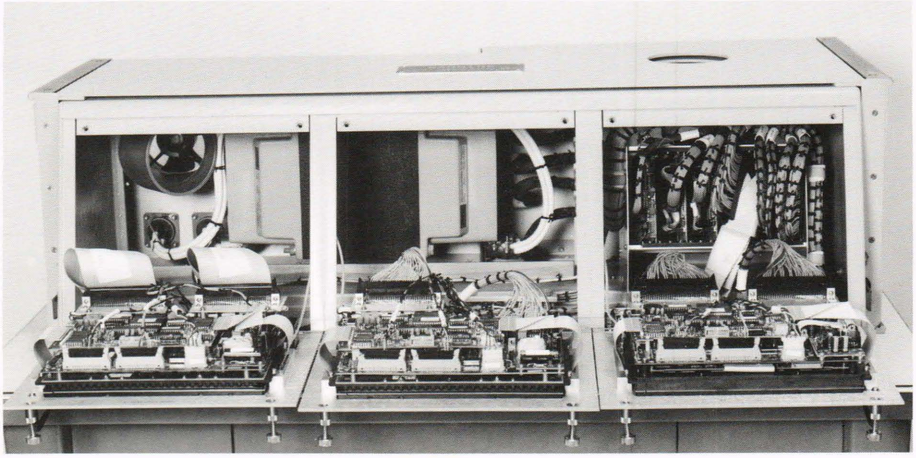

Figure 10. Display console of an electrical signal-processing system showing dense rack and panel construction features and round and flat harnesses.

speed tester can run digital circuit performance verifications at clock speeds greater than 50 MHz. We can also perform microwave tests for frequencies above 20 GHz in both our Calibration Laboratory and our Microelectronics Group. A complete suite of analog test equipment complements both the microwave and fast digital equipment. All electronic testing services are available to our customers through the charge-back system. A complete instrumentation, calibration, maintenance, and loan facility is also maintained by TEO and provides the entire Laboratory with certification and quality assurance functions for its electronic measurements.[14] Automated bare board and substrate testing for continuity and anticontinuity is also available for both printed wiring boards and ceramic-based hybrid substrates. Calibration standards are traceable to the National Institute of Standards and Technology. The branch received a commendation in a recent Jet Propulsion Laboratory audit of APL's quality assurance activities for the operation of its test and measurement equipment.

In addition to the electronic equipment, TEO maintains and operates a complete range of physical test and failure analysis equipment to support our internal hardware fabrication and to provide physical testing services to many of our Laboratory customers. Physical testing includes mechanical stress–strain, hardness, and metallurgical microstructural analysis.

In response to increasing Laboratory and customer quality assurance requirements, TEO has developed a standard procedure for providing certification for critical fasteners. Figure 11 shows a mechanical fastener that has been pull-tested to determine its ultimate failure strength. Ultrasound, eddy current, and other forms of nondestructive physical evaluation can also be performed. We have a full array of chemical and microstructural analysis tools, including a scanning electron microscope, an energy dispersive X-ray analyzer, a Fourier transform infrared spectrometer, and an inductively coupled plasma spectrograph. All of these tools and analytical instruments are collocated in our new materials laboratory facilities in the SMCAT. Figure 12 shows energy dispersive X-ray spectra of tin–lead solder samples that were used to support a failure analysis on the Dual Precision Clock Program.[15]

INSPECTION AND QUALITY ASSURANCE

The Engineering and Fabrication Branch maintains a fully staffed and equipped quality assurance capability.

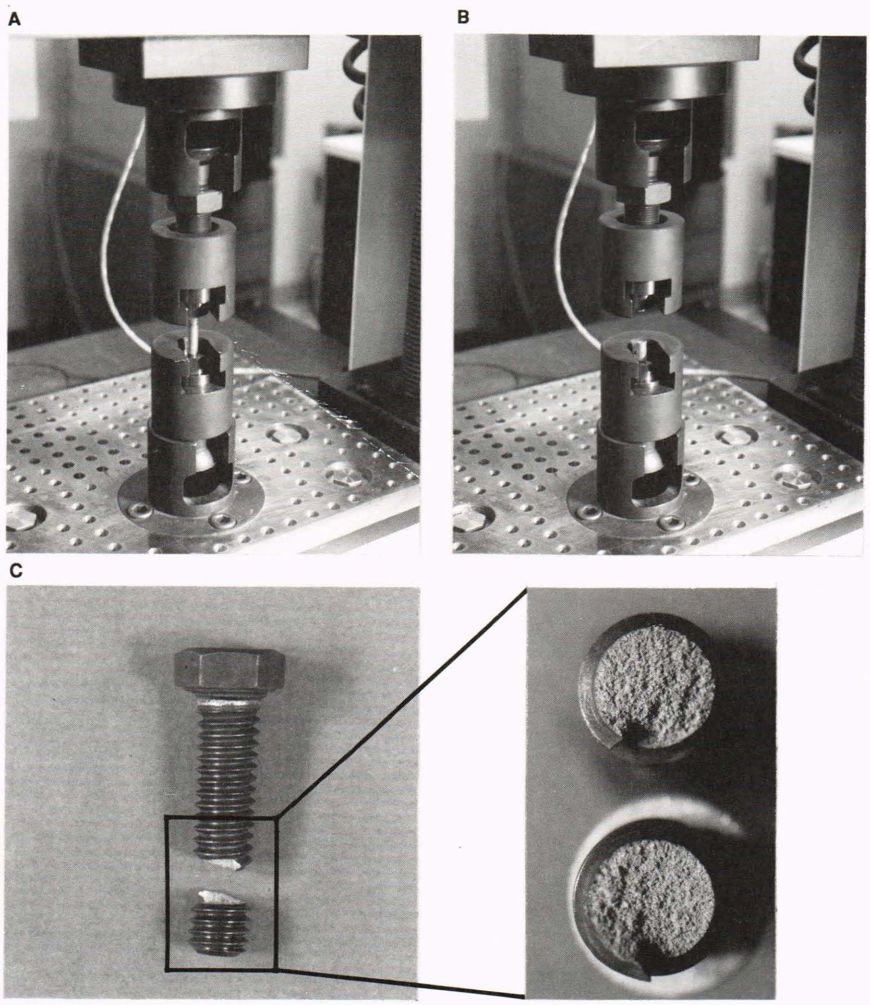

Figure 11. Testing a critical fastener. **A.** Bolt under destructive tensile test. **B.** Failed bolt in tensile test machine. **C.** Views of failed bolt and fracture surfaces.

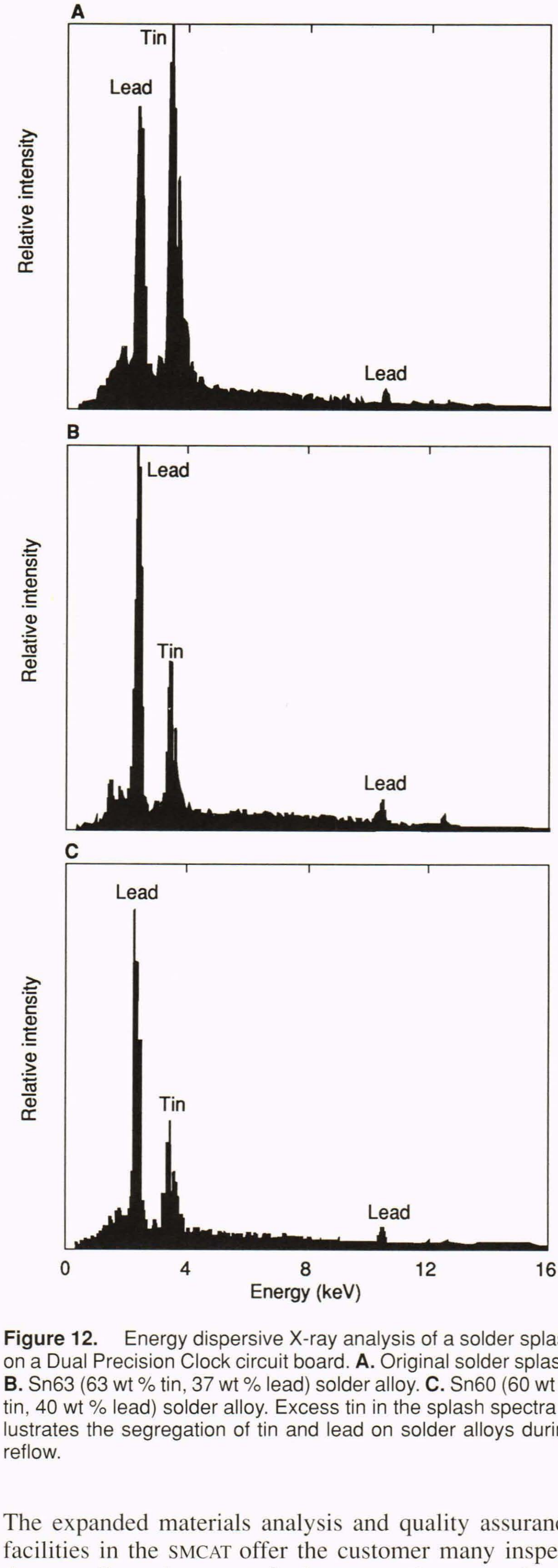

Figure 12. Energy dispersive X-ray analysis of a solder splash on a Dual Precision Clock circuit board. **A.** Original solder splash. **B.** Sn63 (63 wt % tin, 37 wt % lead) solder alloy. **C.** Sn60 (60 wt % tin, 40 wt % lead) solder alloy. Excess tin in the splash spectra illustrates the segregation of tin and lead on solder alloys during reflow.

The expanded materials analysis and quality assurance facilities in the SMCAT offer the customer many inspection, configuration control, documentation control and storage, and parts kitting (preparation of assembly kits) operations. These services are central to TEO's ability to ensure that our customer-generated quality assurance requirements are met. Key documents controlling TEO activities in this area—the hardware configuration and electromechanical hardware workmanship standards manuals[2,16]—both set standards and the general directions for our operations. As part of TEO's quality assurance practice, workers are trained and certified in many skill areas. For example, TEO operates and maintains a fully certified NASA solder training program (and training facility).[17] We have recently certified more than thirty Laboratory employees to solder and inspect according to the NASA standard.

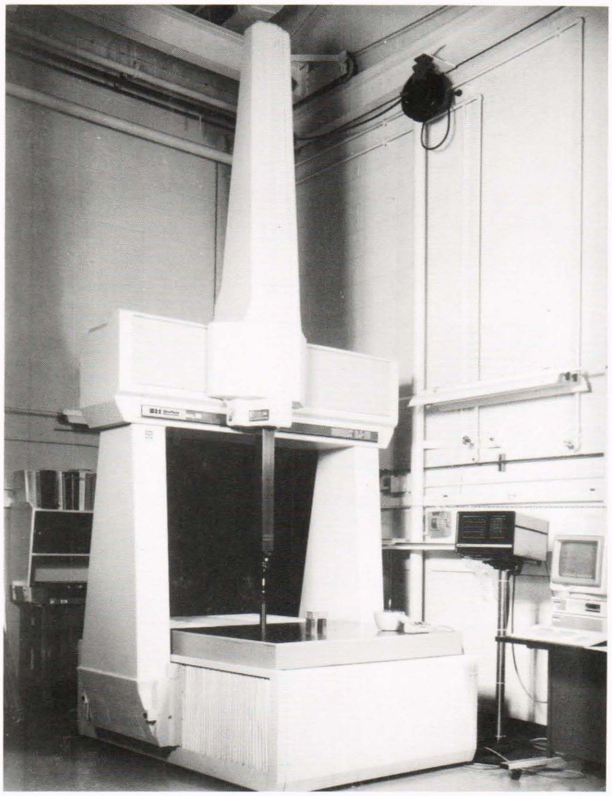

Figure 13. Computer-controlled coordinate measurement apparatus used to check the dimensions and tolerances of manufactured parts.

The branch has developed many other services to support customer and Laboratory quality assurance requirements. Our computer-controlled coordinate measurement apparatus is shown in Figure 13. This machine is used to inspect all fabricated parts to ensure that dimensions and tolerances are held to design specifications. The branch has been a leader in the use of geometric dimensioning and tolerancing (see, e.g., Ref. 18) to permit the widest possible tolerances and to allow industrywide understanding of APL drawings. Measurement results are not only necessary to certify the individual parts but also help improve the processing by statistical control methods. Out-of-tolerance conditions are entered into a computer database, sorted by root cause (primary, secondary, tertiary), and then analyzed to produce Pareto diagrams,[19,20] which help pinpoint areas for internal process improvement, additional worker training, and machine repair (or calibration). (A Pareto diagram is a simple columnar graph used to order collected data and rank them by priority.) Similar information is collected through TEO quality assurance activities to control and improve processes. Figure 14 shows a recent Pareto diagram on the causes of engineering change in the TOPEX program. Results of this analysis will help direct changes in our service options and service quality control to reduce and mitigate the effect of change on the hardware development cycle.

We routinely practice statistical process control in our design, fabrication, and testing operations to ensure the quality of the process and hence the quality of the developed design on fabricated part. Figure 15 is an example of a control chart[21] used to control a wire bonding process in our microelectronics operation. (A control chart is a plot of the process average performance versus time; the data are used to establish the appropriate control limits.) The chart illustrates how machines can exceed their normal control limits and yet totally meet standards or specification limits. In each instance, TEO took corrective action once the trend for exceeding the control limits was confirmed. Such monitoring and intervention prevent the loss of any product (caused by wire bond strength) during the observation period.

Figure 15 illustrates the power of statistical methods in support of TEO's daily operations. Process monitoring places the responsibility for controlling the process in the hands of the operator rather than with an after-the-fact auditing entity. We are committed to total quality principles and fully recognize that the skilled, highly trained worker with the proper work environment and tools is our first line of quality assurance for all activities.

CONCLUSION

The Engineering and Fabrication Branch performs complex and dynamic electronic, electromechanical, and mechanical hardware design and implementation activities within the Laboratory. Our services span from initial concept development to the delivery of a fully tested and qualified hardware product. Such services have been provided by TEO and its predecessors since the inception

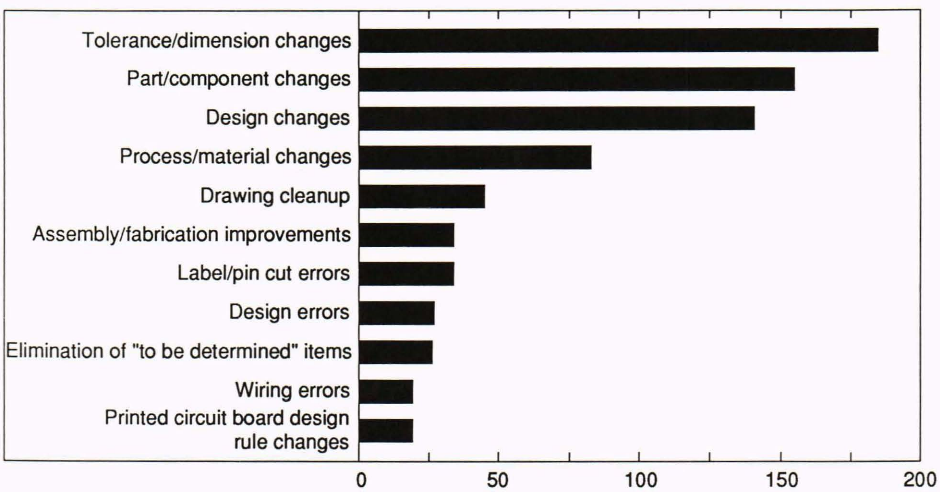

Figure 14. Pareto diagram of the causes of change documentation generation for the TOPEX Program (based on 881 total documents).

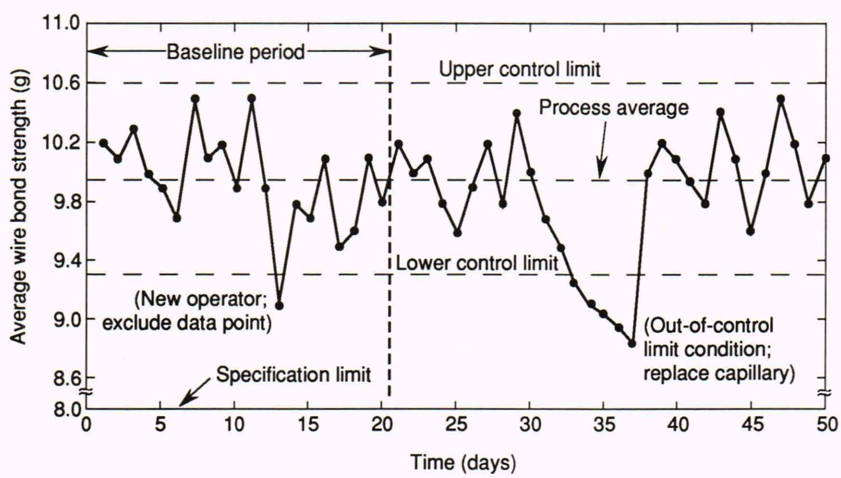

Figure 15. Control chart for hybrid wire bonding application indicating the use of the control charting process (statistical process control). Process monitoring is used to develop control limits for the process during a baseline period. These limits are much tighter than the specification limit allowed by military standards. Here, control charting allowed identification of capillary wear before the product failed the specification limit, thus preventing the loss of valuable circuitry.

of the Laboratory. The ability to design and fabricate hardware in-house has always been a distinctive feature of APL that has set us apart from many similar university and government facilities. The Laboratory has made a major commitment to help ensure TEO's future by building the SMCAT, which has given TEO the resources needed to support modern electronic design and fabrication. These resources have included enough flexibility in the design concept to ensure that our laboratories and facilities remain up-to-date and fully functional for many years to come.

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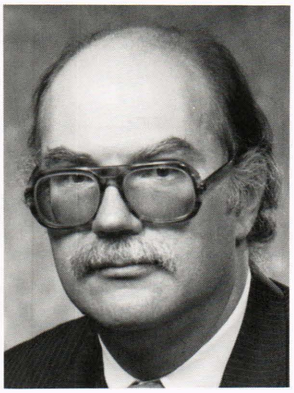
THE AUTHOR



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