

Green Product Manufacturing

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This paper describes tools, systems, and specific programs put in place within AT&T to achieve end-to-end environmentally responsible, or *green*, manufacturing. Together, these incorporate design for environment (DFE) criteria in product and process design phases, monitor and control manufacturing processes to minimize waste and use of materials, conserve water through reuse, and reduce volatile organic compound (VOC) emissions through process and solvent replacement.

Introduction

Environmentally conscious manufacturing requires environmental responsibility—*greening*—in all aspects associated with transforming raw materials into finished product within a factory. To achieve end-to-end green manufacturing, complex operations, such as AT&T product manufacturing, require a careful analysis and quantification of all input and output streams at three levels: the process step, the production line, and the factory. A systems approach of this type includes efficient materials utilization, process monitoring, waste elimination or minimization, and materials recycling. This paper describes a framework for a systems approach to green product manufacturing and illustrates selected aspects. These examples include a framework for rating the greenness of processes and manufacturing lines; an on-line system for tracking process materials utilization to eliminate or minimize waste generation; water conservation and reuse; a real-time process advisor for process optimization and waste minimization; and solvent and process replacement to reduce volatile organic compound (VOC) emissions. (See Panel 1 for definitions of abbreviations, acronyms, and terms.)

Green Product and Process Design

Product design decisions have a significant impact on the environment at all stages of the product life cycle. The designer can make a major contribution to the environmental impact of a product by including

design for environment (DFE) criteria early in the design phase. Incorporating DFE criteria in the initial phase adds design rules and guidelines above and beyond the current design criteria. The interdisciplinary nature of DFE, and, at times, its contradictory criteria, can make its implementation confusing and overwhelming, at least in the beginning. To help alleviate the confusion and facilitate the acceptance and eventual incorporation of DFE as part of product design criteria, the product design, product management, and process engineering communities need a DFE tool that is easy to use. The Green Design Tool described in this paper calculates an environmental figure of merit called the *Green Index*¹ for product and process designs. Using the Green Index, the designer can assess the environmental compatibility of various product and process choices. The greenness of a product design is assessed using attribute hierarchies with 11 top-level attributes: subassembly reusability, label, internal joints, material variety, material identification, recycled content in material(s) used, chemical usage, additives, surface finishes, external joints, and hazard level of the material(s) used.

From a process perspective, the greenness of the subprocesses is based solely on the disposition of the by-products (output streams) that the processes generate. Figure 1 gives an overview of how to assess the greenness of a process step. A totally green process is an ecologically closed-loop

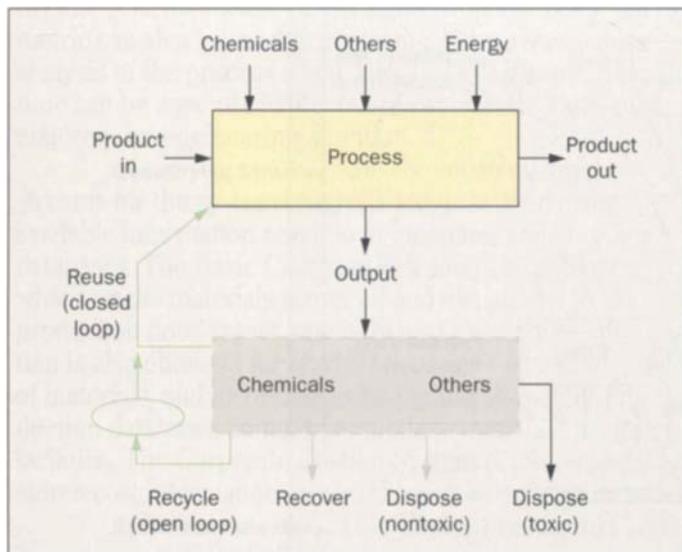


Figure 1. The material disposition of output streams determines the greenness of a process step. A totally green process is an ecologically closed loop system in which outlet streams are completely recycled into process steps. At the other, least desirable, end of the spectrum, outlet streams are disposed of in a landfill as toxic waste.

system in which the outlet streams are completely recycled into the process steps. On the opposite side of the spectrum, the outlet streams are disposed of as toxic wastes into a landfill, the least desirable option from a green design perspective. The Green Design Tool described here guides the green design process in a user-friendly fashion to realize green products.

Green design of products and processes requires detailed information on subassemblies, materials used, and by-products generated by the processes. A major hurdle to performing a detailed evaluation of greenness is the lack of environmental information on many subassemblies in use today. If the information is readily available and can be accessed from local or on-line databases, designers can make a rapid green design assessment and refine it to improve the greenness of product design and manufacturing processes. Wherever possible, the green design architecture incorporates such a feature, which is used to modify the product/process attributes where needed. The Green Design Tool allows the designer to make rapid assessments and gather feedback to optimize the green design.

Panel 1. Abbreviations, Acronyms, and Terms

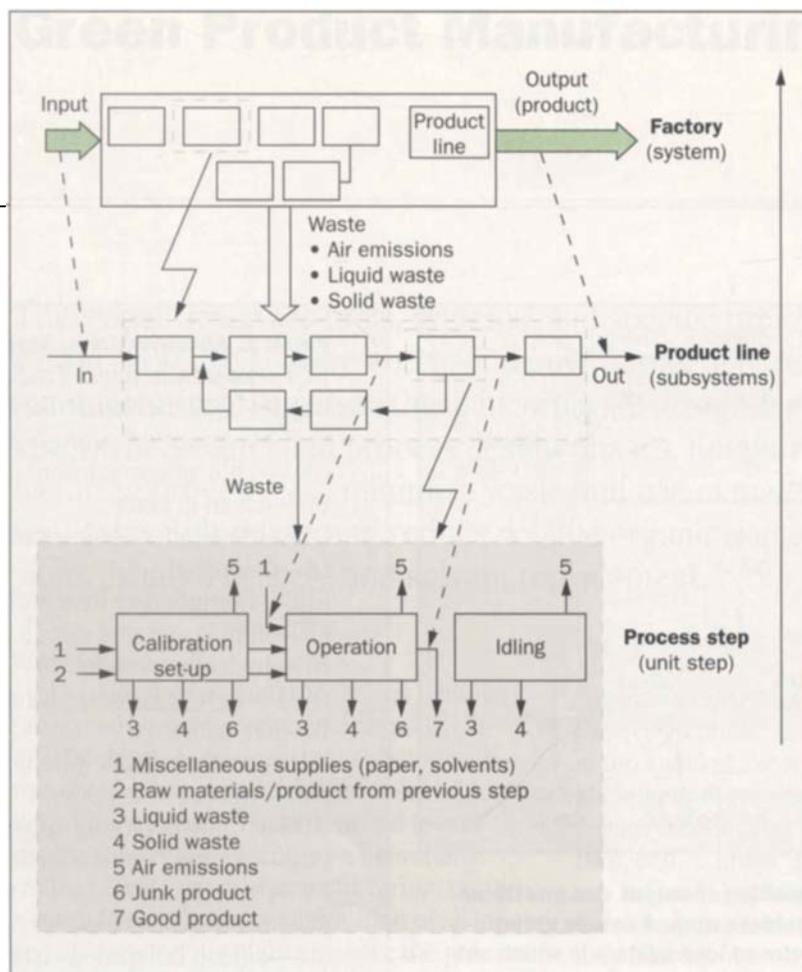
- BCT—Basic Chemical Tracking System
- BEST—bipolar-enhanced self-aligned technology
- CCS—Corporate Costing System
- CFC—chlorofluorocarbon
- CIP—clean in place
- DFE—design for environment
- DI—deionized
- ERC—Engineering Research Center
- FIC—film integrated circuit
- HF—hydrofluoric acid
- IWTP—industrial waste treatment plant
- IX—ion exchange
- MDI—methylenebis (phenylisocyanate)
- NPV—net present value
- ODS—ozone-depleting substances
- PCB—printed circuit board
- PV—present value
- RO—reverse osmosis
- SIC—silicon integrated circuit
- SIR—surface insulation resistance
- TURA—Toxic Use Reduction Act
- VOC—volatile organic compound
- weight percent—the weight of the chemical in question divided by the total weight of all chemicals involved.

This tool was developed on a PC platform by AT&T developers and operates under a Windows* 3.1 or later version with at least a 386 computer. Its event-oriented format gives immediate visual feedback in the form of graphical displays and representation of results for subassemblies, the completed product, and manufacturing processes.

Minimizing Waste

Utilization and waste disposal of manufacturing process materials are becoming increasingly important issues for the manufacturing community. Increased public awareness and concern over the associated environmental considerations have raised everyone's level of consciousness and have brought these issues to the forefront of many agendas throughout the world. Regulations regarding manufacturing process materials utiliza-

Figure 2. A manufacturing process template. At the process level, chemicals, processing materials, and partially finished product are input to manufacturing operations to make products. Waste and emissions, by-products of the manufacturing operations, are then monitored at all stages of operation, namely, set-up, idling, and operation. The waste minimization system uses this information to control material usage and by-product generation at the process, production line, and factory levels.



tion and waste disposal are evolving on state, federal, and international levels, along with more numerous, stringent, and complex regulations. The “cradle-to-grave” tracking of hazardous waste that is required today is being extended to all process materials and waste, with toxic materials usage reduction legislation, such as the Massachusetts Toxic Use Reduction Act (TURA), being implemented in some states.

AT&T has developed a Waste Minimization Tool² for the chemically intensive manufacture of classes of electronic components. Its primary focus is on the processing operations used to manufacture printed circuit boards (PCBs), silicon integrated circuits (SICs), and thin and thick-film integrated circuits (FICs). These operations delineate circuit patterns on polymer, silicon, or ceramic substrates represented by many process-intensive, semi-continuous, and repetitive wet chemical and physical operations. At the factory level, chemicals and various processing materials are supplied to manufacturing operations to make the products that are shipped (see Figure 2). In addition to the products manufactured, these operations generate waste and emissions as by-products. Because they typically involve hundreds of process steps, product

codes, and process chemicals/materials, these operations are considered “large and complex.” Each product code has its own routing sequence through the manufacturing line. Typically, numerous products are manufactured concurrently on the same production line, with varying production volumes for each product code manufactured. During calibration and set-up, product manufacture, and periods of nonproduction or “machine idling,” equipment consumes process chemicals and materials. The end-to-end environmental, or green, efficiency for an entire factory or production line depends on the chemical/material usage efficiency of each process step.

With this in mind, AT&T used systems analysis concepts to develop an on-line Waste Minimization Tool. This tool tracks the utilization of process materials and waste (or by-product) generation per unit of product at each process step, or work center, in one or more manufacturing lines within a factory. The normalized process metric, or chemical/material consumption per unit of product, provides the process baseline against which progress towards waste minimization—that is, pollution prevention—goals can be measured. To iden-

tify and prioritize waste minimization opportunities, the metric can also be used to perform a Pareto/root cause analysis of the process steps. Variations of this metric with time can be used to identify out-of-control situations that may require engineering attention.

Quantifying Streams. The chemical/material streams for the systems analysis are quantified using available information residing in incoming and outgoing databases. The Basic Chemical Tracking (BCT) System, which tracks materials procured and dispatched to the production floor, is just one of these. Quantifiable information is also obtained for product flow, product routing, bill of materials, and incoming and outgoing shop floor production databases common to modern manufacturing facilities. The Corporate Costing System (CCS) database stores cost information for the chemicals/materials used.

System Architecture. The Waste Minimization Tool is implemented in a UNIX* environment and runs on a Sun* workstation. Except for minimal manual inputs, the system automatically updates knowledge from the various information sources on a weekly basis. This information is then assembled in a composite database used to generate reports and respond to user queries through a menu-driven graphical user interface. The interface also provides tabular and graphical visualization of data at both the subsystem (product line) and system (factory) levels.

System Outputs. For each chemical and work center at the product line or factory level, the Waste Minimization Tool provides normalized chemical/material consumption and cost information, per unit of product, on a weekly and year-to-date basis. The normalized process metric provided by this tool governs the environmental cost liability of a process. It serves as the cornerstone for *green accounting* assessments, an activity-based costing methodology that allows factory engineers and management to make informed business decisions and assessments based on the capture of total environmental costs. Another output of this tool is chemical/material cost information (by work center) for specified products and their associated routing sequences.

Summary and Benefits. Among its benefits, the Waste Minimization Tool provides normalized chemical consumption information for each work center per unit of product. The tracking and assignment of process material usage and waste disposal costs for consuming and waste-generating processes are essential for accurate product

costing. They guide efficient material usage and conservation in the spirit of quality. The Waste Minimization Tool described here has been deployed at AT&T's Merrimack Valley Works to identify ways to reduce chemical usage (waste minimization/pollution prevention). As a result, the Merrimack Valley Works has reduced TURA-reportable chemicals by an average of 29 percent, which represents an actual savings of \$180K in 1994 (and \$350K per year on an annualized basis). In addition, acetone, nitric acid, ammonia, and methylenebis (MDI) (phenylisocyanate), which is a chemical in packaging foam, are now below the 10,000-pound TURA-reporting threshold for the Merrimack Valley Works. Reducing chemical usage in manufacturing operations saves money and lowers the potential for future liability, risk, and remediation expenses.

Water Conservation and Reuse

Continuous economic development is increasing the demand for water and for protecting water resources. Within the electronics industry, benchmarking has identified numerous factors motivating water conservation and reuse:

- Cost,
- Replacement of chlorinated solvents with water-based processes,
- Usage restrictions and discharge regulations,
- Public image,
- Pollution prevention and environmental impact, and
- Industry competitiveness.

The last factor is of particular concern in semiconductor manufacturing because of the high cost and large volume of ultrapure water needed in clean room operations. On average, producing a single semiconductor wafer typically requires thousands of gallons. However, a large portion of this is necessary simply to maintain water purity, regardless of wafer throughput. Figure 3 shows this lack of correlation between water usage and wafer production for one semiconductor operation. As a result, much of the effluent is relatively uncontaminated and therefore suitable for recovery.

Economics. Water usage at AT&T factories varies from thousands to millions of gallons per day, in one case corresponding to 20 percent of the local municipal water supply. Typically, the cost of city water is \$1 to \$3 per thousand gallons (kgal), but it can be higher in

some geographical areas. The treatment sequence needed to produce deionized (DI) water can add another \$5 to \$20/kgal. The cost to produce semiconductor grade ultrapure water varies significantly within the industry, but it can be as high as \$40/kgal and cost millions of dollars a year in expenses for a single factory. Operating an on-site industrial waste treatment plant (IWTP) or discharging effluents into a municipal system raises the cost further.

The savings to be gained through water conservation and reuse are significant. At \$1.50/kgal (city water expense alone), recycling at a continuous rate of 10 gallons per minute (gpm) corresponds to a present value (PV) of about \$35K based on a 5-year project life, 3-percent inflation rate, and 10-percent discount rate (cost of capital). This is the maximum capital investment allowable to implement the project if the net present value (NPV) is to be positive. The PV is proportional to both the flow rate and value of the water. Thus, recovery of DI water with a value of \$5/kgal at a rate of 100 gpm would support an investment of more than \$1M.

Product and Process Quality. Water reuse can also have major benefits for manufacturing operations, such as reduced dependence on a municipal source for volume, quality, and consistency. Recovering DI water eliminates the intake of an equivalent amount of city water and the accompanying contaminants. Reducing incoming silica, organics, chlorine, and metals improves the DI water production process. It also reduces the threat to clean room and other processes and lessens the discharge of regulated pollutants. At the process level, water recycling can also improve process effectiveness and product quality by allowing increased water circulation in plating or cleaning rinses and in clean-in-place (CIP) equipment.

Regulatory Factors. Regulatory factors motivating water conservation and reuse include the Clean Water Act goal of zero pollutant discharge, discharge limits based on local water quality requirements rather than the capability of treatment technology, anticipated watershed management, and the trend toward pollution prevention and waste minimization. There also is a trend toward valuation of *externalities*—societal costs due to environmental impact—and imposition of these costs on both producers and consumers through surcharges, taxes, and the like.

Hidden Benefits. Many cost benefits of water conservation and reuse are indirect, such as energy, chemi-

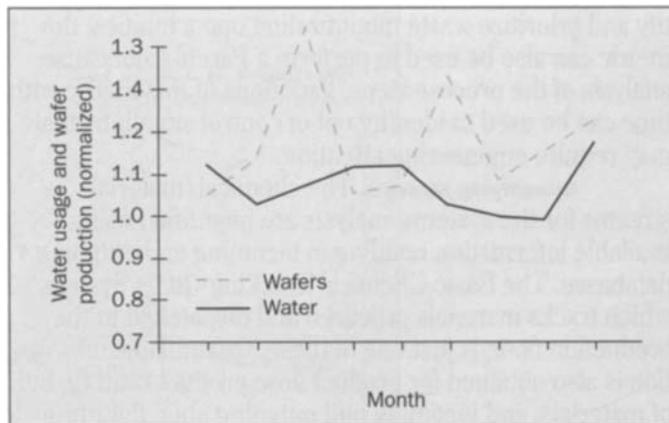


Figure 3. The need to maintain flow rates sufficient to ensure water purity can result in a demand for deionized water that is largely independent of changes in wafer production. A large portion of such effluent is essentially uncontaminated relative to a municipal waste supply, offering both cost savings and process quality improvement.

cal storage, sampling, and record-keeping related to DI water production and IWTP operation. Avoiding potential fines and penalties, legal expenses, civil and criminal actions, liability, and negative publicity also offers considerable savings. Activity-based costing and risk modeling can be used to include these types of factors in the cash flow analysis for the project business case. Saving millions of dollars of liability, even when discounted over twenty years, can have a major impact on the economic feasibility of engineering projects.

Strategy and Technology. Systems engineering is the most effective approach to optimizing a factory water system and includes both manufacturing and physical plant processes as components of the overall solution. This starts with an overall factory water balance analysis and ultimately encompasses water conservation, which optimizes water-intensive processes and minimizes usage; water recycling, which reuses water in the same type of process; and water reclaim, which reuses water in other processes.

In each area, efforts must be properly prioritized. The greatest economic benefit is gained by conserving the purest (most expensive) water or recovering it for a comparable use. Conservation is the first step because it determines the volume of water available for recycling or recla-

mation. Either of these involves a compromise between cost and process requirements. Returning the combined factory effluent—including constituents such as treated manufacturing waste, cooling water, and boiler blow-down—to the beginning of the treatment process may be the most economical choice. Because of the diverse mix of contaminants, however, it is not feasible for most factories. Similarly, installing multiple treatment systems to recycle water separately for each process is prohibitive because of the cost and complexities such as maintenance.

DI and soft water production, cooling systems, IWTP, and manufacturing processes are all areas in which conservation opportunities exist. For example, reverse osmosis (RO) and ion exchange (IX) processes can be optimized to minimize the associated waste flows. By-product streams from high-purity water production processes contain no manufacturing process contaminants and may be much purer than incoming city water. For example, recovery of this type of water by AT&T's Allentown factory recently resulted in a direct savings of more than \$150K/year for IX chemicals, as well as other benefits, such as enhanced quality in its manufacturing processes. Examples of optimization opportunities at the manufacturing process level include design of semiconductor wafer carriers and rinse tanks to minimize the flow necessary, and extending the useful life of chemical baths, as described in the next section. Opportunities in printed circuit board and assembly factories include counterflow rinsing for plating, stripping, and cleaning processes.

Recycling and reclamation opportunities depend on segregation and grouping of both effluents and recovered streams at an appropriate level within the factory and on matching water purity to process requirements. In the Allentown factory, reconfiguring the feed system to make optimum use of the recycled water will produce more than \$100K/year in additional direct savings. Semiconductor wafer shaping and polishing processes produce effluents heavy in suspended abrasives and silicon, which must be segregated from clean room rinses that include acids and organics such as photoresist. Recycling of clean room effluents poses a major challenge to maintaining clean room process integrity. An alternative is to treat and reclaim the effluents for uses such as soft water make-up, which requires significantly less treatment, monitoring, and control. The most effective way to recover plating, stripping, and cleaning effluents in those types of factories is to handle them separately.³

Real-Time Process Advisor

Within the walls of many AT&T factories, chemicals play a critical role in changing the form and value of a product, from starting material to finished goods. How long such chemicals should be used is a decision often made by the process engineer, who is motivated by factors such as impact on product yield, device performance, and throughput. Dumping of chemical baths before the end of their useful life to provide a margin to protect these factors is an area of environmental concern. This is especially true when the costs for waste treatment are not directly reflected in the manufacturing organization's bottom line.

The etching of silicon dioxide films by hydrofluoric (HF) acid solutions is one of the most widely used wet chemical operations in semiconductor and glass manufacturing. If wet chemical benches are well designed, baths are properly prepared, incoming oxide films are of consistent quality, and the operation of the etching process is well controlled, then it is possible to obtain repeatable, uniform etching of the dielectric from lot to lot. From the vantage point of the manufacturing engineer, two significant sources of variation are errors in preparing baths and ineffective use of manually intensive process control procedures. Unfortunately, these shop errors may result in significant over or under etching. Variances can manifest themselves as episodic losses of entire product lots. In the past, the process engineer would rightfully conclude that the longer the bath was run, the further away from optimal control the etch facility would vary.

Advances in chemical sensor technologies suggested a more effective way to control these wet chemical etch processes. HF sensors can signal a PC platform called a Wet Chem Advisor.⁴ Its software code, developed by AT&T, provides significant engineering, process analyst, and shop operation advice. As a result of using the Wet Chem Advisor, bath preparation errors and manual process checks have been completely eliminated. This paper describes some sources of variation in the device line developed as a result of work performed in AT&T; it also discusses how the Wet Chem Advisor has changed the methods used to control etch processes, thereby eliminating these sources of variation.

The device fabrication line in which this work was accomplished is a rather mature 100-mm silicon wafer bipolar device clean room in AT&T's Allentown,

Table I. HF Wet Chem Advisor feature summary

Optional control limits	The engineer has the option to set upper and lower HF concentration control limits around the target.
Operator warning	An out-of-control situation is signaled to both the engineering station (the PC Advisor) and light post at the etch station.
Corrective action	The Advisor calculates the quantity of water or HF required to bring the facility back to target and displays this for the operator and engineer.
Summary status	The default screen on the PC summarizes the current status of all six facilities: HF concentration, etch rate, water to HF ratio, bath temperature, and status relative to target specification.

Pennsylvania, manufacturing location. The line produces a mixture of older bipolar codes and newer bipolar-enhanced self-aligned technology (BEST) devices.⁵ The space limitations of the clean room, small by industry standards, play a critical role in many decisions about wet chemical processing facilities. Shop operators are expected to move the product wafers and to provide process control for more than a half-dozen front-end HF facilities. Although the more senior shop people prepare baths during the first shift on Monday morning, this microelectronics fabrication line, or *fab*, does not have full-time process analysts available to monitor and control the etch facilities.

The manual control of etch baths is based on the use of monitor wafer standards and etch rates derived from the etch deltas measured after a standard etch time in a given bath. The bath is spiked or diluted (by adding either acid or water, respectively, depending on which is needed), and the iteration is repeated until the etch rate specification is met. This had been the existing operator practice within this *fab* for some time; it was used when baths were first prepared, on Monday, and corrected if necessary during a process check throughout the five-day work week in each of the three shifts. The shop recipe for preparing a bath is derived from knowledge of the bottled chemical concentrations and the total volume of the etch facility. Target concentrations expressed as the "standard" volume ratios are either 15:1 or 100:1.

Each HF wet deck is fitted with continuous circulation and HF filtration. The recirculation flow is approximately 4 liters per minute (lpm), with a typical total volume of 20 liters. The facilities have temperature controllers. Most HF wells do not have covers; those that do have covers use them only intermittently. The sinks are all manually operated using digital timers that operators set after checking the scheduling of a *lot* (50 product wafers) with the *shop flow*, a system that tracks each lot as it moves through the *fab*. Shop flow dictates the etch facility and etch time for the process step.

The Wet Chem Advisor. The HF Wet Chem Advisor is a PC platform that receives input signals from two sensors located in each etch facility. The bipolar application described here has six facilities with sensors installed. The sensors—an HF sensor and a temperature sensor—are commercially available units. The HF sensor operates on the induction principle. An ac reference signal in a primary coil induces a signal in a secondary coil connected to the first coil by the conductivity of the HF solution. All sensor components are completely enclosed in HF-compatible polymer compounds. The output signal, 4 to 20 mA dc, serves as one input to the Wet Chem Advisor. To create the trace in the figure, nine data points are monitored every 3 minutes and then averaged. The temperature sensor is a negative thermal coefficient thermistor. This type of sensor was selected for its excellent sensitivity in the operating range of normal room temperature. It is easy to install in the PC platform, because it requires only a 1-mA current loop from the PC's 5V bus. The various HF and temperature signals are input over a 16-channel multiplexed analog/digital (A/D) converter. The source code for the Advisor, written in C programming language, provides easy software access to the multiplexer hardware.

Whether the labor-intensive process control procedures can be replaced with the Wet Chem Advisor depends on the Advisor's ability to demonstrate that it is both accurate and reliable. Algorithms based on sensor input for bath temperature and HF concentration have been developed within the PC-based Advisor to calculate the etch rates of silica. Incorporating temperature coefficients has improved the accuracy of the sensor beyond the commercial vendors' specifications. The software code has been designed to provide the manufacturing engineer and shop operation with advice that is simple to interpret and easy to implement. Table I summarizes these features.

Understanding Sources Of Manufacturing Variation. Figure 4 presents the HF concentration record for one of the 15:1 facilities immediately before and after the shop

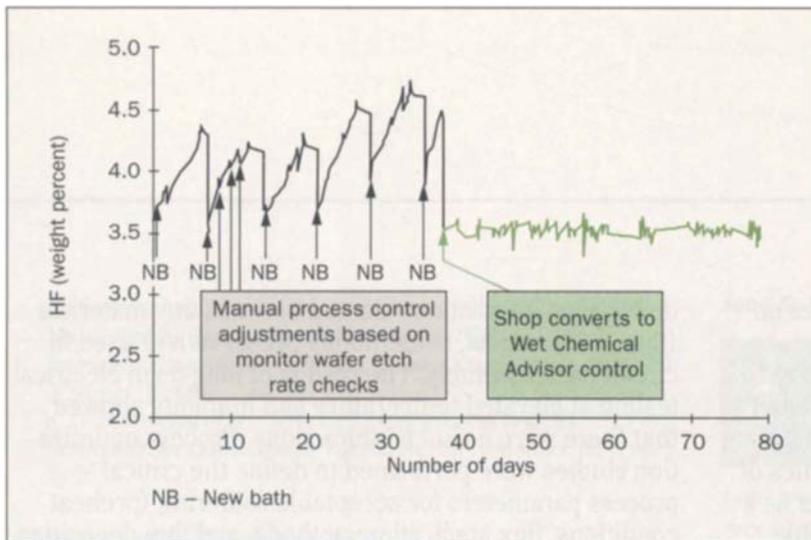


Figure 4. A three-month history of the HF concentration record of one 15:1 facility immediately before and after the operation was converted to the Wet Chem Advisor.

operation was converted to the Advisor. During days 0 through 38, the Advisor network was fully functional, but unavailable for operator use. The concentration trace for this five-and-one-half-week interval clearly identified many sources of variance under normal manufacturing operations. The target concentration was 3.6 *weight percent* HF, the weight of HF divided by the sum of the weight of HF and H₂O.

Advisor Process Control Methodology. The Wet Chem Advisor approach is simple and straightforward: provide an in-line exception-based alarming, process monitoring system that is simple to use and interpret. The Engineering Research Center (ERC) Cleaning Team has permanently placed sensors in each bath's HF recirculation loops, assuring continuous in-line sampling. The sensors calculate and display two levels of status information. For the engineer, process analyst, or layout operator, the multifacility summary display at the Advisor's PC provides a single source for all the real-time data being acquired and for all derived parameters of interest. For the shop operators, the light panel at the etch facility provides a visual "go, no go" indicator. Operators can readily ascertain the bench status, even from other nearby facilities. A red light is illuminated on the panel when the concentration and temperature conditions move the etch rate outside the engineering control limits set for that facility. The Advisor stores several months of sensor data and derived bath parameters, which can be used as input into commercial process control statistical packages. Statistical packages are also available within high-level shop flow and product tracking systems.

Converting to the Wet Chem Advisor has a dramatic impact on process control, as seen in the HF weight percent trace from day 38 to the end of this particular study. This shop has not used, or borne the cost of, a single process monitor wafer since the Advisor system was installed. That alone is worth about \$50K annually for each HF facility. New baths are now set up in minutes instead of hours.

The ERC Cleaning Team has applied similar process control methodologies to other facilities used in AT&T Microelectronics. In many cases, baths were being underutilized. Bath lives have now been extended two, four, and even eight times. The process engineer has the necessary information and confidence in process control to take the risk associated with using chemicals longer, while at the same time reducing waste treatment volumes and costs that would otherwise have to be managed by the environmental engineer.

Reducing VOC Emissions

Ozone-depleting substances (ODSs)—such as chlorofluorocarbons (CFCs)—have been eliminated from manufacturing processes in AT&T circuit pack assembly factories using several approaches, such as converting from cleaning to no cleaning after soldering, or changing the cleaning agent. Because neither approach offered a drop-in replacement for the current process, both required new equipment, and/or new materials, and/or new processes.

After ODSs were successfully eliminated, AT&T circuit pack assembly factories located in ozone nonattainment zones faced another issue—reduction of VOC emissions. The primary contributor to VOC emissions from these locations was the wave solder flux solvent (2-propanol). The obvious choice for a replacement solvent was water, which is inexpensive, nonflammable, nontoxic, and harmless when emitted to the air.

To move to the greener, water-based fluxes, the following issues had to be addressed:

- Soldering performance of the water-based flux,
- Equipment and process changes, and
- Impact of the new material/process on electrical performance.

The manufacturing locations expressed a strong desire for the new material/process to be a drop-in

replacement for the existing process, which implies no changes to the process other than a new flux.

A solder flux provides a clean metal surface to be soldered, reduces the surface tension of the solder to aid wetting, and protects surfaces from oxidation during heating. When the chemical and physical properties of 2-propanol and water were compared, using water as a drop-in replacement for 2-propanol was not possible because water:

- Has a lower vapor pressure,
- Has a much higher surface tension, and
- Is a better solvent for flux activators, which are typically weak organic acids, leading to a more acidic, corrosive solution with a lower pH.

These differences lead to the need for more pre-heat (the part of the soldering process where the solvent is vaporized), additives to reduce the surface tension, and new/modified fluxing equipment to address reaction of the flux with the metals of the equipment (for example, pitting and corrosion). In addition to these concerns, the soldering performance and the effect of the new materials on electrical performance were of critical importance.

To identify VOC-free, no-clean fluxes that meet all of AT&T's needs and requirements, manufacturing research and development partnered with AT&T circuit pack assembly locations, flux manufacturers, and soldering equipment manufacturers to evaluate commercially available no-clean wave solder fluxes that were VOC free. These evaluations included assessments of soldering performance and electrical performance. The replacement candidates had to provide soldering performance equivalent or superior to the performance of current alcohol-based flux, as well as equivalent or superior surface insulation resistance (SIR) performance during extended exposure to elevated temperature and humidity.

The soldering performance of the first series of VOC-free, no-clean fluxes was unacceptable. Using the information gathered from these evaluations, flux manufacturers reformulated their materials. The second series of materials provided acceptable soldering, but unacceptable SIR performance. Two candidates in the third series of materials provided acceptable performance in both areas.

Material and process compatibility studies were conducted with these two fluxes to determine whether

deleterious interactions existed between any materials (flux, solder mask, solderability preservative) used in circuit pack assembly. The results of long-term electrical testing at elevated temperature and humidity showed that there were no such interactions. Process optimization studies were performed to define the critical process parameters for acceptable soldering (preheat conditions, flux application methods, and flux deposition levels). Both of these third-generation VOC-free, no-clean fluxes met the soldering and electrical requirements and have been implemented into the wave soldering process at several AT&T assembly factories. Critical to the success of this effort was the working relationship among all members of the team.

Conclusion

This paper has described tools, systems, and specific processes used to improve the greenness of AT&T's manufacturing operations. Incorporating greenness into the product design stage is crucial to the success of green manufacturing. The five areas presented—green product and process design, waste minimization, water conservation and reuse, the real-time process advisor, and VOC emission reduction—strive to achieve green manufacturing in diverse applications within AT&T.

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