Workshop on Pollution Prevention Research Needs for the Semiconductor and Electronic Industries And Their Suppliers

Held at Orlando, Florida, May 4, 1995

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Research Triangle Institute
PO Box 12194
Research Triangle Park, NC 27709

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Notice

The following report has been written by the Research Triangle Institute (RTI) for the Office of Research and Development (ORD) of the Environmental Protection Agency (EPA). Paul Shapiro, Common Sense Initiative Coordinator for ORD and Chuck Darvin of the EPA's National Risk Management Research Lab of EPA cooperated with the work. This report has been funded wholly or in part by the EPA under cooperative agreement CR 818419-01 to RTI. This report has not been subjected to ORD peer review procedures. The contents of this report and mention of the trade names or commercial products do not necessarily represent the views, policies, or endorsements of the EPA, nor of any other departments or agencies of the federal government.

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1.0 Introduction

Small businesses face a variety of problems as they attempt to comply with environmental regulations at manageable costs. Pollution prevention strategies frequently offer small businesses, such as suppliers, the ability to comply or exceed regulations at a lower cost than with pollution control. In recognition of the difficulties that small businesses face and of the importance of small business to the growth and sustainability of the national economy, the U.S. Environmental Protection Agency (EPA) has linked its effort to assist small businesses with adopting pollution prevention technologies to achieve environmental compliance and risk reduction in an economic manner.

To assist small businesses in adopting pollution prevention technologies and techniques, EPA's Office of Research and Development (ORD) and the Research Triangle Institute (RTI) entered into a cooperative agreement to conduct workshops to identify opportunities for research that can help prevent pollution in four industry sectors with a sizable number of small businesses. These sectors include electronics, metal parts painting, metal finishing, and adhesives used in automotive assembly and automotive parts manufacturing.

The electronics and semiconductor industries, including computers, communications, semiconductors, printed wiring boards, and consumer electronics, are the largest manufacturing employer in the United States. Although these industries have been generally considered to be environmentally clean, there has been increasing concern with environmental issues, including compliance with the Clean Air Act Amendments of 1990. These industries are supported by thousands of supplier companies that produce manufacturing equipment, services, chemicals and other materials. Current international environmental legislation, including regulations in Germany and the Netherlands, would require that electronic equipment contain a record of all components and servicing, thus linking all suppliers into the environmental liability chain. Pollution prevention is the EPA's top recommended approach for reducing the usage and emissions of hazardous chemicals. Many of the companies within the electronics industry have been proactive in using pollution prevention to reduce their environmental burden as well as reduce operating costs.

This report summarizes information from the Workshop on Pollution Prevention Research Needs for the Semiconductor and Electronic Industries and Their Suppliers, held on May 4, 1995. The basic question addressed was how can the semiconductor and electronic industries and their suppliers increase the use of pollution prevention to reduce hazardous chemical usage and emissions (beyond compliance) and also reduce energy and water usage while improving worker safety and reducing cost. There was a focus on suppliers, but since broad input was needed, representatives from manufacturers, suppliers, government, and others attended the meeting in Orlando, Florida. A list of the attendees can be found in Appendix A. The workshop was organized by RTI, in conjunction with EPA. SEMI/SEMATECH co-sponsored the workshop that was held after the Institute of Electronics and Electrical Engineers's (IEEE) International Symposium on Electronics and the Environment. Dr. Jesse Baskir and Ms. Deborah Franke of RTI facilitated the meeting.

The goals of the meeting were to:

1. Develop a list of current pollution prevention research, development, demonstration and technology transfer projects related to the industry roadmaps.

2. Identify pollution prevention research needs addressed in item 1, which are not currently being met.

3. Develop a joint government and industry funding strategy for the agenda of activities in item 2.

The industry roadmaps used as a starting point were *The National Technology Roadmap for Semiconductors,* Semiconductor Industry Association (SIA), 1994 and the *Electronics Industry Environmental Roadmap,* MCC, sponsored by ARPA, EPA, and DOE, 1994. These roadmaps were developed by large teams of people from industry, government, and academia, working together to define future research needs.

The National Technology Roadmap for Semiconductors was the latest in a series of roadmap documents sponsored by SIA which deal with technology requirements for ensuring advancements in the performance of integrated circuits. The primary focus was on silicon CMOS (complementary metal-oxide-semiconductor) integrated circuits, since these products constitute over 75% of the world semiconductor market. Environmental, Safety, and Health (ESH) was one of the eight critical areas of semiconductor research and development, engineering, and manufacturing discussed.

The Electronics Industry Environmental Roadmap was part of an ongoing process by the electronics industry and government to develop environmentally conscious processes and products. General conclusions from the study formed a basis for further study, including:

1. Need for better environmental information and access to information;

2. Disposition of products as a business concern;

3. Manufacturing focus on efficiency and understanding of new technologies; and

4. Voluntary programs to augment and surpass command and control approaches.

Mr. Paul Shapiro welcomed the participants on behalf of EPA’s Office of Research and Development (ORD). He emphasized that, while this workshop was not sponsored by the Common Sense Initiative (CSI), it is part of ORD’s commitment to support CSI, especially with respect to pollution prevention and small business. He also said that the meeting was not intended to produce answers or commitments, but rather be a starting point for exchanging information and ideas among industry, government, and others. The goal was to explore the possibilities for collaborative pollution prevention research and development. During the meeting, the attendees listened to talks from SEMATECH and from EPA, then listed current research and needs. Specific funding strategies were not developed, but participants agreed that further discussions between EPA and industry to discuss this and other topics would be beneficial. The agenda and study questions sent to attendees are shown in Appendix B.

2.0 Presentations

Dr. Walter Worth of SEMATECH presented information on the environmental, safety, and health (ESH) chapter of *The National Technology Roadmap for Semiconductors.* He also discussed current SEMATECH ESH projects. A copy of his viewgraphs can be found in Appendix C. Many of the SEMATECH research projects include pollution prevention/source reduction concepts as part of process optimization. In addition, there are projects targeted specifically to the design for environment. Discussion following his talk included questions on the nature of SEMATECH's research, the roadmap, and other activities. Highlights of the discussion are as follows:

- SEMATECH's research and development is in non-competitive areas.
- The roadmap is aimed at SEMATECH, manufacturers and suppliers serving the industry, and Semiconductor Research Corporation (SRC), which supports university research.
- The ESH roadmap areas and associated research were outlined. Information can be found in Appendix C.
- Not all research defined in the roadmap is being addressed at this time. The projects are prioritized as part of the SEMATECH funding process.
- The roadmap technical working group is charged with updating the roadmap every two years.
- Other industry ad hoc groups are working on specific projects addressed in the roadmap.

Mr. Paul Shapiro from the EPA Office of Research and Development discussed the Common Sense Initiative (CSI) and other EPA programs and research related to the electronics industry. A copy of his viewgraphs can be found in Appendix D. The CSI brings together representatives from federal, state, and local government, industry, environmental, environmental justice, and labor to examine the full range of environmental requirements affecting an industry. The Electronics Sector is one of six pilot industries included in CSI. The overall CSI committee and the six subcommittees operate under the Federal Advisory Committee Act (FACA). The goal of CSI is to encourage the use of common sense, innovation, and flexibility to achieve a cleaner environment at less cost, that is, finding, “cleaner, cheaper, smarter” approaches to environmental protection. The areas addressed by each sector subcommittee are:

- Regulation. Review regulations for opportunities to achieve better environmental results at less cost and look to improve new rules.
- Pollution prevention. Actively promote pollution prevention as a standard business practice and a central ethic of environmental protection.
- Reporting. Make it easier to provide, use, and publicly disseminate relevant pollution and environmental information.
- Compliance. Assist companies that seek to obey and exceed legal requirements, and consistently enforce the law against those that do not.
- Permitting. Change permitting so that it works more effectively, encourages innovation, and creates more opportunities for public participation.
- Environmental technology. Give industry the incentives and flexibility to develop innovative technologies that meet and exceed environmental standards while cutting costs.

EPA hopes that the CSI will demonstrate that the stakeholders can work together to achieve the following results:

- Identify obstacles to pollution prevention and environmental technology facing the industry and recommend solutions to the problems identified (including, but not limited to, regulatory, statutory, and administrative changes).
- Make more extensive use of pollution prevention and voluntary programs.
- Develop a better understanding and improved working relationships among stakeholders.

The Electronics Sector FACA Subcommittee may define working groups as necessary to aid them in their work. Working groups have been established for reporting and information access, pollution prevention and recycling strategies, and alternative regulatory measures. EPA contact for the Electronics Sector FACA Subcommittee: Gina Bushong (202) 260-3797.

3.0 Current Research and Development

Government agencies, universities, and industry are funding and performing pollution prevention research for the semiconductor and electronics industries, as well as in related environmental areas. This section lists current research programs. Abstracts are generally taken directly from project summaries. Walter Worth and Paul Shapiro discussed SEMATECH and EPA research in their workshop presentations. Troy Strouth provided information on U.S. Air Force research. Other research program information was obtained from the World Wide Web (WWW) and Internet. One can start at the EPA home page (http://www.epa.gov/) or gopher location (gopher://gopher.epa.gov/) and then explore the net through links given in these pages. Two other valuable Internet/WWW sources of information on pollution prevention research are Enviroene (http://wastenot.inel.gov/envirosense) (see Section 3.4 for more information) and the Pacific Northwest Pollution Prevention Research Center's Pollution Prevention Research Projects Database (gopher://gopher.pnl.gov:2070/1/.pprc). Table 1 gives an expanded list of pollution prevention information related to electronics which is currently available on the Web. The location information is accurate as of June 1995. A selected bibliography on pollution prevention in the semiconductor and electronics industries can be found in Appendix E. Many of the references discuss industry pollution prevention.

Table 1. Listing of Web Sites Having Pollution Prevention Information Related to Electronics

Site Name or Description	WEB location
P2 Information These sites have information and may also have lists of additional sites	
Enviroene	http://wastenot.inel.gov:80/envirosense
EPA home page	http://www.epa.gov
EPA gopher	gopher://gopher.epa.gov
Pacific Northwest Pollution Prevention Research Center	gopher://gopher.pnl.gov:2070/1/.pprc
SAGE - Solvent Alternatives Guide	http://clean.rti.org
National Pollution Prevention Roundtable (NPPR) P2 Yellow Pages	http://wastenot.inel.gov:80/envirosense/program/regional/rndtable/index.html
Electronics Manufacturing Productivity Facility (EMPF)	http://www.engr.iupui.edu/empf/
Strategic Environmental Research and Development Program (SERDP)	http://prop.wes.army.mil:80/serdp/home.html
The Environmental Research Institute of Michigan (ERIM)	http://www.erim.org

Table 1. Listing of Web Sites (cont.)

Site Name or Description	WEB location
Directories to Other Sites These sites have lists of additional sites, but may not have much direct information	
Environmental WWW Listing at Envirolink (includes organizations, publications, government sites, and services)	http://envirolink.org/envirowebs.html
DOE Pollution Prevention Information Clearinghouse (EPIC)	http://146.138.5.107
The Environmental Conscious Design and Manufacturing lab - other sources	http://ie.uwindsor.ca/other_green.html
Company Information Many large electronics companies can be located on the Web by using their company name. A search can then be done for "pollution prevention" or "environmental"	
IBM	http://www.clearlake.ibm.com/ETS/
Nortel (formerly Northern Telecom)	http://www.nortel.com:8O/english/environ/annual/NTAnnual.html
AT&T	http://www.att.com (then search on pollution prevention
Xerox	http://www.xerox.com (search on environmental)
Intel	http://www.intel.com/intel/intelis/ehs/
Rockwell International	http://www.Rockwell.com/rockwell/environment/environ.html
Digital	http://www.digital.com (search on pollution prevention)
Texas Instruments	http://www.ti.com (search on pollution prevention)

3.1 SEMATECH Research

During Fiscal Year 1994, more than $20 million was invested in 46 projects having environmental, safety, and health objectives. SEMATECH provided leadership in revising the ESH section of *the National Technology Roadmap for Semiconductors.* Through the Semiconductor Research Corporation (SRC), SEMATECH funded approximately $11 million of ESH-oriented university research, including projects in water conservation, aqueous photoresist, chemical vapor deposition (CVD) process optimization, plasma destruction of perfluoro compounds (PFCs) and alternatives to PFCs (see more detailed information on specific SRC projects in Section 3.5. SEMATECH contacts: Ray Kerby (512) 356-3540, Walter Worth (512) 356-7199.

Current SEMATECH ESH-specific research areas include:

1. Air emissions treatment and monitoring, including abatement technologies.

2. Risk assessment methodology, including risk evaluation of process material alternatives for the semiconductor industry and communicating risk decisions to users.

3. Characterizing process by-products.

4. Reducing global warming gases by optimizing processes and decreasing emissions as well as demonstrating abatement equipment and alternatives.

5. Design for the environment (DFE), including determining impact of semiconductor manufacturing on the environment, developing DFE guidelines, and delivering DFE training courses.

6. Silane safety improvement, to benchmark engineering control practices, assess risks, and identify possible silane alternatives.

In addition, many of the research projects in other areas have ESH objectives/approaches, including:

1. Develop a safety standard for minienvironments. Also explore possibilities for reducing usage of hazardous chemicals using minienvironments.

2. Develop real time moisture sensors to prevent failure due to corrosion, thus allowing for optimization of chemical and water consumption.

3. Provide better methods for measuring potentially hazardous organics.

4. Obtain a fundamental understanding of plasma etch chemistry leading to an improved utilization of etch gases and/or replacement of gases currently used with chemistries that are more environmentally safe. Also associated with the etch process is improved use and abatement of perfluorinated compounds.

5. Extend and preserve the environmentally friendly physical vapor deposition (PVD) technology, in lieu of chemical vapor deposition (CVD), for the Ti/TiN contact and via liner application.

6. Screen potential chemistries for chemical mechanical polishing (CMP) to determine which ones may be non-hazardous. Also, study the traditional CMP scrubbing process.

7. Develop point of use chemical generation (POUCG) to reduce hazards associated with transportation and distribution of chemicals.

8. Study the feasibility of alternative cleaning processes, including cryogenic aerosol cleaning to reduce the usage and disposal of cleaning chemicals.

9. Various equipment improvement projects include identifying new safer chemistries and reducing usage of hazardous chemicals and emissions.

3.2 EPA Programs

Current EPA Research and Development specifically related to electronics is about $lM and includes a grant to the University of Arizona to study ultra pure water recycling. Other university projects are shown in Section 3.5. In addition, there are projects related to alternative cleaning methods which could also be applicable to the electronics industry. Some electronic research projects will be funded through the FY95 Environmental Technology Initiative. EPA participates in the White House National Science and Technology Council's Electronics Subcommittee, works with other agencies, and can manage ARPA and other agencies projects. Research contact: Paul Shapiro (202) 260-4969. EPA electronic-related programs include the following:

1. *33/50 Program*
   This is an EPA initiative to promote pollution prevention through voluntary participation by industry. Begun in 1991, the program goal was for the participating companies to reduce their releases and transfers of 17 high-priority toxic chemicals by 33% in 1992 and 50% in 1995. Many of the semiconductor and electronics industries and their suppliers have participated in this program. There is currently a discussion concerning the need for a next generation of the 33/50 program. Contact David Sarokin (202) 260-6907.

2. *Design for the Environment*
   This program provides leadership in information and facilitation for pollution prevention efforts, especially to promote the incorporation of environmental considerations, including risk reduction, in the design of products and services. The program is voluntary and supports partnerships with industry and the public. One of EPA's Design for the Environment projects is related to printed wiring boards. Contact: Debbie Boger (202) *260-0880*

3. *Energy Star*
   The program promotes voluntary working partnerships to reduce energy consumption. Energy Star Office Products include computers, monitors, copiers, printers, and fax machines which power-down when not in use. Contact: (202) 233-9114.

4. *Solvent Alternatives Guide (SAGE)*
SAGE grew out of the 33/50 program, with a focus group priority to centralize available information on cleaning products. With support from EPA's National Risk Management Research Lab (formerly Air and Energy Engineering Laboratory), RTI developed SAGE as an electronic handbook that helps the user to find solvent replacement alternatives. The original DOS version of SAGE is available from an EPA electronic bulletin board. In 1995, a Web version (http://clean.rti.org) has become available and a Macintosh version is being developed. Contacts: Chuck Darvin, EPA (919) 541-7633; Ken Monroe, RTI (919) 541-6916.

5. *EPA Region 9 Merit Partnership for Pollution Prevention Program*
This is a voluntary program to promote clean technologies among area businesses. On May 25, 1995, an initial meeting was held to discuss Merit partnerships with the semiconductor industries and their suppliers. Representatives from industry, EPA, state and local government, national laboratories, and universities discussed potential pollution prevention demonstration projects. A draft of this report was used as input for the meeting. Contact: Dan Reich (415) 744-1343.

6. EPA has supported the transmission of pollution prevention, solvent to replacement, and other environmental information through bulletin boards and the Internet. The World Wide Web location Enviroene (http://wastenot.inel.gov/envirosense) gives a summary of current EPA programs and initiatives as well as provides access to various EPA databases. The EPA Technology Transfer Network hotline is (919) 541-0800, and the BBS is (919) 541-5742 (8-N-l).

7. Through the National Risk Management Research Lab, EPA has funded a number of waste minimization research projects, including projects to study the manufacturing of microelectronic component, electronic circuit components mounting, and printed circuit boards. Information on these projects can be found in the WWW Enviroene. Contacts: Glenn Shaul, Cincinnati (513) 569-7408; Chuck Darvin, Research Triangle Park (919) 541-7633.

3.3 Department of Defense Research

The Advanced Research Projects Agency (ARPA) currently funds research at SEMATECH, as well as programs such as those administered by the Air Force (listed below). ARPA was one of the agencies supporting *the Electronics Industry Environmental Roadmap.* ARPA contacts: Zach Lemnios (703) 696-2278 and Larry DuBois (703) 696-2283. Air Force contact: Richard Remski (513) 255-3812, Army: John Davis (205) 842-6022, Navy: Ron Jennings (317) 226-5602.

Current U.S. Air Force Environmentally Conscious Electronic Systems Manufacturing projects, including contractor, duration, and funding are as follows:

1. *Permanent dry film resist for printed wiring board (PWB) process simplification,* DuPont. 24 months effort, $1,823,556.
   This effort will develop and demonstrate a permanent dry film resist in PWB manufacturing that can be rapidly disseminated into industry, will eliminate excess production steps, reduce waste generation by 30%, require no capital expenditures and reduce operating costs.

2. *"Zero dump" electroplating process development,* PSI Technologies. 24 months, $2,872,875.
   This effort will develop and demonstrate an electroplating system that will yield coating with precise property control without the need for additives in the plating bath. A major source of the contamination in the plating bath is the presence of additives that are used for deposit property control. If high-quality deposits can be obtained without the need for additives, the plating baths will be more robust, more environmentally compatible, easy to control and relatively maintenance free. Additives-free operation will result in an order of magnitude or greater increase in the operational life of the baths.

3. *Revolutionary environmental manufacture of PWBs with electroless plating,* MCC. 24 months, $4,541,317.
   This effort will develop and demonstrate an additive approach, electroless copper plating, for fabrication of high performance PWBs. The core of this approach is a novel, solvent-less photo-dielectric dry film (PDDF) concept.

4. *Alternatives to the use fluoride and hydrogen fluoride in electronics,* Georgia Tech Research Corporation. 24 months, $229,169.
   In this program, it is proposed to greatly reduce or hopefully eliminate the use of free fluoride and hydrofluoric acid in the fabrication of structures formed in silicon for electronics (but non-integrated circuits) uses, with a revolutionary photochemical technology. Silicon wafers have become the platform for many non-integrated circuits (IC) devices. Most of these devices require three-dimensional (3-D) or non-IC type structures in their operation or fabrication. The formation of 3-D features is very restrictive in terms of the final device size, and shape because it relies on crystal plane etching. Today, the 3-D structures needed for these devices (e.g., through wafer electrical connections, thin silicon diaphragms, lenses, granting, etc.) are fabricated using polymer masks and HF (or other corrosive) etchants. The photochemical process proposed here does not require free fluorides or the use of polymer masks. The new technology proposed here can produce higher quality, unique structures which offer enhanced performance at potentially lower cost, with the added bonus of environmental benefits.

5. *Tertiary recycling process for electronic materials,* Adherent Technologies Inc.. 24 months, $850,956.
The objective of this program is to investigate the suitability of an economical tertiary (producing chemicals or fuels) recycling process for recycling of scrap electronic materials. This process can convert a wide variety of polymers and composites into low molecular weight hydrocarbons at temperatures below 200 degrees C. The hydrocarbons can then be reused as chemicals, fuels, or monomers. Metals, glass, ceramics, and fillers are separated from the hydrocarbons for reclamation.

6. *Jet vapor deposition: a new environmentally sound manufacturing process,* Jet Vapor Corp. 24 months, $1.2M.
This program will develop and industrialize an innovative, patented, proprietary process to serve as a clean, dry, efficient, low cost metalization process for large scale use in manufacture of microelectronics packaging and interconnect products. Electroplating processes are now used extensively in industry to deposit metal conductors in a number of electronics components. It is widely recognized that electroplating process waste is a major contributor to ground water pollution nationwide. This proposed project addresses the compelling need for new environmentally benign metallizing processes to replace electroplating in electronics systems manufacturing.

7. *Fluxless, no-clean, solder processing of components, printed wiring boards, and packages,* MCNC Corp. Approx. $1.9M.
The objective of this effort is to eliminate the use of liquid chemicals during the soldering process for components, printed wiring boards, and electronic packages. Specific processes that will be addressed include the liquid fluxes used to chemically dissolve metal oxide prior to solder flow cleaning. This effort will result in less materials used that harm the environment, will require less energy, and reduce costs. This program will develop a scaled-up version of the Plasma Assisted Dry Solder (PADS) process and demonstrate this process in a high volume manufacturing capability on real products (existing production item). MCNC will define system design options capable of giving the throughput required. The program will qualify the process by evaluating the yield, throughput, cost and reliability of the product as compared to previous production items.

8. *"Green card": a biopolymer based and environmentally safe printed wiring board technology,* IBM Research Division. $1.6M
The objective of this effort is to utilize biopolymers and non-toxic metals to reduce environmental concerns in the fabrication, assembly, and disposal of PWBs, a key high-volume U.S. product, These materials will be used to develop a "green card" that is by design easier to reclaim and recycle, reduces dependence on oil-based resources, uses less energy to produce, and efficiently utilizes and reduces the current waste streams. The contractor intends to utilize a design for environment (DFE)/life cycle analysis (LCA) type system approach to: 1) Replace the current fossil fuel epoxy resins used in PWBs with renewable natural polymers derived from plant and wood products such as lignin,

cellulose, and crop oils. The majority of these natural products, while abundantly available, are currently either burned to recover fuel value or contribute to our waste stream. 2) Fabricate a PWB test vehicle to demonstrate feasibility of using these materials in the current manufacturing infrastructure and to verify the reliability of this green PWB.

9. ***Continuation of electronics industry environmental roadmap,*** MCC.
The purpose of this procurement action is to develop an industry-driven roadmap of pertinent actions to be taken to increase the environmental compliance of the United States electronics manufacturing industrial base. The contractor will lead a task force addressing eight sectors: integrated circuits, printed wiring boards, packaging and assembly, displays, electronics disposition, business, regulations and standards, and design for the environment. Each of these sectors is to be addressed by a task group composed of industry, university, consortia and/or industry association team members toward the goal of updating, coordinating, analyzing and disseminating the December 1994 edition of the roadmap published under prior contract.

Other current ARPA-funded Environmentally Conscious Electronic Systems Manufacturing projects include:

1. ***Reliability evaluation of alternatives to ozone depleting substances in DoD manufacturing, including alternative cleaning materials and fluxes for circuit assembly,*** Georgia Tech, Army-MICOM, Air Force - Rome Laboratory, Navy - NAWC, NASA-Goddard, 24 months, $2.24M.

2. ***Liquified metal jet technology: alternative printed wiring board manufacturing process,*** Texas Instruments, University of Texas at Arlington, 24 months, $1.21M.

3. ***Electrolytic metal recovery unit for elimination of toxic sludge in printed circuit board production,*** Faraday Technology, Inc., Case Western Reserve University, NSWC Crane Division, 24 months, $1.55M.

4. ***Elimination of ozone depleting chemicals: an innovative no-clean process for assembly of military surface-mount circuit cards,*** General Electric, Martin Marietta, SUNY Binghamton, Alpha Metals, 24 months, $1,36M.

5. ***On demand direct synthesis of silane,*** University of Illinois, 24 months, $200K.

The Electronics Manufacturing Productivity Facility (EMPF) is a Navy sponsored center for research and education related to electronics manufacturing. Information on their programs can be found in the WWW home page (http://www.engr.iupui.edu/empf/). Their current research projects include:

1. ***Electronics Manufacturing for the Environment.***
This project will develop and deploy knowledge of interactions among various environmentally-safe materials and process technologies, in terms of cost, quality, reliability, and schedule impacts of implementation. Processes and materials such as low-residue fluxes/pastes, alternative board and component finishes, low VOC fluxes/pastes, low VOC conformal coatings, lead-free solders, conductive adhesives, additive board manufacturing, and fluxless soldering will be examined. The EMPF will also coordinate with current efforts underway by other agencies to develop and demonstrate effective, easy-to use life-cycle assessment tools that can be used by designers and manufacturers to document hazardous material usage and waste generation, and identify pollution prevention opportunities. More details on the individual projects can be found on the Internet (gopher://gopher.pnl.gov:2070/l/.pprc). Primary research contacts: John Greaves (3 17) 226-5665, Tim Crawford (3 17) 226-5634.

2. ***CFC Alternative Testing.***
The EMPF is participating in a joint effort with EPA and the Institute for Interconnecting and Packaging Electronic Circuits (IPC) to find alternatives to chlorofluorocarbons (DFCs) used in electronics manufacturing. Phase 1 of this project characterized the cleaning ability of a CFC-based solvent and established the cleanliness results as a benchmark to which alternative candidates would be compared. Phase 2 includes testing CFC alternatives to certify their cleaning effectiveness. As of 12/94, a total of 23 CFC alternative processes have been tested, with a total of 18 processes commercially available. The testing is continuing. Research contacts: Eric Higbie (317) 231-2027, Tim Crawford (317) 226-5634.

3. ***Materials Compatibility.***
In support of the Navy's efforts to eliminate ozone depleting materials from electronics manufacturing and repair/rework, EMPF is performing materials compatibility tests between six CFC alternative cleaning solvents and 123 common polychlorinated biphenyl (PCB) materials. Research contacts: Scott Gilber (317) 231-2022, Tim Crawford (317) 226-5634.

4. ***Residue Analysis.***
This effort is focusing on the AC electrical impedance spectra effects and the corrosion and reliability concerns with residues from water soluble, rosin-based, and no-clean fluxes. The primary focus of this research is to establish relationships between the electrical impedance measurements of flux residues and the corrosive mechanisms they contain. From these relationships, process controls could be in place to quantify these residues and predict their behavior over time as it relates to operational life and reliability of electronic assemblies. The ultimate goal is to establish tools that can be used to control and understand residues from manufacturing processes. These tools will detect slight changes in the residue and be capable of predicting the potential effect on reliability. Research contact: Mike Fredrickson (317) 226-5603.

5. ***Low Residue (No-Clean) Processes***

This is a four-part program to help ease implementation for manufacturers who have chosen, or are considering, the "no-clean" option as an alternative to using CFC cleaning solvents. The program will educate potential users by identifying critical process modifications that need to be considered when using this technology. The areas addressed are hand soldering techniques, component and board solderability testing techniques and acceptance criteria, and issues concerning large project attachment to PWBs. Research contact: Tim Crawford (3 17) 226-5634.

6. ***Conductive Polymer Manufacturing.***

This project will leverage experts within the industry to create processes, methodologies, and implement a product conversion using polymer technologies. It will also attempt to create an understanding of polymer manufacturing technologies within the military and high-reliability commercial manufacturing industry to ensure successful implementation. Specifically, the objectives of this project are to 1) develop and demonstrate polymer circuit manufacturing processes that enable rapid, adaptive, and environmentally safe manufacturing capability for the electronics industry; 2) successfully transfer this process technology to specific product(s) in the military and high reliability commercial industry; and 3) develop an infrastructure that enables the successful implementation of polymers in the circuit card manufacturing industry. Research contacts: Mike Fredrickson (317) 226-5603, John Guy (317) 226-5630.

The Department of Defense has an overall pollution prevention policy to "effectively promote the national policy of pollution prevention through education, training and awareness, acquisition practices, facilities management, energy conservation, and the use of innovative pollution prevention technologies. The goals of this policy include specific numeric targets for reduction of toxic chemicals. Among the DoD projects are the following (more information can be obtained from the WWW Enviroene):

- The National Defense Center for Environmental Excellence (NDCEE).
- Hazardous Substance Management System (HSMS).
- Hazardous Technical Information Services (HTIS).
- National Aerospace Standard 411, "Hazardous Materials Management Program."
- Pollution Prevention Pillar to reduce and eventually eliminate hazardous waste streams, including wastes from DoD production, depot and test options.

3.4. Other Government Research

Environmental research and technology transfer is provided by many agencies within the federal government, in addition to EPA and ARPA discussed above. Programs include:

1. The National Institute of Standards and Technology (NIST) has an Electronics and Electrical Engineering Laboratory, as well the Manufacturing Extension Partnerships (MEP) Manufacturing Extension Centers. There is a pollution prevention center in Santa Monica, CA. NIST MEP contact: Brian Sweeney (301) 975-3591.

2. The Strategic Environmental Research and Development Program (SERDP) is a Department of Defense(DoD) led initiative in partnership with the Department of Energy (DOE) and EPA. SERDP objectives include the promotion of maximum exchange of information and the minimization of duplication regarding environmentally related research, development and demonstration activities. Pollution prevention is one of six major thrust areas. Information can be found on the WEB (http://prop.wes.army.mil:8O/serdp/home.html).

   SERDP is funding the Enviroene WWW development, with work being performed by the Idaho National Energy Laboratory (INEL) and RTI. Enviroene (http://wastenot.inel.gov/envirosense) provides access to the Solvent Alternatives Guide (SAGE), the Hazardous Solvent Substitution Data System (HSSDS), DoD's Pollution Prevention Technical Library, the Solvent Handbook Database System (SHDS), and the National Center for Manufacturing Sciences' (NCMS) databases for solvent alternatives and materials compatibility. There is also information on federal, state, and local pollution prevention programs as well as small business assistance programs. Contacts: Myles Morse, EPA (202) 260-3 161; Greg Ondich, EPA (202) 260-5753; Kevin Twitchell, Enviroene (INEL) (208) 526-6956.

3. The Department of Energy research includes a project with Thomson Consumer Electronics, Inc. to study electrophotographic screening, 24 months, $lM. Current picture tube production processes employ many steps ranging from heat drying to phospher reclamation. A newly patented process of electrophotographic screening (EPS) will eliminate the majority of these steps resulting in a reduction of energy consumption and hazardous waste by-products. EPS involves putting on and taking off phosphor from picture tubes. The Marion, Ohio plant of Thomson Consumer Electronics will design, build, and install a prototype EPS process, develop and debug the process, evaluate manufacturing capability and transfer to fullscale production. The ultimate goal will be to produce 13,100 units per day with a savings of $0.20 per unit in energy cost. Contacts: Randy Strutz, Thomson Consumer Electronics (317) 662-5375; Eric Hass, (MATEC) U.S. DOE (303) 275-4728.

4. The Federal government uses it's extensive buying power to promote pollution prevention and conservation efforts. Executive orders currently in effect include:

- Executive Order 12902, Energy Efficiency and Water Conservation at Federal Facilities (March 8, 1994).
- Executive Order 12856, Federal Compliance with Right-to-Know Laws and Pollution Prevention Requirement (August 3, 1993).
- Executive Order 12845, Requiring Agencies to Purchase Energy-Efficient Computer Equipment (April 21, 1993).
- Executive Order 12844, Federal Use of Alternatively Fueled Vehicles (April 21, 1993).
- Executive Order 12843, Procurement Requirements and Policies for Federal Agencies for Ozone-Depleting Substances (April 21, 1995).
- Executive Order 12780, Federal Agency Recycling and the Council on Federal Recycling and Procurement Policy (October 31, 1991).
- Executive Order 12759, Federal Energy Management (April 17,1991).

3.5 University Research

1. University of Arizona, ***Recycle and Waste Minimization in Ultra-Pure Water Systems,*** Dr. Farhang Shadman, sponsored by SEMATECH/SRC. Contact: Dan Herr, SRC (919) 541-9400.

2. Stanford University, ***Strategies for Optimizing Deionized Water Use in Semiconductor Manufacturing,*** Dr. C.R. Helms, sponsored by SEMATECH/SRC. Contact: Dan Herr, SRC (919) 541-9400.

3. North Carolina State University, ***Environmental Sensing and Simulation in Silane-based Silicon and Silicon Dioxide Chemical Vapor Deposition,*** Dr. Gary Rubloff, sponsored by SEMATECH/SRC. Contact: Dan Herr, SRC (919) 541-9400.

4. The University of Dayton Research Institute, ***Reduction of Arsenic Wastes in the Semiconductor Industry,*** sponsored by EPA's National Risk Management Research Lab (formerly Risk Reduction Engineering Laboratory), 24 months, $300,000.
The project will evaluate technologies for the reduction of arsenic waste generation in the semiconductor industry. The processes of interest include capture of waste arsenic-

bearing growth media (arsine gases or organoarsines), degradation of the captured wastes to recover metallic arsenic for reuse in the process, and the purification of semiconductor solid wastes for reuse. The project experiments will be conducted on the laboratory scale. Contact: Paul Randall, EPA (513) 569-7673.

5. University of California at Los Angeles (UCLA), ***Mercury Life Cycles and Pollution Prevention,*** sponsored by EPA's National Risk Management Research Lab (formerly Risk Reduction Engineering Laboratory), 36 months, $300,000.
This project will study ways to minimize mercury process wastes in fabrication of mercury cadmium telluride optoelectronic devices to improve the efficiency of mercury utilization in the electronics materials industry. Computer modeling will lead to both laboratory and pilot-scale tests being conducted at a University-based research facility. Contact Paul Randall, EPA (513) 569-7673.

6. UCLA's Center for Clean Technology has numerous pollution prevention projects. One specifically targeted to microelectronics is for chemical vapor deposition. Current research is focusing on developing and integrating two reactor flow models with a kinetic model and on constructing a prototype industrial scale reactor that reduces mercury waste per unit product by more than an order of magnitude.

7. Carnegie Mellon has ongoing research in environmental design (not exclusively for electronics) related to green product design, green process design, green chemistry, policy analysis, recycling, risk assessment and communication, management, and sustainable development. Green design projects are multidisciplinary and involve researchers from the Engineering, Science, Design, and Public Policy schools of the university.

3.6 Other Organizations

1. The National Pollution Prevention Roundtable has a voting membership of state and local pollution prevention programs. Affiliate members include federal agencies, non-profit groups, and private sector interests. The Roundtable programs provide information and technical assistance on pollution prevention. An Internet list server (mail-type news group) is available where people can request specific information and immediately receive responses from the various state and local programs, as well as others. The Roundtable also has the WWW Yellow Pages, a directory of state and local pollution prevention programs, which can be accessed through Enviroene. The Roundtable phone number is (202) 543-P2P2.

2. The Pacific Northwest Pollution Prevention Research Center is a non-profit organization which serves as a regional communication link between government, industry, and public interest groups. Among their activities are a database of research projects available on the

Internet (gopher://gopher.pnl.gov:2070/l/.pprc), a pollution prevention newsletter and other reports, and hosting seminars and roundtables. Contact: (206) 223-1151.

3. National Center for Manufacturing Sciences, ***Development of Alternatives to Lead Based Solders,*** 48 months.
The goal of the project is the development and implementation of a lead free solder alloy that can satisfy the demands of the electronic industry including: identifying candidates which will meet performance requirements at -55 ^{o}C to 280 ^{o}C operating temperatures, evaluating candidates in a laboratory environment to identify potential candidates for final selection, validating final selection with environmental stress screening and reliability testing, determining economic and availability impacts of new alloys, and releasing a manufacturing process which is compatible with existing manufacturing equipment.
Contact: Clare Vinton (3 13) 955-0300.

4. Information on industry pollution programs can be found in company environmental reports, in ***The Proceedings of the IEEE International Symposium of Electronics and the Environment*** (1993-1995), in ***Pollution Prevention Magazine,*** and on the WEB (see Table 1). The bibliography in Appendix E contains articles from several electronics and semiconductor companies, including AT&T, Digital Equipment Company, Hewlett-Packard, IBM, Motorola, Northern Telecom, Phillips Semiconductors, Texas Instruments, and Xerox.

4.0 Discussion of Current Research and Needs

The general areas identified in the ESH chapter of ***The National Technology Roadmap for Semiconductors*** (designated by SIA/SEMATECH Roadmap) were used to group research and needs. The areas listed in Tables 2-8 represent the thrust areas in the roadmap:

- design & test
- factory integration
- interconnect
- lithography
- materials & bulk processes
- assembly & packaging
- process integration, devices, & structures, and
- environmental, safety and health.

Reuse and recycle needs have been included along with the strictly pollution prevention needs. Priorities given come from SIA/SEMATECH Roadmap. Standards and information were separated because there was considerable discussion at the workshop on these issues.

Table 2. Hazardous Chemical Use Reduction Research Needs

Item	Comments	Identified in Roadmap	Discussed in Workshop
Develop additive processes/technologies for interconnect, lithography, materials & bulk processes, and process integration, devices, & structures.	High priority research need.	X	X
Use aqueous-based lithography systems.		X	X
Reduce solvent use in lithography processing & mask making, as well as assembly & packaging.		X	X
Reduce chemical hazards through improved controls, warning systems, and material compatibility in factory integration.		X	
Reprocess chemicals for factory integration and interconnect.		X	X
Optimize etch processes to minimize chemical wastes in interconnect.		X	X
Reduce use of PFC's in interconnect.	SEMATECH research.	X	X
Reduce use of heavy metals in lithography mask making.		X	
Extend chemical use life for materials & bulk processes.		X	X
Use no-clean technologies for materials & bulk processes.		X	X
Use dilute chemistries for materials & bulk processes.		X	X
Seek safe alternatives to hydrides in materials & bulk processes.		X	X
Use cyanide-free plating for assembly & packaging.		X	X
Use lead-free solder systems for assembly & packaging.	Secondary priority research need. On-going research.	X	X
Use thermoplastics for assembly & packaging.		X	X
Use nontoxic flame retardants for assembly & packaging.		X	
Reduce organics in binders for assembly & packaging.		X	
Research in and information about alternative cleaning processes.	High priority research need.	X	X
Plastics/packaging.	Dan Rose & Assoc, IPC. DoD/DOE as end user		X

Table 3. Energy and Water Use Reduction Research Needs

Item	Comments	Identified in Roadmap	Discussed in Workshop
Tool suppliers reduce energy, water, ventilation use.		X	X
Design for low power consumption.	Ongoing research.	X	
Recycle water, research to include online monitoring for organics, speciation, and removing surfactants.	SEMATECH/SRC project with Univ. of Arizona	X	X

Table 4. Emission Reduction Research Needs

Item	Comment	Identified in Roadmap	Discussed in Workshop
Develop abatement technologies where needed.		X	X
Reduce emissions of perfluoro compounds for interconnect.	SEMATECH and EPA have current work.	X	X
Reduce solvent emissions for lithography, materials & bulk processes, and process integration, devices & structures.	Secondary priority research need.	X	X
Abatement technologies (point of use).			X
Process optimization (geometries) supplier design issue.	Industry addressing.		X

Table 5. Tool and Factory Mass Balance Research Needs

Item	Comments	Identified in Roadmap	Discussed in Workshop
Characterize by-products of the processes.	High priority development need.	X	X
Implement mass balance on all tools.	High priority development need.	X	X
Plasma process.	Sandia research.		X
Dilution and concentration of emissions.	Political issues, but also need better mass measurements for gases.		X
Need for better sensors - online, quick response, multi-components.			X

Table 6. Cost of Ownership/Risk Reduction Research Needs

Item	Comments	Identified in Roadmap	Discussed in Workshop
Develop ESH cost of ownership model, then use to select chemicals for all processes.	Local or global? Need more information for environmental tradeoffs.	X	X
Develop risk assessment methodology and complete risk assessment ranking of all chemicals. Carri Model. Concerns about actual versus perceived risks, plus need to educate public on what risks mean.	SEMATECH research. Secondary priority development need.	X	X
Need for "Environmental Advisor" software tool, based on earlier tools to aid in process design.			X
DPE into commercial and research tools.	SEMATECH research.		X
Include EPA in discussion of risk assessment and environmental costing.			X

Table 7. Standards and Information Research Needs

Item	Comments	Identified in Roadmap	Discussed in Workshop
Need for better information on international standards.			X
Need for more standards for information and equipment.	EPA Region 9 and SEMI are looking at standards issues.		X
Need for more information to and from suppliers.			X
Need to continue SEMATECH test method development and various testing programs.			X
Need to continue development of SEMI standards for fluids, equipment, & test methods.			X
Need uniformity of information.			X

Table 8. Cross Cutting Technology and Other Issues

Item	Comments	Identified in Roadmap	Discussed in Workshop
Need to transfer technology from semiconductor manufacturing to flat panels, MCM and MIMs.	United States Display Consortium (USDC).		X
Sensors and better metrology are needed for many of the items listed above.	Current research, more needed. Economic issues, including size of market and cost of development.		X
Demonstration projects for next generation technology are needed.			X
Continue EPA and industry dialogue on various issues.			X

5.0 Potential Areas for Joint Federal and Private Sector Research

The following were listed as possible areas where EPA might work with SEMATECH and industry. The listing order does not indicate priority and there was not a specific recommendation that EPA pursue any specific area.

1. Cost of ownership and risk assessment (EPA contacts: Paul Shapiro- research; John Bowser - policy).

2. Photoresist (aqueous) - need funding, could include both SRC and EPA.

3. Cyanide-free plating.

4. Dilution/concentration of emissions (see Table 5) - a single facility pilot (John Bowser will take to CSI).

5. Sensors (work ongoing at Sandia, U of Michigan, etc.).

6. Demonstrations of new technology.

7. Provide technology transfer information, possibly similar to current EPA information already on Internet and available from bulletin boards. This could include solvent usage, alternative cleaning, electronic abatement, combustion technology for PFCs, etc.

In addition, there are areas where there is current work in progress, but participants felt that more research is needed:

8. Perfluorinated compounds, especially abatement.

9. Standards (see Table 7). No specific area was targeted.

6.0 Conclusions and Follow-up

A workshop was held to discuss possible EPA involvement in pollution prevention and research activities related to the semiconductor and electronics industries and their suppliers, based on the current industry roadmaps. Lists of current research and needs were developed, including projects which might benefit from EPA involvement. The needs included:

- Better environmental information and access to that information, especially for small suppliers.

- Emphasis on manufacturing efficiency, thus reducing waste and costs.

- Ensuring that emerging technologies benefit from existing environmental research.

- Continued focus on pollution prevention and other voluntary programs, rather than regulatory approaches.

- Awareness of need for conformity and/or compliance with international environmental standards for improved documentation of company environmental management systems.

Further discussions are planned between industry and EPA to extend the database of existing R&D projects, to further identify and clarify R&D gaps, and to identify and implement collaborative research and funding opportunities.

A draft of this report was sent to all participants, and suggestions were incorporated into this final version. A copy of this final report will be sent to EPA, all attendees, and to others interested in the meeting. The report includes research needs addressed in the roadmaps and suggested by the individuals attending the workshop. The research needs listed are not intended to represent the opinions of the semiconductor and electronics industries, their suppliers or trade associations, and it should be understood also that it was not possible in one workshop to include representatives from all segments of the industries.

There has been interest in further discussion. Workshop participants suggested the following upcoming industry meetings as possible venues for further meetings:

- SEMICON/West 95, July 11-13, San Francisco, CA

- SEMICON/Southwest 95, October 24-25, Austin, TX

- SIA/SEMATECH Roadmap ESH Meeting, late 1995, Austin TX.

For questions, comments, and suggestions for future discussions, as well as interest in participating in them, please contact Ms. Debbie Franke, RTI (919) 541-6826, FAX (919) 541-6936. A followup report will be generated if enough additional information is forthcoming.

Appendix A. List of Attendees

Dr. Jesse Baskir
Research Triangle Institute
PO Box 12194
Research Triangle Park, NC 27709
Tel - (919) 541-5882
Fax - (919) 541-7155
EMAIL-jbaskir@rti.org

Ms. Lisa Bergson
MEECO, Inc.
250 Titus Avenue
Warrington, PA 18976-2426
Tel - (2 15) 343-6600
Fax - (215) 343-4194

Ms. Laurie Beu
Motorola
3501 Ed Bluestein Blvd, MD KlO
Austin, TX 78721
Tel - (512) 933-5457
Fax - (5 12) 933-6962

Ms. Aimee Bordeaux
SEMI
805 East Middlefield Road
Mountain View, CA 94043
Tel - (415) 940-6939
Fax - (415) 940-7943

Mr. John Bowser
US EPA, MS 7405
401 M Street SW
Washington, DC 20460
Tel - 202-260- 1771
Fax - 202-260- 1096

Ms. Lorraine G. Clark
Florida Dept. of Environmental Protection, Small Business Assistance Prg.
2600 Blair Stone Road, MS 5505
Tallahassee, FL 32399
Tel - (904) 4881344
Fax - (904) 922-6979

Mr. Charles Darvin
U.S. Environmental Protection Agency
MD91
Research Triangle Park, NC 27711
Tel - 919-541-7633
Fax - 919-541-0361

Ms. Deborah Franke
Research Triangle Institute
PO Box 12194
Research Triangle Park, NC 27709
Tel - (919) 541-6826
Fax - (919) 541-6936
EMAIL-dlf@rti.org

Ms. Patricia O'Hara
Environmental and Occupational Risk Management, Inc. (EORM)
2460 N. First Street, Suite 280
San Jose, CA 95131
Tel - (408) 321-2850
Fax - (408) 436-l136
EMAIL-oharap@eorm.com

Mr. Steve Pedersen
Microelectronics and Computer Technology Corporation
3500 West Balcones Center Dr.
Austin, Texas 78759-5398
Tel - (512) 338-3245

Mr. Lawrence Rhyne
Phenix Semicron Corporation
P.O. Box 55
Prospect Hill, NC 27314
Tel - (910) 599-5555
Fax - (910) 597-3039

Mr. Herbert M. Richardson
Ashland Chemical Company
5200 Blazer Parkway
Dublin, OH 43017
Tel - (614) 790-4551
Fax - (614) 790-4213

Mr. Paul Shapiro
Office of Research and Development, MC 8301,
U.S. Environmental Protection Agency
401 M Street, SW
Washington, DC 20460
Tel - 202 260-4969
Fax - 202 260-4524

Mr. John Shoaff
US EPA, MS 7409
401 M Street SW
Washington, DC 20460
Tel - 202-260- 1831
Fax - 202-260-0178

Mr. Tom Strahl
UT1 Instruments
2030-C Fortune Drive
San Jose, CA 95131
Tel - (408) 428-9400
Fax - (408) 428-0823

Mr. Troy Strouth
U.S. Air Force Mantech
WL/MTCM Bldg 653,2977 P St. Ste 6
WPAFB, OH 45433-7739
Tel - (5 13) 255-2461
Fax - (5 13) 476-4420

Mr. Patrick Taylor
Praxair, Inc
175 East Park Drive, PO Box 44
Tonawanda, NY 1415l-0044
Tel - (716) 879-7004
Fax - (716) 879-7192

Ms. Alice Tome
Abt Associates
4800 Montgomery Lane
Bethesda, MD 20814
Tel - (301) 913-0552
Fax - (301) 652-7530

Ms. Colleen Wilson
Microelectronics and Computer Technology Corporation
3500 West Balcones Center Dr.
Austin, Texas 78759-5398
Tel - 512 338-3391
Fax - 512 338-3814
EMAIL-cwilson@mcc.com

Ms. Lisa Wisser
Environmental and Occupational Risk Management, Inc. (EORM)
2460 N. First Street, Suite 280
San Jose, CA 95131
Tel - (408) 321-2850
Fax - (408) 436-l136
EMAIL-wisserl@eorm.com

Dr. Walter Worth
SEMATECH
2706 Montopolis Drive
Austin, TX 78741
Tel - (512) 356-7199
Fax - (512) 356-3189

Appendix B. Agenda

Registration and continental breakfast	8:00 a.m.
Welcome from EPA - Paul Shapiro, U.S. EPA	**8:30** a.m.
Introductions - Debbie Franke, RTI	**8:45** a.m.
SIA/SEMATECH roadmap and research - Dr. Walter Worth, SEMATECH	**9:00** a.m.
Roadmap ESH areas of interest: tool and factory mass balance, cost of ownership/risk assessment, hazardous chemical use reduction, emissions reduction, energy/water reduction, worker protection/ergonomics	
Current research	
Future roadmap and research activities	
Current EPA research agenda - Paul Shapiro, U.S. EPA	**9:30** a.m.
Coffee Break	10:00 a.m.
Discussion - Jesse Baskir, RTI	l0:15 a.m.
Develop list of current projects	
Other electronic industry roadmap efforts	
Other ongoing or planned research (private and government)	
Identify pollution prevention needs	
Research needs of industry and suppliers	
Technology transfer, testing, standards, and other issues	
Working lunch	12:00 noon
Discussion and wrap-up - Jesse Baskir, RTI	1:00 p.m.
Develop a joint government and industry funding strategy	
Roles of government, industry, and consortia in research funding	
What else is needed - meetings, timeline, etc.?	
Close - Debbie Franke, RTI	**3:00** p.m.

Sponsored by U.S. EPA and SEMI/SEMATECH, Coordinated by the Research Triangle Institute

Workshop on Pollution Prevention Research Needs for the Semiconductor and Electronic Industries
Issues

Basic issue: How can the industry and its suppliers increase the use pollution prevention to reduce hazardous chemical usage and emissions (beyond compliance) and also reduce energy and water usage while improving worker safety and reducing cost?

Goals of meeting:

1. Develop a list of current pollution prevention research, development, demonstration projects, and technology transfer projects related to the industry roadmaps.
2. Identify pollution prevention research needs to fill the gaps in item 1.
3. Develop a joint government and industry funding strategy for the agenda of activities in item 2.

Preliminary questions for thought:

Industry-wide (Please bring any materials to the meeting so we can include them in the report):

1. Who is doing pollution prevention research to meet the needs addressed in the roadmaps? What is being done?
2. What additional pollution prevention research (or development, demonstration projects, technology transfer) activities are underway by private industry, consortia, or government?
3. What government agencies are funding pollution prevention-related research? Who are the contacts for these projects ? Which funding mechanisms are currently working (or not working), and are these relevant for the future? What should the relative roles of government and industry be to fund future research?
4. How do we develop a realistic industry/consortia/government pollution prevention strategy? If we need more meetings, who should sponsor the meetings, who should attend? What should the timeline be? What order of magnitude funding is needed?

Company Related:

5. What are the top pollution prevention priorities of your company? What additional research (or development, demonstration projects, technology transfer) would help to address these priorities?
6. Does your company use the chemicals on the Roadmap list? Does it build equipment that requires the use of these chemicals? What other chemicals should be discussed?
7. How do the roadmap potential solutions affect your company? What research are you doing in these areas?
8. Do you have hazardous chemicals, emissions, energy or water reduction issues that are not addressed in the roadmaps? What additional research is needed on these problems?
9. What testing methods or standards are needed to promote pollution prevention?
10. Are you using the Internet or World Wide Web to access pollution prevention information specific to the semiconductor and electronics industries? What access methods are you using? Which existing private and government technology transfer programs and methods are you using?
11. Is your company using solvents for cleaning? Have you taken advantage of more environmentally safe replacements? What additional research or information is needed?

EPA FOCUS GROUP MEETING

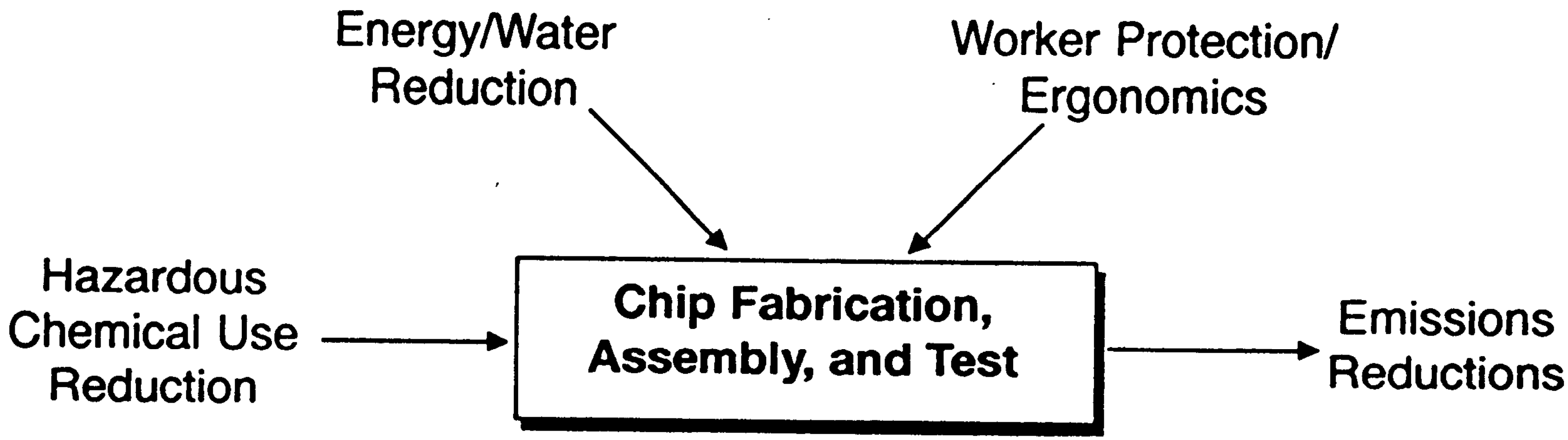
POLLUTION PREVENTION FOR SMALL ELECTRONICS COMPANIES

HYATT REGENCY HOTEL
ORLANDO, FLORIDA
MAY 4, 1995

SEMATECH ESH PROJECTS

Walter Worth
512/356-7199

SEMATECH



Design for ESH Tools:

- Chemical, Energy, and Water Mass Balance
- Cost of Ownership
- Risk Assessment

Industry ESH Roadmap

		1995. 0.35μm	1998 0.25μm	2001 0.18μm	2004 0.13μm	2007 0.10μm	2010 0.07μm
		Design for Environment, Safety and Health					
	ESH Community Ownership → Factory/Supplier Ownership						
	Mostly End-of-Pipe Hazardous Chemical Emissions Abatement → Use Reduction						
	Tool and factory Mass Balance	***Develop mass balance to allow for identification of risks and improvements in process, tool and factory design.***					
1	Models available	On key tools	On all tools and factories →				
2	By-products analysis	On key etch and CVD tools	On all tools	Incorporate DFESH tools into development/packaging/process/tool/facility →			
3	Mass Balance	Tool suppliers provide data	On-line reporting and analysis	Incorporate DFESH tools into development/packaging/process/tool/facility →			
	Cost of Ownership	***Use cost model to drive toward low-cost process, tool, factory, DFESH solutions.***					
4	Cost/m^2 of Si processed	Model completed	Model applied to chemicals	Energy/water use: Incorporate DFESH tools into development/packaging/ process/tool/facility	Full Cost accounting		
	Risk Assessment	***Provide for systematic, data-driven ESH decision making.***					
5	Relative Risk calculation	Chemical model completed	Chemical analysis completed	Incorporate DFESH tools into development/packaging/process/tool/facility →			

Industry ESH Roadmap

		1995. 0.35µm	1998 0.25µm	2001 0.18µm	2004 0.13µm	2007 0.10µm	2010 0.07µm
	Hazardous Chemical Use Reduction/m^2 Si	***Reduce use and waste at the point of use through process efficiency, reuse, substitution, additive technologies, etc.***					
6	Ozone Depleting Substance Use in Process	Total phase out →					
7	Targeted Ethylene Glycol Ethers	Total phase out →					
8	Chemical List A (Focused Use Reduction List)		Decrease 50% from 1988 use	Cyanide-free plating		Pb-free solder systems	Additive processes
9	Chemical List B (General Release Disposal List) Reduce/m^2 Si		No-clean technologies for packaging	< Reportable limits Or 50% of 1988 use	< Reportable limits or 25% or 1988 use		Additive processes
10	Chemical List C (Focused Air Emissions List) Reduce/m^2 Si			Reduce 50% from 1988 use or below permit triggers			Additive processes
11	Perfluoro Compounds			Source reduce to 1990 emission levels by 2000		Non-perfluoro compound available	
12	Hydrides	Safest practice implementation		Point -of-use generation		Safe alternatives available	
13	Plastics		Replace thermoset with thermoplastic packaging	Nontoxic flame retardants in packaging			

TABLE 13
Potential Solutions

Element Thrust	*Tool & Factory Mass Balance*	*Cost of Ownership*	*Risk Assess*	*Hazardous Chemical Use Reduction*	*Emissions Reduction*	*Energy/Water Reduction*	*Worker Protection/Ergonomics*
Design & Test	Incor. DFESH as part of design constraints. Dev. DFESH tools.					Design for low power consumption	
ESH	Char. by-products	Dev. ESH cost of ownership	Dev. risk assessment methodology		Dev. abatement technologies		Dev. real-time sensors for personal monitors. Improve SEMI S2 implementation
Factory Integration	Impl. CIM in situ chem. mass balance	Use chem. cost of ownership to select chems.	Complete risk assessment ranking of all chems.	Red. chem. use. Red. chem. hazards thru improved controls, warning systems, & material compatibility. Reprocess chem.	Dev. abatement technologies	Red. energy use. Recycle, reclaim water. Red. air requirements for cleanrooms.	Increase use of minienvironments. Decrease reliance on garments to prevent contamination. Dev. low pressure gas delivery systems Impl. automated wafer loading.
Interconnect	Impl. mass balance on all tools. Identify & compile all by-products data	Use chem. cost of ownership to select chem.	Complete risk assessment ranking of all chem.	Dev. additive processes. Optimize etch processes to min. chem. waste. Red. use of PFCs. Reprocess chem.	Red. emissions of PFCs	Tool suppliers reduce energy use/wafer	Improve equipment ergonomic design. Red. manual PM of equipment.

TABLE 13 CONTINUED
Potential Solutions

Element Thrust	*Tool & Factory Mass Balance*	*Cost of Ownership*	*Risk Assess*	*Hazardous Chemical Use Reduction*	*Emissions Reduction*	*Energy / Water Reduction*	*Worker Protection / Ergonomics*
Litho.	Impl. mass balance on all tools	Use chem. cost of ownership to select chem.	Complete risk assessment ranking of all chem.	Dev. additive technologies. Use aqueous-based litho systems. Red. solvent use in processing. Red. solvent & heavy metals use in mask making.	Red. solvent emissions		Red. manual PM of equipment. Eliminate odors. Improve equipment ergonomic design.
Materials & Bulk Processes	Impl. mass balance on all tools. Identify & compile all by-products data	Use chem. cost of ownership to select chem.	Complete risk assessment ranking of all chem.	Extend chem use life. Use no-clean technologies. Optimize processes. Seek safe alternatives to hydrides. Dev. additive processes.		Tool suppliers reduce energy use/wafer. Red. water usage thru optimization & recirculation.	Enclose all liquid-clean tools. Improve equipment ergonomic design.

FUTURE ESH RESEARCH NEEDS

Priority of Environment, Safety and Health Technology Needs

		High Priority	*Secondary Priority*
	0.18 µm/ 2001 Needs	Cost-effective, reliable, integrated, specific chemical sensors (D)	Low pressure gas system (R)(D)
BREAK THROUGH NEEDED-SHOW STOPPERS	0.13 µm/ 2004 Needs	Alternative cleaning processes (R)	
	0.10 µm/ 2007 Needs	Hydride alternatives (R)	Non-hazardous emission semiconductor manufacturing tool (R)
			Perfluoro compound alternatives (R)
INNOVATION NEEDS	0.07 µm/ 2010 Needs	Additive process technology (R)	Pb-free solder
CONCEPTS EXIST, BUT NEED TO BE PROVEN	0.35 µm/ 1995 Needs	Chemical mass balance and by-products (D)	Risk assessment (D)
	0.25 µm/ 1998 Needs	Integrated POU abatement at tool (D)	Cost equivalent ultrapure water recycle (D)
	0.13 µm/ 2004 Needs	Integration of DFESH into semiconductor product design (D)	Wafer cleaning without hazardous chemicals (D)

(R) Research *(D) Development*

Priority of Environment, Safety and Health Crosscut Technology Needs

	METROLOGY	*CONTAMINATION-FREE MANUFACTURING*
0.25 µm/ 1998 Needs	(1) Online realtime chemical monitoring (2) DI water recycle process control	(2) SEMI minienvironment ergonomic guideline
0.18 µm/ 2001 Needs		(1) ISO ESH standards compatibility. Reduced gowning requirements in cleanroom.
	MATERIALS	*MODELING /SIMULATION*
0.35 µm/ 1995 Needs		(1) Chemical, energy, and water mass balance (1) Risk assessment (1) CoO (2) Chemical use optimization
0.25 µm/ 1998 Needs	(4) Cyanide-free plating (3) Non-heavy-metal opaquing of masks	
0.18 µm/ 2001 Needs		(2) DFESH integrated with semiconductor design tools
0.10 µm/ 2007 Needs	(1) Hydride alternative (2) Pb-free solder	
	QUALITY AND RELIABILITY	*STANDARDS*
0.35 µm/ 1995 Needs		(2) SEMI ergonomic guideline
0.25 µm/ 1998 Needs	Validate ultrapure water and chemical quality specifications	(2) SEMI S2 certification process (1) ESH CoO (3) Maintain updated SEMI ESH guidelines consistent with technology development
0.18 µm/ 2001 Needs		(1) ISO ESH standards compatibility. Testing and analytical methodologies.
	TRAINING/EDUCATION	
0.35 µm/ 1995 Needs	Train semiconductor process development engineers and suppliers on DFESH	

AIR EMISSIONS AND MONITORING

PROGRAM OBJECTIVES

1. Determine the optimum design and operating parameters for water scrubbers to treat corrosive emissions.

2. Compare the Cost of Ownership and performance of VOC abatement technologies.

3. Evaluate and encourage emerging abatement technologies to treat.

4. Benchmark real-time process tool, exhaust stack and fence line emmission sensors.

Contact: Avtar Jassal (512) 356-3404 Eric Koehler (512) 356-3833

Emerging Technologies Under Consideration

- Biofiltration
- Photocatalytic Oxidation
- Non-Thermal Plasma
- Pulsed Power Corona
- Supercritical Water Oxidation
- Microwave Generation
- Membrane Separation

SEMATECH

RISK ASSESSMENT METHODOLOGY

PROJECT OBJECTIVES

Develop a design methodology for relative risk assessment of hazardous materials based on ESH considerations.

This tool will:

a. Evaluate the risk of process material alternatives for the semiconductor industry

b. Communicate risk decisions to users

c. Address management cost / benefit issues

Contact: Wes Lashbrook (512) 356-7117

SEMATECH

CHARACTERIZE PROCESS BY-PRODUCTS

PROJECT OBJECTIVES

1. Develop methodologies to collect by-products data and characterize air emission and waste by-products for identified priority processes

2. Provide understanding of reaction by-products in order to improve selection of proper personnel protective equipment, waste disposal options and appropriate treatment technologies

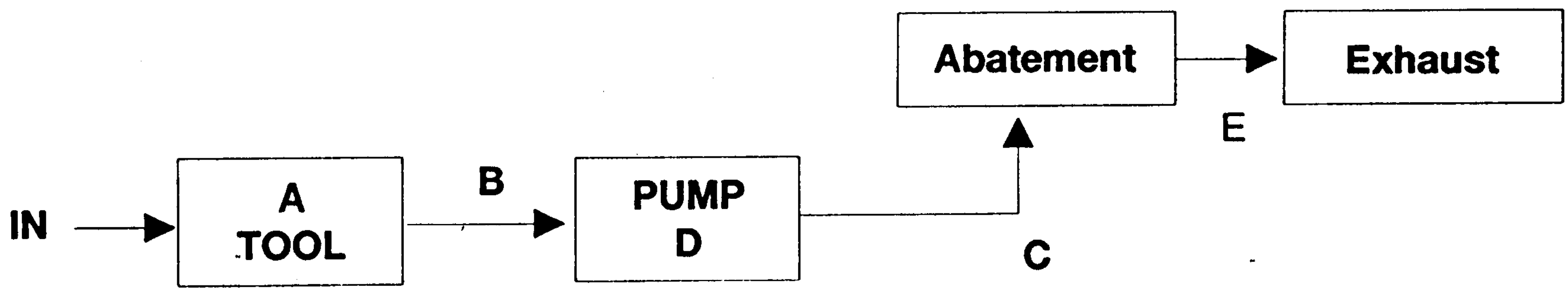
3. Provide template methodology for further process by-products characterization

4. Share results with other process databases to predict process by-products.

Contact: Albert Cheng (512) 356-3307

SEMATECH

CHARACTERIZE PROCESS BY-PRODUCTS
SAMPLING PLAN (TOOL)



Chamber		A	(chamber air and particulates during p.m.)
Pump	(Before)	B	(pump foreline)
	(After)	C	(pump exhaust)
	(Itself)	D	(pump fluid and residual particulates)
Exhaust	(Before)	E	(emission and waste)

SEMATECH

REDUCE GLOBAL WARMING GASES

PROJECT OBJECTIVES

Increase efficient use and decrease emissions of potential global warming semiconductor processing materials:

1. Baseline current semiconductor industry and supplier market data.

2. Develop efficiency and by-product test methods.

3. Work with suppliers to communicate issues and develop partnerships.

4. Demonstrate abatement equipment/alternatives.

Contact: Walter Worth (512) 356-7199

SEMATECH

Combustion Unit Evaluation Results

1. Destruction of PFCs >90%, except for CF_4 (<80%)
2. Fuel (H_2) and oxygen requirements are high
3. Produces NO_x by-products
4. Corrosive HF by-product requires treatment
5. N_2 pump purge a major barrier
6. High Cost of Ownership ($45K - IOOK/year)
   Fuel & wastewater treatment are major costs.

SEMATECH

DESIGN FOR ENVIRONMENT

PROJECT OBJECTIVES

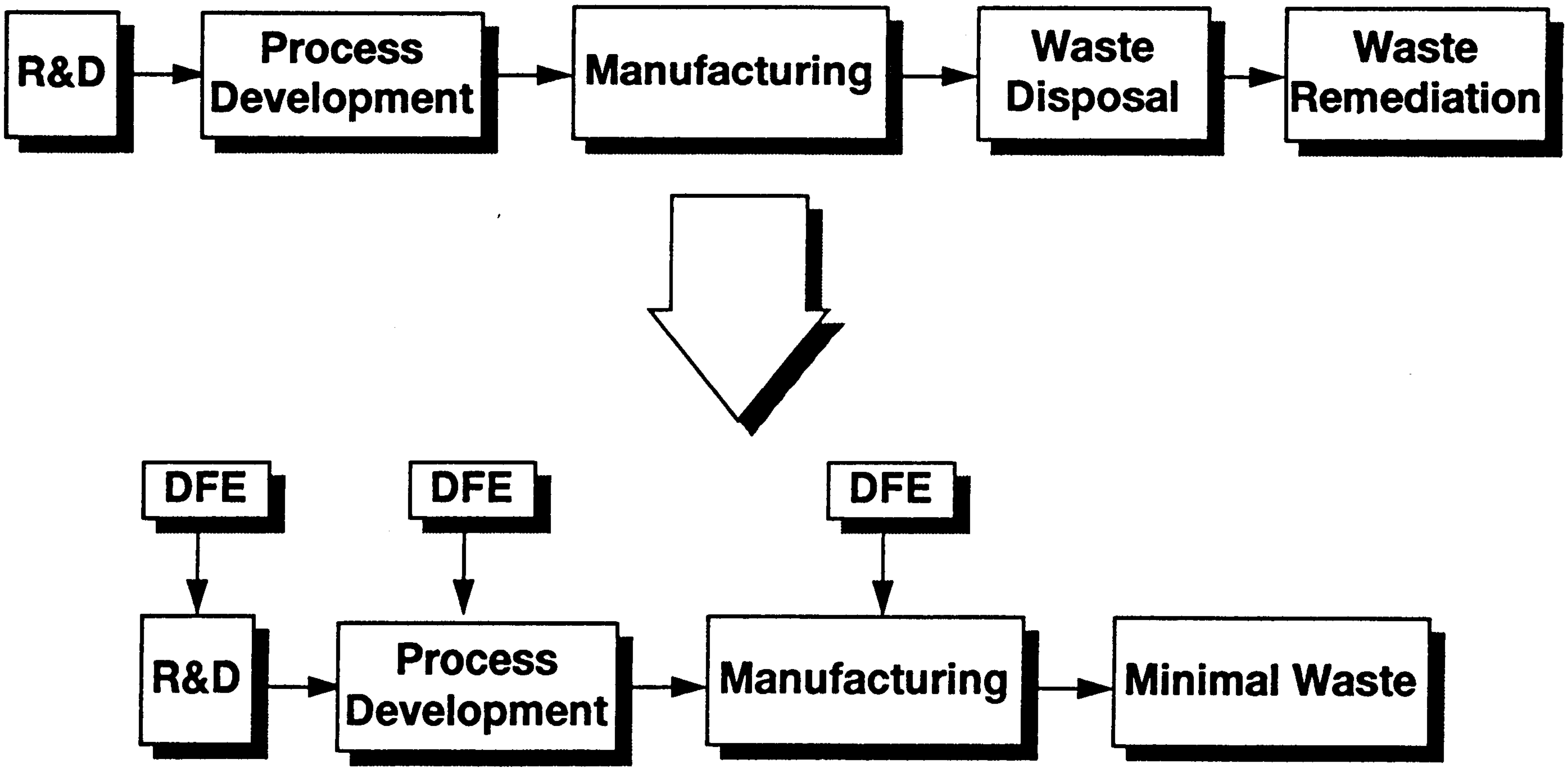
1. Determine the impact of semiconductor manufacturing on the environment
2. Prioritize areas of opportunity for minimization of impact
3. Incorporate those areas into process projects
4. Develop DFE guidelines for design, development and process engineering
5. Deliver DFE training course

Contact: Laura Mendicino (512) 356-3579 Wes Lashbrook (512) 356-7117

SEMATECH

DESIGN FOR ENVIRONMENT

PARADIGM SHIFT



SEMATECH

SILANE SAFETY IMPROVEMENT

PROJECT OBJECTIVES

1. Benchmark and disseminate best industry engineering control practices.
2. Assess risks associated with engineering control practices.
3. Identify possible silane alternatives.
4. Select, estimate cost, schedule and probability of successful development of a silane alternative.

Contact: Mike Visokey (512)356-348.2

SEMATECH

EXAMPLES OF OTHER PROJECTS WITH ESH OBJECTIVES

1. Replace wet chemical wafer cleaning processes with cryogenic aerosol cleaning (Ar or NJ.

2. Explore alternative, less hazardous chemicals for wafer polishing.

3. Improve utilization of etch gases through plasma modeling.

4. Develop point-of-use VOC abatement for photoresist coating operations.

5. Demonstrate advanced wet station to minimize DI water usage, reduced HF waste and chemical usage.

SEMATECH

EPA and Electronics - Initiatives and Research

Paul Shapiro

U.S. EPA Office of
Research and Development

THREE LEVELS OF CSI PARTICIPATION

- CSI Council

- Computers and Electronics FACA Subcommittee

\+ Work groups

CSI FOCUS **AREAS**

- Six areas for improvement:

  Regulation

  Reporting

  Compliance/enforcement

  Permitting

  Pollution prevention

  Environmental technology

EARLY CSI IMPRESSIONS

- Every sector is different.
- Electronics and Computers has different subsectors.
- Balance process and substance.

SMALL BUSINESSES
AT THE CSI TABLE

- Metal finishing
- Printing
- Electronics and computers

EPA AND THE ELECTRONICS AND COMPUTER INDUSTRY: A HISTORY OF WORKING TOGETHER

- CFC substitution
- DfE PWB project
- Some research
- Regional / State / local activities

a

ROLE OF RISK ASSESSMENT

- Identify and quantify risks.
- Identify cross-media trade-offs.
- Identify greatest risk reduction for the environmental management dollar.

NEW DIRECTIONS IN RISK ASSESSMENT

- Facility and process-specific.
- Simplified modeling.
- Multi-media.
- Life-cycle considerations.

POLLUTION PREVENTION AND COMPLIANCE

- More economical- to prevent.
- Provide technical assistance and training on P2 options.
- Link P2 options to risk reduction.

FEDERAL-PRIVATE SECTOR R&D PARTNERSHIP

- Identify R&D needs.
- Match existing R&D to the needs.
- Coordinate and target R&D.
- Verify and diffuse effective P2 technologies.

INDUSTRY PARTICIPATION

- ♦ Original equipment manufacturers
- ♦ Component manufacturers
- ♦ Suppliers
- ♦ End-users

IDENTIFYING P2 RESEARCH NEEDS

- Industry roadmaps are critical.
- Must include environmental performance measures.
- Address international standards (IS0 14000) and benchmarking.
- Industry workshops.

EPA ELECTRONICS R&D

- Approximately $1 million+ in projects.

- Proposed with industry to ETI.

- Participation in NSTC Electronics Subcommittee.

- Can manage ARPA and other agencies' environmental projects.

Appendix D. Pollution Prevention in the Semiconductor and Electronics Industries, A Selected Bibliography Including Related Topics

Research Triangle Institute

Anderson, S., F. Balkau, and C. Gurkok. (Motorola, United Nations), 1994. An Integrated Approach to MOS-Gated Power Semiconductor Manufacturing Based on Cleaner Production Technologies for Waste Minimization by Design. In *Proceedings of the IEEE International Symposium on Electronics and the Environment,* 230-240. San Francisco, May 1994.
MOS-gated power semiconductors are enabling technologies for "efficient end-use" power conversion systems. The use of these technologies for energy savings offers an environmental benefit of reduction in carbon dioxide emissions if the primary energy source is fossil fuel based. The manufacturing of these technologies using clean production processes by design is discussed.

Bailey, P. E. (ICF, Inc.), 1991. Life-Cycle Costing and Pollution Prevention. *Pollution Prevention Review* 1 (1): 27-39.
Life-cycle costing has been widely touted as an aid for exploring pollution prevention alternatives -- paper bags or plastic bags, disposable or reusable diapers, glass or plastic containers. This article explains life-cycle costing, its historical applications, its potential applicability to pollution prevention, and some of its limitations. Examples are given of recent applications of life-cycle costing to environmental issues.

Bast, C. (Hewlett-Packard), 1994. Hewlett-Packard's Approach to Creating a Life Cycle Program. In *Proceedings of the IEEE International Symposium on Electronics and the Environment,* 31- 36. San Francisco, May 1994.
Discussion of the past and current efforts at HP for product stewardship - the philosophy and practice of designing products and their associated accessories and processes to prevent and/or minimize adverse health, safety and ecological impacts throughout their life cycle.

Besnainou, J., and R. Coulon. (Ecobalance, Inc.), 1994. Life Cycle Assessment, An Analytical Tool for Designing Environmentally Sound Electric and Electronic Devices. In *Proceedings of the IEEE International Symposium on Electronics and the Environment,* 199-200. San Francisco, May 1994.
Discusses a LCA project to evaluate two switches, one with a nickel alloy contact and the other with a cadmium-based alloy. Study showed that the most polluting step of the switch life cycle was the use phase, not production.

Brinkley, A., J. R. Kirby, I. L. Wadehra et al. (IBM Corp., Ecobalance, Inc.), 1995. Life Cycle Inventory of PVC: Disposal Options for a PVC Monitor Housing. In *Proceedings of the IEEE International Symposium on Electronics and the Environment,* 145-15 1. Orlando, FL, May 1995.

Callahan, M. S. (Jacobs Engineering Group Inc.), 1994. A Life Cycle Inventory and Tradeoff Analysis: Vapor Degreasing Versus Aqueous Cleaning. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 215-219. San Francisco, May ***1994.***
The life cycle analysis and tradeoff analysis conducted in this study explores the impacts of vapor degreasing with 1,1,l Trichloroethane versus aqueous cleaning. To perform the assessment of tradeoffs, an impact analysis matrix was developed and employed. Results showed that impact comparisons made at the local or shop level cannot be extrapolated to predict impact on a global level. While vapor degreasers may use less energy than an aqueous cleaning system to operate, the production of chlorinated solvent is a major energy consumer which offsets any advantage.

Chen, R. W., D. Navin-Chandra, I. Nair et al. (AT&T, CMU, Stanford, IBM), 1995. ImSelection -- An Approach for Material Selection that Integrates Mechanical Design and Life Cycle Environmental Burden. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 68-74. Orlando, FL, May 1995.
This paper presents an approach and computer program for material selection which integrates the environmental life cycle impacts of materials into traditional engineering material selection process. This computer prototype can be used as a decision support tool for material selection with comprehensive consideration of material properties, manufacturing processes, costs, and environmental impacts of a material's life cycle. This integrated tool makes life cycle analysis more practical and easier for engineers and can help them select materials with considerations of environmental life cycle impacts in the design stages.

Ciocci, R. (University of Maryland), 1995. Evaluative Analysis of No-clean Soldering Technologies for Printed Wiring Boards and Assemblies. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 106-l 09. Orlando, FL, May 1995.
While no-clean technologies do reduce adverse environmental impact, their effect on product reliability must be considered. Manufacturers who choose to convert to no-clean materials and processes need assurance that product performance is not adversely affected. Environmental effect, manufacturing capability, and product reliability are all valid criteria for a materials and process selection method.

Darling, C. (Northern Telecom Ltd.), 1995. Do Firms Benefit from Electing a Voluntary Approach to Environmental Compliance In ***Proceedings of the IEEE International Symposium on Electronics and the Environment, 24-*** 28. Orlando, FL, May 1995.
How will the earth's resources support the rapid population growth and the economic demands for the future, given each of their growth rates? There is a serious concern for sustainability. Consequently, governments have been approaching business to decrease their demands on the environment, and some businesses are responding by taking the initiative to adopt voluntary environmental performance improvement activities. However, it would not

be accurate to suggest that participation is based on a genuine concern for the environment alone. Altruistic rationale cannot explain the degree of participation, or provide justification for the financial ramifications of participation. Firms are choosing voluntary compliance because there exists a good solid business case for doing so.

Dishart, K. T. (E.I. du Pont de Nemours & Company, Inc.), 1993. Environmental Advantages of the Semi-aqueous Cleaning Process. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 1 l-l 7. Arlington, VA, May 1993.
The semi-aqueous cleaning process offers, by design, significant ecological advantages over other cleaning alternatives. As formulations are improved and the process better understood, these advantages can be exploited to their maximum extent. This paper discusses recent formulation improvements in semi-aqueous cleaning agents and how these upgrades improve both the efficacy and ecology of the process. Also discussed are the implications of these formulation changes to equipment designs and process flow.

Doerr, W. W. 1993. Plan for the Future with Pollution Prevention. ***Chemical Engineering Progress 89*** (1): 26-29.

Drotning, W. (Sandia National Laboratory), 1994. Automated Cleaning of Electronic Components. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 62-65. San Francisco, May 1994.
Environmental and operator safety concerns are leading to the elimination of trichloroethylene and chlorofluorocarbon solvents in cleaning processes that remove rosin flux, organic and inorganic contamination, and particulates from electronic components. Present processes depend heavily on these solvents for manual spray cleaning of small components and subassemblies. Use of alternative solvent systems can lead to longer processing times and reduced quality. Automated spray cleaning can improve the quality of the cleaning process, thus enabling the productive use of environmentally conscious materials, while minimizing personnel exposure to hazardous materials. In addition, the use of robotic and automated systems can reduce the manual handling of parts that necessitates additional cleaning. We describe the development of a prototype robotic system for cleaning electronic components in a spray cleaning workcell. An important feature of the prototype system is the capability to generate the robot paths and motions automatically from the CAD models of the part to be cleaned, and to embed cleaning process knowledge into the automatically programmed operations.

Eagan, P., J. Koning, and W. Hoffman. (University of Wisconsin, Motorola), 1994. Developing an Environmental Education Program. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 41-44. San Francisco, May 1994.
Introducing new methods and design principles throughout large corporations is often difficult and can be time consuming. It is particularly challenging to incorporate new concepts or ideas into corporate culture. Motorola's corporate management however decided to do just that by using an educational vehicle to introduce environmental issues into the

company. Motorola approached the Department of Engineering Professional Development at the University of Wisconsin-Madison in the Spring of 1992 with an intriguing proposal: to develop two new environmental courses, in a very short time frame, for their employees. Thus, two special courses, to highlight environmental concerns, were developed jointly by the University and Motorola. This unique training approach was used by Motorola in 1993 to affect corporate culture. This paper describes the educational challenges of course design and course content.

Envirosphere Company and Hewlett Packard. 1988. ***The Reduction of Solvent Wastes in the Electronics Industry: Waste Reduction Grant Program.*** Prepared for the State of California Department of Health Services, 86-TOl lO.

Evans, K., T. Alcom, P. Hadizad et al. (Motorola), 1995. "Green" Process and Productivity Improvements in a GaAs Light Emitting Diode Wafer Fab. In IEEE International Symposium on Electronics & Environment, 253-258. Orlando, FL, May 1995.
A self directed process improvement team was initiated to streamline the GaAs light emitting diode (LED) wafer process flow and enhance product yields. "Green" benefits of this study to improve GaAs LED wafer processing yields included the elimination of a significant number of chemical processing steps. The new process is more environmentally "friendly" through the use of fewer and "milder" chemicals. Thus wafer production is enhanced with both a yield increase and a cost decrease due to lower levels of chemical usage.

Ferrone, R., and C. M. O'Brien. (Digital Equipment Corporation, U.S.EPA), 1993. Environmental Assessment of a Computer Workstation. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 43-48. Arlington, VA, May 1993.
This article provides an overview of the results of a six month study conducted by the computer and electronics industry to assess the life cycle environmental impacts of a computer workstation. The main body of the article summarizes what the authors believe to be the major findings and recommendations identified by the MCC study; the conclusion outlines areas where the authors know of existing work that will help implement some of recommendations.

Fiskel, J. (Decision Focus Inc.), 1993. Design for Environment: An Integrated Systems Approach. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 126- 131. Arlington, VA, May 1993.
Design for environment is motivated by the world-wide thrust of manufacturing industries towards enterprise integration and sustainable development. Effective implementation of design for environment requires the development of design metrics, guidelines, and verification methods. These must be deployed within an integrated system framework in order to provide useful guidance for decision-making during fast-cycle product development.

Fiskel, J., and K. Wapman. (Decision Focus Incorporated), 1994. How to Design for Environment and Minimize Life Cycle Cost. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 75-80. San Francisco, May 1994.

The scope of environmental issues relevant to new product development ranges from traditional health and safety issues to more contemporary concerns about resource conservation and sustainability. To practice eco-efficient design, companies need appropriate support tools that can help both to identify worthwhile design approaches and to decide upon the preferred approach. This paper describes how manufacturing firms can develop a Design for Environment toolkit, including on-line guidance for product developers and performance assessment capabilities for analysis of design trade-offs. Examples are given of a life-cycle approach to product and process design that considers cost and environmental benefits.

Foecke, T. L. (Minnesota Technical Assistance Program), 1988. Waste Minimization in the Electronics Products Industries. ***JAPCA 38 (3):*** 283-291.

An overview is provided of the production processes, waste generation, and waste management of the electronics products industries. Chosen product areas include electron tubes, semiconductors, capacitors/resistors, and printed circuit/wiring boards. Examples are given of specific processes and associated waste streams. Waste minimization activities are identified, and specific examples of successful applications provided. While faced with a wide variety of waste streams, many opportunities for waste minimization exist and await only application.

Franke, D. L., and K. R. Monroe. (Research Triangle Institute), 1995. Innovative Uses of Tools in the Design for the Environment. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 113-l17. Orlando, FL, May 1995.

Software tools are designed for specific applications and specific audiences. Once the tools are available, their use may broaden or diminish due to various unanticipated factors. When these factors deter the use of the tool, innovative ways can be found to facilitate usage. When the factors are positive, then the new uses can be promoted. Using existing tools for new functions can save on software development. This paper will discuss the unplanned uses of two software tools: Solvent Alternative Guide (SAGE) and the Architectural Design and Assessment System (ADAS), developed by the Research Triangle Institute (RTI) for manufacturing and design. Innovative design for the environment uses of standard utilities will also be discussed. A secondary concern is computer technology that can change faster than software applications. Applications that can transcend multiple technologies are most useful. Finding the proper technical delivery vehicles to provide the environmental information to consumers is a challenge. With the SAGE program, the U.S. EPA and RTI are trying several mechanisms to reach the various audiences for the information.

Fraust, C. L., P. L. Comejo, R. B. Davis et al. (AT&T Microelectronics), 1992. Environmental Control in Semiconductor Manufacturing. ***AT&T Technical Journal*** (Mar/Apr): 19-28.

Semiconductor manufacturing is among the world's most important and technologically advanced industries. Although it once enjoyed a reputation as a "clean" industry, in recent years that reputation has been tarnished by allegations of environmental, worker health, and human reproductive problems stemming from semiconductor manufacturing operations. It is well-documented that making semiconductor devices requires hazardous chemicals that, if not properly used or controlled, could result in serious problems to the facility, its work force, or the community where it exists. This paper first discusses early attempts at semiconductor manufacturing, then tracks technology, early environmental controls, growth in regulatory requirements, and programs implemented to insure regulatory compliance in all areas of environmental concern.

Freeman, J., T. Harten, J. Springer et al. (U.S. EPA), 1992. Industrial Pollution Prevention: A Critical Review. ***J Air Waste Manage. Assoc. 42 (5): 618-656.***
In this critical review, the authors present the current state of knowledge regarding pollution prevention approaches to environmental improvement, explore the state of development of various private and public approaches to encouraging the adoption of pollution prevention strategies, highlight selected clean technologies and clean products, and examine various technical and economic issues related to the concept of pollution prevention,

Genca, C. M. (Xerox Corporation), 1995. Xerox CO, Cleaning System Pilot **.** In ***Proceedings of the IEEE International Symposium on Electronics and the Environment, 100-105.*** Orlando, FL, May 1995.
The carbon dioxide cleaning system was adapted by Xerox from a jet-engine cleaning technology and is being used for removal of grease, dirt, and oil from used (field-returned) equipment to enable machine remanufacturing. Prior to the introduction of CO_2 blasting at Xerox, machine cleaning was a two-stage process, which required a variety of chemicals. In the first stage, loose dirt was removed by compressed air blow-off and vacuum suction. In the second stage, a blend of chlorinated solvents was applied, typically in a handwipe application. In the 1980's, Xerox replaced the solvent blend with a citrus-based material for general cleaning but continued to use 1,1,1-trichloroethane on encrusted, stubborn dirt. Xerox made a significant financial investment in adapting CO_2 blasting technology for use in its remanufacturing facility and the cleaning of mechanically and electronically sensitive machine parts. This development effort entailed redesign of the current process equipment and recalibration of the blasting parameters. Furthermore, ergonomic refinement of the equipment was required to permit the use by an operator over an 8 to 12 hour work shift. Development and implementation of this new system allowed Xerox to meet an internal requirement of eliminating all ozone depleting substances from its manufacturing processes by the end of 1992, years ahead of any regulatory initiatives. Moreover, CO_2 blast cleaning resulted in unanticipated cost-savings of 40% and productivity improvements of 50%.

Iman, R. L., D. J. Anderson, and L. R. Lichtenberg. (Sandia National Laboratories, Gram, Inc, Motorola, Inc.), 1993. Case Study: Evaluation of a Low-Residue Soldering Process that Eliminates Solvent Cleaning. ***Pollution Prevention Review 3 (4):*** 417-427.

Sandia National Laboratories and the Government Systems and Technology Group of Motorola, Inc. recently entered into a Cooperative Research and Development Agreement (CRADA) to evaluate a low-residue (no-clean) soldering process that eliminates the need for ozone-depleting solvents for cleaning printed wiring boards. The program showed that this low-residue soldering process represents an ideal opportunity to eliminate solvent cleaning and its associated wastes, energy use, costs, and process turnaround time.

Karpinski, G., and R. Logan. (EMCON Associates), 1993. Silicon Valley Semiconductor Firms Benefit from Pollution Prevention. ***Pollution Prevention Review 3 (2):*** 177-186.
In the 1970's, California's Silicon Valley semiconductor manufacturers prided themselves on being a clean and environmentally benign industry group. That perception changed suddenly in 1981, however, when chemical wastes generated from silicon wafer fabrication were linked to local groundwater contamination. This article examines how the industry has successfully tackled this problem using pollution prevention techniques to reduce four major hazardous wastes - HF acid, solvents, stripper, and photoresist.

Kassahun, B., M. Saminathan, and J. C. Sekutowski. (AT&T Bell Laboratories), 1995. Green Design Tool. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 118-125. Orlando, FL, May 1995.
In this paper we put forth a framework for the development of a user-friendly, easy-to-use software tool that should help both managers and product and process designers evaluate the environmental compatibility of products and their associated manufacturing processes. Of particular interest to the authors is the manufacture of electronic components and assemblies which involve process intensive, semi-continuous and repetitive wet chemical and physical operations that define circuit patterns on polymers, ceramic and silicon substrates and associated component assembly processes. In this paper we outline an environmental figure of merit for product and process designs that provides the designer the capability to assess the environmental compatibility of various product and process choices. A brief discussion of the PC-based tool, its architecture and a sample application in product and process design will be given.

Keoleian, G. A., W. J. Glantschnig, and W. McCann. (University of Michigan, AT&T Bell Laboratories), 1994. Life Cycle Design: AT&T Demonstration Project. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 134-138. San Francisco, May 1994.
The life cycle design framework developed at the University of Michigan guides the integration of environmental requirements into the manufacturing, use, and end-of-life stages of a product system. Elements of the life cycle design framework were applied in AT&T's product realization process for a business phone. This demonstration project tested use of a multicriteria requirements matrix which includes environmental, performance, cost, cultural, and legal dimensions. Critical requirements that shape the design of the business phone were identified and life cycle design strategies used to resolve conflicts between these requirements are highlighted in this paper. In addition, challenges in implementing life cycle

design such as insufficient environmental data and lack of consensus on environmental assessment are discussed.

Keoleian, G.A. and J.E. Koch, Evaluating Environmental Performance: A Case Study in the Flat-Panel Display Industry. (University of Michigan), 1995. Evaluating Environmental Performance: A Case Study in the Flat- Panel Display Industry. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 158-165. Orlando, FL, May 1995.
Researchers at the University of Michigan applied their life cycle design framework in a research project with Optical Imaging Systems (0IS). 0IS is a US manufacturer of high-performance, active-matrix liquid crystal displays, one of the leading flat panel display technologies. The study evaluated OIS's environmental management system and how environmental performance may impact competition in the flat panel display industry. Metrics were developed to measure environmental performance in a factory simulation model. Strategies for improvement are recommended according to incremental, reengineering and future approaches.

Keoleian, G. A., and D. Menerey. (University of Michigan), 1994. Sustainable Development by Design: Review of Life Cycle Design and Related Approaches. ***J Air Waste Manage. Assoc. 44 (5): 645-668.***
The environmental profile of goods and services that satisfy our individual and societal needs is shaped by design activities. Substantial evidence suggests that current patterns of human activity on a global scale are not following a sustainable path. Necessary changes to achieve a more sustainable system will require that environmental issues be more effectively addressed in design. But at present much confusion surrounds the incorporation of environmental objectives into the design process. Although not yet fully embraced by industry, the product life cycle system is becoming widely recognized as a useful design framework for understanding the links between societal needs, economic systems and their environmental consequences.. The product life cycle encompasses all activities from raw material extraction, manufacturing, and use to final disposal of all residuals. Life cycle design, design for the environment, and related initiatives based on this product life cycle are emerging as systematic approaches for integrating environmental issues into design. This review presents the life cycle design framework developed for the U.S. EPA as a structure for discussing the environmental design literature. Specifying environmental requirements and evaluation metrics are essential elements of designing for sustainable development. A major challenge for successful design is choosing appropriate strategies that satisfy cost, performance, cultural, and legal criteria while also optimizing environmental objectives. Various methods for specifying requirements, strategies for reducing environmental burden, and environmental evaluation tools are explored and critiqued. Currently, many organizational and operational factors limit the applicability of life cycle design and other design approaches to sustainable development. For example, lack of environmental data and simple, effective evaluation tools are major barriers. Despite these problems, companies are beginning to pursue aspects of life cycle design. The future of life cycle design and

sustainable development depends on education, government policy and regulations, and industry leadership but fundamental changes in societal values and behavior will ultimately determine the fate of the planet's life support system.

Klafter, B. A. (AT&T Bell Laboratories), 1992. Case Study: AT&T and Intel Pollution Prevention Benchmarking. In ***Proceedings of the Corporate Quality/ Environmental Management II: Measurements and Communication Conference,*** 75-80. Arlington, VA, March 1992. Global Environmental Management Initiative.
In 1991, AT&T and Intel teamed together to benchmark best-in-class corporate pollution prevention programs. This presentation is a case study of that benchmark. It describes the team dynamics, benchmarking process followed, and conditions key to the team's success in each phase.

Maxie, E. (Hewlett-Packard Company), 1994. Supplier Performance and the Environment. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment, 323-*** 327. San Francisco, May 1994.
Suppliers are an integral part of most programs to improve the environment. Therefore measures to understand and communicate differences in supplier performance toward improving the environment should be developed. This paper presents a set of selection criteria for developing a supplier performance measure on the environment that accounts for geographical differences. A methodology for integrating an environmental performance measure into existing traditional supplier performance measures is also presented.

McCall, J., and S. Anderson. (Motorola), 1994. Design Considerations for Potential Environmental Implications Driving Selection of Semiconductor Starting Material. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 246-251. San Francisco, May 1994.
When selecting a material for power device design the parameters of cost, performance and reliability are critical to the selection process. Another equally important parameter is the potential environmental implication of the material. This paper compares a conventional power switch transistor, called an Insulated Gate Bipolar transistor, with a simplified structure, called a non-epi IGBT, that uses fewer processing steps.

Melton, C. (Motorola), 1993. Alternatives of Lead Bearing Solder Alloys. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 94-97. Arlington, VA, May 1993.
Proposed legislation and regulation dealing with the use of lead in commercial products are the main driving forces in the search for lead free solder replacements in printed circuit board assembly. Research into potential replacements to the use of lead-tin solder in surface mount applications has prompted examination of alternative interconnect materials which not only include lead free solder alloys but also address the use of non- metallic based attachment systems.

Nunno, T., S. Palmer, M. Arienti et ***al. 1988. Toxic Waste Minimization in the Printed Circuit Board Industry.*** Park Ridge, NJ: Noyes Data Corporation.

Pedersen, S. W. (MCC), 1995. Electronics Industry Environmental Roadmap. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 285-289. Orlando, FL, May 1995.
The purpose of this paper is to present the results of a comprehensive, focused approach to environmental management in the electronics industry. The roadmap describes in the electronics industry. The roadmap describes the process of building electronic systems, highlights those points of primary environmental sensitivity throughout the process, and identifies specific actions that should be taken to achieve the level of environmental excellence which is both imperative for business success and a responsibility of corporate stewardship.

Perry, T. S. 1993. Cleaning Up. ***IEEE Spectrum 30 (2): 20-26.***
Electronics manufacturers are adopting environmentally kinder processes. They are discovering highly effective alternatives to dangerous chemicals. (Ray Turner of Hughes Aircraft Co., for example, found a lemon-juice solder flux to replace ozone-depleting chlorofluorocarbons.) Companies are also looking at the future effects of their choices of processes and materials.

Planning Research Corporation. 1989. ***Waste Audit Study: Printed Circuit Board Manufacturers.*** Toxic Substances Control Program, California Department of Health Services, San Jose, CA.

Pojasek, R. B. (GE1 Consultants, Inc.), 1993. Looking Beyond the Manufacturing Process for Opportunities to Prevent Pollution. ***Pollution Prevention Review 3 (4): 469-473.***
Most facility pollution prevention programs focus on the manufacturing process. When one takes a closer look at a facility, however, there are many wasteful activities that could be easily prevented. These activities are often referred to as ancillary operations that occur at the loading dock, in the laboratory, in machine shops, the office, and other areas. This article will show how less experienced firms and those with well-developed pollution prevention programs can accelerate their progress by adding ancillary operations to their list of P2 projects.

Reibstein, R. (Massachusetts Office of Technical Assistance for Toxics Use Reduction), 1993. Toxics Use Reduction Planning by Massachusetts Electronics Firms. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 138- 143. Arlington, VA, May 1993.
Several Massachusetts electronics firms have in recent years actively pursued a prevention approach to pollution problems. The state's Office of Technical Assistance for Toxics Use Reduction helps companies using toxic chemicals to implement preventive methods. The following paper describes the state program requiring pollution prevention planning and some examples from field work of the Office.

Risk Reduction Engineering Laboratory and Center for Environmental Research Information. ***1990. Guides to Pollution Prevention: The Printed Circuit Board Manufacturing Industry.*** U.S. Environmental Protection Agency, EPA /625/7-90/007.Cincinnati, OH.

Rooney, C. 1993. Economics of Pollution Prevention: How Waste Reduction Pays. ***Pollution Prevention Review 3 (3):*** 261-276.

Rupp, G., and S. Graham. (DSC Communications Corporation), 1995. Process Design and Optimization for Environmentally Conscious Printed Circuit Board Assemblies. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 95-99. Orlando, FL, May 1995.
This paper discusses an engineering approach to the qualification of water based flux as a substitute for conventional alcohol based volatile organic compound (VOC) flux and utilization of "No-Clean" soldering material, virtually eliminating saponified waste water effluent and VOC emissions typically associated with surface mount technology (SMT) printed circuit board assembly (PCBA). The information and experiences are provided through a discussion of critical equipment, material requirements and evaluations, as well as the selection methodology and criteria.

Salomon, R. K. (United States Air Force), 1994. Implementing Pollution Prevention in DoD System Acquisition Programs -- What More is Needed. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 45-50. San Francisco, May 1994.
Three pollution prevention paradigms currently used in the U.S. aerospace industry are described and the implications for DoD system acquisition policy are presented. The paradigms are identification-evaluation, strategic planning, and goal assignment.

Saminathan, M., J. C. Sekutowski, and G. Williams. (AT&T Bell Laboratories), 1993. Waste Minimization in Electronics Component Processing - A Systems Approach. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** l-6. Arlington, VA, May 1993.
Environmental concerns over waste disposal and efficient utilization of manufacturing process materials, together with evolving state, federal, and international government policy on these issues, have led to the conceptual development of a "Smart" Systems Analysis for tracking process materials flow, consumption, and the generation of waste or by-product (per unit of manufactured product), at each step in the manufacturing process. Of particular interest to the authors is the manufacture of electronic components which involves many process intensive, semi-continuous, and repetitive wet chemical and physical operations, that define circuit patterns on polymer, ceramic, or silicon substrates. The value of the application of systems analysis concepts for environmental considerations to complex sequential manufacturing flow, consumption, and waste generation at all times, at the individual process step, manufacturing line, or factory levels, and to provide process

optimization and control from an environmental perspective. A proposed architecture for the application of Systems Analysis in a typical manufacturing process line in a UNIX System environment is illustrated. A major element incorporated in the platform is the "Smart" Module which provides intelligent manufacturing systems assessments having environmental impact at both the micro and macro manufacturing levels, and recommends process alternatives or control using knowledge of best available process technology.

Schwartz, C., and P. N. Cheremisinoff, (TCMU, Inc., New Jersey Institute of Technology), 1992. Reduction of Hazardous Waste Releases in Semiconductor Operations. In ***Encyclopedia of Environmental Control Technology, Volume 6 : Pollution Reduction and Contaminant Control,*** P.N. Cheremisinoff, Ed., Gulf Publishing Co., pp 277-292.
This engineering study will analyze the semiconductor manufacturing process and consider methods to limit the production and release of toxic materials in the work place and in the environment. Both silicon wafer and gallium arsenic wafer production will be considered. Special interest will be placed on those waste minimization technologies and techniques, substitution of less hazardous materials, and recycling techniques that will allow for reuse of materials rather than dumping. In all cases, the economic consequences of these changes will be considered.

Shire, D., and G. Brownell. (Hewlett-Packard Company), 1993. Hazardous Waste Minimization in III-V Water Fabrication Processes. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 60-63. Arlington, VA, May 1993.
Several coordinated hazardous waste minimization projects are underway at our facilities involved in III-V device manufacturing. These include modifications to existing processes to reduce emissions of CFC's, 1,1,l-TCA, xylenes, ethylene glycol ethers, 1,2,4 trichlorobenzene (in photoresist stripper), and other compounds. These issues are addressed in turn, noting the unique aspects of GaAs and GaP device manufacture that need to be taken into account. Goals achieved have been complete cessation of CFC and 1,1,l-TCA use and 33% reductions in xylene and.1,2,4-trichlorobenzene usage since 1990, despite significant increases in total production volume during the same period. Specific strategies are also described for tracking chemical use and sharing best practices for hazardous waste reduction across functional groups.

Stuart, J. A., J. C. Ammons, L. J. Turbin et al. (Georgia Institute of Technology, AT&T Bell Laboratories), 1995. Evaluation Approach for Environmental Impact and Yield Trade-Offs for Electronics Manufacturing Product and Process Alternatives. In IEEE International Symposium on Electronics & Environment, 166-170. Orlando, FL, May 1995.
This paper develops an approach to evaluate environmental impact and yield trade-offs in electronics manufacturing over the life cycle of the products studied. A mathematical model is described which provides sensitivity analysis of the revenue and cost trade-offs constrained by operational parameters, government regulations, and environmental goals.

Thompson, B. C., and A. C. Rauck. 1993. Applying TQEM Practices to Pollution Prevention at AT&T's Columbus Works Plant. ***Total Quality Environmental Management 2 (4): 373-38*** 1. In recent years AT&T changed its focus on environmental policies from compliance to pollution prevention. Pollution prevention is an integrated program that includes design for the environment, "green" manufacturing, and a comprehensive program to reduce existing waste in production. The principles of Total Quality Management can be applied to pollution prevention as well as the more traditional manufacturing concepts. The project described in this article is one of several concurrent programs being conducted at AT&T's Columbus Works to reduce overall waste produced by the facility by applying TQM practices.

Ufford, D. A. (Texas Instruments), 1995. Design for the Environment at Texas Instruments' Defense Systems and Electronics Group. In IEEE International Symposium on Electronics & Environment, 41-46. Orlando, FL, May 1995.
TI's Defense Systems and Electronics Group is executing a DFE initiative in order to institutionalize the systematic consideration of life cycle environmental concerns and decision- making in its product development and management process. This initiative is part of TI-DSEG's continuing commitment to proactive, "source reduction" practices as the most effective method of pollution prevention.

van der Wijk, A., G. Strating, and P. Schelwald. (Phillips Semiconductors), 1993. Water as a Solution for the Removal of Halogenated Hydrocarbons in the Production Process of Medium Power Diodes. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 56-59. Arlington, VA, May 1993.
The removal of dichloromethane (DCM) from the production process of medium power diodes can be accomplished by replacing the oil-derived adhesives applied in the process by sugar-based adhesives. As a result, tap-water, which is harmless to the environment, can be used in all process steps which previously required the use of DCM. An additional advantage is the considerable costreduction because of the lower prices of the adhesives.

Wells, R., P. Calkins, and H. Balikov. (Abt Associates, Inc., J.M. Huber Corp.), 1994. Measuring Environmental Performance. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 53-57. San Francisco, May 1994.
Measuring environmental performance is a key challenge facing corporate environmental managers. This article describes issues in Environmental Performance Evaluation (EPE). It illustrates the approach to these issues taken by J.M. Huber Corporation to develop a multi-dimensional, readily implemented environmental performance index that is used by senior management to track performance and to report to the Board of Directors. It then describes how the same approach can be used to evaluate life cycle impacts in the electronics industry.

White, A. L., M. Becker, and D. E. Savage. (Tellus Institute), 1993. Environmentally Smart Accounting: Using Total Cost Assessment to Advance Pollution Prevention. ***Pollution Prevention Review 3 (3): 247-259.***

Conventional project financial analysis often fails to capture the full range of costs and savings associated with pollution prevention (P2) investments. Thus, managers need to rethink their approach to cost inventory, cost allocation, time horizon, and profitability analysis to ensure that P2 investments are treated fairly in the capital budgeting process. This article shows how total cost assessment can often help level the playing field for P2 investments that might otherwise be tagged as uncompetitive and unprofitable.

Wixom, M. R. (National Center for Manufacturing Sciences), 1994. NCMS Solvent Substitution and Material Compatibility Databases. In ***Proceedings of the IEEE International Symposium on Electronics and the Environment,*** 224-229. San Francisco, May 1994.

The NCMS Solvent Database collects information on alternatives to ODC-based solvents used in electronics manufacturing. The database contains over 320 pure solvents and trade name mixtures. Each record includes 15 fields of environmental fate, 31 fields of health and safety, 21 fields of regulatory status, 36 fields of health and safety, and 19 fields of descriptive and supplier data. The Solvent Database is a stand-alone PC based application which runs under Paradox Runtime. The NCMS project, Compatibility Testing - Electronic Assembly Materials, examined the compatibility of seven ODC free alternatives and two ODC- based control solvents on 124 materials commonly used in electronic assemblies. The materials groups included metals, metal surface coatings, polymers, composites, elastomers and shrink tubing, adhesives and locking compounds, non-metallic coatings, marking materials, and tapes. Pre- and post-exposure measurements included weight, volume, hardness, salt fog, dielectric strength, lap shear, and dimensional stability. The solutions tested were: Freon TMS, 1,1,1-trichloroethane, isopropyl alcohol, Axare138, Bioact EC-5, Bioact EC-7R, Ionox HC, RADS, and Vertre1245. The compatibility data reflects the results of over 17,000 man-hours of testing. Project results have been released as a 1000 page final report or as a Microsoft Windows application called MatCompat.