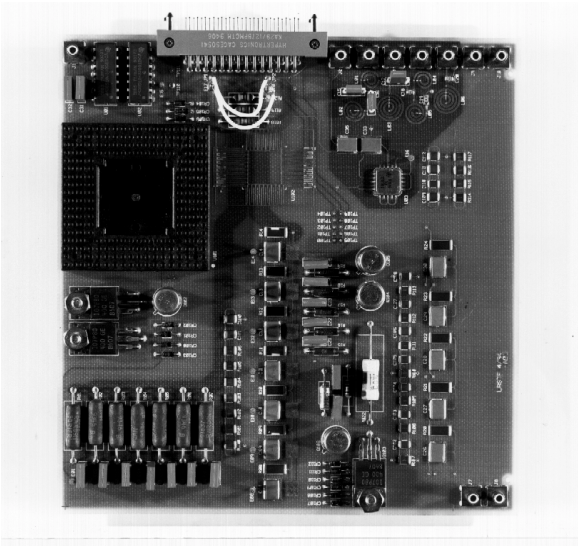
Printed Wiring Board
Surface Finishes



Cleaner Technologies Substitutes Assessment

VOLUME 1

Jack R. Geibig, Senior Research Associate
Mary B. Swanson, Research Scientist
and the
PWB Engineering Support Team

This document was produced by the University of Tennessee Center for Clean Products and Clean Technologies under grant #X825373 from EPA's Design for the Environment Branch, Economics, Exposure, & Technology Division, Office of Pollution Prevention and Toxics.

PWB Engineering Support Team

The PWB Engineering Support Team consisted of University of Tennessee faculty and graduate students who developed analytical models for the project and/or authored sections of this document. Members of the Team and the sections to which they contributed are listed below:

Exposure Assessment and Risk Characterization

Dr. Chris D. Cox, Associate Professor of Civil and Environmental Engineering,
Dr. R. Bruce Robinson, Professor of Civil and Environmental Engineering,
and graduate research assistants in Civil and Environmental Engineering:
Aaron Damrill, Jennie Ducker, Purshotam Juriasingani, and Jeng-hon Su.

Cost Analysis

Dr. Rupy Sawhney, Assistant Professor of Industrial Engineering and Director, Lean Production Laboratory, and graduate research assistants in Industrial Engineering: Aamer Ammer.

Disclaimer

This document was written by the grantee. It has not been through a formal external peer review process. Some information in this document was provided by individual technology vendors and has not been independently corroborated by EPA or the University of Tennessee. The use of specific trade names or the identification of specific products or processes in this document are not intended to represent an endorsement by EPA or the U.S. Government. Discussion of federal environmental statutes is intended for information purposes only; this is not an official guidance document, and should not be relied on by companies in the printed wiring board industry to determine applicable regulatory requirements.

For More Information

To learn more about the Design for the Environment (DfE) Printed Wiring Board Project or the DfE Program, please visit the DfE Program web site at:

www.epa.gov/dfe

The DfE web site also contains the document, *Cleaner Technologies Substitutes Assessment: A Methodology and Resources Guide*, which describes the basic methodology used in this assessment.

To obtain copies of DfE Printed Wiring Board Project technical reports, pollution prevention case studies, and project summaries, please contact:

Pollution Prevention Information Clearinghouse (PPIC)
U.S. Environmental Protection Agency
1200 Pennsylvania Ave., N.W. (7407)
Washington, DC 20460
Phone: (202) 260-1023
Fax: (202) 260-4659
E-mail: ppic@epa.gov
Web site: www.epa.gov/opptintr/library/ppicdist.htm

To learn more about the University of Tennessee Center for Clean Products and Clean Technologies, visit the Center's web site at:

eerc.ra.utk.edu/clean/

Acknowledgments

This Cleaner Technologies Substitutes Assessment (CTSA) was prepared under a grant from the U.S. Environmental Protection Agency's Design for the Environment (DfE) Program, Office of Pollution Prevention and Toxics, by the University of Tennessee (UT) Knoxville Center for Clean Products and Clean Technologies and the PWB Engineering Support Team, with assistance from numerous UT students and staff. The authors would like to acknowledge the outstanding contributions of **Lori Kincaid,** UT Center for Clean Projects and Clean Technologies, who provided guidance throughout the project; **Catherine Wilt,** UT Center for Clean Projects and Clean Technologies, who researched and wrote the Regulatory status section of this document; **James Dee**, UT Center for Clean Projects and Clean Technologies, who assisted with the development of the Human Health and Ecological Hazards Summary; and **Margaret Goergen**, who was the document production manager.

This document was produced as part of the DfE Printed Wiring Board Project, under the direction of the project's Core Group members, including: **Kathy Hart**, Project Lead and Core Group Co-Chair, U.S. EPA, Office of Pollution Prevention and Toxics (OPPT), Economics, Exposure and Technology Division (EETD), DfE Branch; **Holly Evans**, formerly of IPC–Association Connecting Electronics Industries (IPC), and **Fern Abrams**, IPC, Core Group Co-Chairs; **Dipti Singh**, Technical Lead and Technical Workgroup Co-Chair, U.S. EPA, OPPT, EETD, DfE Branch; **John Sharp**, Teradyne Inc., Technical Workgroup Co-Chair; **Michael Kerr**, BHE Environmental, Inc., **John Lott**, DuPont Electronics; **Greg Pitts**, Ecolibrium; **Gary Roper**, Substrate Technologies, Inc.; and **Ted Smith**, Silicon Valley Toxics Coalition. Many thanks also to the industry representatives and other interested parties who participated in the project's Technical Workgroup, especially **David Ormerod** of Dexter Electronic Materials (now Polyclad Technologies - Enthone), **Michael Schectman** of Technic, Inc., **David Hillman** of Rockwell International Corp., and **Eric Brooman** of Concurrent Technologies Corporation.

We would like to acknowledge **Ron Iman** of Southwest Technology Consultants for his work in analyzing and presenting the results of the performance demonstration, and **Terry Munson** of Contamination Studies Laboratory (CSL), Inc., for conducting a failure analysis and helping to present the performance demonstration results. We also appreciate the efforts of **Jeff Koon** of Raytheon Systems Company and **David Hillman** for their help in planning and conducting the performance demonstration. Recognition is also given to **ADI/Isola,** who supplied the materials to build the performance demonstration test boards, to **Network Circuits** for volunteering to build the boards, and to the test facilities that ran the boards through their surface finish lines and provided critical data for the study. Performance demonstration contractor support was provided by Abt Associates, Inc., of Cambridge, MA, under the direction of **Cheryl Keenan**.

EPA Design for the Environment Workgroup

We would like to express appreciation to the U.S. EPA Office of Pollution Prevention and Toxics Design for the Environment Workgroup, who provided valuable expertise in the development of this CTSA and reviewed all draft documents.

Andrea Blaschka
Susan Dillman
Conrad Flessner
Franklyn Hall
Susan Krueger
Tim Lehman
Fred Metz
Dave Monroe
Jerry Smrchek

Participating Suppliers

We would like to thank the suppliers for their participation in the DfE Printed Wiring Board Surface Finishes Project. In addition to supplying critical information regarding the various technologies, these companies also made significant contributions in planning and conducting the performance demonstration.

Alpha Metals
(now Polyclad Technologies-Enthone)
Steve Beigle
50 Burr Ridge Parkway
Burr Ridge, IL 60521
(630) 794-9329

Dexter Electronic Materials
(now Polyclad Technologies-Enthone)
David Ormerod
144 Harvey Road
Londonderry, NH 03053
(603) 645-0021, ext. 203

Electrochemicals, Inc.
Paul Galatis
5630 Pioneer Creek
Maple Plain, MN 55359
(612) 479-2008

Florida CirTech
Mike Scimeca
1309 North 17th Avenue
Greeley, CO 80631
(970) 346-8002

MacDermid, Inc.
Don Cullen
245 Freight Street
P.O. Box 671
Waterbury, CT 06702
(203) 575-5658

Technic, Inc.
Michael Schectman
1 Spectacle Street
Cranston, RI 02910
(401) 781-6100

Performance Demonstration Sites

We would like to recognize the companies and their facilities that participated in our performance demonstration, for donating the time and materials necessary to carry out the testing. We also appreciate the assistance they provided in gathering data necessary to conduct this assessment.

AIK Electronics (UK) Ltd. (formerly Philips Printed Circuits)

Artetch Circuits Ltd.

Central Circuits Inc.

Circuit Connect Inc.

Circuit Wise Inc.

Diversified Systems

GTC Circuits Corp. (formerly General Technology Corp.)

H-R Industries

Parlex Corp.

Quality Circuits Inc.

Sanmina Corp. (formerly Altron Inc.)

Sanmina Corp. (formerly Hadco Corp.)

Solder Station One, Inc.

Table of Contents

Executive Summary ES-1

Chapter 1
Introduction 1-1
1.1 Project Background 1-2
1.1.1 EPA DfE Program 1-2
1.1.2 DfE PWB Program 1-2
1.2 Overview of PWB Industry 1-5
1.2.1 Types of Printed Wiring Boards 1-5
1.2.2 Industry Profile 1-5
1.2.3 Overview of Rigid Multi-Layer PWB Manufacturing 1-7
1.3 CTSA Methodology 1-8
1.3.1 Identification of Alternatives and Selection of Project Baseline 1-8
1.3.2 Boundaries of the Evaluation 1-9
1.3.3 Issues Evaluated 1-10
1.3.4 Primary Data Sources 1-11
1.3.5 Project Limitations 1-13
1.4 Organization of this Report 1-15
References 1-16

Chapter 2
Profile of the Surface Finishing Use Cluster 2-1
2.1 Chemistry and Process Description of Surface Finishing Technologies 2-1
2.1.1 Process Sequence of Surface Finishing Technologies 2-1
2.1.2 Overview of the Surface Finishing Manufacturing Process 2-3
2.1.3 Chemistry and Process Descriptions of Surface Finishing Technologies 2-4
2.1.4 Chemical Characterization of Surface Finishing Technologies 2-17
2.2 Additional Surface Finishing Technologies 2-23
2.2.1 Immersion Palladium 2-23
References 2-25

Chapter 3
Risk Screening and Comparison 3-1
3.1 Source Release Assessment 3-1
3.1.1 Data Sources and Assumptions 3-2
3.1.2 Overall Material Balance for Surface Finishing Technologies 3-3
3.1.3 Source and Release Information for Specific Surface Finishing Technologies 3-17
3.1.4 Uncertainties in the Source Release Assessment 3-34
3.2 Exposure Assessment 3-35
3.2.1 Exposure Setting 3-35
3.2.2 Selection of Exposure Pathways 3-40

3.2.3 Exposure-Point Concentrations 3-43
3.2.4 Estimating Potential Dose Rates 3-56
3.2.5 Uncertainty and Variability 3-75
3.2.6 Summary 3-77
3.3 Human Health and Ecological Hazards Summary 3-80
3.3.1 Carcinogenicity 3-80
3.3.2 Chronic Effects (Other than Carcinogenicity) 3-83
3.3.3 Ecological Hazard Summary 3-96
3.3.4 Summary 3-102
3.4 Risk Characterization 3-104
3.4.1 Summary of Exposure Assessment 3-104
3.4.2 Summary of Human Health Hazards Assessment 3-109
3.4.3 Summary of Ecological Hazards Assessment 3-109
3.4.4 Methods Used to Calculate Human Health Risks 3-110
3.4.5 Results of Calculating Human Health Risk Indicators 3-113
3.4.6 Evaluation of Lead Risks from Tin-Lead Solder Used in the HASL Process 3-125
3.4.7 Results of Calculating Ecological (Aquatic) Risk Indicators 3-128
3.4.8 Uncertainties 3-130
3.4.9 Conclusions 3-132
3.5 Process Safety Assessment 3-137
3.5.1 Chemical Safety Concerns 3-137
3.5.2 Hot Air Solder Leveling (HASL) Process Safety Concerns 3-146
3.5.3 Process Safety Concerns 3-146
References 3-151

Chapter 4

Competitiveness 4-1
4.1 Performance Demonstration Results 4-1
4.1.1 Background 4-1
4.1.2 Performance Demonstration Methodology 4-2
4.1.3 Test Vehicle Design 4-4
4.1.4 Environmental Testing Methodology 4-8
4.1.5 Analysis of the Test Results 4-8
4.1.6 Overview of Test Results 4-13
4.1.7 HCLV Circuitry Performance Results 4-18
4.1.8 HVLC Circuitry Performance Results 4-20
4.1.9 High Speed Digital Circuitry Performance Results 4-21
4.1.10 High Frequency Low Pass Filter Circuitry Performance Results 4-22
4.1.11 High Frequency Transmission Line Coupler Circuitry Performance Results 4-27
4.1.12 Leakage Measurements Performance Results 4-29
4.1.13 Stranded Wires 4-32
4.1.14 Failure Analysis 4-33
4.1.15 Summary and Conclusions 4-40
4.1.16 Boxplot Displays 4-42

4.2 Cost Analysis 4-55
4.2.1 Overview of the Cost Methodology 4-56
4.2.2 Cost Categories and Discussion of Unquantifiable Costs 4-57
4.2.3 Simulation Modeling of Surface Finishing Processes 4-62
4.2.4 Activity-Based Costing 4-68
4.2.5 Cost Formulation Details and Sample Calculations 4-71
4.2.6 Results 4-84
4.2.7 Conclusions 4-86
4.3 Regulatory Assessment 4-88
4.3.1 Clean Water Act 4-88
4.3.2 Clean Air Act 4-93
4.3.3 Resource Conservation and Recovery Act 4-95
4.3.4 Comprehensive Environmental Response, Compensation and Liability Act 4-97
4.3.5 Superfund Amendments and Reauthorization Act and Emergency Planning and Community Right-To-Know Act 4-98
4.3.6 Toxic Substances Control Act 4-100
4.3.7 Summary of Regulations for Surface Finishing Technologies 4-101
References 4-108

Chapter 5

Conservation 5-1
5.1 Resource Conservation 5-1
5.1.1 Consumption of Natural Resources 5-2
5.1.2 Consumption of Other Resources 5-8
5.1.3 Summary and Conclusions 5-10
5.2 Energy Impacts 5-12
5.2.1 Energy Consumption During Surface Finishing Process Operation 5-12
5.2.2 Energy Consumption Environmental Impacts 5-18
5.2.3 Energy Consumption in Other Life-Cycle Stages 5-21
5.2.4 Summary and Conclusions 5-22
References 5-23

Chapter 6

Additional Environmental Improvements Opportunities 6-1
6.1 Pollution Prevention 6-2
6.1.1 Management and Personnel Practices 6-3
6.1.2 Materials Management and Inventory Control 6-6
6.1.3 Material Selection 6-7
6.1.4 Process Improvements 6-8
6.2 Recycle, Recovery, and Control Technologies Assessment 6-19
6.2.1 Recycle and Resource Recovery Opportunities 6-19
6.2.2 Control Technologies 6-28
References 6-38

Chapter 7

Choosing Among Surface Finishing Technologies 7-1
7.1 Risk, Competitiveness, and Conservation Data Summary 7-2
7.1.1 Risk Summary 7-2
7.1.2 Competitiveness Summary 7-8
7.1.3 Resource Conservation Summary 7-14
7.2 Social Benefits/Costs Assessment 7-16
7.2.1 Introduction to Social Benefits/Costs Assessment 7-16
7.2.2 Benefits/Costs Methodology and Data Availability 7-18
7.2.3 Private and External Benefits and Costs Associated with Choice of Surface Finishing Alternative 7-19
7.2.4 Summary of Benefits and Costs 7-28
7.3 Technology Summary Profiles 7-30
7.3.1 HASL Technology 7-30
7.3.2 Nickel/Gold Technology 7-35
7.3.3 Nickel/Palladium/Gold Technology 7-39
7.3.4 OSP Technology 7-44
7.3.5 Immersion Silver Technology 7-47
7.3.6 Immersion Tin Technology 7-51
References 7-56

List of Tables

Table 1-1. Surface Finishing Technologies Submitted by Chemical Suppliers 1-11
Table 1-2. Responses to the PWB Workplace Practices Questionnaire 1-13
Table 2-1. Use Cluster Chemicals and Associated Surface Finishing Processes 2-18
Table 3-1. Water Usage of Surface Finishing Technologies From Questionnaire 3-7
Table 3-2. Reported Use of Chemical Flushing as a Tank Cleaning Method 3-8
Table 3-3. Average Bath Dimensions and Temperatures for All Processes 3-10
Table 3-4. Spent Bath Treatment and Disposal Methods 3-13
Table 3-5. RCRA Wastes and Container Types for Surface Finishing Technologies 3-16
Table 3-6. Workplace Activities and Associated Potential Exposure Pathways 3-40
Table 3-7. Potential Population Exposure Pathways 3-42
Table 3-8. Results of Workplace Air Modeling 3-47
Table 3-9. Results of Ambient Air Modeling 3-51
Table 3-10. Estimated Releases to Surface Water Following Treatment 3-54
Table 3-11. Parameter Values for Workplace Inhalation Exposures 3-57
Table 3-12. General Parameter Values for Workplace Dermal Exposures 3-59
Table 3-13. Parameter Values for Workplace Dermal Exposures for Line Operators on Non-Conveyorized Lines 3-60
Table 3-14. Parameter Values for Workplace Dermal Exposure for Line Operators on Conveyorized Lines 3-61
Table 3-15. Parameter Values for Workplace Dermal Exposure for a Laboratory Technician on Either Conveyorized or Non-Conveyorized Lines. 3-62
Table 3-16. Estimated Average Daily Dose for Workplace Exposure From Inhalation and Dermal Contact 3-63
Table 3-17. Estimated Concentration of Lead in Adult and Fetal Blood from Incidental Ingestion of Lead in Tin/Lead Solder 3-72
Table 3-18. Parameter Values for Estimating Nearby Residential Inhalation Exposure . . . 3-74
Table 3-19. Estimated Average Daily Dose for General Population Inhalation Exposure 3-74
Table 3-20. Children's Blood-Lead Results from the IEUBK Model at Various Lead Air Concentrations 3-75
Table 3-21. Available Carcinogenicity Information 3-81
Table 3-22. Summary of RfC and RfD Information used in Risk Characterization for Non-Proprietary Ingredients 3-84
Table 3-23. NOAEL/LOAEL Values Used in Risk Characterization for Non-Proprietary Ingredients 3-87
Table 3-24. Developmental Toxicity Values Used in Risk Characterization for Non-Proprietary Ingredients 3-88
Table 3-25. Summary of Health Effects Information 3-89
Table 3-26. Overview of Available Toxicity Data 3-93
Table 3-27. Estimated (Lowest) Aquatic Toxicity Values and Concern Concentrations for PWB Surface Finishing Chemicals, Based on Measured Test Data or SAR Analysis 3-96
Table 3-28. Environmental Hazard Ranking of PWB Finishing Chemicals 3-100

Table 3-29. Gastrointestinal (GI) Absorption Factors 3-112
Table 3-30. Summary of Human Health Risks From Occupational Inhalation Exposure for Selected Chemicals 3-116
Table 3-31. Summary of Human Health Risks Results From Occupational Dermal Exposure for Selected Chemicals 3-118
Table 3-32. Summary of Potential Human Health Effects for Chemicals of Concern . . . 3-121
Table 3-33. Data Gaps for Chronic Non-Cancer Health Effects for Workers 3-122
Table 3-34. Risk Evaluation Summary for Lead 3-126
Table 3-35. Summary of Aquatic Risk Indicators for Non-Metal Chemicals of Concern 3-129
Table 3-36. Summary of Aquatic Risk Indicators for Metals Assuming No On-Site Treatment 3-130
Table 3-37. Overall Comparison of Potential Human Health and Ecological Risks for the Non-Conveyorized HASL and Alternative Processes 3-136
Table 3-38. Flammable, Combustible, Explosive, and Fire Hazard Possibilities for Surface Finishing Processes 3-139
Table 3-39. Corrosive, Oxidizer, Reactive, Unstable, and Sudden Release of Pressure Possibilities for Surface Finishing Processes 3-141
Table 3-40. Sensitizer, Acute and Chronic Health Hazards, and Irreversible Eye Damage Possibilities for Surface Finishing Processes 3-143
Table 4-1. Electrical Responses for the Test PWA and Acceptance Criteria 4-6
Table 4-2. Distribution of the Number of LRSTF PWAs by Surface Finish, Site, and Flux 4-7
Table 4-3. Listing of 23 Site/Flux Combinations Used in the Multiple Comparisons Analyses 4-11
Table 4-4. Number of Anomalies Observed at Each Test Time 4-13
Table 4-5. Percentage of Circuits Meeting Acceptance Criteria at Each Test Time 4-14
Table 4-6. Comparison of CCAMTF Pre-Test Ranges with DfE Pre-Test Measurements 4-15
Table 4-7. Frequency Distribution of Post 85/85 Anomalies per PWA by Surface Finish 4-16
Table 4-8. Frequency Distribution of Post-Thermal Shock Anomalies per PWA by Surface Finish 4-17
Table 4-9. Frequency Distribution of Post-Mechanical Shock Anomalies per PWA by Surface Finish 4-18
Table 4-10. P-Values for HCLV Test Results 4-19
Table 4-11. Number of HCLV PTH Anomalies at Post-Mechanical Shock by Surface Finish 4-20
Table 4-12. P-Values for HVLC Test Results 4-21
Table 4-13. P-Values for HSD Test Results 4-22
Table 4-14. P-Values for HF LPF Test Results 4-23
Table 4-15. Frequency Distribution of HF LPF Anomalies at Post-Mechanical Shock per PWA 4-25
Table 4-16. Comparison of the Observed and Expected Number of Anomalies for the HF LPF PTH 50MHz Circuit by Surface Finish 4-26

Table 4-17. Comparison of the Observed and Expected Number of Anomalies Under the Hypothesis of Independence of Surface Finishes 4-26
Table 4-18. P-Values for HF TLC Test Results 4-28
Table 4-19. P-Values for Leakage Test Results 4-30
Table 4-20. P-Values for Stranded Wire Test Results 4-32
Table 4-21. Identification of Assemblies Selected for Ion Chromatography Analysis 4-35
Table 4-22. Ion Chromatography Anion $^{(-)}$ Data (HASL) 4-36
Table 4-23. Ion Chromatography Anion $^{(-)}$ Data (Immersion Tin) 4-36
Table 4-24. Ion Chromatography Anion $^{(-)}$ Data (Immersion Silver) 4-37
Table 4-25. Ion Chromatography Anion $^{(-)}$ Data (Nickel/Gold) 4-37
Table 4-26. Ion Chromatography Anion $^{(-)}$ Data (OSP) 4-37
Table 4-27. Ion Chromatography Anion $^{(-)}$ Data (Nickel/Palladium/Gold) 4-38
Table 4-28. Acceptance Levels for Weak Organic Acids 4-39
Table 4-29. Frequency of Anomalies by Individual Circuit Over Test Times 4-41
Table 4-30. Surface Finishing Processes Evaluated in the Cost Analysis 4-55
Table 4-31. Cost Component Categories 4-58
Table 4-32. Number of Filter Replacements by Surface Finishing Process 4-62
Table 4-33. Bath Volumes Used for Conveyorized Processes 4-64
Table 4-34. Time-Related Input Values for Non-Conveyorized Processes 4-65
Table 4-35. Time-Related Input Values for Conveyorized Processes 4-65
Table 4-36. Bath Replacement Criteria for Nickel/Gold Processes 4-66
Table 4-37. Frequency and Duration of Bath Replacements for Non-Conveyorized Nickel/Gold Process 4-67
Table 4-38. Production Time and Down Time for the Surface Finishing Processes to Produce 260,000 ssf of PWB 4-68
Table 4-39. BOA for Transportation of Chemicals to the Surface Finishing Process Line 4-70
Table 4-40. Costs of Critical Tasks 4-71
Table 4-41. Materials Cost for the Non-Conveyorized Nickel/Gold Process 4-76
Table 4-42. Chemical Cost per Bath Replacement for One Product Line of the Non-Conveyorized Nickel/Gold Process 4-76
Table 4-43. Tiered Cost Scale for Monthly Wastewater Discharges to a POTW 4-79
Table 4-44. Summary of Costs for the Non-Conveyorized Nickel/Gold Process 4-83
Table 4-45. Total Cost of Surface Finishing Technologies 4-84
Table 4-46. Surface Finishing Alternative Unit Costs for Producing 260,000 ssf of PWB 4-86
Table 4-47. CWA Regulations That May Apply to Chemicals in the Surface Finishing Process 4-89
Table 4-48. Printed Circuit Board Facilities Discharging Less than 38,000 Liters per Day PSES Limitations (mg/L) 4-91
Table 4-49. Printed Circuit Board Facilities Discharging 38,000 Liters per Day or More PSES Limitations (mg/L) 4-91
Table 4-50. PSNS for Metal Finishing Facilities 4-92
Table 4-51. Amenable Cyanide Limitation Upon Agreement 4-92
Table 4-52. PSES for All Plants Except Job Shops and Independent PWB Manufacturers 4-92

Table 4-53. CAA Regulations That May Apply to Chemicals in the Surface Finishing Process 4-93
Table 4-54. CERCLA RQs That May Apply to Chemicals in the Surface Finishing Process 4-97
Table 4-55. SARA and EPCRA Regulations That May Apply to Chemicals in the Surface Finishing Process 4-99
Table 4-56. TSCA Regulations and Lists That May Apply to Chemicals Used in Surface Finishing Processes 4-100
Table 4-57. Summary of Regulations that May Apply to Chemicals Used in Hot Air Solder Leveling (HASL) Technology 4-102
Table 4-58. Summary of Regulations that May Apply to Chemicals Used in Nickel/Gold Technology 4-103
Table 4-59. Summary of Regulations that May Apply to Chemicals Used in Nickel/Palladium/Gold Technology 4-104
Table 4-60. Summary of Regulations that May Apply to Chemicals Used in OSP Technology 4-105
Table 4-61. Summary of Regulations that May Apply to Chemicals Used in Immersion Silver Technology 4-106
Table 4-62. Summary of Regulations that May Apply to Chemicals Used in Immersion Tin Technology 4-107
Table 5-1. Effects of Surface Finishing Technology on Resource Consumption 5-2
Table 5-2. Normalized Water Flow Rates of Various Water Rinse Types 5-4
Table 5-3. Rinse Water Consumption Rates and Total Water Consumed by Surface Finishing technologies 5-5
Table 5-4. Metal Deposition Rates and Total Metal Consumed by Surface Finishing Technologies 5-7
Table 5-5. Energy-Consuming Equipment Used in Surface Finishing Process Lines . . . 5-13
Table 5-6. Number of Surface Finishing Process Stages that Consume Energy by Function of Equipment 5-14
Table 5-7. Energy Consumption Rates for Surface Finishing Equipment 5-15
Table 5-8. Hourly Energy Consumption Rates for Surface Finishing Technologies 5-16
Table 5-9. Energy Consumption Rate per ssf of PWB Produced for Surface Finishing Technologies 5-17
Table 5-10. Effects of Automation on Energy Consumption for Surface Finishing Technologies 5-18
Table 5-11. Pollution Resulting From the Generation of Energy Consumed by Surface Finishing Technologies 5-20
Table 5-12. Pollutant Environmental and Human Health Concerns 5-21
Table 6-1. Management and Personnel Practices Promoting Pollution Prevention 6-4
Table 6-2. Materials Management and Inventory Control Pollution Prevention Practices 6-6
Table 6-3. Pollution Prevention Practices to Reduce Bath Contaminants 6-9
Table 6-4. Methods for Reducing Chemical Bath Drag-Out 6-11
Table 6-5. Bath Maintenance Improvement Methods to Extend Bath Life 6-12
Table 6-6. Typical Value of Reclaimed Metals (1999) and Recovery Methods 6-26
Table 6-7. Applicability of Recovery/Reclamation Technologies by Bath Type 6-28

Table 6-8. Treatment Chemicals Used to Remove Metals From Chelated Wastewater . . 6-34
Table 6-9. Treatment Profile of PWB Surface Finishing Process Baths 6-36
Table 7-1. Surface Finishing Processes Evaluated in the CTSA 7-1
Table 7-2. Surface Finishing Chemicals of Concern for Potential Occupational Inhalation Risk 7-4
Table 7-3. Chemicals of Concern for Potential Dermal Risks 7-5
Table 7-4. Aquatic Risk of Non-Metal Chemicals of Concern 7-7
Table 7-5. Chemical Hazards 7-8
Table 7-6. Cost of Surface Finishing Technologies 7-11
Table 7-7. Regulatory Status of Surface Finishing Technologies 7-13
Table 7-8. Energy and Water Consumption Rates of Surface Finishing Alternatives . . . 7-14
Table 7-9. Glossary of Benefits/Costs Analysis Terms 7-17
Table 7-10. Overview of Potential Private and External Benefits or Costs 7-20
Table 7-11. Overall Cost Comparison, Based on Manufacturing 260,000 ssf 7-21
Table 7-12. Summary of Occupational Hazards, Exposures, and Risks of Potential Concern 7-22
Table 7-13. Potential Health Effects Associated with Surface Finishing Chemicals of Concern 7-23
Table 7-14. Number of Chemicals with Estimated Surface Water Concentration Above Concern Concentration 7-26
Table 7-15. Energy and Water Consumption of Surface Finishing Technologies 7-27
Table 7-16. Examples of Private Costs and Benefits Not Quantified 7-28
Table 7-17. Summary of Human Health and Environmental Risk Concerns for the HASL Technology 7-31
Table 7-18. Number of HASL Chemicals Subject to Applicable Federal Regulations 7-34
Table 7-19. Summary of Human Health and Environmental Risk Concerns for the Nickel/Gold Technology 7-35
Table 7-20. Number of Nickel/Gold Chemicals Subject to Applicable Federal Regulations 7-39
Table 7-21. Summary of Human Health and Environmental Risk Concerns for the Nickel/Palladium/Gold Technology 7-40
Table 7-22. Number of Nickel/Palladium/Gold Chemicals Subject to Applicable Federal Regulations 7-43
Table 7-23. Summary of Human Health and Environmental Risk Concerns for the OSP Technology 7-45
Table 7-24. Number of OSP Chemicals Subject to Applicable Federal Regulations 7-47
Table 7-25. Summary of Human Health and Environmental Risk Concerns for the Immersion Silver Technology 7-48
Table 7-26. Number of Immersion Silver Chemicals Subject to Applicable Federal Regulations 7-50
Table 7-27. Summary of Human Health and Environmental Risk Concerns for the Immersion Tin Technology 7-51
Table 7-28. Number of Immersion Tin Chemicals Subject to Applicable Federal Regulations 7-54

List of Figures

Figure 1-1. PWBs Produced for World Market in 1998 (IPC) 1-6
Figure 1-2. Number of PWBs Produced by U.S. Manufacturers in 1998 (IPC) 1-7
Figure 2-1. Typical Process Steps for Surface Finishing Technologies 2-2
Figure 2-2. HASL Process Flow Diagram 2-6
Figure 2-3. Nickel/Gold Process Flow Diagram 2-8
Figure 2-4. Nickel/Palladium/Gold Process Flow Diagram 2-11
Figure 2-5. OSP Process Flow Diagram 2-13
Figure 2-6. Immersion Silver Process Flow Diagram 2-15
Figure 2-7. Immersion Tin Process Flow Diagram 2-16
Figure 3-1. Schematic of Overall Material Balance for Surface Finishing Technologes 3-4
Figure 3-2 Wastewater Treatment Process Flow Diagram 3-5
Figure 3-3. Generic HASL Process Steps and Typical Bath Sequence 3-18
Figure 3-4. Generic Nickel/Gold Process Steps and Typical Bath Sequence 3-21
Figure 3-5. Generic Nickel/Palladium/Gold Process Steps and Typical Bath Sequence . . 3-24
Figure 3-6. Generic OSP Process Steps and Typical Bath Sequence 3-27
Figure 3-7. Generic Immersion Silver Process Steps and Typical Bath Sequence 3-29
Figure 3-8. Generic Immersion Tin Process Steps and Typical Bath Sequence 3-32
Figure 3-9. Relationship Between Intake Rate and Blood-Lead Level for Both Adult and Fetus 3-73
Figure 4-1. Boxplot Displays for HCLV PTH Measurements (volts) at Pre-Test by Surface Finish 4-43
Figure 4-2. Boxplot Displays for HCLV PTH Post 85/85 - Pre-Test Measurements (volts) by Surface Finish 4-43
Figure 4-3. Boxplot Displays for HCLV PTH Post TS - Pre-Test Measurements (volts) by Surface Finish 4-44
Figure 4-4. Boxplot Displays for HCLV PTH Post MS - Pre-Test Measurements (volts) by Surface Finish 4-44
Figure 4-5. Boxplot Displays for HCLV SMT Measurements (volts) by Surface Finish 4-45
Figure 4-6. Boxplot Displays for HCLV PTH Post 85/85 - Pre-Test Measurements (volts) by Surface Finish 4-45
Figure 4-7. Boxplot Displays for HCLV PTH Post TS - Pre-Test Measurements (volts) by Surface Finish 4-46
Figure 4-8. Boxplot Displays for HCLV PTH Post MS - Pre-Test Measurements (volts) by Surface Finish 4-46
Figure 4-9. Boxplot Displays for HF PTH 50MHz Measurements (volts) by Surface Finish 4-47
Figure 4-10. Boxplot Displays for HF PTH 50MHz Post MS - Pre-Test Measurements (volts) by Surface Finish 4-47
Figure 4-11. Boxplot Displays for HF PTH f(-3dB) Post MS - Pre-Test Measurements (MHz) by Surface Finish 4-48
Figure 4-12. Boxplot Displays for HF PTH f(-40dB) Post MS - Pre-Test Measurements (MHz) by Surface Finish 4-48

Figure 4-13. Boxplot Displays for HF SMT 50MHz Post Ms - Pre-Test Measurements (dB) by Surface Finish 4-49
Figure 4-14. Boxplot Displays for HF SMT f(-3dB) Post MS - Pre-Test Measurements (MHz) by Surface Finish 4-49
Figure 4-15. Boxplot Displays for HF PTH f(-40dB) Post MS - Pre-Test Measurements (MHz) by Surface Finish 4-50
Figure 4-16. Boxplot Displays for HF TLC 50MHz Post MS - Pre-Test Measurements (dB) by Surface Finish 4-50
Figure 4-17. Boxplot Displays for HF TLC 500MHz Post MS - Pre-Test Measurements (dB) by Surface Finish 4-51
Figure 4-18. Boxplot Displays for HF TLC RNR Post MS - Pre-Test Measurements (dB) by Surface Finish 4-51
Figure 4-19. Boxplot Displays for 10-Mil Pad Measurements ($\log_{10}$ ohms) at Pre-Test by Surface Finish 4-52
Figure 4-20. Boxplot Displays for 10-Mil Pad 85/85 Pre-Test Measurements ($\log_{10}$ ohms) by Surface Finish 4-52
Figure 4-21. Boxplot Displays for PGA-A Measurements ($\log_{10}$ ohms) at Pre-Test by Surface Finish 4-53
Figure 4-22. Boxplot Displays for PGA-B Measurements ($\log_{10}$ ohms) at Pre-Test by Surface Finish 4-53
Figure 4-23. Boxplot Displays for the Gull Wing Measurements ($\log_{10}$ ohms) at Pre-Test by Surface Finish 4-54
Figure 4-24. Hybrid Cost Analysis Framework 4-56
Figure 5-1. Water Consumption Rates of Surface Finishing Technologies 5-5
Figure 6-1. Solder Reclaim System Diagram 6-21
Figure 6-2. Flow Diagram of Combination Ion Exchange and Electrowinning Recovery System for Metal Recovery 6-24
Figure 6-3. Reverse Osmosis Water Reuse System 6-25
Figure 6-4. Typical PWB Waste Treatment System 6-32
Figure 7-1. Production Costs and Resource Consumption of Conveyorized HASL Technology 7-33
Figure 7-2. Production Costs and Resource Consumption of the Nickel/Gold Technology 7-38
Figure 7-3. Production Costs and Resource Consumption of Nickel/Palladium/Gold Technology 7-43
Figure 7-4. Production Costs and Resource Consumption of OSP Technology 7-46
Figure 7-5. Production Costs and Resource Consumption of Immersion Silver Technology 7-49
Figure 7-6. Production Costs and Resource Consumption of Immersion Tin Technology 7-54

Acronyms

ABC	activity-based costing
ADD	average daily dose
ADI	acceptable daily intake
ACGIH	American Conference of Governmental Industrial Hygenists, Inc.
ALM	Adult Lead Methodology)
ANOVA	an analysis of variance
ASF	alternative surface finishing
AT	averaging time
ATSDR	Agency for Toxic Substances and Disease Registry
BAT	best available control technology economically achievable
BCP	best conventional pollution control technology
BGA	ball grid array
BKSF	biokinetic slope factor
BOA	bill of activities
BOD	biological oxygen demand
BPT	best practicable control technology currently available
Btu	British Thermal Units
BW	body weight
CAA	Clean Air Act
CC	concern concentration
CCAMTF	Circuit Card Assembly and Materials Task Force
CDC	Centers for Disease Control and Prevention
CEB	Chemical Engineering Branch
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CFR	Code of Federal Regulations
CO	carbon monoxide
CO_2	carbon dioxide
COB	chip on board
CSL	Contamination Studies Laboratories, Inc.
CTSA	Cleaner Technologies Substitutes Assessment
$CuSO_4$	copper sulfate
CWA	Clean Water Act
DCT	dimethyl-dithiocarbamate
DfE	Design for the Environment
ED	exposure duration
EDTA	ethylenediaminetetraacedic acid
EF	exposure frequency
EMS	Environmental Management System
EPA	Environmental Protection Agency
EPCRA	Emergency Planning and Community Right-to-Know Act
HCLV	high current low voltage
HVLC	high voltage low current
HSD	high speed digital

HF LPF	high frequency low pass filter
HF TLC	high frequency transmission line coupler
g	gram
gal	gallon
GI	gastrointestinal
GLM	general linear models
gpm	gallons per minute
GRAS	generally recognized as safe
GSD	geometric standard deviation
gpm	gallons per minute
H_2SO_4	sulfuric acid
HASL	hot air solder leveling
H_C	Henry's Law Constant
HCLV	high current low voltage
HEAST	Health Effects Assessment Summary Tables
HF	high frequency
HQ	hazard quotient
HSD	high speed digital
HSDB	Hazardous Substances Data Bank
HVLC	high voltage low current
IARC	International Agency for Research on Cancer
IEUBK	integrated exposure uptake biokinetic model for lead in Children
IPC	Institute for Interconnecting and Packaging Electronics Circuits
IQR	interquartile range
IR	intake rate
IRIS	Integrated Risk Information System
ISO	International Standards Organization
KUB	Knoxville Utilities Board
kW	kilowatt
LADD	lifetime average daily dose
LOAEL	lowest-observed-adverse-effect level
LR	low residue
LRSTF	Low-Residue Soldering Task Force
LSD	least significant difference
LT	lab technical
MACT	Maximum Achievable Control Technology
MHC	making holes conductive
MnO_2	manganese dioxide
MOE	margin of exposure
MRL	minimum risk level
MSDS	material safety data sheet
MTL	Master Testing List
N_aOH	caustic soda
NCP	National Contingency Plan
NIOSH	National Institute for Occupational Safety and Health
NOAEL	no-observed-adverse-effect level

NOx	oxides of nitrogen
NPDES	National Pollutant Discharge Elimination System
NPDWR	National Primary Drinking Water Regulations
NSDWR	National Secondary Drinking Water Regulations
NSPS	New Source Performance Standards
NTP	National Toxicology Program
ON	other networks
OSP	organic solderability preservative
OSHA	Occupational Safety and Health Administration
PEL	permissible exposure limit
PDR	potential dose rate
POTW	publicly owned treatment work
PPE	personal protective equipment
PSES	pretreatment standards for existing xources
PSNS	pretreatment standards for new sources
psi	per square inch
PTH	plated-through holes
PWAs	printed wiring assemblies
PWB	printed wiring board
RCRA	Resource Conservation and Recovery Act
REL	recommended exposure level
RfC	reference concentration
RfD	reference dose
RO	reverse osmosis
RTECS	Registry of Toxic Effects of Chemical Substances
RQ	reportable quantity
SAR	structure-activity relationship
SARA	Superfund Amendments and Reauthorization Act
SAT	Structure-Activity Team
SDWA	Safe Drinking Water Act
SERC	State Emergency Response Commission
SF	slope factor
SIC	standard industrial code
SMT	surface mount technology
SO_x	sulfur oxides
SPC	statistical process control
ssf	surface square feet
STEL	short-term exposure limit
SW	stranded wire
TMT 15	tri-mercaptotriazine
TLC	transmission line coupler
TLV	threshold limit value
TPY	tons per year
TRI	Toxic Release Inventory
TS	thermal shock
TSCA	Toxic Substances Control Act

TSDS	treatment, storage, or disposal facility
TWA	time-weighed average
UC	unit cost
UF	uncertainty factor
UT	University of Tennessee
UR	utilization ratio
VOC	volatile organic compounds
WHO	World Health Organization
WOA	weak organic acid
WOE	weight-of-evidence
WS	water soluble

Executive Summary

The *Printed Wiring Board Surface Finishes Cleaner Technologies Substitutes Assessment: Volume 1* is a technical document that presents comparative risk, competitiveness, and resource requirements information on six technologies for performing the surface finishing function during printed wiring board (PWB) manufacturing. Surface finishing technologies are used by PWB manufacturers to deposit a coating on the outside surfaces of the PWB that provides a solderable surface for future assembly, while also protecting the surface from contamination. The technologies evaluated include hot air solder leveling (HASL), electroless nickel/immersion gold (nickel/gold), electroless nickel/immersion palladium/immersion gold (nickel/palladium/gold), organic solderability preservative (OSP), immersion silver, and immersion tin. Volume I describes the surface finishing technologies, methods used to assess the technologies, and Cleaner Technologies Substitutes Assessment (CTSA) results. Volume II contains appendices, including detailed chemical properties and methodology information.

Information presented in the CTSA was developed by the U.S. Environmental Protection Agency (EPA) Design for the Environment (DfE) Printed Wiring Board (PWB) Project and the University of Tennessee (UT) Center for Clean Products and Clean Technologies. The DfE PWB Project is a voluntary, cooperative partnership among EPA, industry, public-interest groups, and other stakeholders to promote implementation of environmentally beneficial and economically feasible manufacturing technologies by PWB manufacturers. Project partners participated in the planning and execution of this CTSA by helping define the scope and direction of the CTSA, developing project workplans, reviewing technical information contained in this CTSA and donating time, materials, and their manufacturing facilities for project research. Much of the process-specific information presented here was provided by chemical suppliers for the PWB industry, PWB manufacturers who completed project information requests, and PWB manufacturers who volunteered their facilities for a performance demonstration of the baseline and alternative technologies.

The CTSA is intended to provide PWB manufacturers with information that can assist them in making decisions that incorporate environmental concerns, along with performance and cost information, when choosing a surface finishing technology. The DfE PWB Project is especially designed to assist PWB manufacturers who may not have the resources or expertise to compare surface finishing technologies. The primary audience for the CTSA is environmental health and safety personnel, chemical and equipment manufacturers and suppliers in the PWB manufacturing industry, PWB assembly shops, community groups concerned about community health risks, and other technically informed decision-makers.

I. DESIGN FOR THE ENVIRONMENT PRINTED WIRING BOARD PROJECT

The DfE PWB Project is a joint effort of the EPA DfE Program and the UT Center for Clean Products and Clean Technologies in voluntary and cooperative partnerships with the PWB industry national trade association, the IPC-Association Connecting Electronics Industries (IPC); individual PWB manufacturers and suppliers; and public-interest organizations, including the Silicon Valley Toxics Coalition.

EPA's Design for the Environment Program

The EPA DfE Program was established by the Office of Pollution Prevention and Toxics to use EPA's expertise and leadership to facilitate information exchange and research on risk reduction and pollution prevention opportunities. DfE works on a voluntary basis with industry sectors to evaluate the risks, performance, costs, and resource requirements of alternative chemicals, processes, and technologies.

Additional goals of the program include:

- Changing general business practices to incorporate environmental concerns.
- Helping individual businesses undertake environmental design efforts through the application of specific tools and methods.

DfE Partners include:

- industry;
- professional institutions;
- academia;
- public-interest groups; and
- other government agencies.

In part, the project is an outgrowth of industry studies to identify key cleaner technology needs in electronic systems manufacturing. These studies include *Environmental Consciousness: A Strategic Competitiveness Issue for the Electronics Industry* (MCC, 1993), the *Electronics Industry Environmental Roadmap* (MCC, 1994), and the *National Technology Roadmap for Electronic Interconnections* (IPC, 1996). The first two studies identified environmental issues as priority targets for improvement by industry, while concluding that improvement would be accomplished most effectively through collaboration with government, academia, and the public. The final study cited the development of non-tin/lead metallic or organic coatings to retain solderability characteristics as an industry need over the near term. The potential for improvement in these areas led EPA's DfE Program to forge the working partnerships that resulted in the DfE PWB Project.

Since its inception in 1994, the PWB Project has fostered open and active participation in addressing environmental challenges faced by the PWB industry. The Project also has identified, evaluated, and disseminated information on viable pollution prevention opportunities in the industry; conducted a study of industry pollution prevention and control practices; and completed a study of making holes conductive alternatives, among other project efforts. Over the long-term, the Project seeks to encourage companies to consider implementing cleaner technologies that will improve the environmental performance and competitiveness of the PWB industry. Toward this goal, the CTSA presents the complete set of information developed by the Project on the risk, competitiveness (e.g., cost and performance), and resource requirements of cleaner technologies for applying a surface finish to a PWB.

II. OVERVIEW OF SURFACE FINISHING TECHNOLOGIES

Until the late 1980s, virtually all PWB manufacturers employed a HASL process to apply the final surface finish to PWBs. The HASL process applies a thin layer of solder to the panel surface by submerging the panel in molten solder, then removing the excess solder with an air knife as the panel is removed. Although the traditional HASL process is a mature technology that produces reliable surface connections, the finish has become limiting with respect to state-of-the-art component technology that requires special assembly. It is also a significant source of lead consumption in the PWB manufacturing process. In recent years, the advancements in component technology, along with public and private concerns over the use of lead, have led the PWB industry to seek viable alternative surface finishes.

Process Description

Surface finishing processes typically consist of a series of sequential chemical processing stages separated by water rinse tanks. The process can either be operated in a vertical, non-conveyorized immersion-type mode, or in a horizontal, conveyorized mode. In either mode, selected baths may be operated at an elevated temperature to facilitate required chemical reactions, or agitated to improve contact between the panels and the bath chemistry. Agitation methods employed by PWB manufacturers include panel agitation, air sparging, and fluid circulation pumps.

Most process baths are followed by a water rinse tank to remove drag-out (i.e., the clinging film of process solution covering the rack and boards when they are removed from a tank). Rinsing is necessary to clean the surface of the rack and boards to avoid contaminating subsequent process baths. Many PWB manufacturers employ a variety of rinse water reduction methods to reduce rinse water usage and consequent wastewater generation rates. The nature and quantity of wastewater generated from surface finishing process lines are discussed in Section 3.1, Source Release Assessment, while rinse water reduction techniques are discussed in Section 6.1, Pollution Prevention.

In the non-conveyorized mode, etched panels, covered with solder mask, are loaded onto a rack and processed through the surface finishing process line. Racks may be manually moved from tank to tank, or moved by a manually-controlled hoist or other means. Process tanks usually are open to the atmosphere. To reduce volatilization of chemicals from the bath or worker exposure to volatilized chemicals, process baths may be equipped with a local ventilation system, such as a push-pull system, bath covers for periods of inactivity, or floating plastic balls. Conveyorized systems typically are fully enclosed, with air emissions vented to a control technology or to the air outside the plant.

The HASL process combines wet chemistry steps, similar to those described above, with mechanical HASL equipment. First, panels are passed through a series of wet chemistry cleaning and etching steps to prepare the surface of the panel for the solder. Then, the solder is applied to the panel by dipping it into molten solder and removing the excess with high pressure air. After leaving the HASL machine, panels are cleaned by a water-based, high pressure rinse system.

Generic Process Steps and Bath Sequences of Surface Finishing Technologies

Figure ES-1 presents the generic process steps and typical bath sequences evaluated in the CTSA. The process baths depicted in the figure are an integration of the various products submitted for evaluation by chemical suppliers within a technology category. For example, two different OSP processes were submitted by chemical suppliers for evaluation in the CTSA, and these and other suppliers offer additional OSP processes that may have slightly different bath chemistries or bath sequences. In addition, the bath sequences (bath order and rinse tank configuration) were aggregated from data collected from various PWB facilities using the different surface finishing technologies. Thus, Figure ES-1 lists the types and sequences of baths in generic process lines; however, the types and sequences of baths in actual lines may vary.

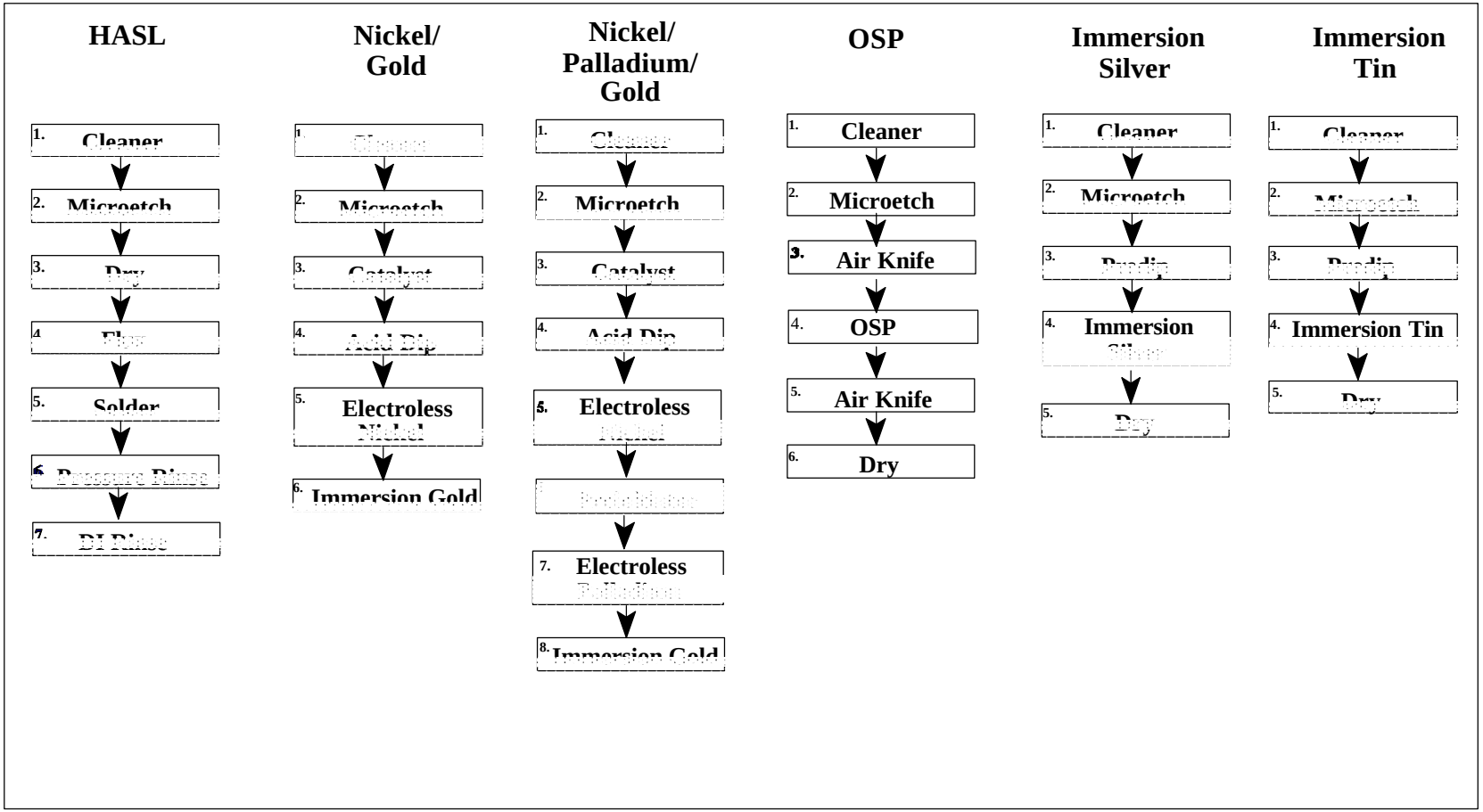
Table ES-1 presents the processes evaluated in the CTSA. These are distinguished both by process technology and equipment configuration (non-conveyorized or conveyorized). The non-conveyorized HASL process is the industry standard for performing the surface finishing function and is the baseline process against which alternative technologies and equipment configurations are compared.

Table ES-1. Surface Finishes Evaluated in the CTSA

Surface Finishing Technology	Equipment Configuration	
	Non-Conveyorized	Conveyorized
HASL (Baseline)	X	X
Nickel/Gold	X	
Nickel/Palladium/Gold	X	
OSP	X	X
Immersion Silver		X
Immersion Tin	X	X

III. CLEANER TECHNOLOGIES SUBSTITUTES ASSESSMENT METHODOLOGY

The CTSA methodology is a means of systematically evaluating and comparing human health and environmental risk, competitiveness (e.g., performance and cost), and resource requirements of traditional and alternative chemicals, manufacturing methods, and technologies that can be used to perform the same function. The publication, *Cleaner Technologies Substitutes Assessment: A Methodology & Resource Guide* (Kincaid et al., 1996), presents the basic CTSA methodology in detail. Particular methods used in this assessment are described in chapters 2 through 6 of this document, and in the appendices (*Printed Wiring Board Surface Finishes Cleaner Technologies Substitutes Assessment: Volume 2).*



Note: One or more intermediate rinse steps typically separate the process steps listed above. For simplicity, these intermediate rinse steps have not been included in the diagram.

Figure ES-1. Typical Process Steps for Surface Finishing Technologies

Key to the successful completion of any CTSA is the active participation of manufacturers and their suppliers. This assessment was open to any surface finishing chemical supplier who wanted to submit a technology, provided the technology met the following criteria:

- it is an existing or emerging technology; and
- the equipment and facilities are available to demonstrate its performance.

In addition, suppliers were required to provide information about their technologies, including complete chemical product formulation data, process schematics, process characteristics and constraints (e.g., cycle time, bath immersion time, thickness of deposit), bath replacement criteria, and cost information.

Issues Evaluated

The CTSA evaluated a number of issues related to the risk, competitiveness, and resource requirements (conservation) of surface finishing technologies. These include the following:

- Risk: occupational health risks, public health risks, ecological hazards, and process safety concerns.
- Competitiveness: technology performance, cost, and regulatory status.
- Conservation: energy and natural resource use.

Occupational and public health risk information is for chronic exposure to long-term, day-to-day releases from a PWB facility, rather than short-term, acute exposures to high levels of hazardous chemicals as could occur with a fire, spill, or periodic release. Risk information is based on exposures estimated for a typical, model facility, rather than exposures estimated for a specific facility. Ecological risks are evaluated for aquatic organisms that could be exposed to surface finishing chemicals in wastewater discharges. Process safety concerns are summarized from material safety data sheets (MSDSs) for the technologies and process operating conditions.

Technology performance is based on a snapshot of the performance of the surface finishing technologies at volunteer test sites in the United States and abroad. Panels were tested under accelerated aging conditions (three weeks of 85 ºC/85 percent humidity), followed by thermal shock testing, and mechanical shock testing to distinguish variability in the performance of the surface finish. Comparative costs of the surface finishing technologies were estimated with a hybrid cost model that combines traditional costs with simulation modeling and activity-based costs. Costs are presented in terms of dollars per surface square feet (ssf) of PWB produced.

Federal environmental regulatory information is presented for the chemicals in the surface finishing technologies. This information is intended to provide an indication of the regulatory requirements potentially associated with a technology, but not to serve as regulatory guidance.

Quantitative resource consumption data are presented for the comparative rates of energy and water use of the surface finishing technologies. The consumption of other non-renewable resources such as process chemicals and metals also are analyzed.

Finally, a socio-economic costs and benefits analysis of the operation of the surface finishing process line is presented for each of the process alternatives. The private costs and benefits to the manufacturer resulting from the use of a technology, as well as the external costs and benefits to workers and the community are evaluated quantitatively or qualitatively.

Data Collection

Determining the risks of the baseline and alternative surface finishing technologies required information on the chemical products for each process. Chemical information provided by chemical suppliers included the following publicly-available sources of information: MSDSs for the chemical products in their surface finishing technology lines and Product Data Sheets, which are technical specifications prepared by suppliers for PWB manufacturers that describe how to mix and maintain the chemical baths. Suppliers also were asked to provide the identities and concentrations of proprietary chemical ingredients to the project.

Data Collection Forms

Appendix A in Volume II of the CTSA presents data collection forms used by the project, including the following:

- The PWB Workplace Practices Questionnaire, which requested detailed information on facility size, process characteristics, chemical consumption, and worker activities related to chemical exposure, water consumption, and wastewater discharges.
- The Facility Background Information Sheet (developed from the PWB Workplace Practices Questionnaire) which was sent to PWB facilities participating in the Performance Demonstration prior to their surface technology test date. This sheet requested detailed information on facility and process characteristics, chemical consumption, and worker activities related to chemical exposure, water consumption, and wastewater discharges.
- The Observer Data Sheet, which was used by an on-site observer to collect data during the Performance Demonstration. In addition to ensuring that the performance test was performed according to the agreed-upon test protocol, the on-site observer collected measured data, such as bath temperature and process line dimensions, and checked survey data for accuracy.
- The Supplier Data Sheet, which included information on chemical cost, equipment cost, water consumption rates, product constraints, and the locations of test sites for the Performance Demonstration.

Chemical Information

Appendix B presents chemical properties and selected environmental fate properties for the non-proprietary chemicals in surface finishing chemical products. Proprietary chemical ingredients are not included to protect proprietary chemical identities. Properties that were measured or estimated (using a variety of standard EPA methods) included melting point, solubility, vapor pressure, octanol-water partition coefficient, boiling point, and flash point.

These properties can be used to determine the environmental fate of the surface finishing chemicals when they are released to the environment.

Health Hazard Assessments

Inherent in determining the risk associated with the surface finishing chemicals is a determination of the hazard or toxicity of the chemicals. Human health hazard information for non-proprietary chemicals is presented in Section 3.3. Detailed toxicity data for proprietary chemicals are not included to maintain the secrecy of the proprietary chemical formulations. Many of the chemicals in the surface finishing chemical products have been studied to determine their health effects, and data from those studies are available in published scientific literature. In order to collect available testing data for the surface finishing chemicals, literature searches were conducted using standard chemical references and online databases, including EPA's Integrated Risk Information System (IRIS) and the National Library of Medicine's Hazardous Substances Data Bank (HSDB).

For many of the chemicals, EPA has identified chemical exposure levels that are known to be hazardous if exceeded or met (e.g., no- or lowest-observed-adverse-effect level [NOAEL or LOAEL]), or levels that are protective of human health (reference concentration [RfC] or reference dose [RfD]). These values were taken from online databases and published literature. For many of the chemicals lacking toxicity data, EPA's Structure-Activity Team (SAT) estimated human health concerns based on analogous chemicals. Hazard information is combined with estimated exposure levels to develop an estimate of the risk associated with each chemical.

Ecological Hazard Assessments

Similar information was gathered on the ecological effects that may be expected if surface finishing chemicals are released to water. Acute and chronic toxicity values were taken from online database searches (TOXNET and ACQUIRE), published literature, or were estimated using structure-activity relationships if measured data were not available. Based on the toxicity values, surface finishing chemicals were assigned concern concentrations (CCs). A CC is the concentration of a chemical in the aquatic environment which, if exceeded, may result in significant risk to aquatic organisms. CCs were determined by dividing acute or chronic toxicity values by an assessment factor (ranging from one to 1,000) that incorporates the uncertainty associated with toxicity data.

Limitations

There are a number of limitations to the project, both because of the limit of the project's resources, the predefined scope of the project, and uncertainties inherent to risk characterization techniques. Some of the limitations related to the risk, competitiveness, and conservation components of the CTSA are summarized below. More detailed information on limitations and uncertainties for a particular portion of the assessment is given in the applicable sections of this document. A limitation common to all components of the assessment is that the surface finishing chemical products assessed in this report were voluntarily submitted by participating suppliers and may not represent the entire surface finishing technology market.

Risk Screening and Comparison

The risk screening and comparison is a screening level assessment of multiple chemicals used in surface finishing technologies. The focus of the risk characterization is chronic (long-term) exposure to chemicals that may cause cancer or other toxic effects rather than acute toxicity from brief exposures to chemicals. The exposure assessment and risk characterization use a "model facility" approach, with the goal of comparing the exposures and health risks of the surface finishing process alternatives to the baseline non-conveyorized HASL technology. Characteristics of the model facility were aggregated from questionnaire data, site visits, and other sources. This approach does not result in an absolute estimate or measurement of risk.

The estimates of exposure and risk reflect only a portion of the potential exposures within a PWB manufacturing facility. Many of the chemicals found in surface finishing technologies also may be present in other process steps of PWB manufacturing, and other risk concerns for human health and the environment may occur from these other process steps. Incremental reduction of exposures to chemicals of concern from a surface finishing process, however, will reduce cumulative exposures from all sources in a PWB facility. Uncertainties and key assumptions are described further in Chapter 3, Risk Screening and Comparison.

Competitiveness

The Performance Demonstration was designed to provide a snapshot of the performance of different surface finishing technologies. The test methods used to evaluate performance were intended to indicate characteristics of a technology's performance, not to define parameters of performance or to substitute for thorough on-site testing. Because the test sites were not chosen randomly, the sample may not be representative of all PWB manufacturing facilities in the United States (although there is no specific reason to believe they are not representative).

The cost analysis presents comparative costs of using a surface finishing technology in a model facility to produce 260,000 ssf of PWB. As with the risk characterization, this approach results in a comparative evaluation of cost, not an absolute evaluation or determination. The cost analysis focuses on the private costs that would be incurred by facilities implementing a technology. However, the analysis is limited to costs that are solely attributable to the surface finishing process and does not evaluate costs associated with product quality or wastewater treatment. Community benefits or costs, such as reduced health effects to workers or the effects on jobs from implementing a more efficient surface finishing technology, also are not quantified. The Social Benefits/Costs Assessment (see Section 7.2), however, qualitatively evaluates some of these external benefits and costs.

The regulatory information contained in the CTSA may be useful in evaluating the benefits of implementing processes which no longer contain chemicals that trigger compliance issues; however, this document is not intended to provide compliance assistance. If the reader has questions regarding compliance concerns, they should contact their federal, state, or local authorities.

Conservation

The analysis of energy and water consumption is also a comparative analysis, rather than an absolute evaluation or measurement. Similar to the cost analysis, consumption rates were estimated based on using a surface finishing technology in a model facility to produce 260,000 ssf of PWB.

IV. CLEANER TECHNOLOGIES SUBSTITUTES ASSESSMENT RESULTS

Occupational Exposures and Health Risks

Health risks to workers are estimated for inhalation exposure to vapors and aerosols from surface finishing baths and for dermal exposure to surface finishing bath chemicals. Inhalation exposure estimates are based on the assumptions that emissions to indoor air from conveyorized lines are negligible, that the air in the process room is completely mixed and chemical concentrations are constant over time, and that no vapor control devices (e.g., bath covers) are used in non-conveyorized lines. Dermal exposure estimates are based on the conservative assumptions that workers do not wear gloves and that all non-conveyorized lines are operated by manual hoist. Dermal exposure to line operators on non-conveyorized lines is estimated for routine line operation and maintenance (e.g., bath replacement, filter replacement), and on conveyorized lines for bath maintenance activities alone.

Based on the number of chemicals with risk results above concern levels, some alternatives to the non-conveyorized HASL process appear to pose lower occupational risks (immersion silver, conveyorized and non-conveyorized immersion tin, and conveyorized HASL), some may pose similar levels of risk (conveyorized and non-conveyorized OSP), and some may pose higher risk (nickel/gold and nickel/palladium/gold). Surface finishing chemicals of concern for potential occupational risk from inhalation are shown in Table ES-2.

There also are occupational risk concerns for dermal contact with chemicals in the non-conveyorized HASL, nickel/gold, nickel/palladium/gold, OSP, and immersion tin processes, and the conveyorized HASL and OSP processes. Table ES-3 presents chemicals of concern for potential occupational risk from dermal contact.

Table ES-2. Surface Finishing Chemicals of Concern for Potential Occupational Inhalation Risk

Chemical	Process (Non-Conveyorized, 260,000 ssf) [a]			
	HASL	Nickel/Gold	Nickel/Palladium/Gold	OSP
Alkyldiol		X	X	
Ethylene glycol	X			X
Hydrochloric acid		X	X	
Hydrogen peroxide		X	X	
Nickel sulfate		X	X	
Phosphoric acid		X	X	
Propionic acid			X	

[a] Non-conveyorized immersion silver process not evaluated. Occupational exposure and risk from all conveyorized process configurations are below concern levels.
X Line operator risk results above concern levels (non-cancer health effects).

Table ES-3. Chemicals of Concern for Potential Dermal Risks

Chemical	HASL (NC)	HASL (C)	Nickel/Gold (NC)	Nickel/ Palladium/Gold (NC)	OSP (NC)	OSP (C)	Immersion Tin (NC)
Ammonia compound A				X			
Ammonium chloride			X				
Ammonium hydroxide			X	X			
Copper ion					XX	XX	
Copper salt C					XX	X	
Copper sulfate pentahydrate	XX	XX	XX	XX	XX	XX	
Ethylene glycol monobutyl ether							X
Hydrogen peroxide			X	X			
Inorganic metallic salt B			XX	XX			
Lead	†	†					
Nickel sulfate			XX	XX			
Urea compound C							X

Note: No risk results were above concern levels for the conveyorized immersion silver or conveyorized immersion tin processes.
X Line operator risk results above concern levels (non-cancer health effects).
XX Line operator and laboratory technician risk results above concern levels (non-cancer health effects).
†: Risk indicators were not calculated for lead as with the other chemicals (see Section 3.4.6). Other information, however, indicates that incidental ingestion of lead from contact with hands could result in lead exposure at levels of concern.
C: Conveyorized (horizontal) process configuration.
NC: Non-conveyorized (vertical) process configuration.

The non-conveyorized nickel/gold process contains the only chemical for which an occupational cancer risk has been estimated (inorganic metallic salt A). The line operator inhalation exposure estimate for inorganic metallic salt A results in an estimated upper bound excess individual life time cancer risk of 2×10^{-7} (one in five million) based on high end exposure. Cancer risks less than 1×10^{-6} (one in one million) are generally considered to be of low concern. Risks to other types of workers[1] were assumed to be proportional to the average amount of time spent in the process area, which ranged from 12 to 69 percent of the risk for a line operator.

Other identified chemicals in the surface finishing processes are suspected or known carcinogens. Lead and thiourea have been determined by the International Agency for Research on Cancer (IARC) to be possible human carcinogens (IARC Group 2B); lead has also been classified by EPA as a probable human carcinogen (EPA Class B2). Lead is used in tin-lead solder in the HASL process. Thiourea is used in the immersion tin process. Urea compound B, a confidential ingredient in the nickel/gold and nickel/palladium/gold processes, is possibly carcinogenic to humans. Exposure for workers from these chemicals has been estimated, but cancer potency and cancer risks are unknown. Additionally, strong inorganic and acid mists of sulfuric acid have been determined by IARC to be a human carcinogen (IARC Group 1). Sulfuric acid is used in diluted form in every surface finishing process in this evaluation. It is not expected, however, to be released to the air as a strong acid mist. There are potential cancer risks to workers from these chemicals, but because there are no slope factors, the risks cannot be quantified.

For non-cancer risk, risk indicators exceeding concern levels – a hazard quotient (HQ) greater than one, a margin of exposure (MOE) based on NOAEL lower than 100, or MOE based on a LOAEL lower than 1,000 – were estimated for occupational exposures to chemicals in the non-conveyorized and conveyorized HASL processes, non-conveyorized nickel/gold process, non-conveyorized nickel/palladium/gold process, non-conveyorized and conveyorized OSP processes, and the non-conveyorized immersion tin process.

Based on calculated occupational exposure levels, there may be adverse health effects to workers exposed to chemicals with a HQ exceeding 1.0 or an MOE less than 100 or 1,000. It should be emphasized, however, that these conclusions are based on screening level estimates. These numbers are used here for relative risk comparisons between processes and should not be used as absolute indicators for actual health risks to surface finishing line workers.

Worker blood-lead levels measured at one PWB manufacturing facility were below any federal regulation or guideline for workplace exposure. Modeling data, however, indicate that blood-lead levels could exceed recommended levels for an adult and fetus, given high incidental ingestion rates of lead from handling solder. Although these results are highly uncertain, this indicates the need for good personal hygiene for HASL line operators, especially wearing gloves and hand washing to prevent accidental hand-to-mouth ingestion of lead.

---

[1] These include laboratory technicians, maintenance workers, and wastewater treatment operators. Other types of workers may be present for shorter or longer times.

Public Exposures and Health Risks

Potential public health risks was estimated for inhalation exposure for the general public living near a PWB facility. Public exposure estimates are based on the assumption that emissions from both conveyorized and non-conveyorized process configurations are vented to the outside. The risk indicators for ambient exposures to humans, although limited to airborne releases, indicate low concern for nearby residents. The upper bound excess individual cancer risk for nearby residents from inorganic metallic salt A in the non-conveyorized nickel/gold process was estimated to be from approaching zero to 2×10^{-11} (one in 50 billion). This chemical has been classified as a human carcinogen.[2] All hazard quotients are less than one for ambient exposure to the general population, and all MOEs for ambient exposure are greater than 1,000 for all processes, indicating low concern from the estimated air concentrations for chronic non-cancer effects.

Estimated ambient air concentrations of lead from a HASL process are well below EPA air regulatory limits for lead, and risks to the nearby population from airborne lead are expected to be below concern levels.

Ecological Hazards

Ecological risk indicators (RI_{ECO}) were calculated for non-metal surface finishing chemicals that may be released to surface water. Risk indicators for metals are not used for comparing alternatives because it is assumed that on-site treatment is targeted to remove metal so that permitted concentrations are not exceeded. Estimated surface water concentrations for non-metals exceeded the CC for the processes as shown in Table ES-4. CCs are discussed in more detail in Section 3.3.3.

Table ES-4. Aquatic Risk of Non-Metal Chemicals of Concern

Chemical	HASL (NC)	HASL (C)	OSP (NC)	OSP (C)	Immersion Silver (C)	Immersion Tin (NC)
1,4-Butenediol	X					
Alkylaryl imidazole			X	X		
Alkylaryl sulfonate	X	X				
Hydrogen peroxide	X	X			X	
Potassium peroxymonosulfate	X	X				X

Estimated surface water concentration > CC after publicly owned treatment works (POTW) treatment.

[2] A cancer classification of known human carcinogen has been assigned by either the EPA, IARC, and/or NTP. Further details about the carcinogen classification are not provided in order to protect the confidential chemical identity.

Process Safety

In order to evaluate the chemical safety hazards of the various surface finishing technologies, MSDSs for chemical products used with each surface finish were reviewed. Table ES-5 summarizes the hazardous properties listed on MSDSs for surface finishing chemical products. Other potential chemical hazards posed by surface finishing chemicals include either the hazardous decomposition of chemical products, or chemical product incompatibilities with other chemicals or materials.

Table ES-5. Hazardous Properties of Surface Finishing Chemical Products

Process	No. of MSDS [a]	Hazardous Property							
		F	C	E	FH	CO	O	SRP	U
HASL [b]	33	1		1	3	4	1	1	1
Nickel/Gold	19					8	1	1	
Nickel/Palladium/Gold	18					12	1	1	
OSP	9	1			2	4	1	1	
Immersion Silver	4			1	1	2	1		1
Immersion Tin	14			1		7			

[a] For alternative processes with more than one product line, the hazard data reported represent the most hazardous bath of each type for the two product lines (e.g., of the microetch baths from the two product lines, the one with the most hazardous chemicals is reported).
[b] Formulations for HASL process baths were unavailable because cleaner and microetch bath chemistries are not made specifically for the HASL process. Hazards reported for HASL bath types were reported as the worst case of the results of similar baths from other processes.
F = Flammable; C = Combustible; E = Explosive; FH = Fire Hazard; CO = Corrosive; O = Oxidizer; SRP = Sudden Release of Pressure; U = Unstable.

Several unique process safety concerns arise from the operation of the HASL process. Solder eruptions during start-up can lead to solder splattering onto workers causing serious burns. The HASL process also poses a fire hazard due to the build-up of residual carbon from the use of oil-based flux or other flammable materials. Other safety concerns include worker exposure to acids in the flux, accidental contact with the molten solder, or exposure to the other chemical hazards on the process line.

Work-related injuries from equipment, improper use of equipment, bypassing equipment safety features, failure to use personal protective equipment, and physical stresses that may appear gradually as a result of repetitive motion are all potential process safety hazards to workers. Reducing the potential for work-related injuries is critical in an effective and ongoing safety training program. Appropriate training can help reduce the number of work-related accidents and injuries regardless of the technology used.

Performance

The performance of the surface finishing technologies was tested using production run tests following a strict testing protocol. Functional test boards were fabricated using a complex test board design (a modified version of the IPC-B-24 board) developed by the Circuit Card Assembly and Materials Task Force (CCAMTF). A surface finish was then applied to test boards at each of thirteen volunteer PWB manufacturing facilities. Test boards were then collected together and assembled at an assembly facility, using either a halide-free low-residue flux or a halide-containing water-soluble flux, before being tested under thermal and mechanical stress, and accelerated aging conditions. Additional residue testing was conducted to determine the mechanism of failure.

The test vehicle measured roughly 6" x 5.8" x 0.062" and was designed to contain at least 80 percent of the circuitry used in military and commercial electronics. The test vehicle also contained a variety of circuits, including high current low voltage (HCLV), high voltage low current (HVLC), high speed digital (HSD), high frequency (HF), stranded wire (SW), and other networks, which were used to measure current leakage. Overall, the vehicle provided 23 separate electrical responses for testing the performance of the surface finish. Types of electrical components in the HCLV, HVLC, HSD, and HF circuits included both plated through hole (PTH) and surface mounted components.

Test sites were submitted by suppliers of the technologies, and included production facilities and supplier testing facilities. Because the test sites were not chosen randomly, the sample may not be representative of all PWB manufacturing facilities (although there is no specific reason to believe that they are not representative). In addition, the number of test sites for each technology ranged from one to four. Due to the smaller number of test sites for some technologies, statistical relevance could not be determined.

The results of the performance testing showed that all of the surface finishes under study were very robust to the environmental exposures, with two exceptions. Failures during the mechanical shock testing, resulting in the separation of the surface mount components, were attributable to the severity of the testing, and were spread evenly across all finishing technologies, including the baseline HASL process. Failures in the high frequency, low pass filter circuits, resulting from open PTH, were found to be attributable to a combination of board fabrication materials and board design. From an overall contamination standpoint, the five non-HASL surface finishes performed as well, if not better than the HASL finish. The few solder joint cracking failures were greater with the HASL finish than with the alternative finishes.

Cost Analysis

Comparative costs were estimated using a hybrid cost model that combined traditional costs with simulation modeling and activity-based costs. The cost model was designed to determine the total cost of producing 260,000 ssf of PWB for each of the surface finishing technologies using a model facility concept. Total costs were normalized to a cost per ssf of PWB produced.

The cost components evaluated include capital costs (primary equipment, installation, and facility costs), materials costs (limited to chemical costs), utility costs (water, electricity, and natural gas costs), wastewater costs (limited to wastewater discharge cost), production costs (production labor and chemical transport costs), and maintenance costs (tank cleanup, bath setup, sampling and analysis, and filter replacement costs). Start-up costs for implementing a surface finishing technology, as well as the costs of other process changes that may be required to implement an alternative technology, were not considered in the cost evaluation. Other cost components that contribute to overall costs, but which also could not be quantified include quality costs, wastewater treatment cost, sludge recycling and disposal cost, and other solid waste disposal costs.

Cost analysis results are presented in Table ES-6. With the exception of the two technologies containing gold, an expensive precious metal, the results indicate that all of the other surface finishing alternatives were more economical than the baseline non-conveyorized HASL process. Three processes had a substantial cost savings of at least 50 percent of the cost per ssf over that of the baseline HASL process (conveyorized OSP at 72 percent, non-conveyorized OSP at 69 percent, and non-conveyorized immersion tin at 50 percent). Three other process alternatives realized a somewhat smaller cost savings over the baseline HASL process (conveyorized immersion tin at 31 percent, conveyorized immersion silver at 22 percent, and the conveyorized HASL process at 3 percent).

In general, conveyorized processes cost less than non-conveyorized processes. Chemical cost was the single largest component cost for all nine of the processes, with the cost of labor a distant second.

Regulatory Status

Discharges of surface finishing chemicals may be restricted by federal, state, or local air, water, or solid waste regulations, and releases may be reportable under the federal Toxic Release Inventory program. Federal environmental regulations were reviewed to determine the federal regulatory status of surface finishing chemicals.[3] Table ES-7 lists the number of chemicals used in each surface finishing technology that are subject to federal environmental regulations. Different chemical suppliers of a technology do not always use the same chemicals in their particular product lines. Thus, all of these chemicals may not be present in any one product line.

Resource Conservation

Energy and water consumption rates were evaluated for each of the surface finishing process alternatives. Other resource consumption by the surface finishing technologies was evaluated qualitatively due to the variability of factors that affect the consumption of these resources. Table ES-8 presents the energy and water consumption rates of the surface finishing technologies.

---

[3] In some cases, state or local requirements may be more restrictive than federal requirements. Due to resource limitations, however, only federal regulations were reviewed.

Table ES-6. Cost Analyses Results [a]

Surface Finishing Technology	Average Cost		Capital Cost		Chemical Cost		Water Cost		Electricity Cost	
	$/ssf	% change	$/ssf	% change	$/ssf`	% change	$/ssf	% change	$/ssf	% change
HASL, Non-conveyorized (BASELINE)	$ 0.36	--	$ 0.038	--	$ 0.288	-	$ 0.003	--	$ 0.003	--
HASL, Conveyorized	$ 0.35	-3%	$ 0.044	16%	$ 0.289	0%	$ 0.002	-20%	$ 0.002	-32%
Nickel/Gold, Non-conveyorized	$ 0.60	67%	$ 0.039	4%	$ 0.419	46%	$ 0.005	67%	$ 0.009	253%
Nickel/Palladium/Gold, Non-conveyorized	$ 1.54	328%	$ 0.083	119%	$ 1.235	329%	$ 0.008	191%	$ 0.016	507%
OSP, Non-conveyorized	$ 0.11	-69%	$ 0.008	-80%	$ 0.071	-75%	$ 0.002	-38%	$ 0.001	-53%
OSP, Conveyorized	$ 0.10	-72%	$ 0.012	-68%	$ 0.072	-75%	$ 0.001	-57%	$ 0.001	-69%
Immersion Silver, Conveyorized	$ 0.28	-22%	$ 0.044	17%	$ 0.203	-29%	$ 0.001	-57%	$ 0.003	11%
Immersion Tin, Non-conveyorized	$ 0.18	-50%	$ 0.015	-61%	$ 0.112	-61%	$ 0.004	46%	$ 0.002	-26%
Immersion Tin, Conveyorized	$ 0.25	-31%	$ 0.074	95%	$ 0.111	-61%	$ 0.003	-1%	$ 0.005	84%

Surface Finishing Technology	Natural Gas Cost		Wastewater Cost		Production Cost		Maintenance Cost	
	$/ssf	% change	$/ssf	% change	$/ssf	% change	$/ssf	% change
HASL, Non-conveyorized (BASELINE)	$ 0.000	---	$ 0.004	--	$ 0.016	---	$ 0.011	---
HASL, Conveyorized	$ 0.000	-50%	$ 0.003	-23%	$ 0.007	-53%	$ 0.007	-36%
Nickel/Gold, Non-conveyorized	$ 0.000	-100%	$ 0.008	86%	$ 0.076	381%	$ 0.042	275%
Nickel/Palladium/Gold, Non-conveyorized	$ 0.000	-100%	$ 0.014	222%	$ 0.101	539%	$ 0.080	610%
OSP, Non-conveyorized	$ 0.000	-24%	$ 0.003	-36%	$ 0.013	-19%	$ 0.013	13%
OSP, Conveyorized	$ 0.000	-65%	$ 0.002	-58%	$ 0.006	-65%	$ 0.008	-33%
Immersion Silver, Conveyorized	$ 0.001	59%	$ 0.002	-52%	$ 0.021	32%	$ 0.010	-15%
Immersion Tin, Non-conveyorized	$ 0.001	82%	$ 0.006	47%	$ 0.027	70%	$ 0.015	28%
Immersion Tin, Conveyorized	$ 0.001	171%	$ 0.005	10%	$ 0.034	118%	$ 0.017	46%

[a] Table lists costs and percent change in cost from the baseline.

Table ES-7. Regulatory Status of Surface Finishing Technologies

Process Chemical	Number of Chemicals Subject to Applicable Regulation														
	CWA				CAA			EPCRA			TSCA			RCRA Waste	
	304b	307a	311	Priority Pollutant	111	112b	112r	313	110	302a	8d HSDR	MTL	8a PAIR	P	U
HASL	1	1	4	1	3	3	1	6	1	3	3	4	3	-	-
Nickel/Gold	6	6	16	6	11	6	1	12	7	3	1	4	3	-	-
Nickel/Palladium/Gold	5	5	12	5	5	5	1	10	6	3	1	4	4	-	-
OSP	2	2	5	2	3	2	1	5	2	2	1	2	1	-	-
Immersion Silver	1	1	5	1	1	1	-	3	1	3	-	1	1	-	-
Immersion Tin	1	1	6	1	3	2	1	7	1	2	2	4	3	-	2

Abbreviations and definitions:

CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants -Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA - Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory
RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
SDWA - Safe Drinking Water Act
SDWA NPDWR - National Primary Drinking Water Rules
SDWA NSDWR - National Secondary Drinking Water Rules
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & Safety Data Reporting Rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

The rate of water consumption is directly related to the rate of wastewater generation. Several processes were found to consume less water than the HASL baseline, including conveyorized versions of the immersion silver and immersion tin technologies and both versions of the OSP process. Conveyorized processes were found to consume less water than non-conveyorized versions of the same process. Primary factors influencing the water consumption rate included the number of rinse tanks and the overall efficiency of the conveyorized processes.

Table ES-8. Energy and Water Consumption Rates of Surface Finishing Technologies

Process Type	Water Consumption (gal/ssf)	Energy Consumption (Btu/ssf)
HASL, Non-conveyorized (BASELINE)	1.24	218
HASL, Conveyorized	0.99	133
Nickel/Gold, Non-conveyorized	2.06	447
Nickel/Palladium/Gold, Non-conveyorized	3.61	768
OSP, Non-conveyorized	0.77	125
OSP, Conveyorized	0.53	73
Immersion Silver, Conveyorized	0.53	287
Immersion Tin, Non-conveyorized	1.81	289
Immersion Tin, Conveyorized	0.88	522

Energy consumption by the surface finishing technologies was driven primarily by the overall throughput efficiency of the technology. Although HASL had the highest BTU per hour rate of all the technologies, after normalizing the rate using the overall throughput (260,000 ssf), only the OSP (conveyorized and non-conveyorized), and the conveyorized HASL were more energy efficient than the HASL process. It also was found that for alternatives with both types of automation, the conveyorized version of the process is typically the more energy efficient (HASL and OSP), with the exception of the immersion tin process.

The rate of deposition of metal was calculated for each technology along with the total amount of metal consumed for 260,000 ssf of PWB produced. It was shown that the consumption of close to 300 pounds of lead (per 260,000 ssf) could be eliminated by replacing the baseline HASL process with an alternative technology (see Section 5.1, Resource Conservation). In cases where waste solder is not routinely recycled or reclaimed, the consumption of as much as 2,500 pounds of lead (per 260,000 ssf) could be eliminated by replacement of the HASL process. Although several of the alternative technologies rely on the use of small quantities of other metals (especially nickel, palladium, gold, silver, and tin) the OSP technology eliminates metal consumption entirely.

Social Benefits/Costs Assessment

The social benefits and costs of the surface finishing technologies were qualitatively assessed to compare the benefits and costs of switching from the baseline technology to an alternative, while considering both the private and external costs and benefits. Private costs typically include any direct costs incurred by the decision-maker and are generally reflected in the manufacturer's balance sheet. By contrast, external costs are not borne by the manufacturer, but by society. Therefore, the analysis considered both the impact of the alternative surface finishing processes on the manufacturer itself (private costs and benefits) and the impact the choice of an alternative had on external costs and benefits.

Table ES-9 presents an overview of potential private and external benefits and costs associated with the operation of the surface finishing line. Changes in the surface finishing technology employed could potentially result in a net benefit (a change in a beneficial direction) or cost (a change in a detrimental direction) in each of the categories listed below. The type of change and the magnitude will vary by facility.

Table ES-9. Overview of Potential Private and External Benefits or Costs

Evaluation Category	Private Benefit or Cost [a]	External Benefit or Cost [a]
Manufacturing costs	Capital costs, Materials (chemical) costs, Utility costs, Wastewater discharge costs, Production costs, and Maintenance costs.	NA
Occupational health/ Worker risk	Worker sick days, and Health insurance costs to the PWB manufacturer.	Medical costs to workers, and Pain and suffering associated with work-related illness.
Public health/ Population risk	Potential liability costs.	Medical costs, and Pain and suffering associated with illness.
Wastewater and Ecological risk	Treatment costs to meet wastewater permit requirements, Possible fines if permits are violated, and Increased liability costs.	Loss of ecosystem diversity; and Reduction in the recreational value of streams and rivers.
Energy use	Direct costs from the use of energy in the manufacturing process.	Increased air emissions, and Depletion of natural resources.
Water use	Direct costs from the use of water in the manufacturing process.	Water costs for the surrounding area, Costs paid to treatment facilities to clean the water, Changes to water quality available to society; and Reduced water supply.

[a] A benefit would be a change in a beneficial direction (e.g., *decreased* capitol costs), while a cost would be a detrimental change (e.g., *increased* worker sick days).

Each alternative presents a mixture of private and external benefits and costs. In terms of worker health risks, conveyorized processes have the greatest benefits for reduced worker inhalation exposure to bath chemicals; they are enclosed and vented to the atmosphere. However, dermal contact from bath maintenance activities can be of concern regardless of the equipment configuration for HASL and OSP processes, as well as non-conveyorized nickel/gold, nickel/palladium/gold, and immersion tin processes. Little or no improvement is seen in public health risks because results were below concern levels for all technologies. Differences in estimated wastewater contaminant levels and aquatic risk concerns suggest that alternatives to non-conveyorized HASL pose lower potential private and external costs (or higher benefits). Conveyorized processes consumed less water than that consumed by non-conveyorized processes, resulting in net private and external benefits. Only the OSP technology, along with the conveyorized HASL technology, are expected to reduce potential private and external costs of energy consumption, resulting in increased social benefits.

V. CONCLUSIONS

The CTSA evaluated the risk, competitiveness, and resource requirements of six technologies for performing the surface finishing function during PWB manufacturing. These technologies are HASL, nickel/gold, nickel/palladium/gold, OSP, immersion silver, and immersion tin.

The results of the CTSA analyses of the surface finishing technologies were mixed. Analyses of process costs, energy, and natural resource consumption each showed that some alternatives performed better than HASL, while others did not. An evaluation of potential occupational risks from both inhalation and dermal exposures indicated that several alternatives posed lower occupational risks than HASL, based on the number of chemicals with risk results above concern concentrations. Ecological risks posed by the alternatives were all lower than the HASL process, also based on the number of chemicals exceeding concern concentrations. None of the surface finishing technologies, including HASL, posed a risk to populations living nearby. Finally, alternatives to the traditional non-conveyorized HASL technology (the baseline process) were demonstrated to perform as well as HASL during performance testing; however, several of the alternatives improve upon the technical limitations of the HASL finish (e.g., wire-bondability, surface planarity).

Table ES-10 summarizes the CTSA analyses results for the surface finishing technologies, relative to the non-conveyorized HASL baseline. It is important to note that there are additional factors beyond those assessed in this CTSA that individual businesses may consider when choosing among alternatives. The actual decision of whether or not to implement an alternative is made outside of the CTSA process.

Table ES-10. Relative Benefits and Costs of Surface Finishing Alternatives Versus Baseline

Surface Finishing Technology	Production Costs ($/ssf)	Number of Chemicals of Concern				Water Consumption (gal/ssf)	Energy Consumption (Btu/ssf)
		Worker Health Risks [a,b,c]		Public Health Risks	High Aquatic Toxicity Concern [a]		
		Inhalation	Dermal	Inhalation			
HASL, Non-Conveyorized (BASELINE)	$0.36	1	2	0	4	1.24	218
HASL, Conveyorized	=	+	=	=	+	+	+
Nickel/Gold, Non-conveyorized	-	--	--	=	++	-	--
Nickel/Palladium/Gold, Non-Conveyorized	--	--	--	=	++	--	--
OSP, Non-conveyorized	++	=	-	=	++	+	+
OSP, Conveyorized	++	+	=	=	++	++	++
Immersion Silver, Conveyorized	+	+	+	=	++	++	-
Immersion Tin, Non-conveyorized	+	+	=	=	++	-	-
Immersion Tin, Conveyorized	+	+	+	=	++	+	--

[a] For technologies with more than one chemical supplier (e.g., nickel/gold, OSP, immersion tin) all chemicals may not be present in any one product line.
[b] For the most exposed individual (e.g., a surface finishing line operator).
[c] Because the risk characterization did not estimate the number of incidences of adverse health outcomes, the amount of reduced risk benefit cannot be quantified. The comparison shown in this table is based on the number of chemicals of concern for the baseline.

Key:

= Neutral, less than 10% increase or decrease from baseline.

- 10 to 100 percent worse.

-- 100 percent worse.

+ Some benefit, 10 to 50 percent decrease from baseline.

++ Greater benefit, +50 percent or greater decrease from baseline.

To assist PWB manufacturers who are considering the implementation of an alternative surface finish, the DfE PWB Project has prepared an implementation guide that describes lessons learned by other PWB manufacturers who have begun using an alternative surface finishing process.[4] In addition, the University of Tennessee Department of Industrial Engineering can provide technical support to facilities that would like to use the cost model developed for the CTSA to estimate their own manufacturing costs should they switch to a surface finishing alternative.

[4] *Implementing Cleaner Printed Wiring Board Technologies: Surface Finishes* (EPA 744-R-00-002, March 2000). This and other DfE PWB Project documents can be obtained by contacting EPA's Pollution Prevention Information Clearinghouse at (202) 260-1023 or from www.epa.gov/dfe/pwb.

REFERENCES

IPC (IPC-Association Connecting Electronics Industries). 1996. *National Technology Roadmap for Electronic Interconnections.*

Kincaid, Lori E., Jed Meline and Gary Davis. 1996. *Cleaner Technologies Substitutes Assessment: A Methodology & Resource Guide*. EPA Office of Pollution Prevention and Toxics. Washington, D.C. EPA 744-R-95-002. December.

MCC (Microelectronics and Computer Technology Corporation). 1993. *Environmental Consciousness: A Strategic Competitiveness Issue for the Electronics and Computer Industry*. March.

MCC (Microelectronics and Computer Technology Corporation). 1994. *Electronics Industry Environmental Roadmap*. December.

Chapter 1
Introduction

This document presents the results of a cleaner technologies substitutes assessment (CTSA) of six technologies for performing the surface finishing function during the manufacture of printed wiring boards (PWBs). Surface finishing technologies deposit a coating on the outside surfaces of the PWB that provides a solderable surface for future assembly, while protecting the surface from exposure to the local environment. The technologies evaluated in the study are hot air solder leveling (HASL), electroless nickel/immersion gold (nickel/gold), electroless nickel/electroless palladium/immersion gold (nickel/palladium/gold), organic solderability preservative (OSP), immersion silver, and immersion tin.

For the purposes of this evaluation, the non-conveyorized HASL process is considered the baseline process against which alternative technologies and equipment configurations (i.e., non-conveyorized or conveyorized) are compared. This CTSA is the culmination of over two years of research by the U.S. Environmental Protection Agency (EPA) Design for the Environment (DfE) PWB Project and the University of Tennessee (UT) Center for Clean Products and Clean Technologies on the comparative risk, performance, cost, and natural resource requirements of the alternative technologies as compared to the baseline.

The DfE PWB Project is a voluntary, cooperative partnership among EPA, industry, public-interest groups, and other stakeholders to promote implementation of environmentally beneficial and economically feasible manufacturing technologies by PWB manufacturers. Project partners participated in the planning and execution of this CTSA by helping define the scope and direction of the CTSA, developing project workplans, donating time, materials, and their manufacturing facilities for project research, and reviewing technical information contained in this CTSA. Much of the process-specific information presented here was provided by chemical suppliers to the PWB industry, PWB manufacturers who responded to project information requests, and PWB manufacturers who volunteered their facilities for a performance demonstration of the baseline and alternative technologies.

Section 1.1 presents project background information, including summary descriptions of the EPA DfE Program and the DfE PWB Project. Section 1.2 is an overview of the PWB industry, including the types of PWBs produced, the market for PWBs, and the overall PWB manufacturing process. Section 1.3 summarizes the CTSA methodology, including a discussion of how technologies were selected for evaluation in the CTSA, the boundaries of the evaluation, issues evaluated, data sources, and project limitations. Section 1.4 describes the organization of the remainder of the CTSA document.

1.1 PROJECT BACKGROUND

The PWB is the connector between the semiconductors, computer chips, and other electronic components that form an electronic circuit. Therefore, PWBs are an irreplaceable part of many "high-tech" products in the electronics, defense, communications, and automotive industries. PWB manufacturing, however, typically generates a significant amount of hazardous waste, requires a substantial amount of water and energy, and uses chemicals that may pose environmental and health risks.

To address these issues, the PWB industry has been actively seeking to identify and evaluate cleaner technologies and pollution prevention opportunities. However, many PWB manufacturers do not have the resources or experience to independently develop the data needed to evaluate new technologies and redesign their processes. The DfE PWB Project was initiated to develop that data, by forming partnerships between the EPA DfE Program, the PWB industry, and other interested parties to facilitate the evaluation and implementation of alternative technologies that reduce health and environmental risks and production costs. The EPA DfE Program and the DfE PWB Project are discussed in more detail below.

1.1.1 EPA DfE Program

EPA's Office of Pollution Prevention and Toxics created the DfE Program in 1991. The Program uses EPA's expertise and leadership to facilitate information exchange and research on risk reduction and pollution prevention opportunities. DfE works on a voluntary basis with industry sectors to evaluate the risks, performance, costs, and resource requirements of alternative chemicals, processes, and technologies. Additional goals of the program include:

- changing general business practices to incorporate environmental concerns, and
- helping individual businesses undertake environmental design efforts through the application of specific tools and methods.

The DfE Program encourages voluntary environmental improvement through stakeholder partnerships. DfE partners include industry, trade associations, research institutions, environmental and public-interest groups, academia, and other government agencies. By involving representatives from each of these stakeholder groups, DfE projects gain the necessary expertise to perform the project's technical work and improve the quality, credibility, and utility of the project's results.

1.1.2 DfE PWB Project

The DfE PWB Project is a voluntary, cooperative partnership among EPA, industry, public-interest groups, and other stakeholders to promote implementation of environmentally beneficial and economically feasible manufacturing technologies by PWB manufacturers. In part, the project is an outgrowth of industry efforts to identify key cleaner technology needs in

electronics manufacturing. The results of these industry studies are presented in two reports prepared by Microelectronics and Computer Technology Corporation (MCC), an industry research consortium: *Environmental Consciousness: A Strategic Competitiveness Issue for the Electronics and Computers Industry* (MCC, 1993) and *Electronics Industry Environmental Roadmap* (MCC, 1994).

The first study identified wet chemistry processes used in PWB fabrication as water- and energy-intensive processes that generate significant amounts of hazardous waste. The study concluded that effective collaboration among government, industry, academia, and the public is imperative to proactively address the needs of environmental technologies, policies, and practices (MCC, 1993). To follow-up, the industry embarked on a collaborative effort to develop an environmental roadmap for the electronics industry. The roadmap project involved more than 100 organizations, including EPA, the Department of Energy, the Advanced Research Projects Agency, and several trade associations. The PWB industry national trade association, the IPC-Association Connecting Electronics Industries (IPC), was instrumental in developing the information on PWBs through its Environmental, Health, and Safety Committee.

The highest priority need identified for PWB manufacturers was for more efficient use, regeneration, and recycling of hazardous wet chemistries. One proposed approach to meet this need was to eliminate formaldehyde from materials and chemical formulations by researching alternative chemical formulations. Another priority need was for industry to reduce water consumption and discharge, which can be accomplished by using wet chemistries that have reduced numbers of rinse steps. The electroless copper technologies for making holes conductive (MHC) use formaldehyde and consume large amounts of water.

The potential for improvement in these areas led EPA's DfE Program to forge working partnerships with IPC, individual PWB manufacturers and suppliers, research institutions such as MCC and UT's Center for Clean Products and Clean Technologies, and public-interest organizations, including the Silicon Valley Toxics Coalition. These partnerships resulted in the DfE PWB Project.

Since its inception in 1994, the goal of the DfE PWB Project has been the identification and evaluation of environmentally preferable alternative technologies for the PWB manufacturing industry. The project initially focused on the evaluation of alternative technologies for the MHC process. Seven MHC processes were evaluated for performance, cost, and their impact on human health and the environment. The project results are published in the *Printed Wiring Board Cleaner Technologies Substitutes Assessment: Making Holes Conductive* (U.S. EPA, 1998a).

The success of the MHC study led project partners to explore the possibility of a second project with the PWB manufacturing industry. Results of the environmental roadmap from 1994 identified a top priority need for PWB manufacturers as the need to minimize the impact of hazardous materials use in PWB fabrication. One proposed approach to meet this need was to eliminate or reduce lead solder use when possible by validating the quality of lead plating alternatives. Another priority need for the industry was to establish better supplier relationships to enhance the development and acceptance of environmentally preferable materials.

As a follow up to the environmental roadmap, the electronics industry embarked on a study of industry technology trends, the results of which were published as *The National Technology Roadmap for Electronic Interconnections* (IPC, 1996). The roadmap detailed trends in PWB manufacturing and assembly technologies, and forecasted the technology needs for the industry over the immediate future. The study concluded that major efforts are needed to overcome the reluctance to trying new and innovative ideas, citing the environmental pressure to reduce hazardous waste and the use of lead. The results also cited the development of non-tin/lead metallic or organic coatings to retain solderability characteristics as an industry need over the near term.

Recognizing the importance of reducing lead consumption in the PWB industry, and building on the strong partnerships established during the previous work, the PWB surface finishing project was begun in 1997 to evaluate alternative surface finishing technologies to HASL. This CTSA is a culmination of this effort. During this time, the project has also:

- Prepared several additional case studies of pollution prevention opportunities (U.S. EPA, 1997a; U.S. EPA, 1997b; U.S. EPA, 1997c; U.S. EPA, 1999).
- Prepared an implementation guide for PWB manufacturers interested in switching from HASL to an alternative surface finishing technology (U.S. EPA, 2000).
- Identified, evaluated, and disseminated information on viable pollution prevention opportunities for the PWB industry through an updated review of a pollution prevention and control practices industry study (U.S. EPA, 1998b).

Further information about the project, along with web-based versions of all the documents listed above and other previous project work, can be obtained by visiting the Design for the Environment Program website, located at www.epa.gov/dfe/pwb.

1.2 OVERVIEW OF PWB INDUSTRY

1.2.1 Types of Printed Wiring Boards

PWBs may be categorized in several ways, either by the number of layers or by the type of substrate. The number of circuit layers present on a single PWB give an indication of the overall complexity of the PWB. The most common categories are multi-layer, double-sided, and single-sided PWBs. Multi-layer PWBs contain more than two layers of circuitry, with at least one layer imbedded in the substrate beneath the surface of the board. Multi-layer boards may consist of 20 or more interconnected layers, but four, six, and eight layer boards are more common. Double-sided boards have circuitry on both sides of a board, resulting in two interconnected layers, while single-sided PWBs have only one layer of circuitry. Double-sided and single-sided PWBs are generally easier to produce than multi-layer boards (U.S. EPA, 1995).

PWB substrates, or base material types, fall into three basic categories: rigid PWBs, flexible circuits, and rigid-flex combinations. Rigid multi-layer PWBs dominate the domestic production of all PWBs (see Section 1.2.2, below) and are the focus of this CTSA.

Rigid PWBs typically are constructed of glass-reinforced epoxy-resin systems that produce a board less than 0.1" thick. The most common rigid PWB thickness is 0.062", but there is a trend toward thinner PWBs. Flexible circuits (also called flex circuits) are manufactured on polyamide and polyester substrates that remain flexible at finished thicknesses. Ribbon cables are common flexible circuits. Rigid-flex PWBs are essentially combinations or assemblies of rigid and flexible PWBs. They may consist of one or more rigid PWBs that have one or more flexible circuits laminated to them during the manufacturing process. Three-dimensional circuit assemblies can be created with rigid-flex combinations (U.S. EPA, 1995).

1.2.2 Industry Profile

The total world market for PWBs is about $31.4 billion, with U.S. production accounting for about one quarter of the total (Wehrspann, 1999a). Although the United States and Japan are the leading suppliers of PWBs, Hong Kong, Singapore, Taiwan, and Korea also have captured a significant share of the world market. The U.S.-dominated world market for PWBs eroded from 1980 to 1990, but has come back slightly in recent years. The market share of the countries with the largest PWB production is shown in Figure 1-1.

IPC estimates that the U.S. market for PWBs in 1998 totaled approximately $8.6 billion for both rigid and flex PWBs. U.S. imports of PWBs were estimated to be approximately $500 to $600 million annually, the majority of which come from Taiwan, Japan, Hong Kong, Korea, and Thailand (Wehrspann, 1999b). The value of U.S. PWB exports reported for 1998 were approximately $100 million, which represents two to three percent of total U.S. PWB production (Wehrspann, 1999b).

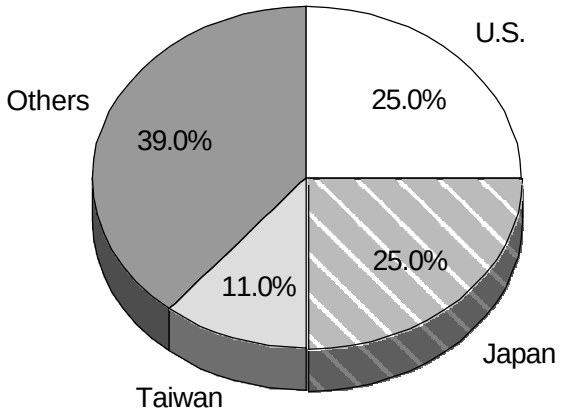


Figure 1-1. PWBs Produced for World Market in 1998 (IPC)

The United States had 652 independent PWB manufacturing plants in 1999 (Abrams, 2000). California, Minnesota, Texas, Illinois, Massachusetts, and Arizona have the highest number of PWB manufacturing plants, but there are PWB manufacturing facilities in virtually all 50 states and territories. More than 75 percent of U.S.-made PWBs are produced by independent shops (U.S. EPA, 1995).

About 80 percent of independent PWB manufacturers are small- to medium-sized businesses with annual sales under $10 million, but these shops only account for 20 to 25 percent of total U.S. sales. Conversely, about five percent of PWB manufacturers are larger independent shops with annual sales over $20 million, but these shops account for about 70 percent of total U.S. sales (Wehrspann, 1999b). Recent industry trends have seen the purchase of many smaller companies by larger corporations with much larger annual sales.

Overall U.S. production accounted for 1.4 billion PWBs produced in 1998. While demand for multi-layer PWBs continues to grow, both single- and double-sided PWBs are still produced in greater numbers. The market for multi-layer boards was about $7.9 billion in 1998 (Wehrspann, 1999b), up from approximately $700 million in 1980 (U.S. EPA, 1995). A breakdown of U.S. production by the type of PWB is shown in Figure 1-2.

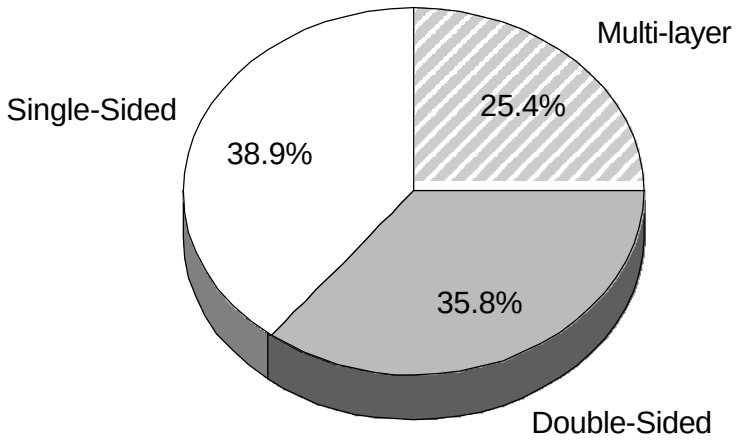


Figure 1-2. Number of PWBs Produced by U.S. Manufacturers in 1998 (IPC)

The PWB industry directly employs about 75,000 people, with about 68 percent of employment in production jobs. This is the highest ratio of production jobs for U.S. electronics manufacturing (U.S. EPA, 1995). Additional jobs related to the industry are generated by PWB material and equipment suppliers and the OEMs that produce PWBs for internal use. Further information about the industry may be found in *Printed Wiring Board Industry and Use Cluster Profile* (U.S. EPA, 1995) or from contacting the industry trade association, IPC.

1.2.3 Overview of Rigid Multi-Layer PWB Manufacturing

Multi-layer boards consist of alternating layers of conductor and insulating material bonded together. Individual circuitry inner-layers are created and then assembled under high temperature into a solid board. Holes are drilled through the boards, and then plated to provide layer-to-layer connection on multi-layered circuits. The outside layers are imaged, plated, and then etched to create the circuitry traces on the outside surfaces of the PWB. A solder mask is then applied to the board prior to applying the final surface finish.

Application of the surface finish is the last major step in the PWB manufacturing process. The function of the surface finish is to provide a clean, solderable surface for subsequent assembly, while also protecting the surface from degradation or contamination from environmental factors, such as water, temperature, and oil from handling. The surface finishing technologies evaluated in this report all deposit this solderable layer, or coating. Traditionally, the surface finish has been tin-lead solder, applied using the HASL technology.

1.3 CTSA METHODOLOGY

The CTSA *methodology* is a means of systematically evaluating and comparing human health and environmental risk, competitiveness (i.e., performance, cost, etc.), and resource requirements of traditional and alternative chemicals, manufacturing methods, and technologies in a particular use cluster. A use cluster is a set of chemical products, technologies, or processes that can substitute for one another to perform a particular function. A CTSA *document* is the repository for the technical information developed by a DfE project on a use cluster. Thus, surface finishing technologies comprise the use cluster that is the focus of this CTSA.

The overall CTSA methodology used in this assessment was developed by the EPA DfE Program, the UT Center for Clean Products and Clean Technologies, and other partners in voluntary, industry-specific pilot projects. The publication, *Cleaner Technologies Substitutes Assessment: A Methodology & Resource Guide* (Kincaid et al., 1996) presents the CTSA methodology in detail. This section summarizes how the various technologies were selected for evaluation in the CTSA, identifies issues evaluated and data sources, and describes the project limitations. Chapters 2 through 6, and appendices, describe in detail the methods used to evaluate the technologies.

1.3.1 Identification of Alternatives and Selection of Project Baseline

Once the use cluster for the CTSA was chosen, industry representatives identified technologies that may be used to accomplish the surface finishing function. Initially, eight technology categories were identified, including six inorganic metal-based technologies, and two organic-based coatings. These include:

- Inorganic: HASL, nickel/gold, nickel/palladium/gold, immersion silver, immersion palladium, and immersion tin.
- Organic: OSP (benzotriazole-based), and OSP (substituted immidizole-based).

Suppliers were contacted by EPA and asked to submit their product lines in these technology categories for evaluation in the CTSA. Criteria for including a technology in the CTSA were the following:

- it is an existing or emerging technology; and
- there are equipment and facilities available to demonstrate its performance.

In addition, suppliers were required to provide information about their technologies, including chemical product formulation data, process schematics, process characteristics and constraints (e.g., cycle time, limitations for the acid copper plating process, substrate and drilling compatibilities, aspect ratio capacity, range of hole sizes), bath replacement criteria, and cost information.

Product lines were submitted, along with confidential process formulation data, for all of the technologies except the benzotriazole-based OSP technology. After further review, it was determined that the immersion palladium technology could not be demonstrated sufficiently under production conditions, preventing the evaluation of the technology's performance and cost of operation. As a result, only a process description of the immersion palladium technology is presented in this CTSA. Thus, seven categories of technologies were carried forward for further evaluation in the CTSA.

The HASL technology was selected as the project baseline for the following reasons:

- It is generally regarded to be the industry standard and holds the vast majority of the market for surface finishing technologies.
- Possible risk concerns associated with lead exposure, the large amount of solid waste generated by the HASL process, and the fact that the solder finish has become technologically limiting with regard to current design and assembly practices have prompted many PWB manufacturers to independently seek alternatives to HASL.

As with other surface finishing technologies, the HASL process can be operated using vertical, immersion-type, non-conveyorized equipment or horizontal, conveyorized equipment. Conveyorized surface finishing equipment is usually more efficient than non-conveyorized equipment, but requires a substantial capital investment. Most facilities in the United States still use a non-conveyorized HASL process to perform the surface finishing function. Therefore, the baseline technology was further defined to only include non-conveyorized HASL processes. Conveyorized HASL processes, and both non-conveyorized and conveyorized equipment configurations of the other technology categories, are all considered to be alternatives to non-conveyorized HASL.

1.3.2 Boundaries of the Evaluation

For the purposes of the environmental evaluation (i.e., human health and ecological hazards, exposure, risk, and resource consumption), the boundaries of this evaluation can be defined in terms of the overall life cycle of the surface finishing products and in terms of the PWB manufacturing process. The life cycle of a product or process encompasses extraction and processing of raw materials, manufacturing, transportation and distribution, use/re-use/ maintenance, recycling, and final disposal. As discussed in Section 1.2.3, rigid, multi-layer PWB manufacturing encompasses a number of process steps, of which the surface finishing process is the last one.

The activities evaluated in this study are primarily the use of surface finishing chemicals at PWB facilities and the release or disposal of surface finishing chemicals from PWB facilities. However, in addition to evaluating the energy consumed during surface finishing line operation, the analysis of energy impacts (Section 5.2) also discusses the pollutants generated from producing the energy to operate the surface finishing line, as well as energy consumed in other life-cycle stages, such as the manufacture of chemical ingredients. In addition, information is presented on the type and quantity of wastewater generated by the surface finishing process line,

and the risk to the environment resulting from the discharge of the wastewater to nearby surface water (Section 3.4). Finally, while information is presented on the generation and disposal of solid waste from surface finishing technologies, there was insufficient information to characterize the risk from these environmental releases. This is discussed in more detail in Section 3.1, Source Release Assessment.

In terms of the PWB manufacturing process, this analysis focused entirely on the surface finishing process, defined as beginning with a panel that has had solder mask applied, and ending after a surface finish has been applied to the connecting surfaces of the PWB and the board has been cleaned of any residual process chemistry. In cases where no solder mask is applied, the use cluster would begin after the stripping of the etch resist from the outside board surfaces.

The narrow focus on surface finishing technologies yields some benefits to the evaluation, but it also has some drawbacks. Benefits include the ability to collect extremely detailed information on the relative risk, performance, cost, and resources requirements of the baseline technology and alternatives. This information provides a more complete assessment of the technologies than has previously been available and would not be possible if every step in the PWB manufacturing process was evaluated. Drawbacks from such focused evaluations include the inability to identify all of the plant-wide benefits, costs, or pollution prevention opportunities that could occur when implementing an alternative to the baseline HASL technology. However, given the variability in workplace practices and operating procedures at PWB facilities, these other benefits and opportunities are expected to vary substantially among facilities and would be difficult to assess in a comparative evaluation such as a CTSA. Individual PWB manufacturers are urged to assess their overall operations for pollution prevention opportunities when implementing an alternative technology.

1.3.3 Issues Evaluated

The CTSA evaluated a number of issues related to the risk, competitiveness, and resource requirements of surface finishing technologies. These include the following:

- Risk: occupational health risks, public health risks, ecological hazards, and process safety concerns.
- Competitiveness: technology performance, cost, and regulatory status.
- Conservation: energy and natural resource use.

Occupational and public health risk information is for chronic exposure to long-term, day-to-day exposure and releases from a PWB facility rather than short-term, acute exposures to high levels of hazardous chemicals as could occur with a fire, spill, or other periodic release. Risk information is based on exposures estimated for a model facility, rather than exposures estimated for a specific facility. Ecological risks are also evaluated for aquatic organisms that could be exposed to surface finishing chemicals through wastewater discharges. Process safety concerns are summarized from material safety data sheets (MSDSs) for the technologies and process operating conditions.

Technology performance is based on a snapshot of the performance of the surface finishing technologies at volunteer test sites in the United States. Panels were electrically prescreened, followed by electrical stress testing, accelerated aging, and mechanical testing, in order to distinguish robustness of the applied surface finishes. Comparative costs of the surface finishing technologies were estimated with a hybrid cost model that combines traditional costs with simulation modeling and activity-based costs. Costs are presented in terms of dollars per surface square feet (ssf) of PWB produced.

Federal environmental regulatory information is presented for the chemicals in the surface finishing technologies. This information is intended to provide an indication of the regulatory requirements associated with a technology, but not to serve as regulatory guidance.

Quantitative resource consumption data are presented for the comparative rates of metal, energy, and water use by the surface finishing technologies. The consumption of other resources, such as process and treatment chemicals, are qualitatively assessed.

1.3.4 Primary Data Sources

Much of the process-specific information presented in this CTSA was provided by chemical suppliers to the PWB industry, PWB manufacturers who responded to project information requests, and PWB manufacturers who volunteered their facilities for a performance demonstration of the baseline and alternative technologies. The types of information provided by chemical suppliers and PWB manufacturers are summarized below.

Chemical Suppliers

The project was open to all interested chemical suppliers, provided that they agreed to disclose confidential chemical formulation data for use in this evaluation, and that their technologies met the criteria described in Section 1.3.1. Table 1-1 lists the suppliers who participated in the CTSA and the categories of surface finishing technologies they submitted for evaluation. It should be noted that this is not a comprehensive list of surface finishing technology suppliers. EPA made every effort to publicize the project through trade associations, PWB manufacturers, industry conferences and other means, but some suppliers did not learn of the project until it was too late to submit technologies for evaluation, or chose not to participate.

Table 1-1. Surface Finishing Technologies Submitted by Chemical Suppliers

Chemical Supplier	Surface Finishing Technology				
	Nickel/Gold	Nickel/Palladium/ Gold	OSP	Immersion Silver	Immersion Tin
Polyclad Technologies-Enthone				X	X
Electrochemicals, Inc.			X		
Florida CirTech, Inc.					X
MacDermid, Inc.	X	X	X		
Technic, Inc.	X				

A supplier for HASL is not shown in Table 1-1 because the HASL technology is not sold as a product line by a supplier. Instead, it consists a series of chemical cleaning and flux steps, followed by HASL equipment, which mechanically applies the solder to PWB surface. The board is then cleaned using a water rinse cleaning system. The chemical baths preceding the HASL equipment are not designed specifically for use with the HASL process, and are similar to those used by other surface finishing technologies. Chemical data from cleaning baths in other processes were substituted for this analysis. HASL equipment is commercially available from a number of suppliers.

Each of the chemical suppliers provided the following: MSDSs for the chemical products in their surface finishing technology lines; Product Data Sheets, which are technical specifications prepared by suppliers for PWB manufacturers that describe how to mix and maintain the chemicals baths; and complete product formulation data. Suppliers were also asked to complete a Supplier Data Sheet, designed for the project, which included information on chemical cost, equipment cost, water consumption rates, product constraints, and the locations of test sites for the Performance Demonstration. Appendix A contains a copy of the Supplier Data Sheet.

PWB Manufacturers

PWB manufacturers were asked to participate in a study of workplace practices. The PWB Workplace Practices Questionnaire requested detailed information on facility size, process characteristics, chemical consumption, worker activities related to chemical exposure, water consumption, and wastewater discharges. The questionnaire was distributed by IPC to PWB manufacturers. PWB manufacturers returned the completed questionnaires to IPC, which removed all facility identification and assigned a code to the questionnaires prior to forwarding them to UT's Center for Clean Products and Clean Technologies. In this manner, PWB manufacturers were guaranteed confidentiality of data.

For the Performance Demonstration project the PWB Workplace Practices Questionnaire was modified and divided into two parts: a Facility Background Information Sheet and an Observer Data Sheet. The Facility Background Information Sheet was sent to PWB facilities participating in the Performance Demonstration prior to their surface finishing technology test date. It requested detailed information on facility and process characteristics, chemical consumption, worker activities related to chemical exposure, and water consumption. The Observer Data Sheet was used by an on-site observer to collect data during the Performance Demonstration. In addition to ensuring that the performance test was conducted according to the agreed-upon test protocol, the on-site observer collected measured data, such as bath temperature and process line dimensions, and difficult to collect data, such as equipment loading rates and energy usage. The observer also checked survey data collected on the Facility Background Information Sheet for accuracy. Appendix A contains copies of the PWB Workplace Practices Questionnaire, the Facility Background Information Sheet, and the Observer Data Sheet forms.

Table 1-2 lists the number of PWB manufacturing facilities that completed the PWB Workplace Practices Questionnaire by type of surface finishing process, excluding responses with poor or incomplete data. Of the 54 responses to the questionnaire, 16 were Performance Demonstration test sites.

Table 1-2. Responses to the PWB Workplace Practices Questionnaire

Surface Finishing Technology	No. of Responses	Surface Finishing Technology	No. of Responses
HASL	29	OSP	9
Nickel/Gold	8	Immersion Silver	2
Nickel/Palladium/Gold	1	Immersion Tin	5

Information from the pollution prevention and control technologies survey conducted by the DfE PWB Project was also used in the CTSA. These data are described in detail in the EPA publication, *Printed Wiring Board Pollution Prevention and Control Technology: Analysis of Updated Survey Results* (U.S. EPA, 1998b).

1.3.5 Project Limitations

There are a number of limitations to the project, both because of the predefined scope of the project and data limitations inherent to the characterization techniques. Some of the limitations related to the risk, competitiveness, and conservation components of the CTSA are summarized below. More detailed information on limitations and uncertainties for a particular portion of the assessment is given in the applicable sections of this document. A limitation common to all components of the assessment is that the surface finishing chemical products assessed in this report were voluntarily submitted by participating suppliers and may not represent the entire surface finishing technology market. For example, the immersion palladium and benzotriazole-based OSP technologies were not evaluated in the CTSA. Alternatives that are evaluated were submitted by at least one supplier, but not necessarily by every supplier who offers that surface finishing technology.

<u>Risk</u>

The risk characterization is a screening level assessment of multiple chemicals used in surface finishing technologies. The focus of the risk characterization is on chronic (long-term) exposure to chemicals that may cause cancer or other toxic effects, rather than on acute toxicity from brief exposures to chemicals. The exposure assessment and risk characterization use a "model facility" approach, with the goal of comparing the exposures and health risks of the surface finishing process alternatives to the baseline HASL technology. Characteristics of the model facility were aggregated from questionnaire data, site visits, and other sources, and are based on the assumption of manufacturing 260,000 ssf per year. This approach does not result in an absolute estimate or measurement of risk.

In addition, the exposure and risk estimates reflect only a portion of the potential exposures within a PWB manufacturing facility. Many of the chemicals found in surface finishing technologies may also be present in other process steps of PWB manufacturing, and other risk concerns for human health and the environment may occur from other process steps. Incremental reduction of exposures to chemicals of concern from a surface finishing process, however, will reduce cumulative exposures from all sources in a PWB facility, provided that increased production does not increase plant-wide pollution.

Finally, information presented in this CTSA is based on publicly-available chemistry data submitted by each of the participating suppliers, as well as proprietary data submitted by the suppliers. Risk information for proprietary ingredients is included in this CTSA, but chemical identities and chemical properties are not listed.

Competitiveness

The Performance Demonstration was designed to provide a snapshot of the performance of different surface finishing technologies. The test methods used to evaluate performance were intended to indicate characteristics of a technology's performance, not to define parameters of performance or to substitute for thorough on-site testing. Because the test sites were not chosen randomly, the sample may not be representative of all PWB manufacturing facilities in the United States (although there is no specific reason to believe they are not representative).

The cost analysis presents comparative costs of using a surface finishing technology in a model facility to produce 260,000 ssf of PWBs. As with the risk characterization, this approach results in a comparative evaluation of cost, not an absolute evaluation or determination. The cost analysis focuses on private costs that would be incurred by facilities implementing a technology. It does not evaluate community benefits or costs, such as the effects on jobs from implementing a more efficient surface finishing technology. However, the Social Benefits/Costs Assessment (see Section 7.2) qualitatively evaluates some of these external (i.e., external to the decision-maker at a PWB facility) benefits and costs.

The regulatory information contained in the CTSA may be useful in evaluating the benefits of moving away from processes containing chemicals that trigger compliance issues. However, this document is not intended to provide compliance assistance. If the reader has questions regarding compliance concerns, they should contact their federal, state, or local authorities.

Conservation

The analysis of energy and water consumption is also a comparative analysis, rather than an absolute evaluation or measurement. Similar to the risk and cost analyses, consumption rates were estimated based on using a surface finishing technology in a model facility to produce 260,000 ssf of PWB.

1.4 ORGANIZATION OF THIS REPORT

This CTSA is organized into two volumes: Volume I summarizes the methods and results of the CTSA; Volume II consists of appendices, including detailed chemical properties and methodology information.

Volume I is organized as follows:

- Chapter 2 gives a detailed profile of the surface finishing use cluster, including process descriptions of the surface finishing technologies evaluated in the CTSA and the estimated concentrations of chemicals present in surface finishing chemical baths.
- Chapter 3 presents risk information, beginning with an assessment of the sources, nature, and quantity of selected environmental releases from surface finishing processes (Section 3.1); followed by an assessment of potential exposure to surface finishing chemicals (Section 3.2) and the potential human health and ecological hazards of surface finishing chemicals (Section 3.3). Section 3.4 presents quantitative risk characterization results, while Section 3.5 discusses process safety concerns.
- Chapter 4 presents competitiveness information, including performance demonstration results (Section 4.1), cost analysis results (Section 4.2), and regulatory information (Section 4.3).
- Chapter 5 presents conservation information, including an analysis of water and other resource consumption rates (Section 5.1) and energy impacts (Section 5.2).
- Chapter 6 describes additional pollution prevention and control technology opportunities (Sections 6.1 and 6.2, respectively).
- Chapter 7 organizes data collected or developed throughout the CTSA in a manner to facilitate decision-making. Section 7.1 presents a summary of risk, competitiveness, and conservation data. Section 7.2 assesses the social benefits and costs of implementing an alternative as compared to the baseline. Section 7.3 provides summary profiles for the baseline and each of the surface finishing alternatives.

REFERENCES

Abrams, Fern. 2000. IPC-Association Connecting Electronics Industries). Personal communication with Jack Geibig, UT Center for Clean Products and Clean Technologies. December.

IPC (IPC-Association Connecting Electronics Industries). 1996. *The National Technology Roadmap for Electronic Interconnections*.

Kincaid, Lori E., Jed Meline and Gary Davis. 1996. *Cleaner Technologies Substitutes Assessment: A Methodology & Resource Guide.* EPA Office of Pollution Prevention and Toxics. Washington, D.C. EPA 744-R-95-002. December.

MCC (Microelectronics and Computer Technology Corporation). 1993. *Environmental Consciousness: A Strategic Competitiveness Issue for the Electronics and Computer Industry*. March.

MCC (Microelectronics and Computer Technology Corporation). 1994. *Electronics Industry Environmental Roadmap*. December.

U.S. EPA (Environmental Protection Agency). 1995. *Printed Wiring board Industry and Use Cluster Profile.* EPA Office of Pollution Prevention and Toxics. Washington, D.C. EPA/744-R-95-005. September.

U.S. EPA (Environmental Protection Agency). 1997a. "Printed Wiring Board Case Study 6: Pollution Prevention Beyond Regulated Materials." EPA Office of Pollution Prevention and Toxics. Washington, D.C. EPA 744-F-97-006. May.

U.S. EPA (Environmental Protection Agency). 1997b. "Printed Wiring Board Case Study 7: Identifying Objectives for your Environmental Management System." EPA Office of Pollution Prevention and Toxics. Washington, D.C. EPA 744-F-97-009. July.

U.S. EPA (Environmental Protection Agency). 1997c. "Printed Wiring Board Case Study 8: Building an EMS, H-R Industries Experience." EPA Office of Pollution Prevention and Toxics. Washington, D.C. EPA 744-F-97-010. December.

U.S. EPA (Environmental Protection Agency). 1998a. *Printed Wiring Board Cleaner Technologies Substitutes Assessment: Making Holes Conductive.* Design for the Environment Printed Wiring Board Project. EPA Office of Pollution Prevention and Toxics. Washington, D.C. EPA/744-R-98-004a and EPA/744-R-98-004b. August.

U.S. EPA (Environmental Protection Agency). 1998b. *Printed Wiring Board Pollution Prevention and Control Technology: Analysis of Updated Survey Results.* Design for the Environment Printed Wiring Board Project. EPA Office of Pollution Prevention and Toxics. Washington, D.C. EPA 744-R-98-003. August.

U.S. EPA (Environmental Protection Agency). 1999. "Printed Wiring Board Case Study 9: Flexible Simulation Modeling of PWB Costs." EPA Office of Pollution Prevention and Toxics. Washington, D.C. EPA 744-F-99-004. May.

U.S. EPA (Environmental Protection Agency). 2000. *Implementing Cleaner Printed Wiring Board Technologies: Surface Finishes*. EPA Office of Pollution Prevention and Toxics. Washington, D.C. EPA 744-R-00-002. March.

Wehrspann, Carla. 1999a. IPC-Association Connecting Electronics Industries. Personal communication with Jeng Hon Su, University of Tennessee Center for Clean Products and Clean Technologies. July.

Wehrspann, Carla. 1999b. IPC-Association Connecting Electronics Industries. Personal communication with Jack Geibig, University of Tennessee Center for Clean Products and Clean Technologies. June.

Chapter 2
Profile of the Surface Finishing Use Cluster

This section of the Cleaner Technologies Substitutes Assessment (CTSA) describes the technologies that comprise the surface finishes use cluster. A *use cluster* is a set of chemical products, technologies, or processes that can substitute for one another to perform a particular function. In this case, the function is the application of a final surface finish to the printed wiring board (PWB). The set of technologies includes hot air solder leveling (HASL), which was selected as the baseline, and the alternative surface finishes, including electroless nickel/immersion gold (nickel/gold), electroless nickel/electroless palladium/immersion gold (nickel/palladium/gold), organic solderability preservative (OSP), immersion silver, and immersion tin.

Section 2.1 presents process descriptions for each of the surface finishing technologies and describes the chemical composition of products that were evaluated in the CTSA. Section 2.2 briefly describes additional technologies that may be used to perform the surface finishing function, but were not evaluated.

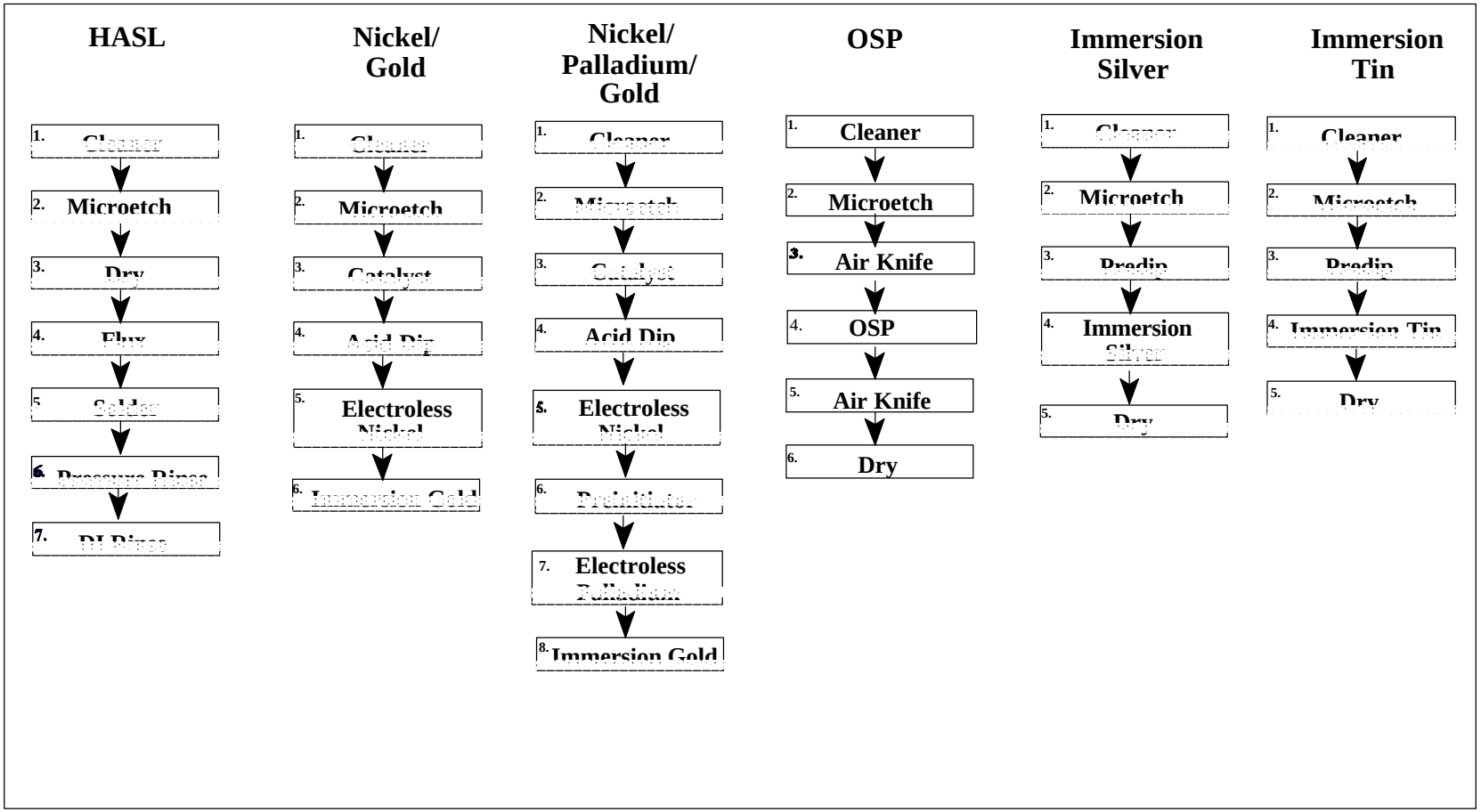
2.1 CHEMISTRY AND PROCESS DESCRIPTION OF SURFACE FINISHING TECHNOLOGIES

This section introduces the surface finishing technologies evaluated in the CTSA and details the process sequences. Typical operating conditions and operating and maintenance procedures are described in an overview of the surface finishing manufacturing process. Then the chemical processes occurring in each bath are detailed, along with additional process information specific to each technology.

2.1.1 Process Sequences of Surface Finishing Technologies

Figure 2-1 depicts the six surface finishing technologies evaluated in the CTSA. Because the function of applying a final surface finish can be performed using any of these technologies, these technologies may be substituted for each other in PWB manufacturing. The surface finishing technologies are all wet chemistry processes consisting of a series of chemical process baths, often followed by rinse steps, through which the PWB panels are passed to apply the final surface finish. The exception is the HASL process, which combines the typical cleaning and etching chemical processes with a mechanical process of dipping a board into molten solder followed by rinsing (described in Section 2.1.3).

For each of the surface finishes evaluated, the process steps depicted in the figure represent an integration of the various commercial products within the technology category. For example, chemical suppliers to the PWB industry submitted product data for two different OSP processes. The chemical suppliers offer additional variations to the OSP process that may have slightly different bath chemistries or process sequences, than the processes submitted. Figure 2-1 lists the process steps in a typical, or generic, OSP surface finishing line. The process steps in an actual line may vary.



Note: One or more intermediate rinse steps typically separate the process steps listed above. For simplicity, these intermediate rinse steps have not been included in the diagram.

Figure 2-1. Typical Process Steps for Surface Finishing Technologies

2.1.2 Overview of the Surface Finishing Manufacturing Process

Surface finishing technologies typically consist of a series of sequential chemical processing tanks (baths) separated by water rinse stages. The process can either be operated in a vertical, non-conveyorized submersive-type mode, or in a horizontal, conveyorized mode. In either mode, selected baths may be operated at elevated temperatures to facilitate required chemical reactions or baths may be agitated to improve contact between the panels and the bath chemistry. Agitation methods employed by PWB manufacturers include panel agitation, ultrasonic vibration, air sparging, and fluid circulation pumps.

Most process baths are followed by a water rinse tank to remove drag-out, the clinging film of process solution covering the rack and boards when they are removed from a tank. Rinsing is necessary to provide a clean panel surface for further chemical activity and to prevent chemical drag-out, which may contaminate subsequent process baths. PWB manufacturers employ a variety of rinse water minimization methods to reduce rinse water usage and consequent wastewater generation rates. The quantities of wastewater generated from surface finishing lines are discussed in Section 5.1, Resource Conservation, while the composition of the wastewater is modeled and presented in Section 3.2, Exposure Assessment. Rinse water reduction techniques are discussed in Section 6.1, Pollution Prevention.

After the application, imaging, and development of the solder mask, panels are loaded into racks (vertical, non-conveyorized mode) or onto a conveyor (horizontal, conveyorized mode) for processing by the surface finishing line. Racks may be manually moved from tank to tank, moved by a manually or automatically controlled hoist, or moved by other means. Process tanks are usually open to the atmosphere. To reduce volatilization of chemicals from the bath or worker exposure to volatilized chemicals, process baths may be equipped with a local ventilation system, such as a push-pull system, or covered during extended periods of latency. Horizontal, conveyorized systems are typically fully enclosed, with air emissions vented to a control technology or to the atmosphere outside the plant.

The HASL process differs from the other alternatives in that it does not rely on a chemical process to apply the final surface finish. Instead, the process combines the chemical processes of board preparation and cleaning with a mechanical step to apply the finish.

Regardless of the mode of operation or type of alternative, process chemical baths are periodically replenished to either replace solution lost through drag-out or volatilization, or to return the concentration of constituents in the bath to within acceptable limits. During the course of normal operations, bath chemistry can be altered by chemical reactions occurring within the bath or by contamination from drag-in. Bath solution may be discarded and replaced with new solution as required, with the frequency of replacement depending on analytical sampling results, the number of panel surface square feet (ssf) processed, or the amount of time elapsed since the last change-out. Process line operators also may clean the tank or conveyorized equipment during bath change-out operations.

Some process baths are equipped with filters to remove particulate matter that may be introduced to the bath or formed as a precipitate through a chemical reaction. Process line operators or other personnel periodically replace the bath filters based on criteria, such as analytical sampling results from the process baths, elapsed time, or volume of product produced.

2.1.3 Chemistry and Process Descriptions of Surface Finishing Technologies

This section describes in detail the processes for applying a solderable and protective coating, or surface finish, to the outside surfaces of a PWB. A brief description of the chemical mechanisms or processes occurring in each of the process steps, along with other pertinent process data such as flux compatibilities, storage limitations, assembly methods required, and modes of operation (e.g., non-conveyorized or conveyorized), are presented for each technology. For technologies with more than one chemical supplier (e.g., nickel/gold, OSP, immersion tin), a process description for each chemical product line was developed in consultation with the chemical supplier and then combined to form a generic process description for that technology. Notable differences in the chemical mechanisms or processes employed in a single product line from that of the generic process are detailed.

Each alternative surface finishing process evaluated in the CTSA uses one of the following mechanisms to apply the final finish.

- Electroless process: This chemical process promotes continuous deposition of a metal onto the PWB surface through an oxidation-reduction chemical reaction, without the use of an external electrical potential. A reducing agent, such as sodium hypophosphite, donates electrons to the positively charged metal ions in solution, thereby reducing the metal and promoting its deposition onto the catalyzed metal surfaces of the PWB. This reaction is considered auto-catalytic because it will continue to plate in the presence of source metal ions and a reducing agent until the board is removed from the plating bath. The thickness of plated deposits vary according to the amount of time spent in the plating bath, but are typically in the 3 to 5 micron range.
- Immersion process: This chemical process uses a chemical displacement reaction to deposit a metal layer onto the exposed metal surface of the PWB. In this reaction, the base metal donates the electrons that reduce the positively charged metal ions in the solution. Driven by the electrochemical potential difference, the metal ions in solution (e.g., gold ions in the immersion gold portion of the nickel/palladium/gold process) are deposited onto the surface of the board, simultaneously displacing ions of the surface metal (e.g., nickel ions for the example above) back into solution. This reaction is considered self-limiting, because once the surface metal is plated, there is no longer a source of electrons and the reaction stops. Surface finish deposits of up to 0.2 microns are considered typical for immersion processes.
- Coating: A protective coating is applied by submerging the PWB into a chemical bath. Although a coating does not require an exchange of electrons to facilitate deposition of the protective layer, some coatings may be formulated to adhere selectively to exposed metal surfaces. Typical coating thicknesses range from 0.1 to 0.5 microns.

Hot Air Solder Leveling (HASL)

HASL has long been the standard surface finishing method used in the manufacture of double-sided and multi-layered boards, because its excellent solderability during assembly. However, due to its technological limitations, environmental concerns, and process safety issues, assemblers and manufacturers have begun to seriously consider other surface finishes as viable alternatives to HASL. During the HASL process, soldermask-coated boards are first cleaned and etched to prepare the contact surfaces for the solder. Following the application of flux to a board, a layer of solder is applied to the copper surfaces by submersing the panel in molten solder. The excess solder is then blown from the board by an air knife, leaving a thin, protective layer of solder on the exposed circuitry.

Any of these three process segments - board preparation, solder application, or cleaning - may be automated or manual, or any combination thereof. These segments may also be integrated into one entire conveyorized process, combining the chemical pretreatment and cleaning steps with the solder application. Flux formulations are altered depending on the mode of operation and the desired flux characteristics. HASL finishes are compatible with surface mount technology (SMT) and typical through hole components; however, the lack of planarity, or flatness, of the finish makes assembly with fine pitch, small components difficult to control. In addition, the HASL finish cannot be wirebonded. Extended shelf life on a typical SMT pad or plated through hole (PTH) annular ring is not a concern with HASL finished boards, because of the durability of the finish. However, large flat surfaces can exhibit solderability problems after storage due to removal of all but a very thin coating of solder by the HASL process. This thin coating allows exposure of intermetallic surfaces that can create solderability problems (Carroll, 1999). Typically HASL finished PWBs have a shelf life of up to a year (Kerr, 1999).

A flow diagram of the process steps in a typical HASL process is presented in Figure 2-2. A brief description of each of the process steps is also given.

Step 1: Cleaner: An acid-based cleaner removes surface oils, oxides, and any organic residues left after the solder mask application. The cleaner provides a clean, consistent copper surface to ensure uniform etching.

Step 2: Microetch: The microetch solution lightly etches the exposed copper surfaces of the panel, including the barrels of the PTH, to remove any chemical contamination and metal oxides present.

Step 3: Dry: The etched panels are then air-dried using a non-heated blower to minimize the formation of oxides on the cleaned and etched copper surfaces.

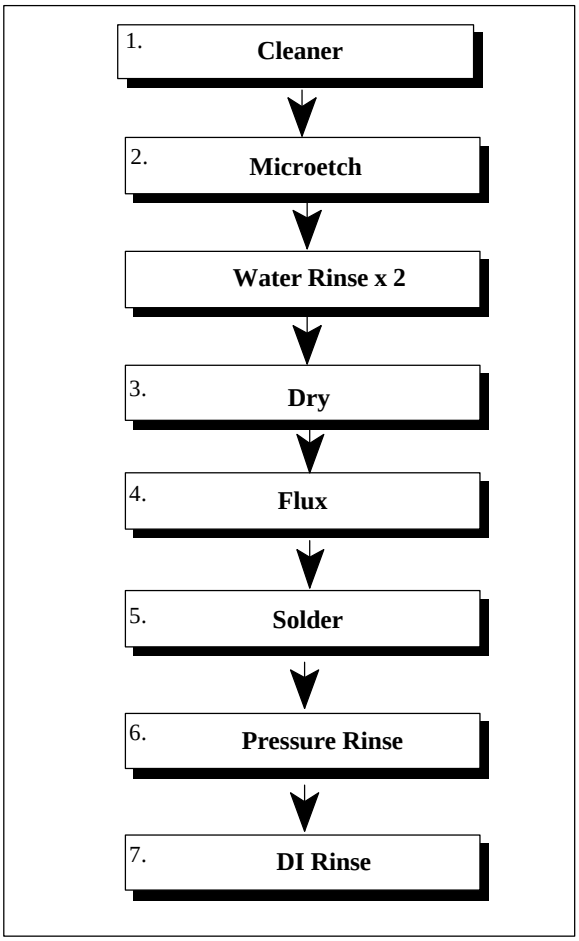


Figure 2-2. HASL Process Flow Diagram

Step 4: Flux: A chemical flux is applied to the panel to reduce the surface tension of the copper pads, thereby maximizing the wetting of the copper surfaces. The flux is composed of a heat transfer fluid, stabilizers, inhibitors, and activating agents. Flux formulations may vary considerably depending on the characteristics desired. Horizontal HASL system fluxes tend to be lower in viscosity and more highly activated than fluxes for vertical, non-conveyorized systems.

Step 5: Solder: Solder is selectively applied to the copper surfaces of the panel by submerging the preheated, fluxed panels in a bath of molten solder. The excess solder is then removed from the board by an air knife when the panel is withdrawn from the solder bath.

Step 6-7: Pressure Rinse: A high-pressure water rinse is used to dislodge any solder balls or excess solder flash that may be present on the PWB. The water rinse also removes any remaining flux residue that was not vaporized in the solder bath. This rinse stage may consist of several rinse tanks and include heated rinses or rinses combined with mechanical scrubbing. A post-solder chemical cleaner may also be used as a rinse aid if desired, or if water rinsing is insufficient. The final step in the post-clean process is rinsing in de-ionized water to reduce ionic contaminants on the surface finish.

Flux selection is critical to the sound operation of the HASL process. The flux is responsible for creating the copper surface conditions required to achieve a high quality solder deposit on the PWB. Fluxes are available in a variety of formulations with differing characteristics such as viscosity, foam level, acidity, volatile content, and type of activator. The type of HASL flux ultimately selected will depend on the type of chemicals and processes used in previous manufacturing stages, type of solder mask, and the solder deposit characteristics required.

The cleaning steps after the application of the solder can vary quite a bit, depending on several factors including the type of flux, type of solder mask, and the cleanliness standards to be met. The most commonly reported post-clean sequence by survey respondents utilized a series of water rinse baths combined with either high pressure rinsing, scrubbing, or a mild detergent. The post-clean system described above was selected to represent the HASL baseline.

Nickel/Gold

The nickel/gold process promotes the deposition of an initial, thick layer of nickel followed by a thin, protective layer of gold onto the exposed copper surfaces of the PWB. Nickel characteristics such as hardness, wear resistance, solderability, and uniformity of the deposit make this process a durable alternative PWB surface finish. The thin layer of immersion gold preserves the solderability of the finish by preventing oxidation of the highly active nickel surface. Nickel/gold finishes can typically withstand as many as six or more thermal excursions (heating cycles) during assembly without losing solderability.

This process can be operated in either a horizontal, conveyorized or vertical, non-conveyorized mode. A nickel/gold finish is compatible with SMT, flip chip, and ball grid array (BGA) technologies, as well as with typical through hole components. The thin layer of gold makes the surface aluminum wire-bondable, with thicker gold deposits also allowing gold wire-bonding. The high plating temperatures and low pH of the nickel/gold plating process can be incompatible with solder masks with high acrylic content, although solder masks high in epoxy content are unaffected by the plating solution. Nickel/gold plated boards have a shelf life of up to two years or more.

A flow diagram of the process baths in a typical nickel/gold process is presented in Figure 2-3, followed by a brief description of each of the process steps.

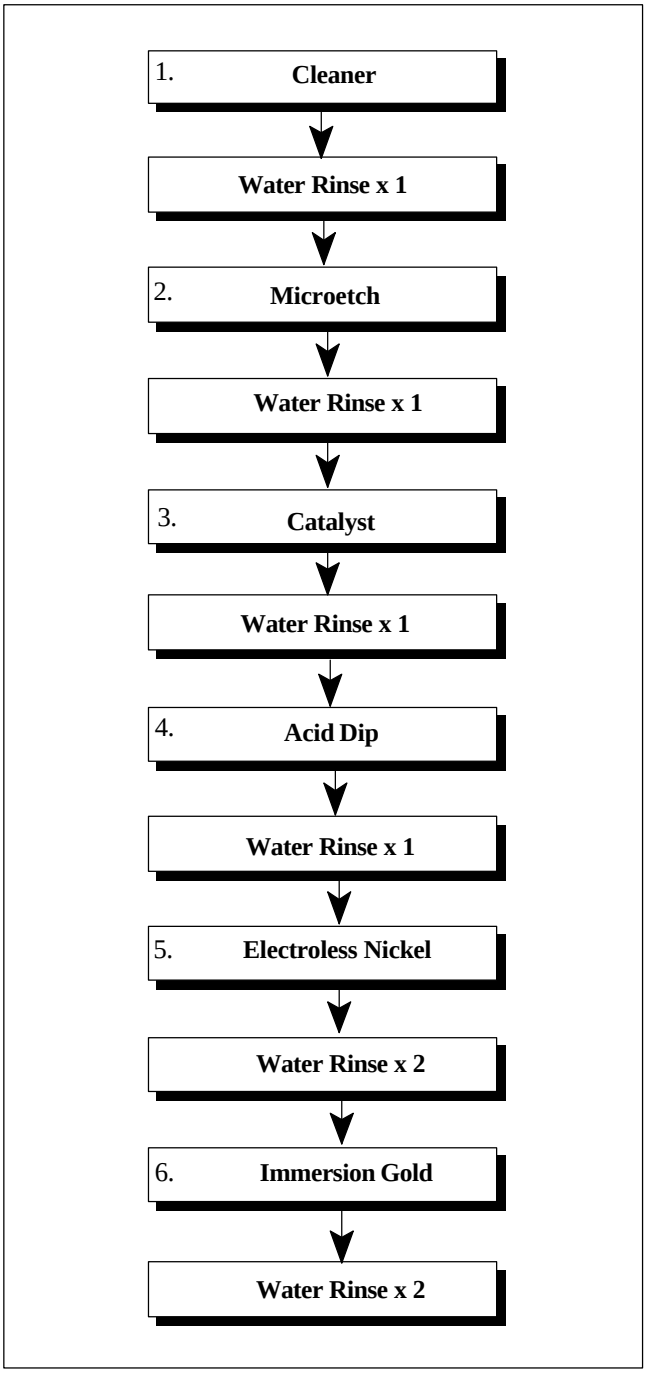


Figure 2-3. Nickel/Gold Process Flow Diagram

Step 1: Cleaner: Grease, contaminants, and any organic solder mask residues are removed from the PWB surface in an acidic cleaner solution. The cleaner provides a clean, consistent copper surface to ensure uniform etching and prepares the board for application of the palladium catalyst.

Step 2: Microetch: The microetch solution lightly etches the exposed copper surfaces of the panel, including the barrels of the PTHs, to remove any chemical contamination and metal oxides present.

Step 3: Catalyst: The catalyst consists of a palladium salt in an acidic solution. Palladium ions are deposited onto the surface of a PWB in a displacement reaction, effectively exchanging the surface copper layer for palladium, thus forming a catalytic layer for subsequent nickel plating.

Step 4: Acid Dip: The acid dip, usually a weak sulfuric or hydrochloric acid, removes any residual catalyst from the non-copper surfaces of the PWB, to prohibit plating on the solder mask or other unwanted areas of the board.

Step 5: Electroless Nickel: An electroless nickel solution is used to plate a layer of nickel onto the surface of the palladium-covered areas in a high temperature, acidic bath. The electroless nickel solution contains a source of nickel ions, phosphorous, and a reducing agent, which is typically either sodium hypophosphite or dimethylamine borane. In the presence of the palladium, the reducing agent provides electrons to the positively charged nickel ions, causing reduction of the nickel and the deposition of elemental nickel onto the exposed palladium catalyst (Parquet and Sedacca, 1996). Phosphorous is co-deposited with the nickel, and the resulting nickel-phosphorous alloy forms a corrosion-resistant layer protecting the underlying copper. Because the bath is autocatalytic, it will continue plating until the panel is removed from the nickel bath. Nickel layer thicknesses for PWBs are typically 3 to 5 microns (120 to 200 microinches).

Step 6: Immersion Gold: A very thin, protective layer of pure gold is deposited onto the surface of the nickel in the immersion gold plating bath. A chemical displacement reaction occurs, depositing the thin layer of gold onto the metal surface while displacing nickel ions into the solution. Because the reaction is driven by the electrochemical potential difference between the two metals, the reaction ceases when all of the surface nickel has been replaced with gold. Gold layer thicknesses are typically 0.2 microns (8 microinches), but can be increased to allow gold wire-bonding of the final surface.

Although electroless nickel plating processes all require the presence of a catalyst to plate nickel onto a copper surface, the catalyst can at times be too aggressive and catalyze areas where plating is undesirable, such as areas of fine pitch circuitry, causing unintended short-circuiting. This problem is handled successfully (with typically less than a 5 percent failure rate) by introducing the panel to an acid dip after the catalyst bath, as described above (Kerr, 1999). The acid dip removes the unintended palladium salt deposits, without harming the elemental palladium deposited onto the copper surfaces.

A second method employed by some manufacturers is to use a less active catalyst, which tends not to bridge fine pitch circuitry or adhere onto solder mask-covered PWB surfaces. A ruthenium-based catalyst is used to deposit a ruthenium seed layer, in place of the more typical palladium-based catalysts. A nickel surface is then plated to the ruthenium seed layer using a sodium-hypophosphite-reduced nickel plating chemistry, until the desired nickel thickness is obtained. The gold is then applied as described above.

Nickel/Palladium/Gold

The nickel/palladium/gold process is similar to the nickel/gold process described above, except it uses a palladium metal layer that is deposited after the nickel layer, but prior to depositing the final gold layer. The palladium layer is much harder than gold, providing added strength to the surface finish for wirebonding and connector attachment, while protecting the underlying nickel from oxidation.

The process can be operated in either a horizontal, conveyorized, or a vertical, non-conveyorized mode. A nickel/palladium/gold finish is compatible with SMT, flip chip, and BGA technologies, as well as with typical through hole components. The finish is also both gold and aluminum wire-bondable. The high plating temperatures and low pH of the nickel/palladium/gold plating process can be incompatible with solder masks with high acrylic content, although solder masks high in epoxy content are unaffected by the plating solution. Nickel/palladium/gold-plated boards can withstand as many as six thermal excursions during assembly, and have a shelf life of up to two years or more.

A flow diagram of the process steps in a typical HASL process is presented in Figure 2-4. A brief description of each of the process steps is also given.

Steps 1- 4: Cleaner/Microetch/Catalyst/Acid Dip: PWBs are cleaned, microetched, and a palladium catalyst is applied to the exposed copper surfaces in a chemical process similar to the one described previously for nickel/gold. An acid dip is then used to remove the catalyst from areas of the board where plating is undesirable.

Step 5: Electroless Nickel: An electroless nickel solution plates a layer of nickel onto the surface of the thin, initial nickel deposit. The electroless nickel bath is a slightly alkaline solution containing a source of nickel ions, and a sodium hypophosphite reducing agent. The reducing agent provides electrons to the positively charged nickel ions, causing the reduction of the nickel and the plating of elemental nickel onto the exposed nickel-boron layer. Phosphorous is co-deposited with the nickel, causing the formation of a corrosion resistant layer of nickel-phosphorous alloy that protects the underlying copper. Because the bath is autocatalytic, it will continue plating until the panel is removed from the nickel bath. Nickel layer thicknesses are typically 3 to 5 microns (120 to 200 microinches).

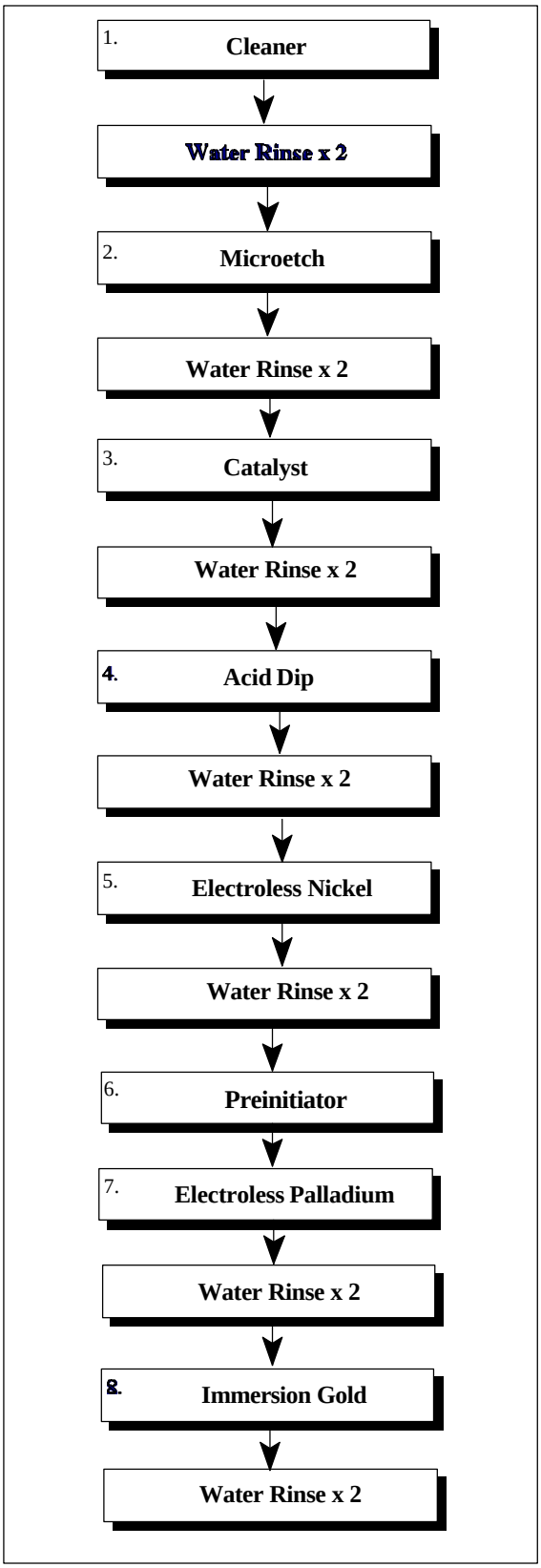


Figure 2-4. Nickel/Palladium/Gold Process Flow Diagram

Step 6: Preinitiator: The preinitiator reactivates the nickel surfaces by using a mineral acid to remove oxide from the surface of the nickel. In addition, the preinitiator deposits trace quantities of a catalytic metal that promotes homogeneous palladium deposition, ensuring that all nickel surfaces begin plating quickly and at the same time.

Step 7: Electroless Palladium: The electroless palladium bath deposits a thin layer of palladium onto the nickel-covered circuitry through an oxidation-reduction reaction. Hypophosphite or formate is used as the reducing agent, providing electrons to the positively charged palladium ions, resulting in the plating of palladium onto the nickel surfaces of the PWB. Palladium layer thicknesses are typically 0.3 to 0.8 microns (12 to 32 microinches).

Step 8: Immersion Gold: A very thin, protective layer of pure gold is deposited onto the surface of the palladium in the immersion gold plating bath. A chemical displacement reaction occurs, depositing the thin layer of gold onto the metal surface while displacing palladium ions into the solution. Because the reaction is driven by the potential difference of the two metals, the reaction ceases when all of the surface palladium has been replaced with gold. Gold layer thickness is typically 0.2 microns (8 microinches).

Organic Solderability Preservative (OSP)

The OSP process selectively applies a flat, anti-oxidation film onto the exposed copper surfaces of the PWB to preserve the solderability of the copper. This coating reacts with the copper in an acid and water mixture to form the nearly invisible protective organic coating. OSP processes can be based on benzimidazole chemistries that deposit thicker coatings, or on benzotriazoles and imidazoles chemistries which deposit thinner coatings. The thicker OSP coatings, which are evaluated in this CTSA, can withstand a minimum of three and up to as many as five thermal excursions while still maintaining coating integrity. Coating thicknesses of 0.1 to 0.5 microns (4 to 20 microinches) are typical for the thicker coatings, as opposed to the monomolecular layer formed by the thinner OSPs.

The process is typically operated in a horizontal, conveyorized mode but can be modified to run in a vertical, non-conveyorized mode. OSP processes are compatible with SMT, flip chip, and BGA technologies, as well as with typical through hole components. The OSP surface finish cannot be wirebonded. OSP surfaces are compatible with all solder masks, can withstand 3 to 4 thermal excursions during assembly, and have a shelf life of up to one year; extended shelf life times may result in a degradation of the coating.

A flow diagram of the process baths in a typical OSP process is presented in Figure 2-5, followed by a brief description of each of the process steps.

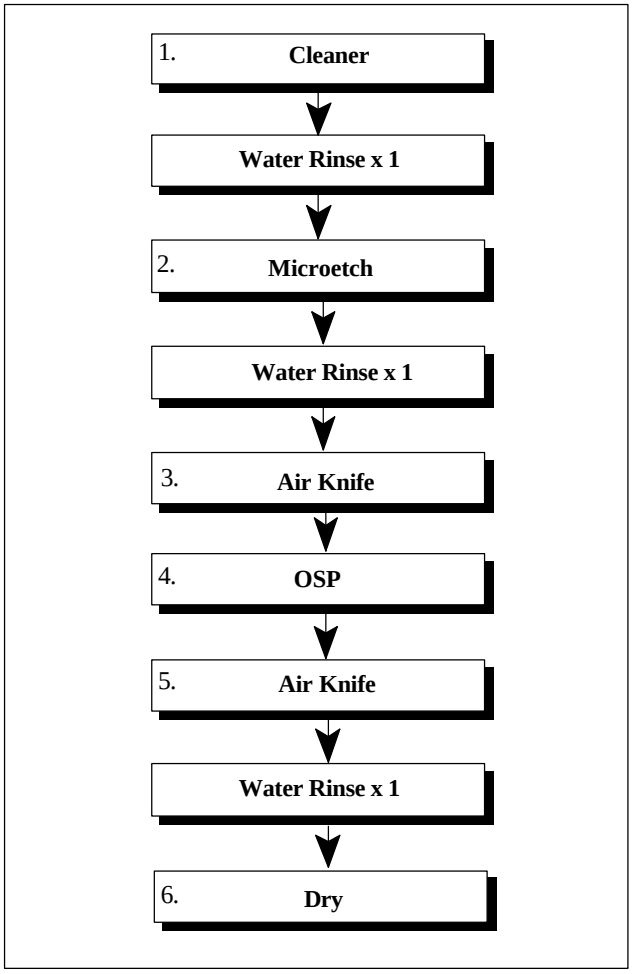


Figure 2-5. OSP Process Flow Diagram

Step 1: Cleaner: Surface oils and solder mask residues are removed from the exposed copper surfaces in a cleaner solution. The acidic solution prepares the surface to ensure the controlled, uniform etching in subsequent steps.

Step 2: Microetch: The microetch solution, typically consisting of dilute hydrochloric or sulfuric acid, etches the existing copper surfaces to further remove any remaining contaminants and to chemically roughen the surface of the copper to promote coating adhesion.

Step 3: Air Knife: An air knife removes excess water from the panel to limit oxidation formation on the copper surfaces prior to coating application. This step also minimizes drag-in of sulfates, which are harmful to the OSP bath.

Step 4: OSP: A protective layer is formed selectively on the exposed copper surfaces by the OSP in an acidic aqueous bath. The deposited protective layer chemically bonds to the copper, forming an organometallic layer that preserves the solderability of the copper surface for future assembly (Mouton, 1997).

Step 5: Air Knife: An air knife removes excess OSP from the panel and promotes even coating across the entire PWB surface. The air knife also minimizes the chemical losses through drag-out from the OSP bath.

Step 6: Dry: A warm-air drying stage cures the OSP coating and helps to remove any residual moisture from the board.

Immersion Silver

The immersion silver process promotes the selective deposition of silver onto the exposed copper surfaces of the PWB through a chemical displacement reaction. Silver surfaces are protected from tarnishing by a co-deposited organic inhibitor that forms a hydrophobic layer on top of the silver, thus preserving the coating's solderability. The final silver finish thickness is typically 0.1 microns (3 to 4 microinches). The silver process submitted for evaluation is operated exclusively as a horizontal, conveyorized process, however the process may be operated in either vertical or horizontal mode. Immersion silver finishes are compatible with SMT, flip chip, and BGA technologies, as well as with typical through hole components. They are also both gold and aluminum wire-bondable. Silver finishes are compatible with all types solder masks, can withstand up to five thermal excursions during assembly, and have a shelf life of at least six months.

A flow diagram of the process steps in a typical HASL process is presented in Figure 2-6. A brief description of each of the process steps is also given.

Step 1: Cleaner: An acid-based cleaner removes surface oils, oxides, and any organic residues left after the solder mask application. The cleaner provides a clean, consistent copper surface to ensure uniform etching.

Step 2: Microetch: The microetch solution lightly etches the exposed copper surfaces of the panel, including the barrels of the PTHs, to remove any chemical contamination and metal oxides present.

Step 3: Predip: Etched panels are processed through a predip solution prior to silver deposition to remove any surface oxidation that may have occurred in the previous rinse stage. The predip, which is chemically similar to that of the silver deposition bath, is also used to protect the bath from any harmful drag-in chemicals that may be detrimental to the deposition bath.

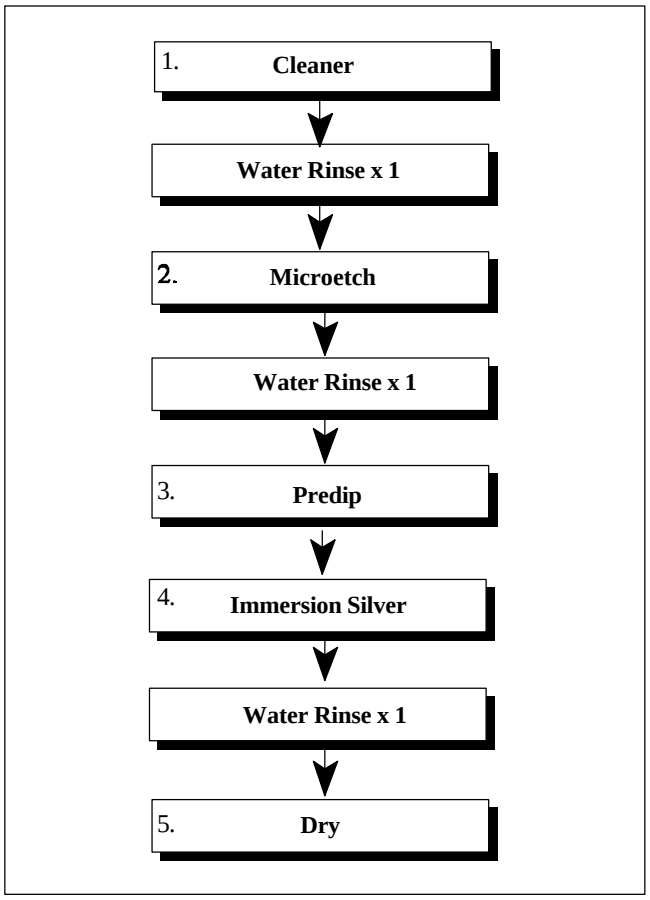


Figure 2-6. Immersion Silver Process Flow Diagram

Step 4: Immersion Silver: The immersion silver bath is a pH-neutral solution that selectively deposits a 0.1 micron (3 to 4 microinch) layer of silver onto all of the exposed copper surfaces of the PWB. Coating proceeds by a simple displacement reaction, with silver ions displacing copper ions from the surface. The liberated copper ions are benign to the bath chemistry and thus do not inhibit the bath effectiveness as copper concentrations increase. Because the bath is an immersion process, plating is self-limiting and will cease when the entire copper surface has been coated.

Step 5: Dry: A drying stage removes any residual moisture from the board to prevent staining and to ensure metal quality in the through holes.

Immersion Tin

The immersion tin process utilizes a thiorea-based reducing agent to create an electrochemical potential between the surface and stannous ions in solution, causing the reduction of a layer of tin onto the copper surfaces of the PWB. An organo-metallic compound, which is co-deposited along with the tin, acts to retard the formation of a tin-copper intermetallic layer, preserving the solderability of the finish. The organo-metallic compound also inhibits the formation of tin whiskers (i.e., dendritic growth). The process is typically operated in a conveyorized fashion, but can be modified to run in a vertical, non-conveyorized mode. Immersion tin surfaces are compatible with SMT, flip chip, BGA technologies, and typical through hole components. The immersion tin surface cannot be wirebonded. Tin surfaces are compatible with all solder masks, have a reported shelf life of one year and can typically withstand a minimum of five thermal excursions during assembly.

A flow diagram of the process steps in a typical immersion tin process is presented in Figure 2-7. A brief description of each of the process steps is given.

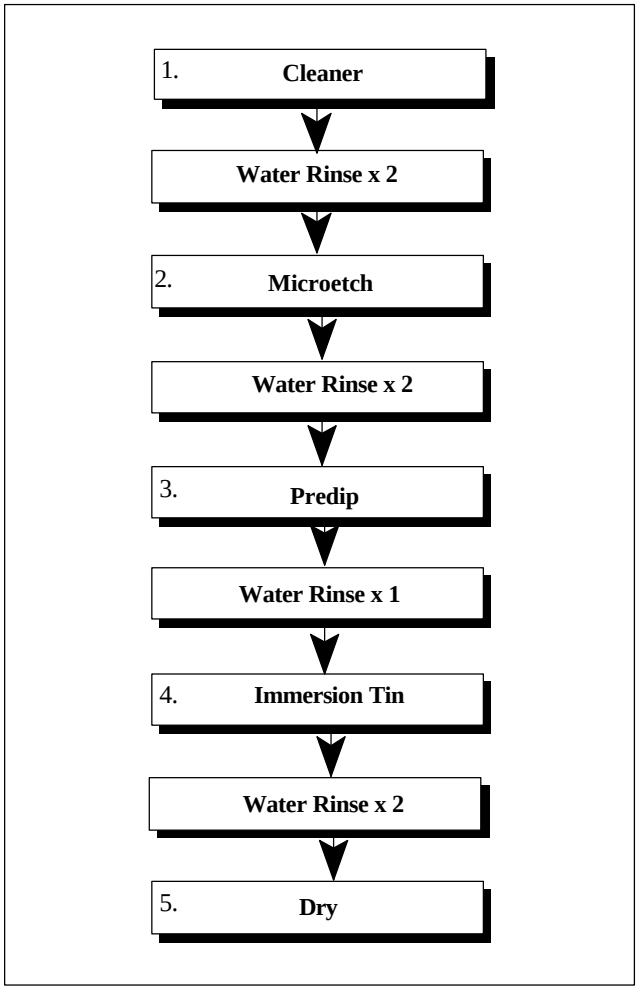


Figure 2-7. Immersion Tin Process Flow Diagram

Step 1: Cleaner: Surface oils and solder mask residues are removed from the exposed copper surfaces in a cleaner solution. The acidic solution prepares the surface to ensure controlled, uniform etching.

Step 2: Microetch: A microetch solution, typically consisting of dilute hydrochloric or sulfuric acid, removes any remaining contaminants from the copper surface. The etching also chemically roughens the copper surface to promote good tin-to-copper adhesion.

Step 3: Predip: Etched panels are processed through a predip solution that is chemically similar to that of the tin bath, thus protecting the plating bath from harmful drag-in chemicals.

Step 4: Immersion Tin: A tin plating bath deposits a thin layer of tin onto the exposed copper circuitry through a chemical displacement reaction that deposits stannous ions while displacing copper ions into the plating solution. The bath is considered self-limiting, because plating continues only until all the copper surfaces have been coated with a tin deposit. The presence of a complexing agent, thiourea, prevents the copper from interfering with the plating process. The complexed copper is removed as a precipitate from solution by decantation.

Step 5: Dry: A drying stage removes any residual moisture from the board to prevent staining and to ensure high metal quality in the through holes.

2.1.4 Chemical Characterization of Surface Finishing Technologies

This section describes the sources of bath chemistry information, methods used for summarizing that information, and the use of bath chemistry data. Publicly-available information, along with proprietary chemical information obtained from the chemical suppliers, was used to assess exposure, risk, and cost for the processes. This section does not identify any proprietary ingredients. Generic names have been submitted for the names of proprietary, confidential chemicals to mask their identity.

Use of Chemical Product and Formulation Data

Assessment of releases, potential exposure, and characterizing risk for the surface finishing technologies requires chemical-specific data, including concentrations for each chemical in the various process baths. Although some bath chemistry data were collected in the PWB Workplace Practices Questionnaire, the decision was made not to use this data because of inconsistencies in the responses to questions pertaining to bath chemistry. Instead, the suppliers participating in the Performance Demonstration each submitted complete chemical formulations along with other publicly-available information on their respective product lines. This information includes:

- material safety data sheets (MSDSs);
- Product Data Sheets;
- proprietary chemical product formulations; and
- patent data, in isolated cases.

The chemical formulations identify the chemicals and concentrations present in the chemical products while the MSDS provides physical property and worker hazard information on the entire formulation. The Product Data Sheets describe how those products are mixed together to make up the individual process baths. Patent information, when available, provided insight into the mechanisms for chemical activity.

Table 2-1 presents all of the chemicals identified in surface finishing process lines and the technologies in which they were used. Generic names have been substituted for the names of proprietary, confidential chemicals to mask their identity. Although the confidential formulations included all of the chemicals listed below, a chemical was considered publicly-available if it was listed on a MSDS or patent.

Table 2-1. Use Cluster Chemicals and Associated Surface Finishing Processes

Chemical	HASL	Nickel/ Gold	Nickel/ Palladium/ Gold	OSP	Immersion Silver	Immersion Tin
Acetic acid				X		
Aliphatic acid A		X				
Aliphatic acid B		X	X			
Aliphatic acid D						X
Aliphatic acid E		X	X			
Aliphatic dicarboxylic acid A		X	X			
Aliphatic dicarboxylic acid C		X	X			
Alkylalkyne diol	X					X
Alkylamino acid A					X	
Alkylamino acid B		X	X			X
Alkylaryl imidazole				X		
Alkylaryl sulfonate	X					X
Alkyldiol	X	X	X			
Alkylimine dialkanol						X
Alkylphenol ethoxylate	X					X
Alkylphenol polyethoxyethanol	X	X				
Alkylpolyol			X			
Amino acid salt			X			
Amino carboxylic acid			X			
Ammonium chloride		X				
Ammonia compound A			X			
Ammonia compound B		X	X			
Ammonium hydroxide		X	X			

Chemical	HASL	Nickel/ Gold	Nickel/ Palladium/ Gold	OSP	Immersion Silver	Immersion Tin
Aromatic imidizole product [a]				X		
Arylphenol	X			X		
Bismuth compound						X
Citric acid	X	X	X			X
Copper ion				X		
Copper salt C				X		
Copper sulfate pentahydrate	X	X	X	X		
Cyclic amide						X
Ethoxylated alkylphenol	X	X	X	X		X
Ethylenediamine			X			
Ethylene glycol	X			X		
Ethylene glycol monobutyl ether	X					X
Fatty amine					X	
Fluoboric acid	X					X
Gum	X			X		
Hydrochloric acid	X	X	X	X		X
Hydrogen peroxide	X	X	X	X	X	
Hydroxy carboxylic acid						X
Hydroxyaryl acid	X	X	X	X		
Hydroxyaryl sulfonate	X			X		
Inorganic metallic salt A		X				
Inorganic metallic salt B		X	X			
Inorganic metallic salt C		X				
Lead	X					
Maleic acid			X			
Malic acid		X	X			
Methane sulfonic acid						X
Nickel sulfate		X	X			
Nitrogen acid					X	
Nonionic surfactant [a]					X	
Palladium chloride		X				
Palladium salt			X			
Phosphoric acid	X	X	X	X	X	X
Potassium compound		X	X			
Potassium gold cyanide		X	X			
Potassium peroxymonosulfate	X	X				X
Propionic acid			X			
Quantenary alkylammonium chlorides						X
Silver nitrate					X	

Chemical	HASL	Nickel/ Gold	Nickel/ Palladium/ Gold	OSP	Immersion Silver	Immersion Tin
Silver salt						X
Sodium benzene sulfonate	X					X
Sodium hydroxide	X	X	X	X	X	
Sodium hypophosphite		X				
Sodium hypophosphite mono hydrate		X	X			
Sodium phosphorus salt						X
Sodium salt		X	X			
Stannous methane sulfonic acid						X
Substituted amine hydrochloride		X	X			
Sulfuric acid	X	X	X	X	X	X
Surfactant [a]			X			
Thiourea						X
Tin	X					
Tin chloride						X
Transition metal salt [a]		X	X			
Unspecified tartrate						X
Urea						X
Urea compound B		X	X			
Urea Compound C						X
Vinyl polymer						X

[a] Dropped due to insufficient identification.

Determining Chemical Formulations

Determining the chemical formulations for each process step is critical for evaluating each surface finishing technology. Each surface finishing product line submitted for evaluation was divided into basic bath steps common to all the processes within that surface finishing category (e.g., both OSP product lines submitted were divided into cleaner, microetch, and OSP baths). The basic bath steps were combined to form a process flow diagram specific to each surface finishing technology, as shown in Figure 2-1. The recommended formula for creating a new bath, along with the individual formulations for each chemical product, were combined to determine the individual chemical concentrations in the final bath. The individual chemical concentrations in the baths were calculated by:

$$C_b = (C_{CHEM})\,(C_{FORM})\,(D)\,(1000\ cm^3/L)$$

where,

C_b	=	concentration of constituent in bath (g/L)
C_{CHEM}	=	chemical concentration, by weight, in the product, from chemical product formulations obtained from chemical suppliers (%)
C_{FORM}	=	proportion of the product formulation volume to the total bath volume, from Product Data Sheets (%)
D	=	density of the product (g/cm^3)

An example calculation for the ethylene glycol concentration in the cleaner bath is shown below for one supplier's OSP process. Each product's formulation lists the chemicals that are contained in that product on a weight percentage basis. For ethylene glycol, this is 40 percent, or 40 grams ethylene glycol per 100 grams of product (C_{CHEM}). The supplier's Product Data Sheet lists how much of that chemical product is used in the total bath make-up on a volume percentage basis: in this case, ten percent, or ten liters of product per 100 liters of the total bath (C_{FORM}). The remaining volume in the bath is made up of deionized water. The MSDS for the product lists the specific gravity or density (D) of the product, which was multiplied by the weight and volume percentages above to obtain the bath concentration (C_b) for that constituent. (In some cases, the Product Data Sheets list chemicals or product packages on a mass per volume basis. This was multiplied by the weight percentage from the MSDS for that product package to obtain a concentration in the bath.) The example calculation is shown here:

$$\frac{40g}{100g}\left(\frac{10L}{100L}\right)\left(\frac{1.27g}{cm^3}\right)\left(\frac{1000cm^3}{L}\right) = 50.8\frac{g}{L}$$

After the product formulation and Product Data Sheet data were combined in the above manner for each supplier's product line, a list of chemicals in each surface finishing technology category (HASL, OSP, etc.) was compiled. This list shows all the chemicals that might be in each bath, by technology, as well as the concentration range for each chemical. However, some of the alternatives (e.g., OSP, nickel/gold, and immersion tin) have more than one chemical supplier using different bath chemistries. It was decided to include all of the identified chemicals in the formulations rather than selecting a typical or "generic" subset of chemicals.

Estimated concentration ranges (low, high, and average) were determined based on the formulation data and are presented in Appendix B. Concentrations are for each bath in each surface finishing process alternative.

Data Limitations

Limitations and uncertainties in the chemical characterization data arise primarily from side reactions in the baths. Side reactions in the baths may result in changing concentrations over time and/or formation of additional chemicals in the baths. This information is not reflected in product formulation data, MSDSs or Product Data Sheets, but would affect bath concentrations over time. As a result, bath concentrations are estimated; actual chemical constituents and concentrations will vary by supplier and facility.

In cases where the formulation data was reported as a “ < ” or “ > ” value, the reported values were assumed in calculating bath concentrations. For example, if “< 5 percent” was reported for a constituent by a product formulation, it is assumed that product contained 5 percent by weight (or volume, where appropriate) of that constituent. Also, some data were reported as ranges. In these cases, mid-points for the ranges were used to estimate bath concentrations (e.g., if 20 to 30 percent by weight was reported, 25 percent by weight was assumed).

Chemical Properties

Appendix C contains chemical properties data for each of the non-proprietary chemicals identified in surface finishing baths. For example, properties listed include molecular weight, vapor pressure, solubility, Henry’s Law Constant, and octanol-water partition coefficient. Basic chemical properties information for each chemical is followed by a summary description of fate and transport mechanisms for that chemical. In order to protect the identity of confidential chemicals, chemical properties data was not included for proprietary chemicals.

2.2 ADDITIONAL SURFACE FINISHING TECHNOLOGIES

The surface finishing technologies described in Section 2.1 represent the technologies that were evaluated in the CTSA. However, additional surface finishing technologies exist which were not evaluated in the CTSA for one or more of the following reasons:

- a product line was not submitted for the technology by any chemical supplier;
- the technology was not available to be tested in the Performance Demonstration; or
- the technology has only recently been commercialized since the evaluation began or was submitted too late to be included in the evaluation.

Despite not being evaluated, these technologies are important because they are alternative methods for surface finishing that accomplish the removal of lead from PWB manufacturing, which is a goal of the PWB manufacturing industry. A brief description of one surface finishing technology not evaluated in this CTSA is presented below. Other technologies may exist, but they have not been identified by the project.

2.2.1 Immersion Palladium

The immersion palladium process uses a three step process to deposit a thin surface finish of palladium on the exposed copper traces of the PWB. The process is similar to other wet processes presented earlier in this chapter. It consists of a series of chemical baths separated by a series of water rinse steps. The recommended bath sequence for the immersion palladium process is as follows:

- cleaner;
- water rinse;
- microetch;
- water rinse;
- immersion palladium;
- water rinse; and
- dry.

A mild alkaline cleaner is first used to clean the surface of copper, removing oil and debris from the boards' surface. The copper is then lightly etched to remove any copper oxide by the microetch, providing a pristine surface for palladium deposition. Finally, a three microinch layer of palladium is deposited onto the board by the immersion palladium bath via a chemical displacement reaction. During the reaction, palladium ions are deposited onto only the exposed copper surfaces of the board, displacing copper ions into the plating solution. Like other immersion processes, the palladium deposition is self-limiting, halting once all of the exposed copper has been covered by a layer of palladium. The displaced copper remains in solution, continuing to build in concentration, until an electrolyte in the bath causes the copper to precipitate out of solution, usually at a concentration of greater than 150 parts per million. The precipitate is then filtered out of the bath. The bath can be operated without replacement as long as the electrolyte and palladium content are maintained (Sedlak, 2000).

The immersion palladium process is typically operated in a vertical, non-conveyorized mode but can be modified to run in a horizontal, conveyorized mode. Immersion palladium finishes are compatible with SMT, flip chip, and BGA technologies, as well as with typical through hole components. The finish is also gold wire-bondable. Immersion palladium finishes are sensitive to some of the more aggressive fluxs, so milder fluxes (e.g., no-clean fluxes) are recommended. They can withstand four thermal excursions during assembly, and have a shelf life of at least 12 months. The immersion palladium process has been run successfully at two prototype facilities. However, the process could not be evaluated by the project because it could not be tested under full production at the time of the Performance Demonstration.

REFERENCES

Carroll, Thomas. 1999. Senior Staff Engineer, Hughes Space Communications Co., Materials and Processes Operations. Electronic Communication to Abbey Hoates at U.S. EPA. June.

Kerr, Michael. 1999. Circuit Center, Inc. Written communication to Kathy Hart at U.S. EPA. July.

Mouton, Roger. 1997. *OSP Technology Improvements*. Circuitree. March.

Parquet, Dan T. and Spence A. Sedacca. 1996. *Electroless Ni/Au as an HASL alternative*. Electronic Packaging and Production. March.

Sedlak, Rudy. 2000. RD Chemical Company. Electronic communication with Jack Geibig, University of Tennessee Center for Clean Products and Clean Technologies. July.

Chapter 3
Risk Screening and Comparison

This chapter of the Cleaner Technologies Substitutes Assessment (CTSA) addresses the health and environmental hazards, exposures, and risks that may result from using a surface finishing technology. The information presented here focuses entirely on the surface finishing technologies. It does not, nor is it intended to, represent the full range of hazards or risks that could be associated with printed wiring board (PWB) manufacturing. This risk evaluation is a screening-level assessment of multiple chemicals belonging to the surface finishing use cluster, and is presented as a screening level rather than a comprehensive risk characterization, both because of the predefined scope of the assessment and because of exposure and hazard data limitations. The intended audience of this risk screening and comparison is the PWB industry and others with a stake in the practices of this industry.

Section 3.1 identifies possible sources of environmental releases from surface finishing and, in some cases, discusses the nature and quantity of those releases. Section 3.2 assesses occupational and general population (i.e., the public living near a PWB facility; fishing streams that receive wastewater from PWB facilities) exposures to surface finishing chemicals. This section quantitatively estimates inhalation and dermal exposure to workers and inhalation exposure to the public living near a PWB facility. Section 3.3 presents human health hazard and aquatic toxicity data for surface finishing chemicals. Section 3.4 characterizes the risks and concerns associated with the exposures estimated in Section 3.2. In all of these sections, the methodologies or models used to estimate releases, exposures, or risks are described along with the associated assumptions and uncertainties. Finally, Section 3.5 summarizes chemical safety hazards from material safety data sheets (MSDSs) for surface finishing chemical products and discusses process safety issues.

3.1 SOURCE RELEASE ASSESSMENT

The Source Release Assessment uses data from the PWB Workplace Practices Questionnaire, together with other data sources, to identify sources and amounts of environmental releases. Both on-site releases (e.g., evaporative or fugitive emissions from the process) and off-site transfers (e.g., off-site recycling) are identified and, for those where sufficient data exist from the questionnaire, numerical results are presented. The objectives of the Source Release Assessment are to:

- identify potential sources of releases;
- characterize the source conditions surrounding the releases, such as a heated bath or the presence of local ventilation; and
- characterize, where possible, the nature and quantity of releases under the source conditions.

Many of the releases may be mitigated and even be prevented through pollution prevention techniques and good operating procedures such at those described in Chapter 6, Additional Environmental Improvement Opportunities. However, they are included in this assessment to illustrate the range of releases that may occur from surface finishing processes.

A material balance approach was used to identify and characterize environmental releases associated with day-to-day operation of surface finishing processes. Air releases and releases of organics to surface waters, which could not be quantified from the questionnaire data, are modeled in Section 3.2, Exposure Assessment.

Section 3.1.1 describes the data sources and assumptions used in the Source Release Assessment. Section 3.1.2 discusses the material balance approach used, release information, and data pertaining to all surface finishing process alternatives. Section 3.1.3 presents source and release information and data for specific surface finishing process alternatives. Section 3.1.4 discusses uncertainties in the Source Release Assessment.

3.1.1 Data Sources and Assumptions

This section presents a general discussion of data sources and assumptions for the Source Release Assessment. Sections 3.1.2 and 3.1.3 present more detailed information about specific inputs and releases for individual surface finishing alternatives.

Sources of data used in the Source Release Assessment include:

- industry data collection forms, such as the PWB Workplace Practices Questionnaire and Performance Demonstration Observer Data Sheets (Appendix A, Data Collection Sheets);
- supplier-provided data, including bath chemistry data and supplier Product Data Sheets describing how to mix and maintain baths (Appendix B, Publicly-Available Bath Chemistry Data);
- engineering estimates; and
- DfE PWB Project publication, *Printed Wiring Board Pollution Prevention and Control Technologies: Analysis of Updated Survey Results* (U.S. EPA, 1998a).

Bath chemistry data were collected in the PWB Workplace Practices Questionnaire, but these data were not used due to inconsistencies in the responses to questions pertaining to bath chemistry. Instead, surface finishing chemical suppliers participating in the Performance Demonstration submitted confidential chemical formulation data along with publicly-available Product Data Sheets on their respective product lines. Bath concentration ranges were determined based on this information using the method discussed in Section 2.1.4, Chemical Characterization of Surface Finishing Technologies. A general description of the PWB Workplace Practices Questionnaire, including its distribution and overall general results, is presented in Section 1.3.4, Primary Data Sources.

Several assumptions or adjustments were made to put the PWB Workplace Practices Questionnaire data into a consistent form for all surface finishing technologies. These include the following:

- Data reported on a daily basis were converted to an annual basis using the number of days per year of process operation (Appendix A, questions 2.2 and 3.2). For data on a weekly or monthly basis, 12 months per year and 52 weeks per year were assumed.
- Data reported on a per shift basis was converted to a per day basis using the number of hours per day the process was in operation, when available. Eight hours of operation was assumed to be equivalent to one shift.
- Bath names provided by questionnaire respondents were revised to be consistent with the generic surface finishing process descriptions provided in Section 2.1.3, Chemistry and Process Descriptions of Surface Finishing Technologies.

There were wide variations in submitted data due to the differences in size of PWB facilities. To adjust for this, data are presented here both as reported in the questionnaire (usually as an annual quantity consumed or produced), as well as normalized by annual surface square feet (ssf) of PWB produced by the individual surface finishing technology. Normalizing the data, however, may not fully account for possible differences in processing methods that could result from different production levels.

3.1.2 Overall Material Balance for Surface Finishing Technologies

A general material balance is presented here to identify and characterize inputs and potential releases from the surface finishing process alternatives. Due to limitations and gaps in the available data, no attempt was made to perform a quantitative mass balance of inputs and outputs. This approach is still useful, however, as an organizing tool for discussing the various inputs to, and outputs from, surface finishing processes, and presenting the available data. Figure 3-1 depicts inputs to a generalized surface finishing process line, along with possible outputs, including PWB product, solid waste, air emissions, and wastewater discharges.

Many PWB manufacturers have an on-site wastewater treatment system for pretreating wastewater prior to direct discharge to a stream or lake, or indirect discharge to a publicly owned treatment works (POTW). Figure 3-2 describes a simplified PWB wastewater treatment system, including the inputs and outputs of interest in the Source Release Assessment.

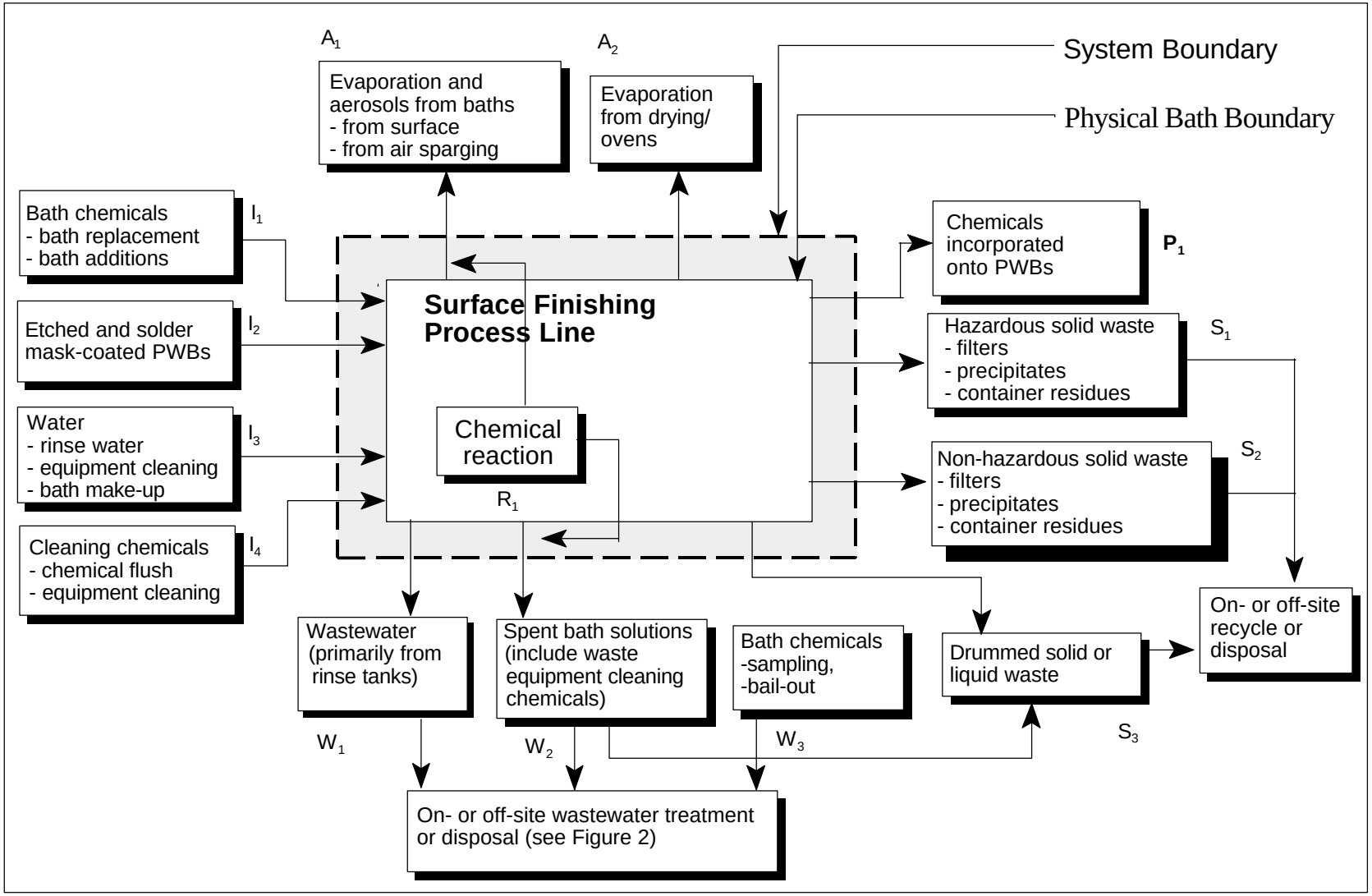


Figure 3-1. Schematic of Overall Material Balance for Surface Finishing Technologies

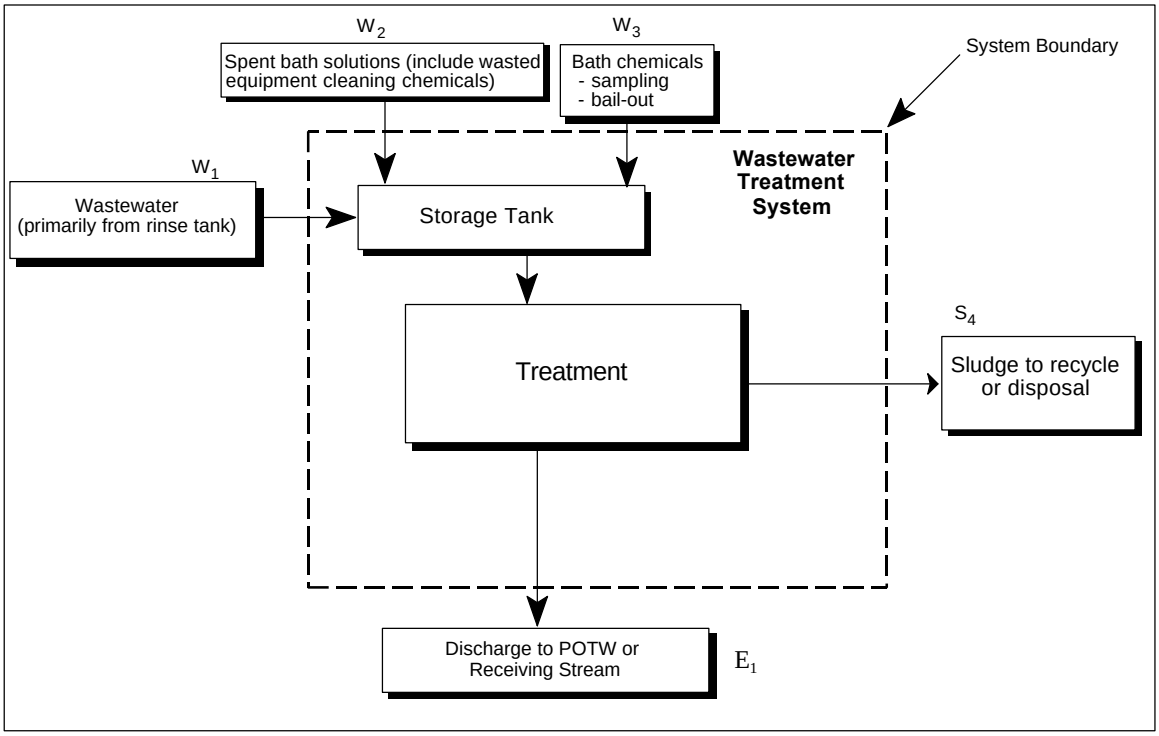


Figure 3-2. Wastewater Treatment Process Flow Diagram

Inputs

Possible inputs to a surface finishing process line include process chemicals and materials, etched and solder mask-coated PWBs that have been processed through previous PWB manufacturing process steps, water, and cleaning chemicals.

The total inputs for the process are described by the equation:

$$I_{total} = I_1 + I_2 + I_3 + I_4$$

where,

I_1 = bath chemicals
I_2 = etched and solder mask-coated PWBs
I_3 = water
I_4 = cleaning chemicals

These terms are discussed below.

I_1 *Bath chemicals.* This includes chemical formulations used for initial bath make-up, bath bailout and additions, and bath replacement. Bath formulations and the chemical constituents of those formulations were characterized based on Product Data Sheets and bath formulation data provided by the chemical suppliers. A detailed description of the

calculation of bath chemical concentrations is presented in Section 2.1.4, Chemical Characterization of Surface Finishing Technologies. Calculated chemical bath concentrations are reported in Appendix B. PWB manufacturers were asked to report the quantity of surface finishing chemicals they use annually in the PWB Workplace Practices Questionnaire. However, the resulting data were variable and poor in quality, preventing the quantification of total chemical usage for process chemicals.

I_2 *Etched and solder mask-coated PWBs.* PWBs with solder mask-coated copper circuitry that enter the surface finishing line could lose a small amount of copper to the process line due to etching and dissolution. Trace amounts of other additives such as arsenic, chromium, and phosphate may also be lost to the process. This applies to all surface finishing alternatives where copper is etched off the boards in the microetch bath at the beginning of the process.

PWB panels are the only source of copper for the surface finishing process. The rate at which the copper is lost can vary depending on process conditions (e.g., bath temperature, chemical concentration of bath, etc.) and the type of bath (whether a microetch bath or a plating bath). The amount of copper lost through etching and through displacement plating mechanisms is expected to be small, relative to other chemical additions. This input is not quantified.

I_3 *Water.* Water, usually deionized, is used in the surface finishing process for rinse water, bath make-up, and equipment cleaning. The water consumption of surface finishing technologies varies according to the number and size of rinse tanks used by the process. However, the number of rinse tanks can also vary from facility to facility within a technology category due to differences in facility operating procedures, rinse configuration, and water conservation measures.

Water usage data collected by the PWB Workplace Practices Questionnaire include the daily volume of water used for rinse water and bath make-up. Daily water usage in gallons was converted to annual water usage by multiplying by the number of days per year the process was in operation. The value was then normalized by dividing the annual water usage in gallons by the annual production in ssf of PWB produced for the same line. Both annual and normalized water consumption data from the questionnaire for each surface finishing technology are summarized in Table 3-1.

From the normalized data it can be seen that the nickel/gold and nickel/palladium/gold processes consume more water per ssf than the other technologies. The increased water consumption is due to the bath sequences of these technologies which are typically longer and thus use more rinse tanks. Drawing other conclusions from this data is difficult, given the variation in PWB throughput between reporting facilities and the relatively few number of responses within some technology categories.

Table 3-1. Water Usage of Surface Finishing Technologies From Questionnaire

Process Type	No. of Responses	Water Usage (I_3) (thousand gal/year)[a]	Water Usage (I_3) (gal/ssf)
HASL			
Non-conveyorized	6	0.3 - 750 (254)	0.970
Conveyorized	17	910 - 3,740 (1,250)	4.89
Nickel/Gold			
Non-conveyorized	8	17 - 1,620 (538)	101
Nickel/Palladium/Gold			
Non-conveyorized	2	216 - 1,710 (961)	164
OSP			
Non-conveyorized	5	42 - 150 (89.1)	1.93
Conveyorized	5	8 - 1,580 (440)	14.3
Immersion Silver			
Conveyorized	2	698 - 1,120 (907)	36.8
Immersion Tin			
Non-conveyorized	4	3.3 - 385 (209)	11.0
Conveyorized	2	11.5 - 199 (105)	0.333

[a] Average values from the PWB Workplace Practices Questionnaire data are shown in parentheses. Refer to Section 1.3.4 for a detailed discussion of questionnaire responses.

I_4 *Cleaning chemicals.* This includes chemicals used for conveyor equipment cleaning, tank cleaning, chemical flushing, rack cleaning, and other cleaning pertaining to the surface finishing process line. Data were collected by the PWB Workplace Practices Questionnaire regarding the use of chemicals to clean conveyors and tanks (questions 2.8, 3.8, 2.13, and 3.13). Three respondents with OSP, one with immersion tin, and one with the hot air solder leveling (HASL) technology use chemicals to clean their conveyor systems.

Table 3-2 shows the number of times that chemical flushing was reported by respondents as the method for tank cleaning for each process bath. The electroless nickel bath in the nickel/gold process, and both the activator and electroless nickel baths in the nickel/palladium/gold process are the only process baths that were consistently reported to require chemical cleaning. The use of chemicals to clean other process baths was reported infrequently and appeared to be based upon the operating practices of the particular facility, rather than on any cleaning requirement specific to the technology.

Table 3-2. Reported Use of Chemical Flushing as a Tank Cleaning Method

Process Type	Bath Type	Number of Respondents Using Chemical Flushing[a]
HASL	Microetch	1 (27)
	Flux	2 (27)
	Solder	5 (28)
	Pressure Rinse	1 (22)
Nickel/Gold	Acid Dip	1 (8)
	Electroless Nickel	8 (8)
	Immersion Gold	1 (8)
	Microetch	1 (8)
	Other Bath	5 (9)
Nickel/Palladium/Gold	Microetch	1 (1)
	Acid Dip	1 (1)
	Activator	2 (2)
	Electroless Nickel	2 (2)
	Electroless Palladium	1 (2)
	Immersion Gold	1 (1)
OSP	OSP	4 (9)
Immersion Silver	Predip	1 (2)
	Immersion Silver	2 (2)
Immersion Tin	Immersion Tin	1 (4)

[a] Total number of questionnaire responses for process bath are shown in parentheses.

Outputs

Possible outputs from a surface finishing process line include finished PWBs, air emissions, wastewater discharges, and solid wastes.

Product Outputs. Product outputs include the following:

P_1 *Chemicals incorporated onto PWBs during the surface finishing process*. This includes the PWBs along with lead, tin, silver, palladium, nickel, gold, and/or organic compounds that are coated onto the PWB surface. This output is not quantified.

Air Releases. Chemical emission rates and air concentrations are estimated by air modeling performed in Section 3.2, Exposure Assessment. The sources of air releases and factors affecting emission rates are summarized below.

The total outputs to air are given by the equation:

$$A_{total} = A_1 + A_2$$

where,

A_1 = evaporation and aerosol generation from baths

A_2 = evaporation from drying/ovens

These terms are discussed below.

A_1 *Evaporation and aerosol generation from baths.* Potential air releases from the process include volatilization from open surfaces of the baths as well as volatilization and aerosols generated from air sparging, which is used in some baths for mixing. These releases to both the occupational and outside environments are quantified in Section 3.2, Exposure Assessment. Gases formed by chemical reactions, side reactions, and by chemical plating in baths also contribute to air releases. However, they are expected to be small compared to volatilization and aerosol losses, and are not quantified.

Air releases may be affected by open bath surface area, bath temperature, bath mixing methods, and vapor control methods employed. Questionnaire data for bath agitation and vapor control methods are summarized below:[1]

- Most facilities using conveyorized processes use fluid circulation pumps to mix the baths. Panel agitation is also used as a mixing method by several facilities, while air sparging was seldom reported (more than one method can be used simultaneously).
- The majority of vapor control methods reported are fully-enclosed and vented to the outside. Only a few of the conveyorized processes use a push-pull[2] system for vapor control.
- For facilities using non-conveyorized processes, most use either panel agitation or circulation pumps to mix the tanks. Only about ten percent of the facilities use air sparging as a tank mixing method, which could generate aerosols and enhance volatilization from the baths.
- Frequently-used vapor control methods for non-conveyorized process baths include vent-to-outside (approximately 60 percent) and bath covers (20 percent), while seldom-reported methods include push-pull systems or fully enclosed baths.

Table 3-3 lists average bath surface area, volume, and bath temperature data from the PWB Workplace Practices Questionnaire. Some of this information (both surface area and temperature) is used to model air releases in the Exposure Assessment. Surface areas are calculated from reported bath length and width data. Larger bath surface areas enhance evaporation. Most of the baths are maintained at elevated temperatures, which also enhance evaporation.

---

[1] From Questionnaire, questions 2.10 and 3.10.

[2] Push-pull ventilation combines a lateral slot hood at one end of the tank with a jet of push air from the opposite end. It is used primarily for large surface area tanks where capture velocities are insufficient to properly exhaust fumes from the tank.

Table 3-3. Average Bath Dimensions and Temperatures for All Processes [a]

Bath	No. of Responses	Length (in.)	Width (in.)	Surface Area [b] (sq. in.)	Volume (gal.)	Temp. (°F)
HASL, Non-conveyorized						
Cleaner	3	28	20	540	33	74
Microetch	5	28	27	720	57	105
Dry	1	!	!	!	!	135
Flux	7	33	22	760	5	76
Preheat	1	!	!	!	!	244
Solder	6	34	23	870	10	515
Air Knife	1	!	!	!	!	123
Pressure Rinse	6	63	32	1900	41	91
HASL, Conveyorized						
Cleaner	6	24	24	580	40	70
Microetch	16	50	32	1700	92	90
Dry	1	37	9	330	!	140
Flux	15	29	25	810	15	80
Preheat	1	38	37	1400	!	180
HASL	15	35	25	990	18	523
Air Knife	2	38	37	1400	!	231
Pressure Rinse	15	67	34	2255	104	97
Nickel/Gold, Non-conveyorized						
Cleaner	6	25	17	310	44	118
Microetch	7	26	17	370	43	93
Catalyst	6	23	17	300	33	165
Acid Dip	7	26	17	360	42	75
Electroless Nickel	7	27	19	430	52	185
Immersion Gold	7	26	17	370	43	181
Nickel/Palladium/Gold, Non-conveyorized						
Cleaner	2	29	20	540	26	119
Microetch	2	25	21	440	55	97
Catalyst	2	33	10	330	50	134
Acid Dip	2	21	14	250	34	!
Electroless Nickel	2	24	14	270	36	181
Electroless Palladium	1	35	10	350	43	125
Immersion Gold	2	21	14	250	32	183
OSP, Non-conveyorized						
Cleaner	4	27	24	580	83	121
Microetch	5	25	25	570	82	83

Bath	No. of Responses	Length (in.)	Width (in.)	Surface Area [b] (sq. in.)	Volume (gal.)	Temp. (°F)
OSP	4	27	24	580	86	124
OSP, Conveyorized						
Cleaner	3	36	30	1100	56	113
Microetch	5	35	34	1300	63	99
OSP	5	72	34	2600	125	108
Immersion Silver, Conveyorized						
Cleaner	2	34	31	1000	65	81
Microetch	2	42	31	1300	80	73
Predip	2	47	31	1600	60	86
Immersion Silver	2	143	31	4400	142	113
Dry	1	!	!	!	!	149
Immersion Tin, Non-conveyorized						
Cleaner	2	27	18	500	49	104
Microetch	2	27	18	500	49	103
Predip	1	30	24	720	60	!
Immersion Tin	2	27	18	500	47	150
Immersion Tin, Conveyorized						
Cleaner	2	39	31	1500	100	105
Microetch	2	39	31	1500	100	95
Predip	2	31	14	450	33	101
Immersion Tin	3	47	31	1400	140	133
Dry	2	!	!	!	!	165

[a] Based on PWB Workplace Practices Questionnaire data.
[b] All of the surface areas present in the table are average values of individual bath areas; they are not obtained by multiplying the average length by the average width.
! No responses were given to this question in the questionnaire.

A_2 *Evaporation from drying/ovens.* Air losses due to evaporation from drying steps apply to HASL, OSP, immersion tin, and immersion silver processes with air knife, oven, or air cool steps. Releases for each process type are discussed qualitatively in Section 3.1.3.

Water Releases. Potential outputs to water include chemical-contaminated wastewater from rinse tanks, equipment cleaning, spent bath solutions, and liquid discharges from bath sampling and bail-out. Wastewater streams from the surface finishing process line are typically pre-treated by an on-site treatment system prior to being discharged from the facility. Spent bath chemicals that are considered hazardous, or are too difficult to treat on-site, are drummed and sent off-site for treatment. Waste streams with similar treatment requirements (e.g., chelated waste streams) may be segregated from the other wastes and batch treated together. All remaining liquid wastes are combined with similar wastes from other PWB manufacturing

processes prior to treatment. The co-mingled wastewater streams are then treated to meet the discharge limits for the facility. Once treated, the wastewater is discharged to a POTW or directly to a receiving stream. Facilities that directly discharge to a stream require a National Pollution Discharge Elimination System (NPDES) permit. Out of the 47 total survey respondents, 36 facilities indirectly discharge to POTWs while 10 facilities directly discharge to receiving streams. A detailed description of on-site treatment systems is presented in Section 6.2, Recycle, Recovery, and Control Technologies Assessment.

The total outputs to water are given by the equation:

$$W_{total} = W_1 + W_2 + W_3$$

where,

W_1 = wastewater
W_2 = spent bath solution
W_3 = bath sampling and bail-out

These terms are discussed below.

W_1 *Wastewater*. Chemical-contaminated rinse water is the largest source of wastewater from the surface finishing process line, resulting primarily from drag-out. The term drag-out refers to the process chemicals that are 'dragged' from chemical baths into the following water rinse stages, where they are washed from the board, resulting in contamination of the rinse water. Drag-out losses account for approximately 95 percent of uncontrolled bath losses [i.e., losses other than from bath replacement, bail-out, and sampling (Bayes, 1996)]. Because the volume of water consumed by the rinse steps greatly exceeds the water consumed by all other water uses, the quantity of wastewater generated by the process is assumed to be equal to the overall water usage (I_3). Daily water usage data were collected in the PWB Workplace Practices Questionnaire (questions 2.6 and 3.6), with the resulting data of variable to poor quality. The previous discussion of water usage data also applies to wastewater amounts.

In the absence of quality data from industry, a model was developed to estimate the mass loading of constituents within the wastewater, resulting from drag-out, during the production of 260,000 ssf of PWB by the surface finishing process. The mass of chemical transferred per day to the wastewater, as well as other model results, are presented in Appendix E. A detailed description of the model along with the methods of model development, validation and testing, and model limitations are presented in *Prediction of Water Quality from Printed Wiring Board Processes* (Robinson et al., 1999), part of which has been included in Appendix E. Operational practices, such as increased drainage time, that can be used to reduce chemical losses, are described in Section 6.1, Pollution Prevention.

W_2 *Spent bath solution.* The concentration of chemicals within the process baths will vary, both as PWBs are processed through them, and as the baths age (e.g., volatilization,

evaporation, side reactions, etc.). These chemical baths are considered 'spent' once they have become too contaminated or depleted to properly perform, and are replaced with a new bath. During replacement, the spent bath chemistry is removed and the tank is cleaned, sometimes with cleaning chemicals, before a new bath is created. Depending on the chemicals involved, the spent bath chemistry will either undergo treatment on-site, or may be drummed and shipped off-site for treatment when hazardous. Waste equipment cleaning chemicals are also included in this waste stream.

Though requested, the data provided by industry respondents to the survey regarding the annual volume of bath chemistry disposed for each bath type (questions 2.13, 2.15, 3.13, and 3.15) was found to be of variable to poor quality. Instead, the annual volume of chemical solution disposed per bath type was calculated by determining the number of times a bath would require changing to produce a specific surface area of PWB, as described in Section 4.2, Cost Analysis. For the purposes of this assessment, chemical concentrations within the spent baths were assumed to be the same as concentrations at the time of bath make-up.

The methods of on-site treatment or disposal for individual spent baths were identified by questionnaire respondents. A summary of the spent bath treatment and disposal responses by technology type is presented in Table 3-4.

W_3 *Bath sampling and bail-out.* This includes bath samples disposed of after analysis and bath solution discarded through bail-out (sometimes done prior to bath additions). In some cases sampling may be performed at the same time as bail-out if the process bath is controlled by an automated monitoring system.

Routine bail-out activities, the practice of removing bath solution to make room for more concentrated chemical additions, could result in large volumes of bath disposal. Bail-out and bath addition data (e.g., frequency, duration and quantity) were collected in the PWB Workplace Practices Questionnaire, with the resulting data being of poor quality. Chemical loss due to bath sampling was assumed to be negligible.

Table 3-4. Spent Bath Treatment and Disposal Methods

Process Alternative	Total No. of Baths	Precipitation Pretreatment [a]	pH Neutralization [a]	Disposed to Sewer [a]	Drummed [a]	Recycled On-Site [a]	Recycle Off-Site [a]	Others
HASL	113	29	24	1	11	6	29	8
Nickel/Gold	55	35	25	0	2	2	4	5
Nickel/Palladium/ Gold	14	8	3	0	7	1	1	0
OSP	28	14	15	0	4	1	0	0
Immersion Silver	8	3	3	1	2	0	0	0
Immersion Tin	17	3	6	0	5	3	0	0

[a] Number of affirmative responses for any bath from the PWB Workplace Practices Questionnaire, for all facilities using a technology category.

Wastewater Treatment. Figure 3-2 depicts the overall water and wastewater treatment flows, including wastewater, bath chemicals, and spent bath solution inputs to treatment, treatment performed on-site or off-site, sludge generated from either on-site or off-site treatment, and final effluent discharge to a POTW or receiving streams. PWB manufacturers typically combine wastewater effluent from other PWB manufacturing processes prior to on-site wastewater treatment. Sludge from on-site wastewater treatment is typically sent off-site for recycling or disposal. Detailed treatment system diagrams for each surface finishing technology are presented and discussed in Section 6.2, Recycle, Recovery, and Control Technologies Assessment.

E_1 *Wastewater effluent from treatment.* The mass-loading of chemical constituents within the wastewater effluent is dependent on several factors including the type and mass-loading of chemical inputs to the treatment process, the treatment technology employed, the duration of treatment of the wastewater, and the discharge limit, if applicable. Facilities that discharge to a POTW must treat their wastewater to meet the permit levels set by the receiving POTW for targeted contaminants such as metals and biochemical oxygen demand (BOD). Facilities that discharge wastewater directly to a receiving stream must obtain a NPDES permit, which establishes limits for similar chemical contaminants.

No data were collected for this waste stream due to dependance on factors outside of the surface finishing technology. However, organic chemical constituents resulting from the mass-loading into the treatment process are calculated and organic releases to the receiving stream are modeled in Section 3.2, Exposure Assessment.

Solid Waste. Solid wastes are generated by day-to-day surface finishing line operation and by wastewater treatment of process effluent. Some of these solid wastes are recycled, while others are sent to incineration or land disposal. The total solid waste outputs are given by the equation:

$$S_{total} = S_1 + S_2 + S_3 + S_4$$

where,

S_1 = hazardous solid waste
S_2 = non-hazardous solid waste
S_3 = drummed solid or liquid waste
S_4 = sludge from on-site wastewater treatment

These terms are discussed below.

S_1 *Hazardous solid waste.* Hazardous solid waste could include spent bath filters, solder dross, packaging or chemical container residues, and other solid waste from the process line which is contaminated with any hazardous material, as defined by the Resource Conservation and Recovery Act (RCRA). For example, lead, which is a component of the solder used in the HASL technology, is considered a hazardous solid waste (the

RCRA waste code D008 is for lead).[3] Container residue is estimated by EPA to be up to four percent of the chemicals use volume (Froiman, 1996). An industry reviewer indicated this estimate would only occur with very poor housekeeping practices and is not representative of the PWB industry. RCRA waste codes which are applicable to the surface finishing technologies are discussed in Section 4.3, Regulatory Status. Hazardous solid waste is typically sent off-site to a hazardous waste landfill for disposal or is incinerated.

S_2 *Non-hazardous solid waste.* Non-hazardous solid wastes could include any spent bath filters, packaging or chemical container residues, and other solid waste from the process line that does not contain any RCRA-defined hazardous materials listed in CFR Section 261. These wastes may be recycled or sent to off-site disposal in a landfill.

S_3 *Drummed solid or liquid waste.* This includes other liquid or solid wastes that are drummed for off-site recycling or disposal. This includes spent bath chemicals which cannot be treated on-site because they are considered hazardous or require treatment beyond what can be provided by the facility. Hazardous chemical wastes are sent to a hazardous waste treatment facility. Table 3-5 is a summary of responses indicating the presence of a RCRA listed waste and the type of container in which it was stored.

Other chemical wastes are drummed and sent out for recycling to reclaim the metal content from the solution (e.g., gold, silver, nickel, etc.). The number of responses which indicated that a bath was drummed for disposal was shown in Table 3-4.

S_4 *Sludge from on-site wastewater treatment.* Facilities were asked to report the amount of sludge generated during on-site wastewater treatment that could be attributed to surface finishing line effluents (question 1.3). Many PWB manufacturers have indicated that the amount of sludge resulting from the surface finishing process cannot be reliably estimated since effluents from various PWB manufacturing process steps are combined prior to wastewater treatment. Other factors that also influence the amount of sludge generated during wastewater treatment include the size of the facilities, the surface finishing technology used, the treatment method used, facility operating procedures, the efficiency with which bath chemicals and rinse water are used, and so on. Thus, the actual and comparative amount of sludge generated due to the choice of surface finishing technology could not be determined, nor were data available to characterize the concentrations of metals contributed by the surface finishing line.

However, many respondents did report the annual amount of sludge generated from their on-site waste treatment facility. The average sludge generated annually by the respondents to the PWB Workplace Practices Questionnaire is 214,900 pounds. The average water content of the sludge, which is typically pressed prior to disposal, ranges from 60 to 70 percent (Sharp, 1999).

---

[3] It is important to note that solder dross and solder pot dumps are excluded from the RCRA definition of solid waste when they are recycled. Therefore, when they are recycled they are not considered a hazardous solid waste.

Table 3-5. RCRA Wastes and Container Types for Surface Finishing Technologies

Process Alternatives	Bath Name	No. of Baths	No. of RCRA Wastes	Open Head Drum	Close Head Drum	Others
HASL	Cleaner	12	1	0	2	0
	Microetch	25	8	0	9	4
	Flux	26	7	0	12	0
	Solder	26	7	8	6	5
	Pressure Rinse	21	2	1	1	3
Nickel/Gold	Cleaner	7	1	0	2	0
	Microetch	8	2	0	3	0
	Catalyst	5	1	0	2	0
	Acid dip	18	3	0	6	0
	Electroless. Nickel	8	0	0	3	0
	Immersion Gold	8	3	0	4	0
OSP	Cleaner	7	2	0	1	2
	Microetch	8	1	0	1	2
	OSP	7	0	0	1	1
Immersion Tin	Cleaner	5	0	0	1	0
	Immersion Tin	4	0	0	1	0

Transformations

Transformations within the surface finishing system boundary could include:

R_1 *Chemical reaction gains or losses*. This includes any chemical species consumed, transformed, or produced in chemical reactions and side reactions occurring in the process baths. Reactions and side reactions within the baths could result in either chemical losses or production of new chemicals as degradation products. Although there are almost certainly side reactions which occur, little research has been conducted to identify them when they do not obstruct the desired reactions. This is not quantified.

Material Balance

A material balance approach is often used to describe and analyze a process. The approach is based on the principle that the mass of the material inputs must equal the mass of the material outputs if the process is at steady-state (i.e., there is no accumulation of material within the process). Although the PWB Workplace Practices Questionnaire did not collect enough data to quantify every stream, the approach is a useful way to identify and organize input and output streams that cross the boundary of the system (the process in this case).

The general mass balance equation for a specific chemical is:

$$\text{Input} - \text{Output} + \text{Production} - \text{Consumption} = \text{Accumulation}$$

Since there were no chemical transformations identified, the production and consumption terms are dropped from the equation. When the system is considered to be running at steady-state, the accumulation term is equal to zero and the mass balance equation becomes:

$$\text{Inputs} = \text{Outputs}$$

The material balance for Figure 3-1 (surface finishing process line prior to wastewater treatment) includes the inputs I_1, I_2, I_3, and I_4, and the outputs P_1, A_1, A_2, W_1, W_2, W_3, S_1, S_2, and S_3.

Since the inputs must equal the outputs, the material balance for Figure 3-1 is:

$$I_1 + I_2 + I_3 + I_4 = P_1 + A_1 + A_2 + W_1 + W_2 + W_3 + S_1 + S_2 + S_3$$

or:

$$I_{total} = P_1 + A_{total} + W_{total} + S_1 + S_2 + S_3$$

The material balance for Figure 3-2 (wastewater treatment) includes the inputs W_1, W_2, and W_3, and the outputs E_1 and S_4.

Thus, the material balance equation for Figure 3-2, wastewater treatment, is:

$$W_1 + W_2 + W_3 = E_1 + S_4$$

or:

$$W_{total} = E_1 + S_4$$

These equations are presented to indicate that all the material flows have been accounted for.

3.1.3 Source and Release Information for Specific Surface Finishing Technologies

This section applies the material balance approach described previously to the individual surface finishing technologies. Each input and output is discussed as it applies to that surface finishing technology, and quantified when possible. The numbers reported in this section represent the actual responses to the PWB Workplace Practices Questionnaire, and thus, may reflect wide variations in the data corresponding to the different operating profiles of the respondents. To facilitate comparison among process alternatives and to adjust for wide variations in the data due to differences in facility size and production levels, data are presented both as reported in the PWB Workplace Practices Questionnaire, and normalized by production amounts (annual ssf of PWB produced). Values reported in this summary are average values calculated from questionnaire responses.

The limited number of responses to the questionnaire for some technologies along with differences in production levels and operating practices between facilities make it difficult to make a comparison of technologies. To facilitate a comparative evaluation, the individual technologies were modeled using a consistent production throughput in ssf of PWB produced. The modeling of the surface finishing technologies is presented in Section 4.2, Cost Analysis.

Hot Air Solder Leveling

Figure 3-3 illustrates the generic HASL process steps and typical bath sequence evaluated in the CTSA. The number and location of rinse steps shown in the figure are based on the PWB Workplace Practices Questionnaire data. Thus, Figure 3-3 describes the types and sequence of baths in a generic HASL line, but the types and sequence of baths in an actual line could vary. A detailed description of HASL process stages is presented in Section 2.1.3, Chemistry and Process Descriptions of Surface Finishing Technologies.

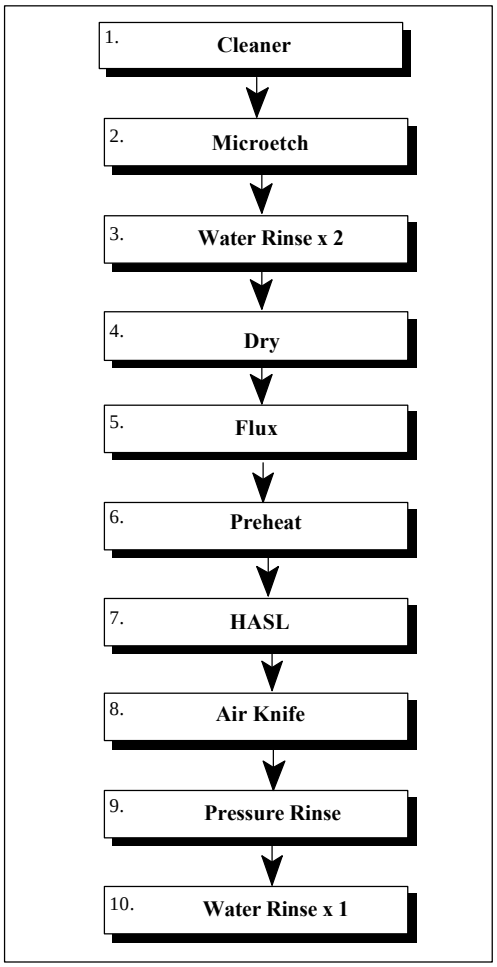


Figure 3-3. Generic HASL Process Steps and Typical Bath Sequence

Water Usage (I_3) and Wastewater (W_1). Water usage data from the PWB Workplace Practices Questionnaire is presented in Table 3-1; the volume of wastewater generated was assumed to be equal to the amount of water used (I_3). Of respondents using a HASL process, 21 facilities use the conveyorized process, while 9 facilities use the non-conveyorized process. In summary:

- Reported water usage for the facilities using the conveyorized HASL process average 1.2 million gallons per year, or about 4.9 gallons per ssf of PWB produced.
- Reported water usage for the facilities using the non-conveyorized HASL process average 250 thousand gallons per year, or 0.97 gallons per ssf of PWB produced.

Chemical constituents and concentrations in wastewater could not be adequately characterized from questionnaire data. In the absence of quality data from industry, a model was developed to estimate the mass loading of constituents within the wastewater, resulting from drag-out, during the production of 260,000 ssf of PWB by the surface finishing process. The term drag-out refers to the process chemicals that are 'dragged' from chemical baths into the following water rinse stages, where they are washed from the board, resulting in contamination of the rinse water. The mass of chemical transferred per day to the wastewater, as well as other model results, are presented in Appendix E.

Bath Chemicals Used (I_1). Bath concentrations of individual chemical constituents are presented in Appendix B. The volume of chemicals consumed per year was determined by modeling the time it would take the generic HASL process described in Figure 3-3 to produce a specific PWB throughput. A detailed description of the process modeling is presented in Section 4.2, Cost Analysis. The number of bath replacements (calculated from the modeled time) was then multiplied by the volume of the bath to determine the volume of a bath chemical consumed per year. The mass of solder consumed per year was calculated by using an estimate of the amount of solder applied per ssf of PWB produced, then adjusted to account for solder waste. When waste solder is not routinely recycled, as much as 2,500 lbs of solder is consumed when producing 260,000 ssf of PWB. Solder consumption is discussed further in Section 5.1, Resource Conservation. Bath chemical consumption is presented Appendix G.

Cleaning Chemicals (I_4). Nine out of 129 HASL baths were reported to be cleaned using chemicals, however, data concerning the type of cleaning chemical(s) were not collected by the questionnaire. The majority of chemical flushing reported for the HASL processes was used for solder tank cleaning during bath replacement. Water is most frequently used to clean tanks prior to new bath make-up.

Spent Bath Solutions (W_2). The quantity of spent bath solution could not be determined directly from the questionnaire data. However, the volume of spent bath chemistry was calculated by determining the number of bath changes required per year and multiplying by the average volume of the process tank (see Section 4.2, Cost Analysis). The concentrations of chemical constituents within the spent bath solutions were assumed to be the same as make-up bath concentrations.

Spent bath treatment and disposal methods were presented in Table 3-4. Off-site recycling, precipitation pretreatment, and pH neutralization are reported as common treatment methods for the conveyorized HASL processes. Respondents for both the non-conveyorized, vertical process and the mixed HASL processes reported that precipitation pretreatment, pH neutralization, and off-site recycling are common treatment methods.

Evaporation From Baths (A_1). Air releases are modeled in Section 3.2, Exposure Assessment. A summary of data collected from the questionnaire is presented below:

- For the conveyorized HASL processes, circulation pumps are used to mix all process baths except for the cleaner bath. Full enclosure and venting are the most common methods of vapor control reported by respondents for all baths and process steps.
- For non-conveyorized HASL facilities, both panel agitation and circulation pumps are the most reported mixing methods for all baths. Venting to the outside is the prevalent form of vapor control reported, though 25 percent of the baths were reported to use bath covers.
- Table 3-3 lists the bath surface area, volume, and bath temperature data reported by respondents to the PWB Workplace Practices Questionnaire.

Evaporation From Drying/Ovens (A_2). Air knife and oven drying occur after the microetch and HASL baths. Any solution adhering to the PWBs would be either blown off the boards and returned to the sump, or volatilized in the oven. Air emissions from air knife or oven drying were not quantified.

Chemicals Incorporated Onto PWBs (P_1). A coating of tin/lead solder is applied to the surface of PWB panels in the HASL process. The amount of solder added to the panels depends on the exposed surface area of the PWB panels being processed. The amount of solder incorporated onto a PWB was calculated at 0.0369 oz/ssf. Solder consumption is discussed further in Section 5.1, Resource Conservation.

Drummed Solid or Liquid Waste (S_3). Questionnaire respondents indicated that approximately 25 percent of HASL baths contain hazardous waste constituents as defined by RCRA. These wastes were associated by respondents with the microetch, flux, and solder baths. RCRA wastes are discussed in further detail in Section 4.3, Regulatory Status. In response to a separate question regarding spent bath treatment (see Table 3-4), 11 out of 113 HASL baths were reported by respondents to be drummed and sent off-site for recycling or disposal.

Nickel/Gold Process

Figure 3-4 depicts the generic nickel/gold process steps and typical bath sequence evaluated in the CTSA. The process baths shown in the figure represent an amalgamation of the various products offered within the nickel/gold technology category. The number and location of rinse steps displayed in the figure are based on PWB Workplace Practices Questionnaire responses. Thus, Figure 3-4 describes the types and sequence of baths in a generic nickel/gold line, but the types and sequence of process baths used by any particular facility could vary. A detailed description of the nickel/gold process is presented in Section 2.1.3, Chemistry and Process Descriptions of Surface Finishing Technologies.

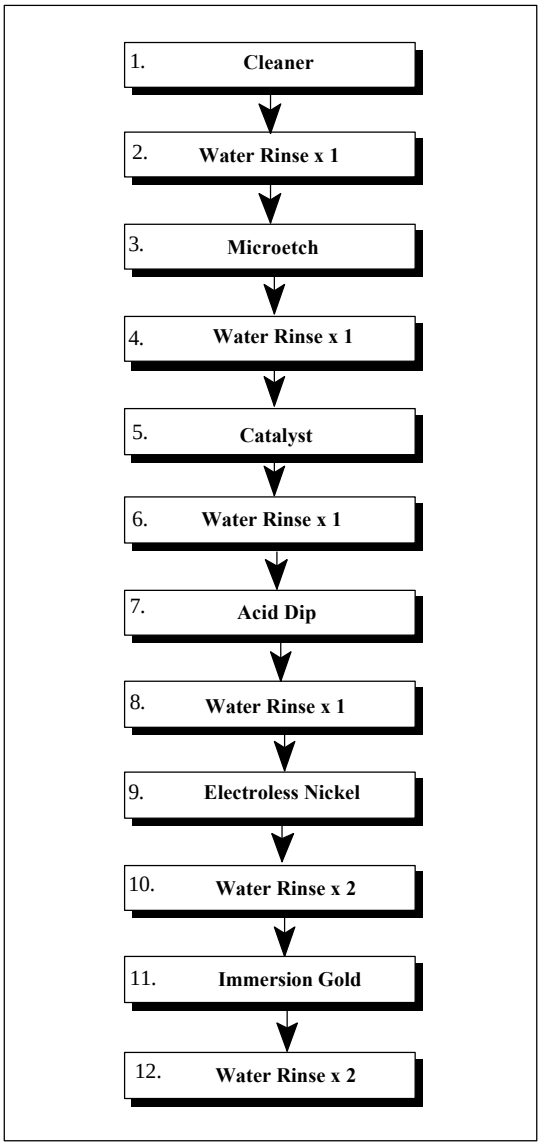


Figure 3-4. Generic Nickel/Gold Process Steps and Typical Bath Sequence

Water Usage (I_3) and Wastewater (W_1). Water usage data from the PWB Workplace Practices Questionnaire is presented in Table 3-1; the volume of wastewater generated was assumed to be equal to the amount of water used (I_3). All eight respondents report using the non-conveyorized nickel/gold process. In summary:

- Reported water usage for the facilities using the non-conveyorized nickel/gold process average 540 thousand gallons per year, or 100 gallons per ssf of PWB produced.

Chemical constituents and concentrations in wastewater could not be adequately characterized from questionnaire data. In the absence of quality data from industry, a model was developed to estimate the mass loading of constituents within the wastewater, resulting from drag-out, during the production of 260,000 ssf of PWB by the surface finishing process. The mass of chemical transferred per day to the wastewater, as well as other model results, are presented in Appendix E.

Bath Chemicals Used (I_1). Bath concentrations of individual chemical constituents are presented in Appendix B. The volume of chemicals consumed per year was determined by modeling the time it would take the generic nickel/gold process described in Figure 3-4 to produce a specific PWB throughput. A detailed description of the process modeling is presented in Section 4.2, Cost Analysis. The number of bath replacements (calculated from the modeled time) was then multiplied by the volume of the bath to determine the volume of a bath chemical consumed per year. Nickel/gold process chemical consumption is presented in Appendix G.

Cleaning Chemicals (I_4). Twelve out of 47 reported nickel/gold baths require chemicals to clean the tanks, however, data concerning the type of cleaning chemical(s) were not collected by the questionnaire. Seven of the tanks that were reported to require chemical flushing belong to electroless nickel baths. The remaining tanks requiring chemical flushing belong to baths which are not part of the generic process sequence described in Figure 3-4. Water is most frequently used to clean tanks prior to new bath make-up.

Spent Bath Solutions (W_2). The quantity of spent bath solution could not be determined directly from the questionnaire data. However, the volume of spent bath chemistry was calculated by determining the number of bath changes required per year and multiplying by the average volume of the process tank (see Section 4.2, Cost Analysis). The concentrations of chemical constituents within the spent bath solutions were assumed to be the same as make-up bath concentrations.

Spent bath treatment and disposal methods were presented in Table 3-4. Respondents for the non-conveyorized, vertical process reported that pH neutralization and precipitation pretreatment are common treatment methods. Off-site recycling was also reported as a treatment option.

Evaporation From Baths (A_1). Air releases are modeled in Section 3.2, Exposure Assessment. A summary of data collected from the questionnaire is presented below:

- For non-conveyorized nickel/gold processes, panel agitation and circulation pumps are the most reported mixing methods for all baths. Venting to the outside is the most prevalent form of vapor control reported (33 percent), though the use of bath covers and push-pull systems are also reported.
- Table 3-3 lists the bath surface area, volume, and bath temperature data reported by respondents to the PWB Workplace Practices Questionnaire.

Evaporation From Drying/Ovens (A_2). The nickel/gold process does not require the use of a drying oven or air knife.

Chemicals Incorporated Onto PWBs (P_1). The nickel/gold process promotes the deposition of an initial, thick layer of nickel followed by a thin, protective layer of gold onto the exposed metal surfaces of the PWB. The amount of nickel incorporated onto a PWB was calculated at 0.0337 oz/ssf, while gold was deposited at the rate of 0.0028 oz/ssf. Both nickel and gold deposition rates are discussed further in Section 5.1, Resource Conservation.

Drummed Solid or Liquid Waste (S_3). Questionnaire respondents indicated that approximately 20 percent of nickel/gold baths contain hazardous waste constituents as defined by RCRA. These wastes were associated by respondents with the microetch, acid dip, catalyst, and immersion gold baths. RCRA wastes are discussed in further detail in Section 4.3, Regulatory Status. In response to a separate question regarding spent bath treatment (see Table 3-4), two out of 55 nickel/gold baths (3.6 percent) were reported by respondents to be drummed and sent off-site for recycling. Section 5.1, Resource Conservation, presents methods commonly used to recover gold on-site.

Nickel/Palladium/Gold Process

Figure 3-5 depicts the generic nickel/palladium/gold process steps and typical bath sequence evaluated in the CTSA. The number and location of rinse steps displayed in the figure are based on PWB Workplace Practices Questionnaire responses. Thus, Figure 3-5 describes the types and sequence of baths in a generic nickel/palladium/gold line, but the types and sequence of process baths used by any particular facility could vary. A detailed description of the nickel/palladium/gold process is presented in Section 2.1.3, Chemistry and Process Descriptions of Surface Finishing Technologies.

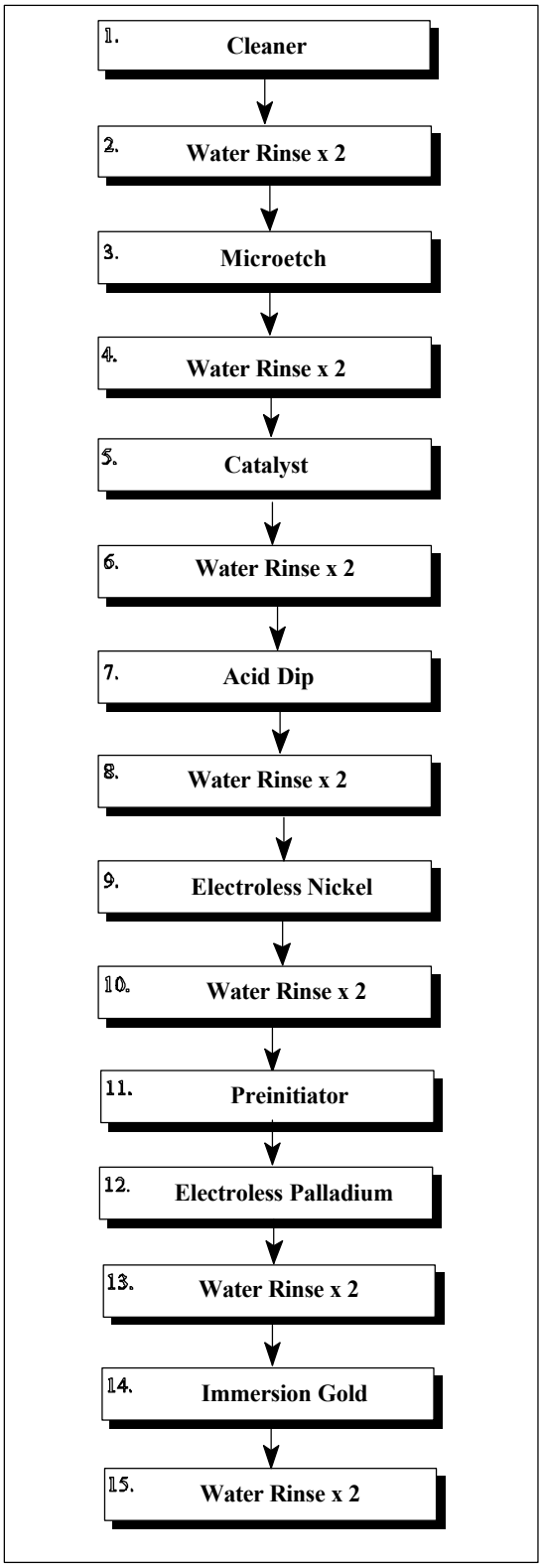


Figure 3-5. Generic Nickel/Palladium/Gold Process Steps and Typical Bath Sequence

Water Usage (I_3) and Wastewater (W_1). Water usage data from the PWB Workplace Practices Questionnaire is presented in Table 3-1; the volume of wastewater generated was assumed to be equal to the amount of water used (I_3). Of the two facilities using the nickel/palladium/gold process included in this study, both report using the non-conveyorized process configuration. In summary:

- Reported water usage for the facilities using the non-conveyorized nickel/palladium/gold process average 960 thousand gallons per year, or 160 gallons per ssf of PWB produced.

Chemical constituents and concentrations in wastewater could not be adequately characterized from questionnaire data. In the absence of quality data from industry, a model was developed to estimate the mass loading of constituents within the wastewater, resulting from drag-out, during the production of 260,000 ssf of PWB by the surface finishing process. The mass of chemical transferred per day to the wastewater, as well as other model results, are presented in Appendix E.

Bath Chemicals Used (I_1). Bath concentrations of individual chemical constituents are presented in Appendix B. The volume of chemicals consumed per year was determined by modeling the time it would take the generic nickel/palladium/gold process described in Figure 3-5 to produce a specific PWB throughput. A detailed description of the process modeling is presented in Section 4.2, Cost Analysis. The number of bath replacements (calculated from the modeled time) was then multiplied by the volume of the bath to determine the volume of a bath chemical consumed per year. Nickel/palladium/gold process chemical consumption is presented in Appendix G.

Cleaning Chemicals (I_4). Eight out of 14 reported nickel/palladium/gold baths require chemicals to clean the tanks, however, data concerning the type of cleaning chemical(s) were not collected by the questionnaire. Chemical flushing was reported at least once for the microetch, acid dip, electroless nickel, electroless palladium, and immersion gold tanks. The remaining tanks requiring chemical flushing belong to baths which are not part of the generic process sequence described in Figure 3-5. Water is most frequently used to clean tanks prior to new bath make-up. Hand scrubbing was also required for tank cleaning by several of the respondents.

Spent Bath Solutions (W_2). The quantity of spent bath solution could not be determined directly from the questionnaire data. However, the volume of spent bath chemistry was calculated by determining the number of bath changes required per year and multiplying by the average volume of the process tank (see Section 4.2, Cost Analysis). The concentrations of chemical constituents within the spent bath solutions were assumed to be the same as make-up bath concentrations.

Spent bath treatment and disposal methods were presented in Table 3-4. Respondents for the non-conveyorized, vertical process reported that precipitation pretreatment was the prevalent treatment method for spent bath solutions. Drummed for off-site treatment and pH neutralization were also reported.

Evaporation From Baths (A_1). Air releases are modeled in Section 3.2, Exposure Assessment. A summary of data collected from the questionnaire is presented below:

- For non-conveyorized nickel/palladium/gold processes, panel agitation and circulation pumps are the most reported mixing methods for all baths, while the use of air sparging for the electroless nickel bath was also reported. Vapor control methods were only identified for two process baths by survey respondents. Both baths were reported to use bath covers.
- Table 3-3 lists the bath surface area, volume, and bath temperature data reported by respondents to the PWB Workplace Practices Questionnaire.

Evaporation From Drying/Ovens (A_2). The nickel/palladium/gold process does not require the use of a drying oven or air knife.

Chemicals Incorporated Onto PWBs (P_1). Layers of nickel, palladium, and gold are deposited onto the exposed metal surfaces of the PWBs through a series of chemical plating reactions. The amount of nickel incorporated onto a PWB was calculated at 0.0337 oz/ssf, palladium at 0.0015 oz/ssf, and gold at a rate of 0.0028 oz/ssf. The deposition rates of all three metals are discussed further in Section 5.1, Resource Conservation.

Drummed Solid or Liquid Waste (S_3). Questionnaire respondents indicated that none of the nickel/palladium/gold baths contain hazardous waste constituents as defined by RCRA. A detailed discussion of RCRA wastes can be found in Section 4.3, Regulatory Status. In response to a separate question regarding spent bath treatment (see Table 3-4), seven out of 14 nickel/palladium/gold baths (50 percent) were reported by respondents to be drummed and sent off-site for recycling or disposal. Section 5.1, Resource Conservation, presents methods commonly used to recover gold on-site.

Organic Solderability Preservative

Figure 3-6 depicts the generic OSP process steps and typical bath sequence evaluated in the CTSA. The process baths shown in Figure 3-6 represent an amalgamation of the various products offered within the OSP technology category. The number and location of rinse steps displayed in the figure are based on PWB Workplace Practices Questionnaire responses. Thus, Figure 3-6 describes the types and sequence of baths in a generic OSP line, but the types and sequence of OSP process baths used by any particular facility could vary. A detailed description of the OSP process is presented in Section 2.1.3, Chemistry and Process Descriptions of Surface Finishing Technologies.

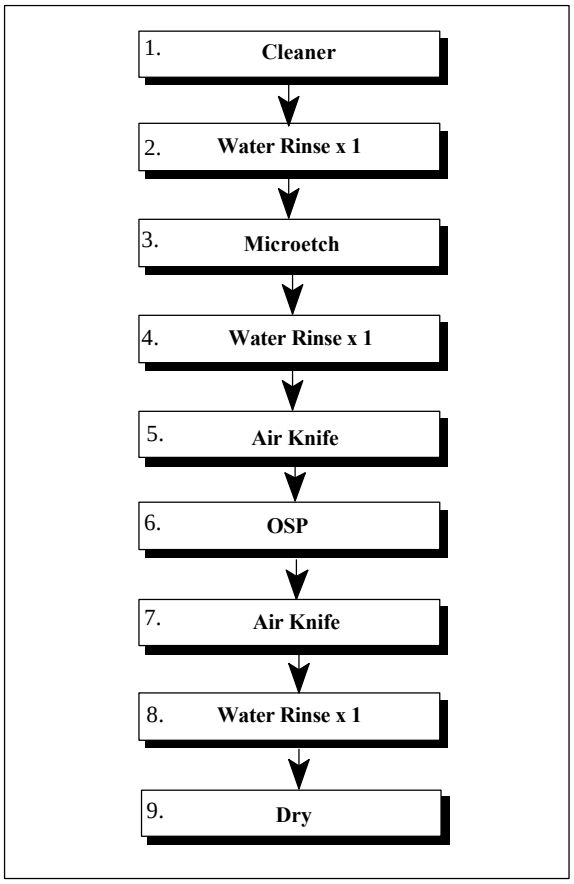


Figure 3-6. Generic OSP Process Steps and Typical Bath Sequence

Water Usage (I_3) and Wastewater (W_1). Water usage data from the PWB Workplace Practices Questionnaire is presented in Table 3-1; the volume of wastewater generated was assumed to be equal to the amount of water used (I_3). Of respondents using the OSP process, five facilities use the conveyorized OSP process while five other facilities use the non-conveyorized OSP process. In summary:

- Reported water usage for the facilities using the conveyorized OSP process average 440 thousand gallons per year, or about 14 gallons per ssf of PWB produced.
- Reported water usage for the facilities using the non-conveyorized OSP process average 89 thousand gallons per year, or 1.9 gallons per ssf of PWB produced.

Chemical constituents and concentrations in wastewater could not be adequately characterized from questionnaire data. In the absence of quality data from industry, a model was developed to estimate the mass loading of constituents within the wastewater, resulting from drag-out, during the production of 260,000 ssf of PWB by the surface finishing process. The mass of chemical transferred per day to the wastewater, as well as other model results, are presented in Appendix E.

Bath Chemicals Used (I_1). Bath concentrations of individual chemical constituents are presented in Appendix B. The volume of chemicals consumed per year was determined by modeling the time it would take the generic OSP process described in Figure 3-6 to produce a specific PWB throughput. A detailed description of the process modeling is presented in Section 4.2, Cost Analysis. The number of bath replacements (calculated from the modeled time) was then multiplied by the volume of the bath to determine the volume of a bath chemical consumed per year. OSP process chemical consumption is presented in Appendix G.

Cleaning Chemicals (I_4). Three out of 31 OSP baths were reported to be cleaned using chemicals, however, data concerning the type of cleaning chemical(s) were not collected by the questionnaire. All of the chemical flushing reported for OSP processes was used for cleaning the OSP tank during bath replacement. Water is most frequently used to clean tanks prior to new bath make-up.

Spent Bath Solutions (W_2). The quantity of spent bath solution could not be determined directly from the questionnaire data. However, the volume of spent bath chemistry was calculated by determining the number of bath changes required per year and multiplying by the average volume of the process tank (see Section 4.2, Cost Analysis). The concentrations of chemical constituents within the spent bath solutions are assumed to be the same as make-up bath concentrations.

Spent bath treatment and disposal methods were presented in Table 3-4. Precipitation pretreatment, pH neutralization, and drummed for off-site treatment are reported as common treatment methods for the conveyorized OSP processes. Respondents for the non-conveyorized, vertical process reported that pH neutralization and precipitation pretreatment are common treatment methods.

Evaporation From Baths (A_1). Air releases are modeled in Section 3.2, Exposure Assessment. A summary of data collected from the questionnaire is presented below:

- For the conveyorized OSP processes, circulation pumps are used to mix all process wet chemistry baths. Full enclosure and venting are the most common methods of vapor control reported by respondents for all baths and process steps.
- For non-conveyorized OSP processes, both panel agitation and circulation pumps are the most reported mixing methods for all baths. Venting to the outside is the most prevalent form of vapor control reported (66 percent), though a push-pull vapor control system is also reported (33 percent).
- Table 3-3 lists the bath surface area, volume, and bath temperature data reported by respondents to the PWB Workplace Practices Questionnaire.

Evaporation From Drying/Ovens (A_2). Air knife and oven drying occur after the microetch and OSP baths. Any solution adhering to the PWBs would be either blown off the boards and returned to the sump, or volatilized in the oven. Air emissions from air knife or oven drying were not modeled.

Chemicals Incorporated onto PWBs (P_1). A thin coating of a protective organic compound is applied to the surfaces of the PWB to protect the solderability of the copper surfaces.

Drummed Solid or Liquid Waste (S_3). Questionnaire respondents indicated that approximately 15 percent of OSP baths contain hazardous waste constituents as defined by RCRA. These wastes were primarily associated by respondents with the cleaner bath. RCRA wastes are discussed in further detail in Section 4.3, Regulatory Status. In response to a separate question regarding spent bath treatment (see Table 3-4), four out of 28 OSP baths were reported to be drummed and sent off-site for recycling or disposal.

Immersion Silver Process

Figure 3-7 depicts the generic immersion silver process steps and typical bath sequence evaluated in the CTSA. The number and location of rinse steps displayed in the figure are based on PWB Workplace Practices Questionnaire responses. Thus, Figure 3-7 describes the types and sequence of baths in a generic immersion silver line, but the types and sequence of immersion silver process baths used by any particular facility could vary. A detailed description of the immersion silver process is presented in Section 2.1.3, Chemistry and Process Descriptions of Surface Finishing Technologies.

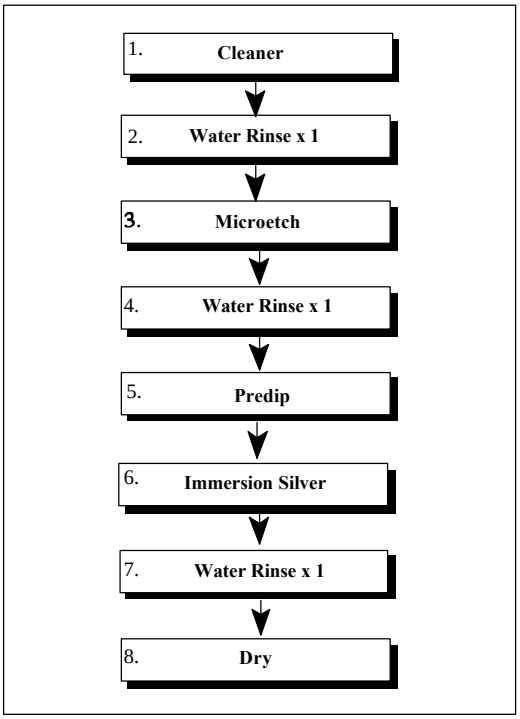


Figure 3-7. Generic Immersion Silver Process Steps and Typical Bath Sequence

Water Usage (I_3) and Wastewater (W_1). Water usage data from the PWB Workplace Practices Questionnaire is presented in Table 3-1; the volume of wastewater generated was assumed to be equal to the amount of water used (I_3). Of the two respondents using the immersion silver process, both reported using the conveyorized process configuration. In summary:

- Reported water usage for the facilities using the conveyorized immersion silver process average 910 thousand gallons per year, or about 37 gallons per ssf of PWB produced.

Chemical constituents and concentrations in wastewater could not be adequately characterized from questionnaire data. In the absence of quality data from industry, a model was developed to estimate the mass loading of constituents within the wastewater, resulting from drag-out, during the production of 260,000 ssf of PWB by the surface finishing process. The mass of chemical transferred per day to the wastewater, as well as other model results, are presented in Appendix E.

Bath Chemicals Used (I_1). Bath concentrations of individual chemical constituents are presented in Appendix B. The volume of chemicals consumed per year was determined by modeling the time it would take the generic immersion silver process described in Figure 3-7 to produce a specific PWB throughput. A detailed description of the process modeling is presented in Section 4.2, Cost Analysis. The number of bath replacements (calculated from the modeled time) was then multiplied by the volume of the bath to determine the volume of a bath chemical consumed per year. Immersion silver process chemical consumption is presented in Appendix G.

Cleaning Chemicals (I_4). Three out of nine immersion silver baths were reported to be cleaned using chemicals, however, the type of cleaning chemical(s) were not collected by the questionnaire. The immersion silver process tanks reported to require chemical flushing prior to bath replacement included two immersion silver process tanks and one pre-dip tank. Water is most frequently used to clean tanks prior to new bath make-up.

Spent Bath Solutions (W_2). The quantity of spent bath solution could not be determined directly from the questionnaire data. However, the volume of spent bath chemistry was calculated by determining the number of bath changes required per year and multiplying by the average volume of the process tank (see Section 4.2, Cost Analysis).

The concentrations of chemical constituents within the spent bath solutions are expected to vary significantly as PWBs are processed through the bath. Some new constituents, such as copper displaced by an immersion-type plating reaction, will be present in solution, although they are not part of the original bath chemistry. While the concentrations of these chemical constituents can be significant, they are difficult to accurately estimate and will vary widely. For the purposes of this analysis, the concentrations of chemical constituents within the spent bath solutions were assumed to be the same as make-up bath concentrations.

Spent bath treatment and disposal methods were presented in Table 3-4. Precipitation pretreatment, pH neutralization, and drummed for off-site treatment are reported as common treatment methods for the conveyorized immersion silver processes.

Evaporation From Baths (A_1). Air releases are modeled in Section 3.2, Exposure Assessment. A summary of data collected from the questionnaire is presented below:

- For conveyorized immersion silver processes, circulation pumps are used to mix all process wet chemistry baths. The spraying of chemicals onto the surface of the PWB in the cleaner and microetch baths is also reported. All of the process baths were reported as fully enclosed. Only one out of ten process baths was reported to be vented to the outside.
- Table 3-3 lists bath the surface area, volume, and bath temperature data reported by respondents to the PWB Workplace Practices Questionnaire.

Evaporation From Drying/Ovens (A_2). Oven drying occurs directly after the immersion silver bath. Any solution adhering to the PWBs is volatilized during the drying of the PWBs by the oven. Air emissions resulting from oven drying were not modeled. No air knife is required by this process.

Chemicals Incorporated Onto PWBs (P_1). Silver is added to the boards in the immersion silver processes. A hydrophobic layer, formed with a co-deposited organic inhibitor, is also coated on top of the silver layer. The amount of silver incorporated onto a PWB was calculated at 0.0013 oz/ssf. Silver consumption is discussed further in Section 5.1, Resource Conservation.

Drummed Solid or Liquid Waste (S_3). Questionnaire respondents indicated that none of the immersion silver baths contain hazardous waste constituents as defined by RCRA. A detailed discussion of RCRA wastes can be found in Section 4.3, Regulatory Status. In response to a separate question regarding spent bath treatment (see Table 3-4), two out of eight immersion silver baths were reported to be drummed and sent off-site for recycling.

<u>Immersion Tin Process</u>

Figure 3-8 depicts the generic immersion tin process steps and typical bath sequence evaluated in the CTSA. The process baths shown in the figure represent an amalgamation of the various products offered within the immersion tin technology category. The number and location of rinse steps displayed in the figure are based on PWB Workplace Practices Questionnaire responses. Thus, Figure 3-8 describes the types and sequence of baths in a generic immersion tin line, but the types and sequence of immersion tin process baths used by any particular facility could vary. A detailed description of the immersion tin process is presented in Section 2.1.3, Chemistry and Process Descriptions of Surface Finishing Technologies.

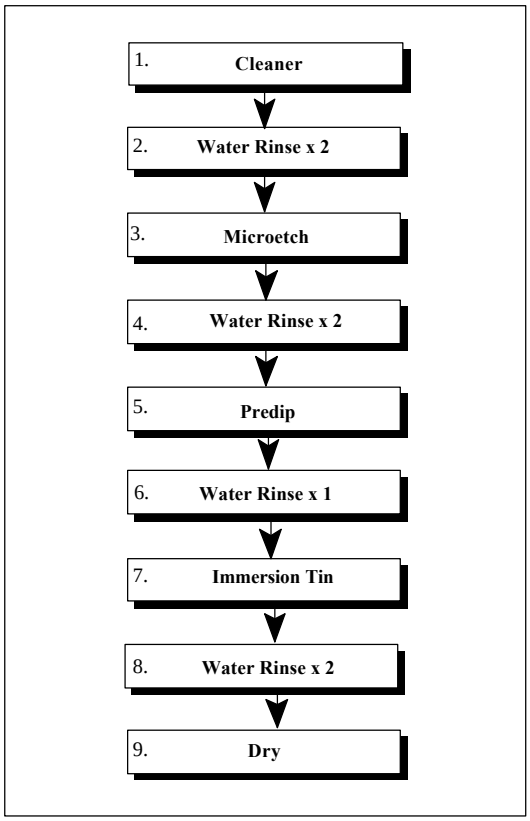


Figure 3-8. Generic Immersion Tin Process Steps and Typical Bath Sequence

Water Usage (I_3) and Wastewater (W_1). Water usage data from the PWB Workplace Practices Questionnaire is presented in Table 3-1; the volume of wastewater generated was assumed to be equal to the amount of water used (I_3). Of respondents using the immersion tin process, two facilities use the conveyorized immersion tin process while four other facilities use the non-conveyorized process. In summary:

- Reported water usage for the facilities using the conveyorized immersion tin process average 110 thousand gallons per year, or about 0.33 gallons per ssf of PWB produced.
- Reported water usage for the facilities using the non-conveyorized immersion tin process average 210 thousand gallons per year, or 11 gallons per ssf of PWB produced.

Chemical constituents and concentrations in wastewater could not be adequately characterized from questionnaire data. In the absence of quality data from industry, a model was developed to estimate the mass loading of constituents within the wastewater, resulting from drag-out, during the production of 260,000 ssf of PWB by the surface finishing process. The mass of chemical transferred per day to the wastewater, as well as other model results, are presented in Appendix E.

Bath Chemicals Used (I_1). Bath concentrations of individual chemical constituents are presented in Appendix B. The volume of chemicals consumed per year was determined by modeling the time it would take the generic immersion tin process described in Figure 3-8 to produce a specific PWB throughput. A detailed description of the process modeling is presented in Section 4.2, Cost Analysis. The number of bath replacements (calculated from the modeled time) was then multiplied by the volume of the bath to determine the volume of a bath chemical consumed per year. Immersion tin process chemical consumption is presented in Appendix G.

Cleaning Chemicals (I_4). One out of 15 immersion tin baths were reported to be cleaned using chemicals, however, data concerning the type of cleaning chemical(s) were not collected by the questionnaire. The bath reported to require chemical flushing to clean the tank during bath replacement was the immersion tin bath. Water is most frequently used to clean tanks prior to new bath make-up.

Spent Bath Solutions (W_2). The quantity of spent bath solution could not be determined directly from the questionnaire data. However, the volume of spent bath chemistry was calculated by determining the number of bath changes required per year and multiplying by the average volume of the process tank (see Section 4.2, Cost Analysis). The concentrations of chemical constituents within the spent bath solutions were assumed to be the same as make-up bath concentrations.

Spent bath treatment and disposal methods were presented in Table 3-4. Drummed for off-site treatment and pH neutralization are reported as common treatment methods for the conveyorized immersion tin processes. Respondents for the non-conveyorized, vertical process reported that pH neutralization, precipitation pretreatment, ion exchange with on-site metal reclaim and drummed for off-site treatment are all treatment options reported by respondents.

Evaporation From Baths (A_1). Air releases are modeled in Section 3.2, Exposure Assessment. A summary of data collected from the questionnaire is presented below:

- For the conveyorized immersion tin processes, circulation pumps are the most reported mixing methods for all baths. Full enclosure and venting are the most common methods of vapor control reported by respondents for baths other than the pre-dip bath.
- For non-conveyorized immersion tin processes, panel agitation and circulation pumps are the most reported mixing methods for all baths. Venting to the outside is the most prevalent form of vapor control reported (33 percent), though the use of bath covers are also reported.
- Table 3-3 lists the bath surface area, volume, and bath temperature data reported by respondents to the PWB Workplace Practices Questionnaire.

Evaporation From Drying/Ovens (A_2). Oven drying occurs directly after the immersion tin bath. Any solution adhering to the PWBs is volatilized during the drying of the PWB by the oven. Air emissions resulting from oven drying were not modeled. No air knife is required by this process.

Chemicals Incorporated Onto PWBs (P_1). A layer of metallic tin is deposited onto the PWB by the immersion tin processes. The amount of tin incorporated onto a PWB was calculated at 0.0038 oz/ssf. Tin consumption is discussed further in Section 5.1, Resource Conservation.

Drummed Solid or Liquid Waste (S_3). Questionnaire respondents indicated that none of the immersion tin baths contain hazardous waste constituents as defined by RCRA. A detailed discussion of RCRA wastes can be found in Section 4.3, Regulatory Status. In response to a separate question regarding spent bath treatment (see Table 3-4), five out of 17 immersion tin baths were reported by respondents to be drummed and sent off-site for recycling or disposal.

3.1.4 Uncertainties in the Source Release Assessment

Uncertainties and variations in the data include both gaps in knowledge (uncertainty) and variability among facilities and process alternatives. These are discussed below.

For the PWB Workplace Practices Questionnaire data:

- There may be uncertainties due to misinterpretation of a question, not answering a question that applies to that facility, reporting inaccurate information or numbers in different units (e.g., using a mass unit to report a volumetric measurement). Also, because of a limited number of responses for the alternative processes, information more typical for that process may not be reported.
- Variation can occur within or among process alternatives, or from difference due to varying amounts of PWB produced. According to the questionnaire database query results, data from facilities with small amounts of PWB produced often produce unrealistic results. Again, for surface finishing process alternatives with a limited number of responses, statistical summaries of the data may be precluded, and data may not be representative of most PWB facilities.

For the supplier-provided data:

- Knowledge gaps include a lack of information on proprietary chemicals, incomplete bath composition data, and the reporting of wide ranges of chemical concentrations on a MSDS rather then specific amounts in the formulations.
- Variation in bath chemistries and process specifications among suppliers can occur for a given process alternative. The publicly-available bath chemistry data, chemical concentrations, and supplier recommendations may not apply to a specific facility due to variation in process set-up and operation procedures.

Other uncertainties pertain to the applicability and accuracy of estimates and assumptions used in this assessment.

3.2 EXPOSURE ASSESSMENT

Evaluating exposure for the PWB CTSA involves a series of sequential steps. The first step is characterizing the exposure setting, which includes describing the physical setting and characterizing the populations of interest and their activities that may result in exposure. These are described in Section 3.2.1 for both workplace and surrounding population (ambient) exposure.

The next step is selecting a set of workplace and population exposure pathways for quantitative evaluation from the set of possible exposure pathways. This is discussed in Section 3.2.2.

Next, chemical concentrations are collected or estimated in all media where exposure could occur. For the surface finishing processes, this consists of estimating the chemical concentrations in the surface finishing baths, and performing fate and transport modeling to estimate workplace and ambient air concentrations and surface water concentrations (Section 3.2.3).

The exposure-point concentrations and other exposure parameters are combined in exposure models to estimate potential dose rates (PDRs) for all quantified pathways. These exposure models, parameter values, and resulting exposure estimates are presented in Section 3.2.4. The final step, characterizing uncertainties, is in Section 3.2.5. The exposure assessment is summarized in Section 3.2.6.

Because this CTSA is a comparative evaluation, and standardization is necessary to compare results for the surface finishing processes, this assessment focuses on a "model" (generic) PWB facility and uses aggregated data. In addition, this assessment focuses on exposure from chronic, long-term, day-to-day releases from a PWB facility, rather than short-term exposures to high levels of hazardous chemicals as there could be with a fire, spill, or periodic releases. Due to the fixed amount of resources available to the project and the lack of information to characterize such releases, high level, acute exposures could not be assessed.

3.2.1 Exposure Setting

Characterizing the exposure setting includes the following analyses:

- characterizing the physical environment (in this case, a model PWB facility, its surface finishing process area, and the surrounding environment);
- identifying potentially exposed workers and their activities, and any potentially exposed populations, human or ecological, that may be exposed through releases to the ambient environment from PWB facilities;
- defining the workplace exposure scenarios to evaluate (where a *scenario* describes a specified physical setting, exposed population, and activities that may result in exposure); and
- defining ambient exposure scenarios to evaluate.

Physical Environment

The surface finishing technologies are all wet chemistry processes consisting of a series of chemical process baths, often followed by rinse steps, through which the PWB panels are passed to apply the final surface finish. The exception is the HASL process, which combines the typical cleaning and etching chemical processes with a mechanical process of dipping a board into molten solder. (Details of each process are presented in Section 2.1, Chemistry and Process Description of Surface Finishing Technologies.)

PWB Workplace Practices Questionnaire and Performance Demonstration data, collected for 54 PWB facilities and their surface finishing process areas, were used to characterize a model PWB facility. The PWB Workplace Practices Questionnaire database includes information from 29 facilities using the HASL process, eight using nickel/gold, one using nickel/palladium/gold, nine using OSP, two using immersion silver, and five using immersion tin. Data from the questionnaire database used in the exposure models are discussed further in Section 3.2.4.

Potentially Exposed Populations

Potentially exposed populations include both workers in the PWB facilities and ecological and human populations in the vicinity of the facilities. Each of these are discussed below.

PWB Facility Employees. The questionnaire included questions about the types of workers who might be present in the surface finishing process area. These include:

- line operators;
- laboratory technicians;
- maintenance workers;
- supervisory personnel;
- wastewater treatment operators;
- quality inspectors; and
- other employees.

General Population Outside the Facility. PWB facilities that are included in the PWB Workplace Practices Questionnaire and Performance Demonstration database are located throughout the U.S. This assessment estimates potential exposure to a hypothetical community living near a model PWB facility, based on a residential scenario. The primary exposure route is inhaling airborne chemicals originating from a PWB facility.

Surface Water. Exposure to ecological populations could also occur outside a PWB facility. In this assessment we evaluated exposure to aquatic organisms in a stream that receives treated wastewater from a facility.

Workplace Exposure Scenarios

A scenario describes the exposure setting, potentially exposed populations or individuals, and activities that could lead to exposure. For workplace exposures, the setting involves the surface finishing process in a PWB facility. PWB Workplace Practices Questionnaire data are used here to determine the types of workers that may be exposed and to characterize their activities. Worker activities include working in the process area, surface finishing line operation, chemical bath sampling, chemical bath additions, chemical bath replacement, rack cleaning, conveyor equipment cleaning, and filter replacement.

Working in the Process Area. Workers may inhale airborne chemicals in the surface finishing process area. Line operators are expected to have the highest inhalation exposure, because they are typically in the process area for the longest time each day. For other types of workers, their inhalation exposure would be proportional to their time spent in the process area.

Surface Finishing Line Operation. Potential for exposure during surface finishing line operation is expected to vary significantly among process methods. Non-conveyorized process configurations can be operated manually, automatically, or with a semi-automated system. In manual methods, a line operator stands at the bath and manually lowers and raises the panel racks into and out of each bath. A vertical/automated method is completely automated, where panel racks are lowered and raised into vertical tanks by a robotic arm; line operators load and unload panels from the racks. A manually-controlled vertical hoist is a semi-automated system where racks are lowered into and raised out of a series of vertical chemical baths by a line operator-controlled hoist. The hoist is controlled by a hand-held control panel attached to the hoist by a cable. The conveyorized process configuration uses an automated method where panels are transported horizontally into and out of process baths by means of a conveyor; line operators load and unload panels from the conveyor system. Based on the workplace practices data:

- For HASL, eight out of 29 facilities reported using non-conveyorized lines, and 21 reported conveyorized lines.
- The eight nickel/gold and one nickel/palladium/gold facilities all reported using non-conveyorized lines.
- For facilities using OSP, four reported non-conveyorized lines and five reported conveyorized lines.
- Both facilities using immersion silver use conveyorized lines.
- For immersion tin, three facilities reported using non-conveyorized and two facilities use conveyorized lines.

Of the non-conveyorized systems described in the questionnaire, ten are vertical/automated systems, ten are completely manual, one uses a manually-controlled hoist, one HASL line is partly conveyorized, and two other systems were undefined. As a conservative but consistent assumption, we assumed that workers manually lower and raise panel racks for all non-conveyorized process alternatives.

Chemical Bath Sampling. Based on the questionnaire database, chemical baths are normally sampled manually by dipping/ladling. Other methods include manual sampling with a pipette or other device, and automated sampling. We assumed there could be dermal contact with bath chemicals from this activity, and quantified dermal exposure for laboratory technicians and for line operators on conveyorized lines.

Chemical Bath Additions. Methods of chemical additions, from the database, are as follows:

- Most facilities pour chemicals directly into the bath or tank.
- Other reported methods include manual pumping, or some combination of pumping, pouring, and/or scooping chemical formulations into a bath.

Data were collected for the length of time required to make chemical additions, and on the criteria used to determine when to add chemicals to the baths. Some facilities base chemical addition requirements on time elapsed, some on the surface area of boards processed, and some on the concentration of key constituents. For these reasons, complicated by the fact that most facilities running alternatives to HASL do not run those lines at full capacity, a typical addition frequency could not be determined. Therefore, exposure was not quantified separately for this activity.

Chemical Bath Replacement. This process includes removing the spent bath, cleaning the empty tank, and making up fresh bath solutions. In this process, a worker could be exposed to chemicals in the spent bath, on the inside walls of the emptied bath, or to chemicals in the new bath solution.

Rack Cleaning. The racks that hold PWB panels can be cleaned in a variety of ways. These include cleaning in a chemical bath on the surface finishing line or using non-chemical cleaning methods. Of the six facilities that provided information on rack cleaning, four reported using non-chemical methods, one reported using a chemical bath on the surface finishing line, and one reported shipping racks offsite for cleaning. Dermal exposure for rack cleaning is not quantified separately for this activity.

Conveyor Equipment Cleaning. Conveyor equipment cleaning involves regular equipment maintenance for conveyorized surface finishing lines. Methods include chemical baths on the surface finishing line, chemical rinse, manual scrubbing with chemicals, non-chemical cleaning, and continuous cleaning as part of the process line. It was assumed that workers could be exposed to bath chemicals during cleaning.

Filter Replacement. Filter replacement could result in exposure to the material on the filter or in the bath. Whether the pathway is significant to worker risk will depend, in part, on the chemical constituents in the bath.

Use of Personal Protective Equipment (PPE). It is assumed that the only PPE used is eye protection, and that the line operator's hands and arms may contact bath solutions. This is a

conservative but consistent assumption for all process alternatives and worker activities, particularly for dermal exposure. While many PWB facilities reported that line operators do wear gloves for various activities, the assumption that the line operator's hands and arms may contact bath solutions is intended to account for the fraction of workers who do not. For workers who do wear gloves, dermal contact exposure is expected to be negligible.

Summary of Occupational Scenarios

Surface Finishing Line Operators. In general, line operators perform several activities, as described above, including working in the surface finishing process area, surface finishing line operation, chemical bath replacement, conveyor equipment cleaning, filter replacement, chemical bath sampling, and making chemical bath additions. Some kind of local ventilation is typically used for the process line.

There are two different scenarios for line operators depending on process configuration. For non-conveyorized processes, dermal exposure could occur through routine line operation as well as bath maintenance activities. Inhalation exposure could occur throughout the time period a line operator is in the surface finishing process area. Conveyorized processes are enclosed and the line operator does not contact the bath solutions in routine line operation; he or she only loads panels at the beginning of the process and unloads them at the end of the process. For conveyorized processes, dermal exposure is primarily expected through bath maintenance activities such as bath replacement, filter replacement, bath sampling, and conveyor equipment cleaning. Because the conveyorized lines are enclosed and typically vented to the outside, inhalation exposure to line operators and other workers is much lower than for the conveyorized processes and are not presented separately.[4]

Laboratory Technicians. In general, laboratory technicians perform one activity pertaining to the surface finishing line, chemical bath sampling, in addition to working in the surface finishing process area. Bath sampling exposure is quantified separately for laboratory technicians.

Other Workers in the Surface Finishing Process Area. Other workers in the surface finishing process area may include maintenance workers, supervisory personnel, wastewater treatment operators, contract workers, and other employees. They perform activities not directly related to the surface finishing line, but typically spend some time in the surface finishing process area. Because the line operators spend the most amount of time per shift, exposure via inhalation is quantified for them (for non-conveyorized processes), and is characterized for the other employees in terms of the time spent in the process area relative to line operators.

---

[4] Inhalation exposures for conveyorized process configurations were initially assumed to be negligible, and are not presented separately here. Some inhalation exposure is possible, however, during sampling and bath replacement, when the baths are opened for a short period of time. After characterizing risks from inhalation for non-conveyorized lines, inhalation exposures and risks were estimated for the subset of inhalation chemicals of concern for conveyorized lines. No chemical exposures from inhalation resulted in risks above concern levels for conveyorized lines.

Ambient Exposure Scenarios

Ambient refers to the nearby area outside of a PWB facility. As discussed in Section 3.1, Source Release Assessment, chemicals may be released to air, surface water, and/or possibly land. Receptors include members of general population living near a PWB facility and aquatic organisms, such as fish, in surface water receiving treated wastewater from a PWB facility. Exposure is also possible to animals on land or birds. The ecological assessment focused on aquatic life because much more data are available.

3.2.2 Selection of Exposure Pathways

The definition of exposure scenarios leads to selection of the exposure pathways to be evaluated. An exposure scenario may comprise one or several pathways. A complete exposure pathway consists of the following elements:

- a source of chemical and mechanism for release;
- an exposure point;
- a transport medium (if the exposure point differs from the source); and
- an exposure route.

Tables 3-6 and 3-7 present an overview of the pathway selection for workplace and surrounding population exposures, respectively. For the workplace, a potential pathway not quantified is oral exposure to vapors or aerosols. For example, oral exposure could occur if inhaled chemicals are coughed up and then swallowed.

Table 3-6. Workplace Activities and Associated Potential Exposure Pathways

Activities	Potential Pathways	Evaluation Approach and Rationale
Line Operators [a]		
Surface Finishing Line Operation	Dermal contact with chemicals in surface finishing baths.	Exposure quantified for non-conveyorized lines; the highest potential dermal exposure is expected from this activity. Exposure for conveyorized lines assumed to be negligible for this activity.
	Inhalation of vapors or aerosols from surface finishing baths.	Exposure quantified initially only for non-conveyorized lines. Exposure for conveyorized lines assumed to be much lower. [b]
Working in Process Area	Inhalation of vapors or aerosols from surface finishing baths.	Exposure quantified for non-conveyorized lines.

Activities	Potential Pathways	Evaluation Approach and Rationale
Chemical Bath Replacement; Conveyor Equipment Cleaning; Filter Replacement; Chemical Bath Sampling	Dermal contact with chemicals in bath or on filters.	Exposure quantified for conveyorized lines for all activities together (bath sampling quantified separately for laboratory technicians). Exposure not quantified separately for these activities on non-conveyorized lines.
	Inhalation of vapors or aerosols from surface finishing baths.	Not quantified separately. Included in "working in process area" for non-conveyorized lines; not quantified due to modeling limitations for conveyorized lines. [b]
Rack Cleaning	Dermal contact with chemicals on racks.	Not quantified; limited data indicate this is not performed by many facilities.
	Inhalation of vapors or aerosols from surface finishing baths.	Not quantified separately. Included in "working in process area" for non-conveyorized lines; not quantified due to modeling limitations for conveyorized lines.
Chemical Bath Additions	Dermal contact with chemicals added.	Not quantified separately from chemicals already in the baths.
	Inhalation of vapors or aerosols from surface finishing baths or while making bath additions.	Not quantified separately. Included in "working in process area" for non-conveyorized lines; not quantified due to modeling limitations for conveyorized lines.
Laboratory Technicians		
Chemical Bath Sampling	Dermal contact with chemicals in surface finishing baths.	Exposure quantified for conveyorized and non-conveyorized lines.
	Inhalation of vapors or aerosols from surface finishing baths.	Not quantified separately (included in "working in process area").
Working in Process Area	Inhalation of vapors or aerosols from surface finishing baths.	Exposure quantified for line operators for non-conveyorized lines; exposure for other workers is proportional to their exposure durations.
Maintenance Workers, Supervisory Personnel, Wastewater Treatment Operators, Contract Workers, and Other Workers		
Working in Process Area	Inhalation of vapors or aerosols from surface finishing baths.	Exposure quantified for line operators for non-conveyorized lines; exposure for other workers is proportional to their exposure durations.
	Dermal contact with chemicals in surface finishing baths.	Not quantified. [a]

[a] This assumes surface finishing line operators are the most exposed individuals and perform all direct maintenance on the surface finishing line, including filter replacement and equipment cleaning.

[b] Inhalation exposures for conveyorized process configurations were initially assumed to be negligible. Some inhalation exposure is possible, however, during sampling and bath replacement, when the baths are opened for a short period of time. After characterizing risks from inhalation for non-conveyorized lines, inhalation exposures and risks were estimated for the subset of inhalation chemicals of concern for conveyorized lines. No chemical exposures from inhalation resulted in risks above concern levels for conveyorized lines.

Table 3-7. Potential Population Exposure Pathways

Population	Potential Pathways	Evaluation Approach and Rationale
Residents Living Near a PWB Facility	Inhalation of chemicals released to air.	Exposure quantified for all potential carcinogens and any other chemical released at a rate of at least 23 kg/year.
	Contact with chemicals released to surface water directly or through the food chain.	Not evaluated. Direct exposure to surface water is not expected to be a significant pathway; modeling exposure through the food chain (e.g., someone catching and eating fish) would be highly uncertain.
	Exposure to chemicals released to land or groundwater.	Not evaluated. Not expected to be a significant pathway; modeling releases to groundwater from a landfill would be highly uncertain.
Ecological	Exposure to chemicals released to surface water.	Screening-level evaluation performed.
	Exposure to chemicals released to air or land.	Not evaluated. The human (residential) evaluation air exposure could be used as a screening-level assessment for animals living nearby. Releases directly to land are not expected, and animals are not directly exposed to groundwater.

Population exposures may occur through releases to environmental media (i.e., releases to air, water, and land). The pathways for which exposure is estimated are inhalation of chemicals released from a facility to a nearby residential area and releases of chemicals in wastewater to a receiving stream, where aquatic organisms, such as fish, may be exposed through direct contact with chemicals in surface water.

Air releases from the surface finishing process are modeled for the workplace. These modeled emission rates are used in combination with an air dispersion model to estimate air concentrations to a nearby population.

Exposures and risks from surface water are evaluated by identifying chemicals potentially released to surface water from process rinse steps following wastewater treatment. This exposure pathway is described in Section 3.2.3.

Possible sources of releases to land from surface finishing processes include bath filters and other solid wastes from the process line, chemical precipitates from baths, and sludge from wastewater treatment. These sources are discussed in Section 3.1, Source Release Assessment. Reliable characterization data for potential releases to land are not available; therefore, the exposure assessment does not estimate the nature and quantity of leachate from landfills or effects on groundwater.

3.2.3 Exposure-Point Concentrations

An exposure-point concentration is a chemical concentration in its transport or carrier medium, at the point of contact (or potential point of contact) with a human or environmental receptor. Sources of data for estimating exposure-point concentrations include monitoring data, publicly-available bath chemistry data, some proprietary bath chemistry data, and fate and transport models used to estimate air releases and air concentrations. Bath concentrations for dermal exposure were estimated from bath chemistry data. Monitoring data were used for lead from the HASL process. Fate and transport modeling were performed to estimate air concentrations for workplace and surrounding population exposures. Use of monitoring data and modeling used to estimate air concentrations are described in this section.

Monitoring Data

Air monitoring data for lead have been provided by one PWB manufacturing facility. A combination of personal monitoring for HASL line operators and air samples from the HASL process area result in an average air concentration of 0.003 mg/m^3. It should be noted that these monitoring data are limited to only one PWB manufacturer, and may vary from facility to facility. In addition, air sampling results from hand soldering operations were reported in one study (Monsalve, 1984), ranging from < 0.001 mg/m^3 to 2 mg/m^3.

Modeling Workplace Air Concentrations

Air emission models, combined with an indoor air dilution model, were used to estimate chemical air concentrations for worker inhalation exposure from PWB surface finishing lines (Robinson et al., 1997). Three air emission models were used to estimate worker exposure:

1. Volatilization of chemicals from the open surface of surface finishing tanks.
2. Volatilization of chemicals induced by air sparging.
3. Aerosol generation induced by air sparging.

The first model was applied to determine volatilization of chemicals from un-sparged baths. For the air-sparged baths, the total air emission rate for chemicals was determined by summing the releases from all three models. Modeled emission rates were then put into an indoor air dilution model to estimate workplace air concentrations. For models 1 and 2, volatilization was modeled only for those chemicals with a vapor pressure above 10^{-3} torr (a vapor pressure less than 10^{-3} torr was assumed for inorganic salts even if vapor pressure data were not available). A review of the relevant literature, descriptions of the models, and examples demonstrating the use of the models are available in the December 22, 1995, Technical Memorandum, *Modeling Worker Inhalation Exposure* (Appendix D).

Volatilization of Chemicals from the Open Surface of Surface Finishing Tanks. Most plating tanks have a free liquid surface from which chemicals can volatilize into the workplace air. Air currents across the tank will accelerate the rate of volatilization. The

following model for evaporation of chemicals from open surfaces was used, based on EPA's Chemical Engineering Branch (CEB) Manual (U.S. EPA, 1991a):

$$F_{y,o} \;'\; 1{,}200\, c_{L,y}\, H_y\, A\, [D_{y,air} v_Z/(\,)\; z)]^{0.5}$$

where,

$F_{y,o}$	=	volatilization rate of chemical *y* from open tanks (mg/min)
$c_{L,y}$	=	concentration of chemical *y* in bulk liquid (mg/L)
H_y	=	dimensionless Henry's Law Constant (H_c) for chemical *y*
A	=	bath surface area (m^2)
$D_{y,air}$	=	molecular diffusion coefficient of chemical *y* in air (cm^2/sec)
v_z	=	air velocity (m/sec)
)z	=	pool length along direction of air flow (m)

Concentration of chemical in bulk liquid ($c_{L,y}$) is the bath concentration. The coefficient of 1,200 includes a factor of 600 for units conversion.

Henry's constants were corrected for bath temperature. Bath temperature varies by process type and bath type; bath temperature data from the questionnaire database were determined by specific process type and bath type.

Bath surface areas used in the air modeling were determined from the questionnaire database. For non-conveyorized lines, an overall average for all baths and all processes of 422 sq in (0.280 m^2) was used. For conveyorized lines, an average was used for each type of process bath, as follows:

Conveyorized Bath Type	Average Surface Area (sq in)
Cleaner baths	1,078
Immersion silver	4,364
Immersion tin	1,436
Microetch baths	1,629
OSP	2,573
Predip baths	1,004

Some limitations of the model should be pointed out. The model was developed to predict the rate of volatilization of pure chemicals, not aqueous solutions. The model was also derived using pure chemicals. As a result, the model implicitly assumes that mass transfer resistance on the gas side is the limiting factor. The model may overestimate volatilization of chemicals from solutions when liquid-side mass transfer is the controlling factor.

Volatilization of Chemicals from Air-Sparged Surface Finishing Tanks. Volatilization and aerosol generation from air-sparged baths were modeled only for those baths that are mixed by air sparging, as indicated in the PWB Workplace Practices Questionnaire and Performance Demonstration data; this includes the electroless nickel baths in nickel/gold and nickel/palladium/gold processes. Mixing in the baths is commonly accomplished by sparging the tank with air. The equation used for predicting the mass transfer rate from an aerated system is based on volatilization models used in research of aeration in wastewater treatment plants:

$$F_{y,s} = Q_G H_y c_{L,y} \left[1 - \exp\left(-\frac{K_{OL,y} a V_L}{H_y Q_G} \right) \right]$$

where,

$F_{y,s}$	=	mass transfer rate of chemical *y* out of the system by sparging (mg/min)
Q_G	=	air sparging gas flow rate (L/min)
H_y	=	dimensionless Henry's Law Constant (H_C) for chemical *y*
$c_{L,y}$	=	concentration of chemical *y* in bulk liquid (mg/L)
$K_{OL,y}$	=	overall mass transfer coefficient for chemical *y* (cm/min)
a	=	interfacial area of bubble per unit volume of liquid (cm^2/cm^3)
V_L	=	volume of liquid (cm^3)

Data for the sparging air flow rate (Q_G) come from information supplied by a PWB manufacturer.

Aerosol Generation from Air-Sparged Surface Finishing Tanks. Aerosols or mists are also potentially emitted from process baths. This was estimated for electroless nickel baths in nickel/gold and nickel/palladium/gold processes. The rate of aerosol generation has been found to depend on the air sparging rate, bath temperature, air flow rate above the bath, and the distance between bath surface and the tank rim. The following equation is used to estimate the rate of aerosol generation (Berglund and Lindh, 1987):

$$R_A = \left[5.5 x 10^{-5} (Q_G / A) + 0.01 \right] F_T \, F_A \, F_D$$

where,

R_A	=	aerosol generation rate ($ml/min/m^2$)
Q_G	=	air sparging gas flow rate (cm^3/min)
A	=	bath surface area (m^2)
F_T	=	temperature correction factor
F_A	=	air velocity correction factor
F_D	=	distance between the bath surface and tank rim correction factor

The emission of contaminants resulting from aerosols depends on both the rate of aerosol generation and the concentration of contaminants in the aerosol. The following equation is used to estimate contaminant emission (flux) from aerosol generation:

$$F_{y,a} \;\; ' \;\; \frac{M_I}{M_b} f_{IE} \; F_{y,s}$$

where,

$F_{y,a}$	=	rate of mass transfer from the tank to the atmosphere by aerosols (mg/min)
f_{IE}	=	fraction of bubble interface ejected as aerosols (dimensionless)
M_I	=	mass of contaminant at the interface (mg)
M_b	=	mass of contaminant in gas bubble (mg)

The literature on aerosol generation indicates that the typical size of aerosols is one to ten microns; this is important to note because particles in this range are more inhalable. Larger sized particles tend to fall back into baths rather than remaining airborne and dispersing throughout the room.

Calculation of Chemical Concentration in Workplace Air from Emission Rates. For unsparged baths, the total emission rate is equal to $F_{y,o}$ calculated by the first equation. For sparged baths, the total emission rate is equal to $F_{y,o} + F_{y,s} + F_{y,a}$, as calculated by the three equations described above. The indoor air concentration is estimated from the total emission rate using the following equation (U.S. EPA, 1991a):

$$C_y \;\; ' \;\; F_{y,T}/(Q\,k)$$

where,

C_y	=	workplace contaminant concentration (mg/m^3)
$F_{y,T}$	=	total emission rate of chemical from all sources (mg/min)
Q	=	ventilation air flow rate (m^3/min)
k	=	dimensionless mixing factor

The CEB Manual commonly uses values of the ventilation rate (Q) from 500 cubic feet per minute (cfm) to 3,500 cfm; a ventilation rate for surface finishing lines of 13.6 m^3/min (480 cfm) was determined by taking the 10th percentile air flow rates from the facility questionnaire database for general ventilation. An average room volume of 505 m^3 (18,200 ft^3) was determined by assuming a ten foot room height and using the average room size from the questionnaire database. The combination of room volume and ventilation rate is equivalent to an air turnover rate of 0.026 per minute (1.56 per hour). The mixing factor (k) could be used to account for slow and incomplete mixing of ventilation air with room air; however, a value of 1.0 was used for this factor consistent with the assumption of complete mixing.

Other assumptions pertaining to these air models include the following:

- Deposition on equipment, condensation of vapors, and photodegradation are negligible.
- Incoming air is contaminant-free.
- The concentration of contaminant at the beginning of the day is zero.

- As much air enters the room as exits through ventilation (mass balance).
- Room air and ventilation air mix ideally.

Sensitivity Analysis. Model sensitivity and uncertainty was examined for the making holes conductive (MHC) project (U.S. EPA, 1998b) using Monte Carlo analysis, with the air transport equations outlined above, and probability distributions for each parameter based on data from the PWB Workplace Practices Questionnaire. The analysis was conducted using a Monte Carlo software package (Crystal Ball™, Decisioneering, Inc., 1993) in conjunction with a spreadsheet program. Because the same models are used for this surface finishing evaluation, and the model facility is similar to that developed for MHC, the results of this sensitivity analysis are relevant to surface finishing air modeling as well.

The sensitivity analysis suggested that a few parameters are key to modeling chemical emissions from PWB tanks. These key parameters are air turnover rate, bath temperature, chemical concentration in the bath, and H_C. The air turnover rate assumption contributes most to overall model variance. The chemical bath concentration and bath temperature also contribute variance to the model, but are less important than air turnover rate. This statement is supported by the fact that relatively accurate information is available on their distributions. H_C appears to be least important of the four, but may have more variability associated with it. The models appear to be largely indifferent to small changes in most other parameters.

Modeled emission rates and workplace air concentrations are presented in Table 3-8.

Table 3-8. Results of Workplace Air Modeling

Chemical [a]	Total Emission Rate ($F_{y,T}$) (mg/min)	Workplace Air Conc. (Cy) (mg/m^3)	Federal OSHA and/or NIOSH Permissible Inhalation Exposure Limits (mg/m^3) [b]
HASL, Non-conveyorized			
1,4-Butenediol	9.8	0.75	none
Alkylaryl sulfonate	0.018	0.0014	NR
Arylphenol	0.0060	4.6E-04	NR
Ethylene glycol	12	0.94	no OSHA PEL or NIOSH REL
Ethylene glycol monobutyl ether	120	8.9	NIOSH REL: 24 (5 ppm) OSHA PEL: 240 (50 ppm)
Hydrochloric acid	0.89	0.068	NIOSH REL, C: 7 (5 ppm) OSHA PEL, C: 7 (5 ppm)
Hydrogen peroxide	5.2	0.40	NIOSH REL: 1.4 (1 ppm) OSHA PEL 1.4 (1 ppm)
Phosphoric acid	1.5	0.12	NIOSH REL: 1, STEL: 3 OSHA PEL: 1
Nickel/Gold, Non-conveyorized			
Aliphatic acid A	77	5.9	NR
Aliphatic acid B	5.4E-04	4.1E-05	NR
Aliphatic acid E	100	7.8	NR

Chemical [a]	Total Emission Rate ($F_{y,T}$) (mg/min)	Workplace Air Conc. (Cy) (mg/m^3)	Federal OSHA and/or NIOSH Permissible Inhalation Exposure Limits (mg/m^3) [b]
Aliphatic dicarboxylic acid A	0.10	0.0080	NR
Aliphatic dicarboxylic acid C	0.049	0.0038	NR
Alkyldiol	22	1.6	NR
Ammonia compound B	0.025	0.0019	NR
Ammonium hydroxide	1.2	0.094	none
Hydrochloric acid	26	2.0	NIOSH REL, C: 7 (5 ppm) OSHA PEL, C: 7 (5 ppm)
Hydrogen peroxide	3.8	0.29	NIOSH REL: 1.4 (1 ppm) OSHA PEL: 1.4 (1 ppm)
Inorganic metallic salt A	3.1E-05	2.4E-06	NR
Inorganic metallic salt B	2.1E-03	1.6E-04	NR
Inorganic metallic salt C	2.2E-05	1.7E-06	NR
Malic acid	0.22	0.017	none
Nickel sulfate	0.55	0.042	NIOSH REL, Ca: 0.015 OSHA PEL: 1
Phosphoric acid	1.2	0.092	NIOSH REL: 1, STEL: 3 OSHA PEL: 1
Potassium compound	1.0	0.079	NR
Sodium hypophosphite	0.64	0.048	none
Urea compound B	7.6E-04	5.8E-05	NR
Nickel/Palladium/Gold, Non-conveyorized			
Aliphatic acid B	5.6E-04	4.2E-05	NR
Aliphatic acid E	140	11	NR
Aliphatic dicarboxylic acid A	0.11	0.0082	NR
Aliphatic dicarboxylic acid C	0.051	0.0039	NR
Alkyldiol	22	1.7	NR
Ammonia compound B	0.026	0.0020	NR
Ammonium hydroxide	2.0	0.16	none
Ethylenediamine	0.064	0.0048	NIOSH REL: 25 (10 ppm) OSHA PEL: 25 (10 ppm)
Hydrochloric acid	28	2.1	NIOSH REL, C: 7 (5 ppm) OSHA PEL, C: 7 (5 ppm)
Hydrogen peroxide	3.7	0.28	NIOSH REL: 1.4 (1 ppm) OSHA PEL: 1.4 (1 ppm)
Inorganic metallic salt B	0.0021	1.6E-04	NR
Malic acid	0.23	0.018	none
Nickel sulfate	0.90	0.068	NIOSH REL, Ca: 0.015 OSHA PEL: 1
Phosphoric acid	1.2	0.092	NIOSH REL: 1, STEL: 3 OSHA PEL: 1
Potassium compound	1.1	0.082	NR

Chemical [a]	Total Emission Rate ($F_{y,T}$) (mg/min)	Workplace Air Conc. (Cy) (mg/m^3)	Federal OSHA and/or NIOSH Permissible Inhalation Exposure Limits (mg/m^3) [b]
Propionic acid	26	2.0	NIOSH REL: 30 (10 ppm) STEL: 45 (15 ppm)
Sodium hypophosphite	0.85	0.065	none
Urea compound B	0.0015	1.2E-04	NR
OSP, Non-conveyorized			
Acetic acid	74	5.6	NIOSH REL: 25 (10 ppm), STEL: 37 (15 ppm) OSHA PEL: 25 (10 ppm)
Arylphenol	0.0059	4.5E-04	NR
Ethylene glycol	23	1.7	no OSHA PEL or NIOSH REL
Hydrochloric acid	2.0	0.15	NIOSH REL, C: 7 (5 ppm) OSHA PEL, C: 7 (5 ppm)
Hydrogen peroxide	1.8	0.14	OSHA PEL, NIOSH REL: 1.4 (1 ppm)
Phosphoric acid	1.2	0.092	NIOSH REL: 1, STEL 3 OSHA PEL: 1
Immersion Tin, Non-conveyorized			
Aliphatic acid D	27	2.1	NR
Alkylaryl sulfonate	0.026	0.0020	NR
Cyclic amide	22	1.7	NR
Hydrochloric acid	0.090	0.069	NIOSH REL, C: 7 (5 ppm) OSHA PEL, C: 7 (5 ppm)
Hydroxy carboxylic acid	37	2.8	NR
Phosphoric acid	0.74	0.056	NIOSH REL: 1, STEL: 3 OSHA PEL: 1
Urea compound C	250	19	NR

[a] Only chemicals with calculated values are presented. A number was not calculated for a chemical if its vapor pressure is below the 1 x 10^{-3} torr cutoff and it is not used in any air-sparged bath. For these chemicals, air concentrations are expected to be negligible.

[b] Source: NIOSH, 1999. RELs and/or PELs for proprietary chemicals are not presented in order to protect confidential chemical identities. Notes about these values follow:

NIOSH REL: Recommended exposure limit, a time-weighted average (TWA) concentrations for up to a 10-hour workday during a 40-hour workweek.

OSHA PEL: The OSHA permissible exposure limits, as found in Tables Z-1, Z-2, and Z-3 of the OSHA General Industry Air Contaminants Standard (29 CFR 1910.1000). Unless noted otherwise, PELs are TWA concentrations that must not be exceeded during any 8-hour workshift of a 40-hour workweek.

STEL: A short-term exposure limit; unless noted otherwise, this is a 15-minute TWA exposure that should not be exceeded at any time during a workday.

C: A ceiling REL or PEL is designated by "C"; unless noted otherwise, the ceiling value should not be exceeded at any time.

Ca: Any substance that NIOSH considers to be a potential occupational carcinogen is designated by the notation "Ca."

Note: The numeric format used in these tables is a form of scientific notation, where the "E" replaces the " x 10^{x}". Scientific notation is typically used to present very large or very small numbers. For example, 1.2E-04 is the same as 1.2 x 10^{-4}, which is the same as 0.00012 in common decimal notation.

Modeling Air Concentrations for Population Exposure

The following approach was used for dispersion modeling of air emissions from a single facility:

- The Industrial Source Complex Long Term ISC(2)LT model was used from the Risk*Assistant™ software program.
- A building (release) height of 3 meters was assumed.
- An area source with dimensions of 10 x 10 m was assumed.
- Meteorological data for Oakland, California, Denver, Colorado, and Phoenix, Arizona were used. (PWB facilities are located throughout the U.S., and many are in Southern California. These three areas give the highest modeled concentrations around a facility for any available city data in the model.)
- Regulatory default values were used for other model parameters. (These are model defaults pertaining to plume rise, stack-tip downwash, buoyancy-induced dispersion, wind profile exponents, vertical temperature gradient, and buildings adjacent to the emission source.)
- An urban mode setting was used. (The setting can be either rural or urban. The urban setting is appropriate for urban areas or for large facilities.)
- Because of the short time expected for chemical transport to nearby residents, chemical degradation was not taken into account.
- A standard polar grid[5] with 36 vector directions and one distance ring (at 100m) was used; the highest modeled air concentration in any direction at 100 meters was used to estimate population exposure.

An average emission rate-to-air concentration factor of 2.18×10^{-6} min/m^3 was determined using model results for the three locations. This factor was multiplied by the total emissions rate for each chemical (in mg/min) to yield air concentrations at the receptor point, in units of mg/m^3. The emission rates calculated for workplace inhalation exposures (Table 3-8) are used for the source emission rates to ambient air. Except for the carcinogen, inorganic metallic salt A, ambient air concentrations are not reported for those chemicals with facility emission rates less than 23 kg/year (44 mg/min), which is a screening threshold typically used by EPA.[6] In addition, ambient air concentrations for lead were estimated, based on this air dispersion model and HASL workplace air monitoring data. Results of ambient air modeling are presented in Table 3-9.

---

[5] A polar grid is a coordinate system that describes the location of a point by means of direction and distance in relation to a central point (e.g., two miles northeast of the center). In the model, a series of regularly-spaced concentric distance rings are defined at chosen intervals along with a defined number of direction vectors (e.g., north, south, east, west, northeast, northwest, southeast, and southwest would be eight directions).

[6] Under conservative assumptions, inhalation exposure to fugitive releases less than 23 kg/yr result in exposures of less than 1 mg/yr for an individual.

Table 3-9. Results of Ambient Air Modeling

Chemical	Emission Rate [a] (mg/min)	Air Concentration [b] (mg/m^3)
HASL, Non-conveyorizd		
Ethylene glycol monobutyl ether	120	2.55E-04
Lead	0.039 [c]	9.0E-08
HASL, Conveyorized		
Ethylene glycol monobutyl ether	230	5.05E-04
Lead	0.039 [c]	9.0E-08
Nickel/Gold, Non-conveyorized		
Aliphatic acid A	77	1.68E-04
Aliphatic acid E	100	2.22E-04
Inorganic metallic salt A	3.12E-05	6.81E-11
Nickel/Palladium/Gold, Non-conveyorized		
Aliphatic acid E	140	3.06E-04
OSP, Non-conveyorized		
Acetic acid	74	1.62E-04
OSP, Conveyorized		
Acetic acid	280	6.15E-04
Ethylene glycol	46	9.94E-05
Immersion Tin, Non-conveyorized		
Urea compound C	250	5.40E-04
Immersion Tin, Conveyorized		
Aliphatic acid D	67	1.46E-04
Cyclic amide	53	1.16E-04
Hydroxy carboxylic acid	90	1.96E-04
Urea compound C	610	1.32E-03

[a] Only those chemicals with an emission rate of at least 23 kg/year (44 mg/min) are listed. Immersion silver had no modeled emission rates above this cut-off.

[b] The numeric format used in this column is a form of scientific notation, where "E" replaces the " x 10^x. Scientific notation is typically used to present very large or very small numbers. For example, 1.2E-04 is the same as 1.2 x 10^{-4}, which is the same as 0.00012 in common decimal notation.

[c] Based on air monitoring data from one facility, with an average workplace air concentration of 0.003 mg/m^3.

Surface Water

PWB manufacturers typically combine wastewater effluent from the surface finishing process line with effluent from other PWB manufacturing processes prior to on-site wastewater pretreatment. The pretreated wastewater is then discharged to a POTW. Consequently, characterizing the process wastewater has been problematic. Because many of the chemical constituents expected in the wastewater of the surface finishing process are also found in other PWB manufacturing processes, testing data obtained from industry was not sufficient to characterize what portion of the overall wastewater contamination was actually attributable to the operation of the surface finishing process. Therefore, a model was developed to estimate environmental releases to surface water for chemical constituents and concentrations in the wastewater as a result of the operation of the surface finishing process alone.

In the absence of quality data from industry, this model was developed using laboratory testing to determine the amount of drag-out from a wet chemistry process involving PWBs and the amount of chemical disposed through bath replacement. The MHC process, which is similar in operation to the surface finishing process, was used as the basis for the model because of the availability of chemical formulation data at time of development. The term drag-out refers to the process chemicals that are 'dragged' (lost) from chemical baths into the following water rinse stages, during the processing of PWB panels through the surface finishing line. Residual process chemicals are washed from the surface of the PWB by the rinse water stages resulting in contamination of the rinse water. Industry has estimated that up to 95 percent of the chemical contamination in the wastewater is attributable to drag-out (the remaining contamination results from spent bath treatment and bath maintenance practices). The drag-out model is given by the following linear regression equation:

$$DO = 18 + 201\,(SIZE) - 60.1\,(ELCTRLS) + 73\,(WR/DT) - 20.9\,(ALK) + 26\,(HOLES) + 26.1\,(WR) - 0.355\,(DT)$$

where,

DO	=	drag-out from bath, ml/m^2
SIZE	=	board area, m^2
WR	=	withdraw rate, m/sec
DT	=	drain time, sec
ALK	=	1 if the bath is an alkaline cleaner bath and = 0 otherwise
HOLES	=	1 if the board is drilled and = 0 for undrilled boards (we assumed that all boards were drilled)
ELCTRLS	=	1 if the bath is an electroless copper bath and = 0 otherwise

The model was used to estimate the mass loading of constituents to the wastewater resulting from drag-out during the production of 260,000 ssf of PWB by the surface finishing process, by the following equation:

$$MDij = P * Cij * DOij / 1{,}000{,}000$$

where,

MDij = drag-out mass of constituent I from bath j, g/d
P = PWB production rate, m^2/day
Cij = concentration of constituent I in bath j, mg/L

The amount of chemical going to wastewater from bath replacement was calculated by:

$$Mbij = Fj/T * Vj * Cij / 1{,}000$$

where,
MBij = mass of constituent I from dumping bath j, g/d
Fj = replacement frequency for bath j, times/yr
T = operating time (from cost model, total production time minus down time), days/yr
V = volume of bath j, L

For non-conveyorized lines, the total mass per day going to wastewater is the sum of drag-out mass and bath dumping mass for the constituent in all baths:

$$Mi = \sum_{j=1}^{n} (MDij + MBij)$$

where,
Mi = total mass of constituent i going to wastewater, g/d, from all baths j containing constituent i

Because conveyorized lines are designed to operate with minimal drag-out, and the drag-out model was developed only for vertical configurations, bath replacement alone was considered in estimating chemical amounts to wastewater. For conveyorized lines,

$$Mi = \sum_{j=1}^{n} MBij$$

A detailed description of the model, along with the methods of model development, validation and testing, and model limitations, are presented in *Prediction of Water Quality from Printed Wiring Board Processes* (Robinson et al., 1999) and Appendix E.

Preliminary in-stream concentrations were then calculated from the mass loading by considering dilution in the receiving stream and assuming no treatment, by:

$$Ci,_{SW} = 1000\ Mi / (Q_{SW} + Q_{WW})$$

where,
$Ci,_{SW}$ = preliminary surface water concentration of constituent i, assuming no treatment, mg/L
Q_{SW} = surface water flow rate, L/day
Q_{WW} = wastewater flow rate, L/day

For surface water flow, we used a rate of 13.3 million liters/day. This is the 10th percentile low flow rate (7Q10) for the distribution of streams associated with facilities with the Electronic Components Manufacture SIC code. This type of flow rate is typically used by EPA for comparisons of screening-level estimates of in-stream chemical concentrations versus concern concentrations (CCs) for aquatic species.

These concentrations were then screened against CCs for toxicity to aquatic life (CCs are discussed in Section 3.3.3 and Appendix H). For any chemicals with preliminary in-stream concentrations exceeding CCs, a typical treatment efficiency was determined. For this purpose, it was assumed that wastewater treatment consisted of primary treatment by gravitational settling followed by complete-mix activated sludge secondary treatment and secondary settling (clarification), as typically employed at POTWs. Treatment efficiencies were estimated on a chemical-by-chemical basis using a combination of readily available data on the chemical or close structural analogs and best professional judgment. Information sources included EPA's Treatability Database, the Environmental Fate Data Base (Syracuse Research Corp., updated periodically), the *Handbook of Environmental Degradation Rates* (Howard et al., 1991), wastewater engineering handbooks such as Metcalf and Eddy, and various journal articles from the published literature.

Treatment efficiencies were then applied to the chemical concentrations, and revised in-stream concentrations were calculated. Select inorganic constituents that are targeted by industry for treatment, such as metals, were assumed to be treated effectively by on-site treatment to required effluent levels. These metals are not included in the surface water evaluation. (Pretreatment is discussed further in Section 6.2, Control Technologies.) Results for chemicals, excluding metals, where the initial stream concentration (without treatment) exceeded the CC for that chemical are presented in Table 3-10. Full results are presented in Appendix E.

Table 3-10. Estimated Releases to Surface Water Following Treatment

Chemical [a]	Conc. in Wastewater Released to Stream (mg/L)	Stream Conc. w/o POTW Treatment (mg/L)	Treatment Efficiency (%)	Stream Conc. after POTW Treatment (mg/L)
HASL, Non-conveyorized				
1,4-Butenediol	49	0.10	90	0.010
Alkylaryl sulfonate	2.3	0.0049	0	0.0049
Citric acid	94	0.20	93	0.014
Ethylene glycol monobutyl ether	71	0.15	90	0.015
Hydrogen peroxide	195	0.41	90	0.041
Potassium peroxymonosulfate	390	0.82	90	0.082
HASL, Conveyorized				
1,4-Butenediol	23	0.076	90	0.0076
Alkylaryl sulfonate	1.0	0.0035	0	0.0035
Citric acid	42	0.14	93	0.0099

Chemical [a]	Conc. in Wastewater Released to Stream (mg/L)	Stream Conc. w/o POTW Treatment (mg/L)	Treatment Efficiency (%)	Stream Conc. after POTW Treatment (mg/L)
Ethylene glycol monobutyl ether	32	0.11	90	0.011
Hydrogen peroxide	90	0.30	90	0.030
Potassium peroxymonosulfate	180	0.61	90	0.061
Nickel/Gold, Non-conveyorized				
Hydrogen peroxide	62	0.045	90	0.0045
Substituted amine hydrochloride	97	0.070	80	0.014
Nickel/Palladium/Gold, Non-conveyorized				
Hydrogen peroxide	36	0.034	90	0.0034
Substituted amine hydrochloride	55	0.053	80	0.011
OSP, Non-conveyorized				
Alkylaryl imidazole	200	0.33	90	0.033
Hydrogen peroxide	110	0.18	90	0.018
OSP, Conveyorized				
Alkylaryl imidazole	75	0.18	90	0.018
Hydrogen peroxide	61	0.15	90	0.015
Immersion Silver, Conveyorized				
1,4-Butenediol	48	0.029	90	0.0029
Fatty amine	7.7	0.0047	95	0.00023
Hydrogen peroxide	430	0.26	90	0.026
Immersion Tin, Non-conveyorized				
Alkylaryl sulfonate	1.2	0.0021	0	0.0021
Citric acid	660	1.2	93	0.082
Ethylene glycol monobutyl ether	36	0.064	90	0.0064
Potassium peroxymonosulfate	200	0.36	90	0.036
Quantenary alkylammonium chlorides	42	0.074	90	0.0074
Thiourea	170	0.30	90	0.030
Urea compound C	35	0.062	90	0.0062
Immersion Tin, Conveyorized				
Potassium peroxymonosulfate	68	0.041	90	0.0041

[a] This includes any chemicals, except metals, where the initial stream concentration (without treatment) exceeded the CC for that chemical. Metals are not included; it was assumed that metals are targeted for effective on-site treatment.

3.2.4 Estimating Potential Dose Rates

This section contains information on exposure models, parameter values, and resulting exposure estimates for potential workplace and population exposures. Data on frequency and duration of most activities were derived from the PWB Workplace Practices Questionnaire database, Product Data Sheets from chemical suppliers (e.g., bath change out rates), and the process simulation model (e.g., days of process operation). The general models for calculating inhalation and dermal potential dose rates are discussed below.

Inhalation Exposures

The general model for inhalation exposure to workers is from CEB (U.S. EPA, 1991a):

$$I = (Ca)(IR)(ET)$$

where,

I	=	daily inhalation potential dose rate (mg/day)
Ca	=	airborne concentration of substance (mg/m^3)
		(Note: this term is denoted "C_y" in air modeling equation in Section 3.2.3.)
IR	=	inhalation rate (m^3/hr)
ET	=	exposure time (hr/day)

Daily exposures are averaged over a lifetime (70 years) for carcinogens, and over the exposure duration (e.g., 25 years working in a facility) for non-carcinogens.[7] The following equations are used to estimate average daily doses for inhalation:

$$LADD = (I)(EF)(ED)/[(BW)(AT_{CAR})]$$
$$ADD = (I)(EF)(ED)/[(BW)(AT_{NC})]$$

where,

LADD	=	lifetime average daily dose (mg/kg-day) (for carcinogens)
ADD	=	average daily dose (mg/kg-day) (for non-carcinogens)
I	=	daily inhalation potential dose rate (mg/day)
EF	=	exposure frequency (days/year)
ED	=	exposure duration (years)
BW	=	body weight (kg)
AT_{CAR}	=	averaging time for carcinogenic effects (days)
AT_{NC}	=	averaging time for non-carcinogenic effects (days)

[7] Different averaging times are used for characterizing risk for carcinogenic and non-carcinogenic effects. For carcinogenic agents, because even a single incidence of exposure is assumed to have the potential to cause cancer throughout an individual's lifetime, the length of exposure to that agent is averaged over a lifetime. An additional factor is that the cancer latency period may extend beyond the period of working years before it is discernible. For chemicals exhibiting non-cancer health effects from chronic (longer-term) exposure, where there is an exposure threshold (a level below which effects are not expected to occur); only the time period when exposure is occurring is assumed to be relevant and is used as the averaging time.

Parameter values for estimating workers' potential dose rates from inhalation are presented in Table 3-11.

Table 3-11. Parameter Values for Workplace Inhalation Exposures

Parameter	Units	Value	Source of Data, Comments
Air Concentration (Ca)	mg/m^3	Modeled from bath concentrations (see Table 3-9).	
Inhalation Rate (IR)	m^3/hr	1.25	U.S. EPA, 1991a (data from NIOSH, 1976).
Exposure Time (ET)			
Line Operation	hrs/day	8	Default value for occupational exposure.
Working in Process Area	hrs/day	laboratory technician . . . . . 2.8 maintenance worker . . . . . 1.6 supervisors . . . . . 5.5 wastewater treatment operator . . 1 other employee 9	90th percentile of hours/week reported from PWB Workplace Practices Questionnaire, assuming a 5-day work week.
Exposure Frequency (EF)			
Line Operation & Working in Process Area	days/yr	HASL (NC) . . . . . 44 HASL (C) . . . . . 22 Nickel/Gold (NC) . . . . . 212 Nickel/Palladium/Gold (NC) . 280 OSP (NC) . . . . . 35 OSP (C) . . . . . 16 Immersion Silver (C) . . . . . 64 Immersion Tin (NC) . . . . . 75 Immersion Tin (C) 107	From process cost model, based on the number of days per year required to produce 260,000 ssf of finished PWB. Assumed this is the time worked per year.
Exposure Duration (ED)	years	25	95th percentile for job tenure (Bureau of Labor Statistics, 1990). (Median tenure for U.S. males is 4 years; Bureau of Labor Statistics, 1997.)
Body Weight (BW)	kg	70	Average for adults (U.S. EPA, 1991b).
Averaging Time (AT) AT_{CAR} AT_{NC}	days	 25,550 9,125	 70 yrs (average lifetime) x 365 d/yr 25 yrs (ED) x 365 d/yr

Workplace Dermal Exposures

Two approaches were considered for evaluating dermal exposure. The general model for potential dose rate via dermal exposure to workers from the CEB Manual (U.S. EPA, 1991a) is as follows:

$$D = SQC$$

where,

D	=	dermal potential dose rate (mg/day)
S	=	surface area of contact (cm^2)
Q	=	quantity typically remaining on skin (mg/cm^2)
C	=	concentration of chemical (percent)

Because a line operator is expected to have dermal contact with the chemicals in a given bath several times a day in the course of normal operations, the total time of contact combined with a flux rate (rate of chemical absorption through the skin) is believed to give a more realistic estimate of dermal exposure. An equation based on flux of material through the skin (from on U.S. EPA, 1992a), is as follows:

$$D = (S)(C)(f)(ET)(0.001)$$

where,

D	=	dermal potential dose rate (mg/day)
S	=	skin surface area of contact (cm^2)
C	=	chemical concentration (mg/L)
f	=	flux through skin (cm/hour)
ET	=	exposure time (hours/day)
		with a conversion factor of 0.001 L/cm^3

This second equation was used for all workplace dermal exposure estimates.[8]

As indicated earlier, daily exposures are averaged over a lifetime (70 years) for carcinogens, and over the exposure duration (e.g., 25 years working in a facility) for non-carcinogens. The following equations are used to estimate average daily doses from dermal contact:

$$LADD = (D)(EF)(ED)/[(BW)(AT_{CAR})]$$
$$ADD = (D)(EF)(ED)/[(BW)(AT_{NC})]$$

where,

D	=	dermal potential dose rate (mg/day)

General parameter values for estimating workers' potential dose rates from dermal exposure are presented in Table 3-12.

[8] This permeability coefficient-based approach is recommended over the absorption fraction approach for compounds in an aqueous media or in air (U.S. EPA 1992a).

Table 3-12. General Parameter Values for Workplace Dermal Exposures

Parameter	Units	Value	Source of Data, Comments
Chemical Concentration (C)	%	Range of reported values and average determined from bath chemistry data.	
Skin Surface Area (S)	cm^2	800	CEB, routine immersion, 2 hands, assuming gloves not worn.
Flux Through Skin (f)	cm/hr	Default for inorganics: 0.001 estimate for organics by: $\log f = -2.72+0.71 \log K_{ow} - 0.0061(MW)$ (K_{ow} = octanol/water partition coefficient, MW = molecular weight)	U.S. EPA, 1992a.
Exposure Duration (ED)	years	25	95th percentile for job tenure (Bureau of Labor Statistics, 1990). (Median tenure for U.S. males is 4 years; Bureau of Labor Statistics, 1997.)
Body Weight (BW)	kg	70	U.S. EPA, 1991b.
Averaging Time (AT)	days		
AT_{CAR}		25,500	70 yrs (average lifetime) x 365 d/yr
AT_{NC}		9,125	25 yrs (ED) x 365 d/yr

Dermal exposure was quantified for line operators performing routine line operation activities on non-conveyorized lines. Parameter values used in the dermal exposure equations are provided in Table 3-13.

Table 3-13. Parameter Values for Workplace Dermal Exposures for Line Operators on Non-Conveyorized Lines

Parameter/ *Activity* [a]	Units	Value		Source of Data, Comments
Exposure Time (ET)				
Line Operation [a]	hrs/day	Process / no. baths or steps HASL (NC) / 10 Nickel/Gold (NC) / 14 Nickel/Palladium/Gold (NC) / 22 OSP (NC) / 9 Immersion Tin (NC) / 12	Value 0.80 0.57 0.36 0.89 0.67	Based on a default value of 8 hrs/day; corrected for typical number of baths in a process, including rinse baths, by dividing 8 hrs/day by the number of baths and/or steps in a typical process line.
Exposure Frequency (EF)				
Line Operation [a]	days/yr	HASL (NC) . . . . . 44 HASL (C) . . . . . 22 Nickel/Gold (NC) . . . . . 212 Nickel/Palladium/Gold (NC) . . . . . 280 OSP (NC) . . . . . 35 OSP (C) . . . . . 16 Immersion Silver (C) . . . . . 64 Immersion Tin (NC) . . . . . 75 Immersion Tin (C) 107		From cost process simulation model, based on a throughput of 260,000 ssf.

[a] Dermal exposure on non-conveyorized lines was quantified for line operation activities only, because this would result in higher line operator exposure than any other activities that may be performed (e.g., bath sampling, filter replacement).

Dermal exposure was quantified for line operators on conveyorized lines for chemical bath replacement, conveyor equipment cleaning, filter replacement, and bath sampling activities. Because conveyorized lines are enclosed and the boards are moved through the line automatically, it was assumed that dermal exposure from line operation would be negligible. Parameter values used in the exposure equations for conveyorized lines are provided in Table 3-14.

Table 3-14. Parameter Values for Workplace Dermal Exposure for Line Operators on Conveyorized Lines

Parameter/ *Activity* [a]	Units [b]	Value	Source of Data, Comments
Exposure Time (ET)			
Chemical Bath Replacement	min/occur	HASL . . . . . 264 OSP . . . . . 190 Immersion Silver . . . . . 198 Immersion Tin 120	90th percentile from survey. Questionnaire data for replacement duration were combined regardless of process configuration
Filter Replacement	min/occur	15	90th percentile from PWB Workplace Practices Questionnaire, combined for all process types.
Chemical Bath Sampling	min/occur	HASL . . . . . 15 OSP . . . . . 22 Immersion Silver . . . . . 1.0 Immersion Tin 5.0	90th percentile from PWB Workplace Practices Questionnaire. Questionnaire data for sampling duration were combined regardless of process configuration.
Exposure Frequency (EF)			
Chemical Bath Replacement	occur/year	HASL, cleaner . . . . . 6 HASL, microetch . . . . . 6 OSP, cleaner . . . . . 6 OSP, microetch . . . . . 6 OSP, OSP bath . . . . . 1 Immersion Silver, cleaner & microetch . 6 Immersion Silver, predip . . . . . 5 Immersion Silver, imm. silver bath . . . . 1 Immersion Tin, cleaner & microetch . . . 6 Immersion Tin, predip . . . . . 5 Immersion Tin, imm. tin bath 1	From cost process simulation model, based on a throughput of 260,000 ssf.
Filter Replacement	occur/year	HASL . . . . . 28 OSP . . . . . 9 Immersion Silver . . . . . 4 Immersion Tin 57	From cost process simulation model, based on a throughput of 260,000 ssf.
Chemical Bath Sampling	occur/year	HASL . . . . . 67 OSP . . . . . 200 Immersion Silver . . . . . 253 Immersion Tin 485	From cost process simulation model, based on a throughput of 260,000 ssf.

Parameter/ *Activity* [a]	Units [b]	Value	Source of Data, Comments
Exposure Frequency and Time combined (EF x ET)			
Conveyor Equipment Cleaning	min/year	10,488	90th percentile of total duration per year from PWB Workplace Practices Questionnaire for conveyorized lines. Because a correlation between EF and ET was apparent, we did not take the 90th percentile of each term separately.

[a] Dermal exposure on conveyorized lines is quantified for specific routine activities other than line operation because on an enclosed, conveyorized line it is assumed that dermal contact from line operation would be negligible.

[b] min/occur = minutes per occurance; occur/year = number of occurances per year.

Dermal exposure was also quantified for a laboratory technician on all conveyorized and non-conveyorized lines for chemical bath sampling activities. Parameter values used in the exposure equations for a laboratory technician are provided in Table 3-15.

Table 3-15. Parameter Values for Workplace Dermal Exposure for a Laboratory Technician on Either Conveyorized or Non-Conveyorized Lines

Parameter/ *Activity*	Units [a]	Value	Source of Data, Comments
Exposure Time (ET)			
Chemical Bath Sampling	min/occur	HASL . . . . . 15 Nickel/Gold . . . . . 10 Nickel/Palladium/Gold . . . . . 1.5 OSP . . . . . 22 Immersion Silver . . . . . 1.0 Immersion Tin 5.0	Questionnaire data for sampling duration were combined regardless of process configuration.
Exposure Frequency (EF)			
Chemical Bath Sampling	occur/year	HASL (NC) . . . . . 135 HASL (C) . . . . . 67 Nickel/Gold (NC) . . . . . 954 Nickel/Palladium/Gold (NC) . . . 2,406 OSP (NC) . . . . . 436 OSP (C) . . . . . 200 Immersion Silver (C) . . . . . 253 Immersion Tin (NC) . . . . . 341 Immersion Tin (C) 485	From cost process simulation model, based on a throughput of 260,000 ssf.

[a] min/occur = minutes per occurance; occur/year = number of occurances per year.

Results

Table 3-16 presents results for estimating ADDs for inhalation and dermal workplace exposure for line operators and laboratory technicians.

Table 3-16. Estimated Average Daily Dose for Workplace Exposure From Inhalation and Dermal Contact

Chemical	ADD [a] (mg/kg-day)		
	Inhalation	Dermal	
	Line Operator	Line Operator	Laboratory Technician
HASL, Non-conveyorized			
1,4-Butenediol	1.28E-02	2.05E-03	2.82E-05
Alkylalkyne diol	NA	1.31E-05	1.81E-07
Alkylaryl sulfonate	2.43E-05	5.50E-07	7.58E-09
Alkylphenol ethoxylate	NA	1.59E-27	2.18E-29
Alkylphenolpolyethoxyethanol	NA	1.50E-26	2.06E-28
Aryl phenol	7.86E-06	1.98E-03	2.73E-05
Citric acid	NA	4.25E-03	5.85E-05
Copper Sulfate Pentahydrate	NA	4.93E-02	6.79E-04
Ethoxylated alkylphenol A	NA	1.26E-27	1.73E-29
Ethoxylated alkylphenol B	NA	8.97E-28	1.24E-29
Ethylene glycol	1.60E-02	5.17E-03	7.13E-05
Ethylene glycol monobutyl ether	1.53E-01	3.53E-02	4.86E-04
Fluoboric acid	NA	1.35E-02	1.86E-04
Gum	NA	NA [b]	NA [b]
Hydrochloric acid	1.16E-03	2.28E-02	3.15E-04
Hydrogen peroxide	6.81E-03	5.55E-02	7.66E-04
Hydroxyaryl acid	NA	9.52E-04	1.31E-05
Hydroxyaryl sulfonate	NA	3.35E-05	4.62E-07
Phosphoric acid	2.01E-03	6.69E-02	9.22E-04
Potassium peroxymonosulfate	NA	1.11E-01	1.53E-03
Sodium benzene sulfonate	NA	1.85E-07	2.55E-09
Sodium hydroxide	NA	1.86E-04	2.57E-06
Sulfuric acid	NA	2.34E-01	3.23E-03
HASL, Conveyorized			
1,4-Butenediol	NA	8.53E-05	6.35E-06
Alkylalkyne diol	NA	5.47E-07	4.07E-08
Alkylaryl sulfonate	NA	2.29E-08	1.71E-09
Alkylphenol ethoxylate	NA	6.61E-29	4.92E-30
Alkylphenolpolyethoxyethanol	NA	6.23E-28	4.64E-29

Chemical	ADD [a] (mg/kg-day)		
	Inhalation	Dermal	
	Line Operator	Line Operator	Laboratory Technician
Aryl phenol	NA	8.26E-05	6.15E-06
Citric acid	NA	1.77E-04	1.32E-05
Copper sulfate pentahydrate	NA	2.05E-03	1.53E-04
Ethoxylated alkylphenol A	NA	5.24E-29	3.90E-30
Ethoxylated alkylphenol B	NA	3.74E-29	2.78E-30
Ethylene glycol	NA	2.15E-04	1.60E-05
Ethylene glycol monobutyl ether	NA	1.47E-03	1.09E-04
Fluoboric acid	NA	5.62E-04	4.19E-05
Gum	NA	NA [b]	NA [b]
Hydrochloric acid	NA	9.51E-04	7.08E-05
Hydrogen peroxide	NA	2.31E-03	1.72E-04
Hydroxyaryl acid	NA	3.97E-05	2.95E-06
Hydroxyaryl sulfonate	NA	1.40E-06	1.04E-07
Phosphoric acid	NA	2.79E-03	2.08E-04
Potassium peroxymonosulfate	NA	4.64E-03	3.45E-04
Sodium benzene sulfonate	NA	7.72E-09	5.75E-10
Sodium hydroxide	NA	7.75E-06	5.77E-07
Sulfuric acid	NA	9.76E-03	7.27E-04
Nickel/Gold, Non-conveyorized			
Aliphatic acid A	4.86E-01	2.35E-02	1.53E-03
Aliphatic acid B	3.38E-06	1.56E-03	1.02E-04
Aliphatic acid E	6.43E-01	1.41E-02	9.16E-04
Aliphatic dicarboxylic acid A	6.59E-04	4.94E-03	3.21E-04
Aliphatic dicarboxylic acid C	3.12E-04	1.75E-03	1.13E-04
Alkylamino acid B	NA	5.38E-06	3.49E-07
Alkyldiol	1.37E-01	1.66E-02	1.08E-03
Alkylphenolpolyethoxyethanol	NA	5.18E-26	3.36E-27
Ammonia compound B	1.61E-04	2.65E-04	1.72E-05
Ammonium chloride	NA	2.08E-01	1.35E-02
Ammonium hydroxide	7.76E-03	1.34E-01	8.71E-03
Citric acid	NA	4.79E-03	3.11E-04
Copper sulfate pentahydrate	NA	1.71E-01	1.11E-02
Ethoxylated akylphenol B	NA	3.11E-27	2.02E-28
Hydrochloric acid	1.63E-01	2.08E+00	1.35E-01
Hydrogen peroxide	2.40E-02	1.36E-01	8.84E-03
Hydroxyaryl acid	NA	3.30E-03	2.14E-04

Chemical	ADD [a] (mg/kg-day)		
	Inhalation	Dermal	
	Line Operator	Line Operator	Laboratory Technician
Inorganic metallic salt A	1.97E-07	8.00E-06	5.19E-07
Inorganic metallic salt A (LADD) [c]	7.04E-08	2.85E-06	1.85E-07
Inorganic metallic salt B	1.31E-05	5.31E-04	3.45E-05
Inorganic metallic salt C	1.37E-07	5.55E-06	3.61E-07
Malic acid	1.41E-03	2.10E-03	1.37E-04
Nickel sulfate	3.49E-03	1.41E-01	9.17E-03
Palladium chloride	NA	5.01E-03	3.25E-04
Phosphoric acid	7.67E-03	1.93E-01	1.25E-02
Potassium compound	6.59E-03	2.66E-01	1.73E-02
Potassium gold cyanide	NA	1.14E-02	7.39E-04
Potassium peroxymonosulfate	NA	NA [d]	NA [d]
Sodium salt	NA	3.41E-01	2.22E-02
Sodium hydroxide	NA	6.45E-04	4.19E-05
Sodium hypophosphite	4.02E-03	1.62E-01	1.05E-02
Substituted amine hydrochloride	NA	2.27E-01	1.48E-02
Sulfuric acid	NA	8.55E-01	5.55E-02
Transition metal salt	NA	2.27E-03	1.48E-04
Urea compound B	4.80E-06	2.40E-05	1.56E-06
Nickel/Palladium/Gold, Non-conveyorized			
Aliphatic acid B	4.63E-06	1.32E-03	3.23E-05
Aliphatic acid E	1.17E+00	1.58E-02	3.88E-04
Aliphatic dicarboxylic acid A	8.98E-04	4.16E-03	1.02E-04
Aliphatic dicarboxylic acid C	4.26E-04	1.47E-03	3.61E-05
Alkylamino acid B	NA	8.01E-06	1.97E-07
Alkyldiol	1.85E-01	1.40E-02	3.43E-04
Alkylpolyol	NA	3.56-03	8.76E-05
Amino acid salt	NA	6.39E-04	1.57E-05
Amino carboxylic acid	NA	1.11E-05	2.73E-07
Ammonia compound A	NA	1.60E-01	3.92E-03
Ammonia compound B	2.20E-04	2.23E-04	5.48E-06
Ammonium hydroxide	1.71E-02	1.91E-01	4.70E-03
Citric acid	NA	4.91E-03	1.21E-04
Copper sulfate pentahydrate	NA	1.43E-01	3.53E-03
Ethoxylated alkylphenol	NA	2.61E-27	6.42E-29

Chemical	ADD [a] (mg/kg-day)		
	Inhalation	Dermal	
	Line Operator	Line Operator	Laboratory Technician
Ethylenediamine	5.32E-04	4.14E-04	1.02E-05
Hydrochloric acid	2.35E-01	3.92E-01	9.63E-03
Hydrogen peroxide	3.11E-02	1.14E-01	2.81E-03
Hydroxyaryl acid	NA	2.77E-03	6.81E-05
Inorganic metallic salt B	1.79E-05	2.07E-03	5.08E-05
Maleic acid	NA	1.36E-03	3.35E-05
Malic acid	1.92E-03	1.77E-03	4.34E-05
Nickel sulfate	7.50E-03	1.87E-01	4.59E-03
Palladium salt	NA	1.02E-02	2.51E-04
Phosphoric acid	1.01E-02	1.62E-01	3.98E-03
Potassium compound	8.98E-03	2.24E-01	5.50E-03
Potassium gold cyanide	NA	9.56E-03	2.35E-04
Propionic acid	2.13E-01	2.69E-02	6.60E-04
Sodium hydroxide	NA	5.42E-04	1.33E-05
Sodium hypophosphite	7.11E-03	1.93E-01	4.75E-03
Sodium salt	NA	4.78E-01	1.18E-02
Substituted amine hydrochloride	NA	1.91E-01	4.70E-03
Sulfuric acid	NA	4.99E-01	1.23E-02
Surfactant	NA	3.19E-04	7.83E-06
Transition metal salt	NA	1.91E-03	4.70E-05
Urea compound B	1.28E-05	3.94E-05	9.67E-07
OSP, Non-conveyorized			
Acetic acid	7.79E-02	3.75E-02	2.45E-03
Alkylaryl imidazole	NA	5.50E+00	3.59E-01
Aromatic imidizole product	NA	6.33E-03	4.13E-04
Arylphenol	6.18E-06	1.77E-03	1.16E-04
Copper ion	NA	4.95E-02	3.23E-03
Copper salt C	NA	1.36E-03	8.89E-05
Copper sulfate pentahydrate	NA	4.41E-02	2.88E-03
Ethoxylated alkylphenol	NA	8.03E-28	5.24E-29
Ethylene glycol	2.38E-02	4.63E-03	3.02E-04
Gum	NA	NA [b]	NA [b]
Hydrochloric acid	2.04E-03	2.33E-02	1.52E-03
Hydrogen peroxide	1.92E-03	1.78E-02	1.16E-03

Chemical	ADD [a] (mg/kg-day)		
	Inhalation	Dermal	
	Line Operator	Line Operator	Laboratory Technician
Hydroxyaryl acid	NA	8.52E-04	5.57E-05
Hydroxyaryl sulfonate	NA	3.00E-05	1.96E-06
Phosphoric acid	1.27E-03	4.98E-02	3.25E-03
Sodium hydroxide	NA	1.67E-04	1.09E-05
Sulfuric acid	NA	2.55E-01	1.66E-02
OSP, Conveyorized			
Acetic acid	NA	1.78E-03	5.30E-04
Alkylaryl imidazole	NA	2.61E-01	7.78E-02
Aromatic imidizole product	NA	3.00E-04	8.94E-05
Aryl phenol	NA	8.93E-05	2.51E-05
Copper ion	NA	2.34E-03	6.99E-04
Copper salt C	NA	6.45E-05	1.92E-05
Copper sulfate pentahydrate	NA	2.22E-03	6.23E-04
Ethoxylated alkylphenol	NA	4.04E-29	1.13E-29
Ethylene glycol	NA	2.33E-04	6.54E-05
Gum	NA	NA [b]	NA [b]
Hydrochloric acid	NA	1.17E-03	3.30E-04
Hydrogen peroxide	NA	8.96E-04	2.51E-04
Hydroxyaryl acid	NA	4.29E-05	1.20E-05
Hydroxyaryl sulfonate	NA	1.51E-06	4.24E-07
Phosphoric acid	NA	2.50E-03	7.03E-04
Sodium hydroxide	NA	8.38E-06	2.35E-06
Sulfuric acid	NA	1.28E-02	3.60E-03
Immersion Silver, Conveyorized			
1,4-Butenediol	NA	3.07E-04	6.48E-06
Alkylamino acid A	NA	1.71E-04	3.79E-06
Fatty amine	NA	5.75E-01	1.28E-02
Hydrogen peroxide	NA	1.85E-02	3.91E-04
Nitrogen acid	NA	3.95E-03	8.75E-05
Nonionic surfactant	NA	9.23E-03	2.04E-04
Phosphoric acid	NA	2.02E-02	4.26E-04
Silver nitrate	NA	1.51E-04	3.48E-06
Sodium hydroxide	NA	8.72E-03	1.93E-04
Sulfuric acid	NA	7.55E-04	1.59E-05

Chemical	ADD [a] (mg/kg-day)		
	Inhalation	Dermal	
	Line Operator	Line Operator	Laboratory Technician
Immersion Tin, Non-conveyorized			
Aliphatic acid D	6.14E-02	8.22E-03	9.54E-05
Alkylalkyne diol	NA	1.88E-05	2.19E-07
Alkylamino acid B	NA	1.79E-06	2.08E-08
Alkylaryl sulfonate	5.74E-05	7.88E-07	9.15E-09
Alkylimine dialkanol	NA	1.84E-05	2.13E-07
Alkylphenol ethoxylate	NA	2.27E-27	2.64E-29
Bismuth compound	NA	4.02E-05	4.66E-07
Citric acid	NA	7.65E-02	8.88E-04
Cyclic amide	4.90E-02	1.15E-02	1.34E-04
Ethoxylated alkylphenol	NA	1.80E-27	2.09E-29
Ethylene glycol monobutyl ether	3.75E-01	5.06E-02	5.87E-04
Fluoboric acid	NA	1.94E-02	2.25E-04
Hydrochloric acid	2.03E-03	1.13E-02	1.31E-04
Hydroxy carboxylic acid	8.26E-02	7.03E-03	8.16E-05
Methane sulfonic acid	NA	1.62E+00	1.88E-02
Phosphoric acid	1.66E-03	4.75E-02	5.51E-04
Potassium peroxymonosulfate	NA	1.60E-01	1.85E-03
Quantenary alkylammonium chlorides	NA	7.60E-04	8.83E-06
Silver salt	NA	6.03E-06	7.00E-08
Sodium benzene sulfonate	NA	2.66E-07	3.08E-09
Sodium phosphorus salt	NA	1.41E-01	1.64E-03
Stannous methane sulfonic acid	NA	2.18E-02	2.53E-04
Sulfuric acid	NA	4.62E-01	5.37E-03
Thiourea	NA	1.89E-02	2.20E-04
Tin chloride	NA	2.19E-02	2.55E-04
Unspecified tartrate	NA	1.77E-03	2.06E-05
Urea	NA	3.68E-03	4.27E-05
Urea compound C	5.55E-01	2.37E-02	2.75E-04
Vinyl polymer	NA	1.81E-32	2.10E-34
Immersion Tin, Conveyorized			
Aliphatic acid D	NA	1.33E-03	2.32E-04
Alkylalkyne diol	NA	3.17E-06	5.31E-07
Alkylamino acid B	NA	2.89E-07	5.05E-08
Alkylaryl sulfonate	NA	1.33E-07	2.22E-08

Chemical	ADD [a] (mg/kg-day)		
	Inhalation	Dermal	
	Line Operator	Line Operator	Laboratory Technician
Alkylimine dialkanol	NA	2.98E-06	5.17E-07
Alkylphenol ethoxylate	NA	3.83E-28	6.41E-29
Bismuth compound	NA	6.50E-06	1.13E-06
Citric acid	NA	1.24E-02	2.16E-03
Cyclic amide	NA	1.87E-03	3.25E-04
Ethoxylated alkylphenol	NA	3.04E-28	5.08E-29
Ethylene glycol monobutyl ether	NA	8.52E-03	1.43E-03
Fluoboric acid	NA	3.26E-03	5.46E-04
Hydrochloric acid	NA	1.82E-03	3.18E-04
Hydroxy carboxylic acid	NA	1.14E-03	1.98E-04
Methane sulfonic acid	NA	2.69E-01	4.56E-02
Phosphoric acid	NA	8.00E-03	1.34E-03
Potassium peroxymonosulfate	NA	2.69E-02	4.50E-03
Quantenary alkylammonium chlorides	NA	1.23E-04	2.14E-05
Silver salt	NA	9.75E-07	1.70E-07
Sodium benzene sulfonate	NA	4.48E-08	7.49E-09
Sodium phosphorus salt	NA	2.33E-02	3.98E-03
Stannous methane sulfonic acid	NA	3.52E-03	6.14E-04
Sulfuric acid	NA	7.69E-02	1.30E-02
Thiourea	NA	3.05E-03	5.33E-04
Tin chloride	NA	3.54E-03	6.19E-04
Unspecified tartrate	NA	2.86E-04	4.99E-05
Urea	NA	5.94E-04	1.04E-04
Urea compound C	NA	3.82E-03	6.88E-04
Vinyl polymer	NA	2.92E-33	5.09E-34

[a] Average Daily Dose (ADD) unless otherwise noted.
[b] Dermal absorption not expected due to large molecular size.
[c] LADD is used for calculating cancer risk, and is calculated using a carcinogen averaging time (AT_{CAR}) of 70 years.
Note: The numeric format used in these tables is a form of scientific notation, where "E" replaces the " x 10^x". Scientific notation is typically used to present very large or very small numbers. For example, 1.2E-04 is the same as 1.2 x 10^{-4}, which is the same as 0.00012 in common decimal notation.
[d] Bath concentration not available.
NA: Not Applicable. Unless otherwise noted, a number was not calculated because the chemical's vapor pressure is below the 1 x 10^{-3} torr cutoff and it is not used in any sparged bath. Inhalation exposures are therefore expected to be negligible.
ND: Not determined because a required value was not available.

Occupational Exposure to Elemental Lead

Modeling Occupational Lead Exposure. We estimated occupational exposure to lead based on EPA guidelines for lead ingestion in soil (U.S. EPA, 1996a). This includes modeling worker blood-lead levels using the following equation:

$$PbB_{adult_{central}} = PbB_{adult_0} + (Pb_S)(BKSF)(IR_s)(AF_s)(EF_s) \div AT$$

where,

$PbB_{adult,\ central}$	=	central estimate of adult blood-lead concentrations (Fg/dl)
$PbB_{adult,\ 0}$	=	typical background adult blood-lead concentration (Fg/dl)
Pb_S	=	lead concentration (Fg/g)
BKSF	=	biokinetic slope factor (Fg/dl)
IR_s	=	intake rate (g/day)
AF_s	=	gastrointestinal absorption factor (unitless fraction)
EF_s	=	exposure frequency (days/year)
AT	=	averaging time (days/year)

Lead can be easily passed along to an unborn fetus via the placenta. Using the EPA guidelines (U.S. EPA, 1996a), we also estimated fetal blood-lead levels, assuming a pregnant worker, by:

$$PbB_{fetal,\ 0.95} = PbB_{adult,central} \times GSD_{i,\ adult} \times R_{fetal/maternal}$$

where,

$PbB_{fetal,\ 0.95}$	=	95 percent estimate of fetal blood-lead levels (Fg/dl)
$PbB_{adult,central}$	=	central estimate of adult blood-lead concentrations (Fg/dl)
$GSD_{i,\ adult}$	=	estimated value of the individual geometric standard deviation (dimensionless)
$R_{fetal/maternal}$	=	fetal/maternal lead concentration at birth (dimensionless)

These equations were developed for exposure to lead in soil and dust, and were modified for the surface finishing situation by considering lead in solder, rather than soil. Our treatment of each term in the model is discussed below.

Estimated Adult Blood-Lead Concentration ($PbB_{adult,\ central}$). This represents the central estimate of blood-lead in adults exposed to the HASL process, measured in Fg/dl.

Background Blood-Lead Concentration ($PbB_{adult,\ 0}$). This value represents the typical blood-lead concentration of adults who are not exposed to lead at the site that is being assessed, and is measured in Fg/dl. A value of 1.95 is used, based on a typical range of 1.7 - 2.2 (Fg/dl) (U.S. EPA, 1996a).

Lead Concentration in Source (Pb_S). This is an average estimate of the amount of lead that is present in solder, and is measured in Fg/g. For PWB facilities, the lead concentration of solder was used instead of soil lead concentration. A value of 37,000 Fg/g (37 percent) was used, based on typical proportion of lead in tin/lead solder.

Biokinetic Slope Factor. The biokinetic slope factor (BKSF) relates the increase of typical adult blood-lead concentrations to the average daily lead uptake. The recommended default value is 0.4 Fg Pb/dl blood per Fg Pb absorbed/day. This value is derived from Pocock et al. (1983) and Sherlock et al. (1984) as cited by the U.S. EPA (1996a). (Both studies involved the amount of lead in tap water, and both predict higher blood-lead concentrations than expected in today's average U.S. population.)

Intake Rate. The use of this model is based on the assumption that solder could adhere to a workers' hands from routine handling, and be subsequently ingested. Although no studies were found that address the amount of lead that might be ingested by a worker handling solder specifically for a HASL process, Monsalve (1984) investigated hand soldering and pot tinning operations. Based on surface wipe samples and samples from worker's hands, a "conservative overestimate" of 30 Fg Pb per day ingested was calculated.[9] In addition to this intake rate (IRs), two values based on soil ingestion studies were used in the model: an average soil ingestion rate for adults, based on tracer studies, of 10 mg (Stanek et al., 1997) and the adult central estimate for soil ingestion of 50 mg from the EPA's *Exposure Factors Handbook* (U.S. EPA, 1997a).

Gastrointestinal Absorption Factor. The gastrointestinal absorption factor (AF_s) represents the absolute gastrointestinal absorption fraction for ingested lead in soil. This value was determined by multiplying the absorption factor for soluble lead by the bioavailiability of lead in soil. Three factors that were considered in determining this value are the variability of food intake, lead intake, and lead form/particle size (U.S. EPA, 1996a). The soil value of 0.12 is used due to the lack of information on the absorption of ingested metallic lead from tin-lead solder.

Exposure Frequency. This represents the exposure frequency (EF_s) to lead solder for a worker in a PWB manufacturing facility. This is the number of days that a worker is exposed to lead and is determined in days/year. The exposure frequency was increased from EPA's value of 219 (U.S. EPA, 1996a) to 250 days/year as a standard default value for occupational exposure.

Averaging Time. The averaging time (AT) is the total period of time that lead contact may occur. We used one year, or 365 days, as the AT.

Estimated Fetal/Maternal Blood Lead Concentration ($PbB_{fetal, 0.95}$). This represents the 95th percentile estimate of fetal/maternal blood-lead, and is measured in Fg/dl. These results are also based on the intake rate, as discussed above.

---

[9] Wipe samples from surfaces in the area ranged from 13 to 92 Fg Pb per 100 cm^2, and samples from solderer's hands ranged from 3 to 32 Fg Pb per 100 cm^2.

Individual Blood Lead Geometric Standard Deviation (GSD_i). The GSD_i is used to measure the inter-individual variability of blood-lead concentrations in a population whose members are exposed to the same non-residential environmental lead levels. A value of 1.8 is recommend for homogeneous populations and 2.1 for heterogeneous populations. The values for GSD_i are estimated in the population of concern. If this is not possible, the GSD_i is estimated using a surrogate population. Factors used to estimate the GSD_i are variability in exposure, biokinetics, socioeconomic/ethnic characteristics, degree of urbanization, and geographical location. Using these factors can cause a high degree of uncertainty (U.S. EPA, 1996a).

Fetal/Maternal Blood Lead Concentration Ratio ($R_{fetal/maternal}$). The $R_{fetal/maternal}$ describes the relationship between the umbilical cord and the maternal blood-lead concentration. The U.S. EPA Technical Working Group for Lead recommends a default value of 0.9 (dimensionless). This is based on two separate studies: one conducted by Goyer (1990) and the other by Graziano et al. (1990). This value was derived by comparing the fetal/maternal blood-lead concentrations at delivery. The 0.9 fetal/maternal blood-lead concentration can change due to physiological changes that include the mobilization of bone/lead stores during pregnancy, and iron and calcium deficiency due to poor nutrition (U.S. EPA, 1990; Franklin et al., 1995). The blood-lead concentration also can decrease in the later stages of pregnancy due to an increase in plasma volume, which dilutes the concentration, and an increased rate of transfer of lead to the placenta or to fetal tissue (Alexander and Delves, 1981).

Modeling Results. According to the results of the blood-lead solder model, incidental ingestion could result in blood-lead concentration for workers of 2 to 63 Fg/dL, and of 3.2 to 102 for a fetus (Table 3-17). Estimated blood-lead levels will be compared to federal health-based standards and guidlines in Section 3.4.

Table 3-17. Estimated Concentration of Lead in Adult and Fetal Blood from Incidental Ingestion of Lead in Tin/Lead Solder

Intake Rate (mg/day)	Ingestion Rate source, notes	$PbB_{adult, central}$ (Fg/dl)	$PbB_{fetal, 0.95}$ (Fg/dl)
0.03	"Conservative overestimate" based on surface wipe samples in hand-soldering operations (Monsalve, 1984).	2.0	3.2
10	Average soil ingestion rate for adults, based on tracer studies (Stanek et al., 1997).	14	23
50	Adult central estimate for soil ingestion (U.S. EPA, 1997a).	63	102

$PbB_{adult,0}$ = 1.95 Fg/dl; PbS = 37,000 Fg/g; BKSF = 0.4 Fg/dL; AF_s = 0.12; EF_s = 250 days/yr; AT = 365 days/yr; $GSD_{i, adult}$ = 1.8; and $R_{fetal/maternal}$ = 0.9

The intake rate is a major source of uncertainty in estimating exposure to workers from handling solder. A range of intake rates were used to provide a possible range of modeled blood-lead concentrations. These values provide bounding estimates only. It is expected that a smaller, but unknown, amount of solder would be ingested from a workers hands than the estimates that have been used here. Figure 3-9 shows the relationship between intake rate and blood-lead level for both an adult and fetus.

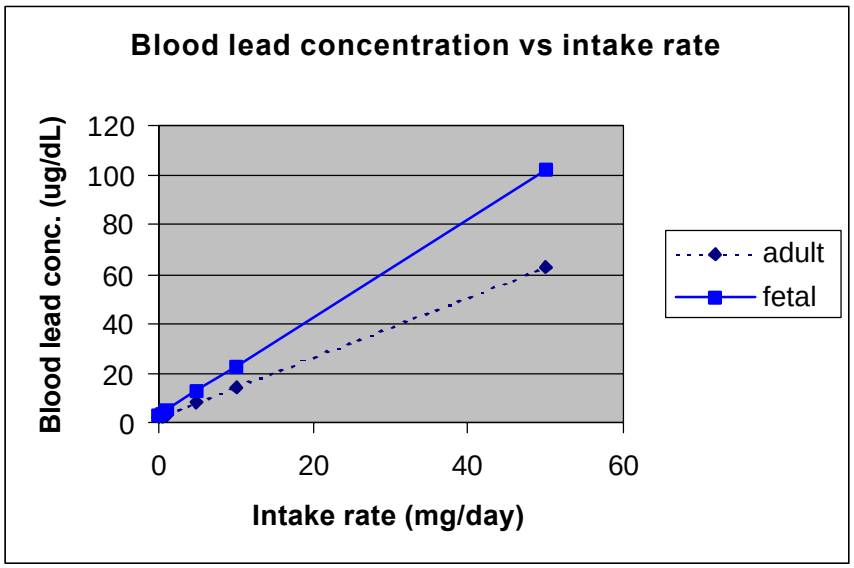


Figure 3-9. Relationship Between Intake Rate and Blood-Lead Level for Both Adult and Fetus

Monitoring Data. Lead monitoring data for HASL line operators were made available by one PWB manufacturer. For seven line operators monitored from 1986 to 1998, blood-lead levels ranged from 5 to 12 µg/dL.

<u>Population Exposure</u>

The equation for estimating ADDs from inhalation for a person residing near a facility is:

$$LADD = (Ca)\ (IR)\ (EF)\ (ED)/[(BW)\ (AT_{CAR})]$$
$$ADD = (Ca)\ (IR)\ (EF)\ (ED)/[(BW)\ (AT_{NC})]$$

where,

LADD	=	lifetime average daily dose (mg/kg-day) (for carcinogens)
ADD	=	average daily dose (mg/kg-day) (for non-carcinogens)
Ca	=	chemical concentration in air (mg/m^3) (from air dispersion modeling, described in Section 3.2.3)
IR	=	inhalation rate (m^3/day)
EF	=	exposure frequency (day/yr)
ED	=	exposure duration (years)
BW	=	average body weight (kg)
AT_{CAR}	=	averaging time for carcinogenic effects (days)
AT_{NC}	=	averaging time for non-carcinogenic chronic effects (days)

Table 3-18 presents values used for these parameters. Results for general population inhalation exposure are presented in Table 3-19.

Table 3-18. Parameter Values for Estimating Nearby Residential Inhalation Exposure

Parameter	Units	Value	Source of Data, Comments
Air Concentration (Ca)	mg/m^3	Modeled, varies by chemical and process type.	
Inhalation Rate (IR)	m^3/day	15	Total home exposures for adults based on activity patterns and inhalation rates (U.S. EPA, 1997a).
Exposure Frequency (EF)	days/yr	350	Assumes 2 wks per year spent away from home (U.S. EPA, 1991b).
Exposure Duration (ED)	years	30	National upper 90th percentile at one residence (U.S. EPA, 1990).
Body Weight (BW)	kg	70	Average value for adults (U.S. EPA, 1991b).
Averaging Time (AT) AT_{CAR} AT_{NC}	days	 25,550 10,950	 70 yrs x 365 days/year ED x 365 days/year

Table 3-19. Estimated Average Daily Dose for General Population Inhalation Exposure

Chemical [a]	ADD (mg/kg-day) [b]
HASL, Non-conveyorized	
Ethylene glycol monobutyl ether	5.25E-05
HASL, Conveyorized	
Ethylene glycol monobutyl ether	1.04E-04
Nickel/Gold, Non-conveyorized	
Aliphatic acid A	3.45E-05
Aliphatic acid E	4.56E-05
Inorganic metallic salt A (LADD)	5.99E-12
Nickel/Palladium/Gold, Non-conveyorized	
Aliphatic acid E	6.29E-05
OSP, Non-conveyorized	
Acetic acid	3.33E-05
OSP, Conveyorized	
Acetic acid	1.26E-04
Ethylene glycol	2.04E-05
Immersion Tin, Non-conveyorized	
Urea compound C	1.11E-04
Immersion Tin, Conveyorized	
Aliphatic acid D	2.99E-05
Cyclic amide	2.39E-05
Hydroxy carboxylic acid	4.03E-05
Urea compound C	2.72E-04

[a] Only inorganic metallic salt A plus those chemicals with an emission rate of at least 23 kg/year (44 mg/min) are listed (see Table 3-9). Immersion silver had no modeled emission rates above this cut-off.
[b] Unless otherwise noted.
Note: The numeric format used in this table is a form of scientific notation, where "E" replaces the " x 10^x". Scientific notation is typically used to present very large or very small numbers. For example, 1.2E-04 is the same as 1.2×10^{-4}, which is the same as 0.00012 in common decimal notation.

For lead, we did not calculate an ADD. The recommended approach for evaluating lead exposure to nearby residents is to apply an EPA model, the Integrated Exposure Uptake Biokinetic (IEUBK) Model for Lead in Children (U.S. EPA, 1994), to estimate blood-lead concentrations in children based on local environmental concentrations (air, soil/dust, drinking water, food, etc). The model includes defaults based on typical concentration levels in an urban setting (U.S. EPA, 1994). The default air concentration used in the IEUBK model is 0.1 µg/m^3, which is approximately the average 1990 U.S. urban air lead concentration (U.S. EPA, 1991b). This default/background concentration is 1,000 times higher than the ambient air concentration of 0.00009 µg/m^3 estimated from a HASL process (Section 3.2.3). The model was run at various air concentrations down to 0.001 µg/m^3 (the model does not accept air concentration values less than 0.001 µg/m^3). At those levels, such small changes to the air concentration result in no real difference in estimated blood-lead concentrations compared to results obtained from using the default values (i.e., typical urban levels of lead to which a child may be exposed). These results are shown in Table 3-20. Since the estimated air concentration of lead from HASL is so far below the default/background level in air, and the model could not discern any change in children's blood-lead levels from those at average urban air concentrations, it can be concluded that general population exposure to airborne lead from the HASL process is negligible.

Table 3-20. Children's Blood-Lead Results from the IEUBK Model at Various Lead Air Concentrations

Age (year)	Blood-Lead Results (µg/dL) at Various Airborne Lead Concentrations			
	1 (µg/m^3 in air)	0.1 (µg/m^3 in air)	0.01 (µg/m^3 in air)	0.001 (µg/m^3 in air)
0.5 - 1	4.2	4.1	4.1	4.1
1-2	4.7	4.5	4.5	4.5
2-3	4.4	4.2	4.2	4.2
3-4	4.2	4.0	4.0	4.0
4-5	3.6	3.4	3.4	3.4
5-6	3.2	3.0	2.9	2.9
6-7	2.9	2.7	2.7	2.7

Note: Model default values were used for concentrations in soil/dust, drinking water, and diet.

3.2.5 Uncertainty and Variability

Because of both the uncertainty inherent in the parameters and assumptions used in estimating exposure, and the variability that is possible within a population, there is no one number that can be used to describe exposure. In addition to data and modeling limitations, discussed in Sections 3.2.3, sources of uncertainty in assessing exposure include the following:

- Accuracy of the description of exposure setting: how well the model facility used in the assessment characterizes an actual facility; the likelihood of exposure pathways actually occurring (scenario uncertainty).
- Missing data and limitations of workplace practices data: this includes possible effects of any chemicals that may not have been included (e.g., minor ingredients in the

formulations; possible effects of side reactions in the baths which were not considered; and questionnaire data with limited facility responses).

- Estimating exposure levels from averaged data and modeling in the absence of measured, site-specific data.
- Data limitations in the Source Release Assessment: releases to land could not be characterized quantitatively, as discussed in Section 3.1.
- Chemical fate and transport model applicability and assumptions: how well the models and assumptions represent the situation being assessed, and the extent to which the models have been validated or verified (model uncertainty).
- Parameter value uncertainty, including measurement error, sampling error, parameter variability, and professional judgement.
- Uncertainty in combining pathways for an exposed individual.

A method typically used to provide information about the position an exposure estimate has in the distribution of possible outcomes is the use of exposure (or risk) descriptors. EPA's *Guidelines for Exposure Assessment* (U.S. EPA, 1992b) provides guidance on the use of risk descriptors, which include the following:

- *High-end*: approximately the 90th percentile of the actual (measured or estimated) distribution. This is a plausible estimate of individual risk for those persons at the upper end of the exposure distribution, and is not higher than the individual in the population who has the highest exposure.
- *Central tendency*: either an average estimate (based on average values for the exposure parameters) or a median estimate (based on 50th percentile or geometric mean values).
- *What-if:* represents an exposure estimate based on postulated questions (e.g., what if the air ventilation rates were ...), in this case, making assumptions based on limited data so that the distribution is unknown. If any part of the exposure assessment qualifies as a "what-if" descriptor, then the entire exposure assessment is considered "what-if."

This exposure assessment uses whenever possible a combination of central tendency (either an average or median estimate) and high-end (90th percentile)[10] assumptions, as would be used for an overall high-end exposure estimate. The 90th percentile is used for:

- hours per day of workplace exposure;
- exposure frequency (days per year);
- exposure duration in years (90th percentile for occupational and 95th percentile for residential exposures);
- time required for chemical bath replacement; and
- the time and frequency of filter replacements, conveyor equipment cleaning and chemical bath sampling (minutes per occurrence and number of occurrences per year).

Average values are used for:

[10] For exposure data from the PWB Workplace Practices Questionnaire, this means that 90 percent of the facilities reported a lower value, and ten percent reported a higher value.

- body weight;
- concentration of chemical in bath;
- frequency of chemical bath replacements;
- the number of baths in a given process; and
- bath size.

However, because some data, especially pertaining to bath concentrations and inhalation exposure are limited, and this exposure assessment does not apply to a specific facility, the entire exposure assessment should be considered "what-if."

3.2.6 Summary

This exposure assessment uses a "model facility" approach, with the goal of comparing the exposures and health risks of one surface finishing technology to the exposures and risks associated with switching to another technology. As much as possible, reasonable and consistent assumptions are used across alternatives. Data to characterize the model facility and exposure patterns for each surface finishing technology were aggregated from a number of sources, including PWB shops in the U.S., supplier data, and input from PWB manufacturers at project meetings. Thus, the model facility is not entirely representative of any one facility, and actual exposure (and risk) could vary substantially, depending on site-specific operating conditions and other factors.

Chemical exposures to PWB workers and the general population from day-to-day surface finishing line operations were estimated by combining information gathered from industry (PWB Workplace Practices Questionnaire, MSDSs, and other available information) with standard EPA exposure assumptions for inhalation rate, surface area of dermal contact, and other parameters. The pathways identified for potential exposure from surface finishing process baths were inhalation and dermal contact for workers, and inhalation contact only for the general populace living near a PWB facility.

The possible impacts of short-term exposures to high levels of hazardous chemicals addressed have not been addressed, such as those that could occur from chemical fires, spills, or other episodic releases.

Inhalation exposure could occur by breathing air containing vapor or aerosol-phase chemicals from the surface finishing process line. Inhalation exposures to workers are estimated only for non-conveyorized lines; inhalation exposure to workers from conveyorized surface finishing lines was assumed to be much lower because the lines are typically enclosed and vented to the outside.[11]

---

[11] Inhalation exposures for conveyorized process configurations were initially assumed to be negligible, and are not presented separately here. Some inhalation exposure is possible, however, during sampling and bath replacement, when the baths are opened for a short period of time. After characterizing risks from inhalation for non-conveyorized lines, inhalation exposures and risks were estimated for conveyorized lines. No chemical exposures from inhalation resulted in risks above concern levels for conveyorized lines.

The daily intake for inhalation exposure to workers was calculated by first modeling chemical emissions from surface finishing baths with three air-transport mechanisms: liquid surface diffusion (desorption), bubble desorption, and aerosol generation and ejection. These chemical emission rates were combined with information from the PWB Workplace Practices Questionnaire regarding process room size and air turnover rate to estimate an average indoor air concentration for each chemical for the process area. General room ventilation was assumed, although the majority of shops have local ventilation on chemical tanks. An uncertainty and sensitivity analysis of the air transport models (U.S. EPA, 1998b) suggests that the air turnover (ventilation) rate assumption greatly influences the estimated air concentration in the process area because of its large variability.

Inhalation exposure to the human population surrounding PWB plants was estimated using the Industrial Source Complex - Long Term (ISCLT) air dispersion model. The modeled air concentrations of each contaminant were determined at 100 meters radially from a PWB facility, and the highest estimated air concentration was used. This model estimates air concentration from the process bath emission rates. These emissions were assumed to be vented to the ambient environment at the rate emitted from the baths, for all process alternatives. Inhalation exposures estimated for the public living 100 meters away from a PWB facility were very low (approximately 10,000 times lower than occupational exposures).

Dermal exposure could occur when a worker's skin comes in contact with the bath solution while dipping boards, adding replacement chemicals, etc. Although the data suggest that surface finishing line operators often do wear gloves, it was assumed in this evaluation that workers do not wear gloves to account for the fraction that do not. Otherwise, dermal exposure is expected to be negligible. For dermal exposure, the duration of contact for workers was obtained from the PWB Workplace Practices Questionnaire information. A permeability coefficient (rate of penetration through skin) was estimated for organics, and a default rate assumption was used for inorganics. Another source of uncertainty in dermal modeling lies with the assumed duration of contact. For non-conveyorized processes, the worker is assumed to have potential dermal contact for the entire time spent in the surface finishing area, divided equally among the baths. [This does not mean that a worker has both hands immersed in a bath for that entire time; but that the skin is in contact with bath solution (i.e., the hands may remain wet from contact).] This assumption may result in an overestimate of dermal exposure.

Assumptions and parameter values used in these equations are presented throughout this section. Exposure estimates are based on a combination of high end (90th percentile)[12] and average values, as would be used for a high-end exposure estimate. The 90th percentile was used for hours per day of workplace exposure, exposure frequency (days per year), exposure duration in years (90th percentile for occupational and 95th percentile for residential exposures), and the time and frequency of chemical bath and filter replacements, conveyor equipment cleaning and chemical bath sampling (minutes per occurrence and number of occurrences per year) and estimated workplace air concentrations. The average value was used for body weight,

[12] For exposure data from the PWB Workplace Practices Questionnaire, this means that 90 percent of the facilities reported a lower value, and ten percent reported a higher value.

concentration of chemical in bath, and the number of baths in a given process. However, because some data, especially pertaining to bath concentrations and inhalation exposure, are limited and this exposure assessment does not apply to a specific facility, the entire exposure assessment should be considered "what-if."

As a "what if" exposure assessment, this evaluation is useful for comparing alternative surface finishing processes to the baseline (non-conveyorized HASL) on a consistent basis. It is also useful for risk screening, especially if actual facility conditions meet those that were assumed (i.e., given similar production rates, what chemicals may be of concern if workers do not wear gloves; what chemicals may be of concern if ventilation rates are similar to those assumed?). Finally, this assessment points to the importance of preventing dermal contact by using gloves, and of proper ventilation.

Surface water concentrations were estimated for bath constituents, with a focus on those constituents that are not typically targeted for pre-treatment by PWB facilities. This was done for conveyorized lines by estimating the amount of chemical going to wastewater from routine bath replacement, and for non-conveyorized lines by estimating the amount of chemical going to wastewater from bath replacement plus an estimated amount due to drag-out from the baths to rinse water. These amounts were then included in a stream dilution model, and if estimated surface water concentrations exceeded CCs for aquatic life, the model was refined using estimated POTW treatment efficiencies.

These exposure results, taken by themselves, are not very meaningful for evaluating surface finishing alternatives; it is the combination of hazard (Section 3.3) and exposure that defines risk. Quantitative exposure estimates are combined with available hazard data in the risk characterization (Section 3.4) for risk screening and comparison of the surface finishing process configurations.

3.3 HUMAN HEALTH AND ECOLOGICAL HAZARDS SUMMARY

This section presents a summary of the human health and ecological hazards data that are used in the risk characterization. This information is summarized from toxicity profiles prepared for chemicals identified as constituents in the baths for the surface finishing technologies evaluated. Table 2-1 lists these chemicals and identifies the surface finishing process or processes in which these chemicals are used. HASL is the predominant method now used for surface finishing. Section 2.1.4 includes more detailed information on bath constituents and concentrations. Throughout this section, proprietary chemicals are identified only by generic name, with limited information presented, in order to protect proprietary chemical identities.

3.3.1 Carcinogenicity

The potential for a chemical to cause cancer is evaluated by weight-of-evidence (WOE) classifications and by cancer potency factors, typically determined from laboratory or epidemiological studies. There are a large number of chemicals in commerce, however, (approximately 15,000 non-polymeric chemicals produced in amounts greater than 10,000 lb/year), and many of these chemicals have not yet been tested or assigned carcinogenicity classifications. The WOE classifications referenced in this risk assessment are defined below.

In assessing the carcinogenic potential of a chemical, EPA classifies the chemical into one of the following groups, according to the WOE from epidemiologic, animal and other supporting data, such as genotoxicity test results:

- Group A: Human Carcinogen (sufficient evidence of carcinogenicity in humans).
- Group B: Probable Human Carcinogen (B1 - limited evidence of carcinogenicity in humans; B2 - sufficient evidence of carcinogenicity in animals with inadequate or lack of evidence in humans).
- Group C: Possible Human Carcinogen (limited evidence of carcinogenicity in animals and inadequate or lack of human data).
- Group D: Not Classifiable as to Human Carcinogenicity (inadequate or no evidence).
- Group E: Evidence of Non-Carcinogenicity for Humans (no evidence of carcinogenicity in adequate studies).

EPA has proposed a revision of its guidelines that would eliminate the above discrete categories while providing a more descriptive classification.[13]

The International Agency for Research on Cancer (IARC) uses a similar WOE method for evaluating potential human carcinogenicity based on human data, animal data, and other supporting data. A summary of the IARC carcinogenicity classification system includes:

---

[13] The "Proposed Guidelines for Carcinogen Risk Assessment" (U.S. EPA, 1996b) proposes the use of WOE descriptors, such as "Likely" or "Known," "Cannot be determined," and "Not likely," in combination with a hazard narrative, to characterize a chemical's human carcinogenic potential, rather than the classification system described above.

- Group 1: Carcinogenic to humans.
- Group 2A: Probably carcinogenic to humans.
- Group 2B: Possibly carcinogenic to humans.
- Group 3: Not classifiable as to human carcinogenicity.
- Group 4: Probably not carcinogenic to humans.

Both of these classification schemes represent judgements regarding the likelihood of human carcinogenicity. Table 3-21 lists all surface finishing chemicals that have been classified by EPA or IARC. The National Toxicology Program (NTP) is an additional source used to classify chemicals, but its classifications are based only on animal data from NTP studies.

Table 3-21. Available Carcinogenicity Information

Chemical Name [a]	Cancer Slope Factor (Inhalation Unit Risk) $(\mu g/m^3)^{-1}$	Cancer Slope Factor (Oral) $(mg/kg\text{-}day)^{-1}$	Comments/Classification
Known, probable, or possible human carcinogens			
Inorganic metallic salt A	Not reported [b]	ND	Human carcinogen or probable human carcinogen. [c]
Sulfuric acid [d]	ND	ND	IARC Group 1 [e] (IARC 1992).
Lead	ND	ND	EPA Class B2 [f] (IRIS, 1999); IARC Group 2B [g] (IARC, 1987).
Thiourea	ND	ND	IARC Group 2B [g] (IARC 1974).
Urea compound B	ND	ND	Possible human carcinogen. [c]
Other weight-of-evidence (WOE) or other information available			
Nickel sulfate	ND	ND	Nickel refinery dust is IARC Group 1 [e] (IARC, 1990). No assessment available for soluble salts of nickel.
Copper ion, Copper salt, and Copper sulfate pentahydrate	ND	ND	Copper is EPA Class D [h] (IRIS, 1998).
Hydrochloric acid	ND	ND	IARC Group 3 [i] (HSDB, 1998), excess lung and laryngeal cancer occurred in workers exposed to HCL mist; however, many of these cases involved exposure to acid mixtures (Perry et al., 1994).
Hydrogen peroxide	ND	ND	IARC Group 3 [i] (IARC, 1987), stomach tumors occurred in mice (Ito et al., 1981).
Vinyl polymer	ND	ND	Not classifiable according to EPA and/or IARC. [c]
Silver nitrate	ND	ND	Silver is EPA Class D [h] (IRIS, 1998).

Chemical Name [a]	Cancer Slope Factor (Inhalation Unit Risk) $(\mu g/m^3)^{-1}$	Cancer Slope Factor (Oral) $(mg/kg\text{-}day)^{-1}$	Comments/Classification
Silver salt	ND	ND	Not classifiable according to EPA and/or IARC. [c]
Stannous methane sulfonic acid	ND	ND	EPA Class D [h] (U.S. EPA, 1987a).
Tin chloride	ND	ND	EPA Class D [h] or IARC Group 3[i] (U.S. EPA, 1987a).
Palladium chloride	ND	ND	No classification; mice administered palladium in drinking water had a significantly higher incidence of malignant tumors (Schroeder and Mitchener, 1971).
Propionic acid	ND	ND	No classification; tumors in forestomach of rats (Clayson et al., 1991).

[a] Only those chemicals with available data or classifications are listed.
[b] The unit risk value is not reported here to protect confidential ingredient identity.
[c] Specific EPA and/or IARC groups not reported in order to protect proprietary chemical identities.
[d] Classification pertains to the strong inorganic acid mist.
[e] IARC Group 1: Human Carcinogen.
[f] EPA Class B2: Probable Human Carcinogen (sufficient evidence of carcinogenicity in animals with inadequate or lack of evidence in humans).
[g] IARC Group 2B: Possibly carcinogenic to humans.
[h] EPA Class D: Not classifiable as to human carcinogenicity.
[i] IARC Group 3: Not classifiable as to its carcinogenicity to humans.
ND: No Data, a cancer slope factor has not been determined for this chemical.

For carcinogenic effects, there is presumably no level of exposure that does not pose a small, but finite, probability of causing a response. This type of mechanism is referred to as "non-threshold." When the available data are sufficient for quantification, EPA develops an estimate of the chemical's carcinogenic potency expressed as a "slope factor." The slope factor (q_1*) is a measure of an individual's excess risk or increased likelihood of developing cancer if exposed to a chemical (expressed in units of $[mg/kg\text{-}day]^{-1}$). More specifically, q_1* is an approximation of the upper bound of the slope of the dose-response curve using the linearized, multistage procedure at low doses. "Unit risk" is an equivalent measure of potency for air or drinking water concentrations and is expressed as the upper bound excess lifetime cancer risk per Fg/m^3 in air, or as risk per Fg/L in water, for continuous lifetime exposures. (Unit risk is simply a transformation of slope factor into the appropriate scale.) Slope factors and unit risks can be viewed as quantitatively derived judgements of the magnitude of carcinogenic effect. These estimates will continue to be used whether the current EPA WOE guidelines are retained or the new proposals are adopted. Their derivation, however, may change for future evaluations.

EPA risk characterization methods require a slope factor or unit risk to quantify the upper bound, excess cancer risk from exposure to a known or suspected carcinogen. There is only one chemical, inorganic metallic salt A, with a slope factor. Therefore, this is the only chemical for which cancer risk can be characterized (see Section 3.4, Risk Characterization).

3.3.2 Chronic Effects (Other than Carcinogenicity)

Adverse effects, other than cancer and gene mutations, are generally assumed to have a dose or exposure threshold. Therefore, a different approach is used to evaluate toxic potency and risk for these "systemic effects." Systemic toxicity means an adverse effect on any organ system following absorption and distribution of a toxicant to a site in the body distant from the toxicant's entry point. A reference dose (RfD) is an estimate (with uncertainty spanning perhaps an order of magnitude) of the daily exposure through ingestion to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious non-cancer effects during a lifetime (in mg/kg-day). Similarly, a reference concentration (RfC) is an estimate (with uncertainty spanning perhaps an order of magnitude) of the daily inhalation exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious non-cancer effects during a lifetime (in mg/m^3) (Barnes and Dourson, 1988). RfDs and RfCs also can be derived from developmental toxicity studies. However, this was not the case for any of the surface finishing chemicals evaluated. RfDs and RfCs are derived from EPA peer-reviewed study results (for values appearing in EPA's Integrated Risk Information System [IRIS]), together with uncertainty factors regarding their applicability to human populations. Table 3-22 presents a summary of the available RfC and RfD information obtained from IRIS and EPA's Health Effects Assessment Summary Tables (HEAST) for non-proprietary chemicals. An additional proprietary chemical has an RfC and an RfD; these data are not reported in order to protect the identity of the confidential ingredient.

Table 3-22. Summary of RfC and RfD Information Used in Risk Characterization for Non-Proprietary Ingredients

Chemical Name [a]	Inhalation RfC [b] (mg/m^3)	Comments [c] (Inhalation)	Oral/Dermal RfD [b] (mg/kg/day)	Comments [c] (Oral/Dermal)
Ammonium chloride, Ammonium hydroxide	0.1 [d] (IRIS)	Ammonia: decreased lung function (IRIS, 1999).	0.2 [e] (IRIS)	Ammonium sulfamate: rats, drinking water, 90 days, decreased body weight (Gupta et al., 1979; IRIS, 2000).
Ethylenediamine	ND		0.02 (HEAST)	Rats, 3 months, increased heart weight and hematologic changes (U.S. EPA, 1997b).
Ethylene glycol	ND		2 (IRIS)	Rats, kidney toxicity (IRIS, 1999).
Ethylene glycol monobutyl ether	13 (IRIS)	Changes in red blood cell count (IRIS, 1999).	0.5 (IRIS)	Changes in mean corpuscular volume (IRIS, 1999).
Hydrochloric acid	0.02 (IRIS)	Rats, hyperplasia of nasal mucosa, larynx, and trachea (IRIS, 1998).	ND	
Lead [f]	ND: Some health effects of lead, particularly changes in the levels of certain blood enzymes and in aspects of children's neurobehavioral development, may occur at blood- lead levels so low as to be essentially without a threshold. EPA considers it inappropriate to develop an RfD for inorganic lead (IRIS, 2000).			
Nickel sulfate	0.00053 [g] (MRL)	Rats, lung inflammation (ATSDR, 1997a).	0.02 (IRIS) (soluble salts of nickel)	Rats, decreased body and organ weight (IRIS, 1998).
Phosphoric acid	0.01 (IRIS)	Rats, histologic lesions in tracheobronchiolar region (IRIS, 1998).	221 (ADI)	(U.S. EPA, 1997c; WHO, 1974).
Potassium gold cyanide	ND		0.02 [h] (IRIS)	Cyanide: rats, 2 year, weight loss, thyroid effects and myelin degeneration, (IRIS, 1998).
Silver nitrate	ND		0.005 [i] (IRIS)	Silver-argyria (benign but permanent bluish-gray discoloration of skin) (Gaul and Staud, 1935).

Chemical Name [a]	Inhalation RfC [b] (mg/m^3)	Comments [c] (Inhalation)	Oral/Dermal RfD [b] (mg/kg/day)	Comments [c] (Oral/Dermal)
Stannous methane sulfonic acid, Tin, and Tin chloride	ND		0.6 [j] (HEAST)	Tin and inorganic compounds: rats, 2 year, histopathologic study (U.S. EPA, 1997b).
Sulfuric acid	0.07 (HEAST)	Acceptable air concentration for humans based on respiratory effects (U.S. EPA, 1997b).	ND [k]	

[a] Only non-proprietary chemicals with available data are listed.
[b] The type of value is noted in parentheses:
IRIS: EPA-derived and peer-reviewed values listed in the Integrated Risk Information System. IRIS values are preferred and used whenever available.
HEAST: EPA-derived RfD or RfC listed in the Health Effects Assessment Summary Tables. These values have not undergone the same level of review as IRIS values.
ADI: Acceptable daily intake, developed by the World Health Organization (WHO).
MRL: Minimal risk level, developed by the Agency for Toxic Substances and Disease Registry (ATSDR) in a manner similar to EPA-derived values.
[c] Comments may include exposure route, test animal, duration of test, effects, and source of data.
[d] In the risk calculations, conversion factors are used based on the molecular weights of ammonia, ammonium chloride, and ammonium hydroxide.
[e] In the risk calculations, conversion factors are used based on the molecular weights of ammonium sulfamate, ammonium chloride, and ammonium hydroxide.
[f] More information on lead is presented in Section 3.4.6 of the Risk Characterization.
[g] Value given represents a chronic inhalation minimum risk level (MRL). Although the test substance was nickel sulfate hexahydrate, the reported value is 0.0002 mg/m^3 *as nickel.* This was converted in the risk calculations based on the molecular weights of nickel and nickel sulfate.
[h] A conversion factor is used in the risk calculations based on molecular weights of cyanide and potassium gold cyanide. This RfD is only relevant to the oral route; potassium gold cyanide is expected to be chemically stable except under highly acidic conditions such as those found in the stomach (pH 1-2).
[i] A conversion factor is used in the risk calculations based on molecular weights of silver and silver nitrate.
[j] Conversion factors are used in the risk calculations based on molecular weights of tin, tin chloride, and stannous methane sulfonic acid.
[k] Although chronic toxicity values have not been established, repeated skin contact with low concentrations of sulfuric acid causes skin dessication, ulceration of the hands, and chronic inflammation around the nails.
ND: No data, RfC or RfD not available.

When an RfD or RfC was not available for a chemical, other toxicity values were used, preferably in the form of a “no-observed-adverse-effect level” (NOAEL) or “lowest-observed-adverse-effect level” (LOAEL). These toxicity values were obtained from the published scientific literature, as well as unpublished data submitted to EPA on chemical toxicity in chronic or subchronic studies. Typically, the lowest NOAEL or LOAEL value from a well-conducted study was used. (If study details were not presented or the study did not appear to be valid, the reported NOAEL/LOAELs were not used.) But, unlike the majority of RfD/RfCs, NOAEL/LOAELs have not received EPA peer-review of the studies on which the values are based, and uncertainty factors have not been considered.

The LOAEL is the lowest dose level in a toxicity test at which there are statistically or biologically significant increases in frequency or severity of adverse effects in the exposed population over its appropriate control group (in mg/kg-day, or mg/m^3 for inhalation). The NOAEL is the highest dose level in a toxicity test at which there is no statistically or biologically significant increase in the frequency or severity of adverse effects in the exposed population over its appropriate control (in mg/kg-day, or mg/m^3 for inhalation). LOAEL values are presented only where NOAELs were not available. Table 3-23 presents a summary of the available NOAEL and LOAEL values for non-proprietary chemicals. Chemicals having potential developmental toxicity were identified based on the data provided in the toxicity profiles. These data are summarized in Table 3-24. An additional 5 proprietary chemicals have inhalation NOAELs or LOAELs, and 13 have oral NOAELs or LOAELs; these data are not reported in order to protect the identity of confidential ingredients.

Neither RfDs/RfCs nor LOAELs/NOAELs were available for some chemicals in each surface finishing process alternative. For these chemicals, no quantitative estimate of risk could be calculated. EPA's Structure-Activity Team (SAT)[14] has reviewed the chemicals without relevant toxicity data to determine if these chemicals are expected to present a toxicity hazard. This review was based on available toxicity data on structural analogues of the chemicals, expert judgement, and known toxicity of certain chemical classes and/or moieties. Chemicals received a concern level rank of high, moderate-high, moderate, moderate-low, or low. Results of the SAT evaluation are presented in Table 3-25. A summary of toxicity data available for the chemicals is presented in Table 3-26.

[14] The SAT is a group of expert scientists at EPA who evaluate the potential health and environmental hazards of new and existing chemicals.

Table 3-23. NOAEL/LOAEL Values Used in Risk Characterization for Non-Proprietary Ingredients

Chemical Name [a]	Inhalation NOAEL/ LOAEL [b] (mg/m^3)	Comments [c] (Inhalation)	Oral/Dermal NOAEL/ LOAEL [b] (mg/kg-day)	Comments [c] (Oral/Dermal)
Acetic acid	ND [d]		195 (N)	Rats, drinking water, 2-4 months, no deaths (Sollmann, 1921).
Copper ion, Copper sulfate pentahydrate	0.6 (L) [e]	Cupric chloride: rabbits, 6 hrs/day, 5 days/wk for 4-6 wks, increase in lung tumors (U.S. Air Force, 1990).	0.056 (L) [f]	Copper: humans, 1.5 years, abdominal pain and vomiting (ATSDR, 1990a).
Ethylenediamine	145 (N) [g]	Rats, 7 hrs/day, 5 days/wk for 30 days, depilation (Pozzani and Carpenter, 1954).	NA	RfD is available (Table 3-22).
Ethylene glycol	31 (L)	Humans, 20-22 hrs/day for 30 days, respiratory irritation, headache, and backache (ATSDR, 1997b).	NA	RfD is available (Table 3-22).
Hydrogen peroxide	79 (L) [h]	Mouse, 6 weeks, 7/9 died (U.S. EPA, 1988a).	290 (L)	Mice, 35 weeks, liver, kidney, and GI effects (IARC, 1985).
Lead [i]	10 µg/dL in blood	Children, level concern in blood (CDC, 1991).	10 µg/dL in blood	Children, level concern in blood (CDC, 1991).
Propionic acid	23 (TClo) [j]	Rats, subchronic exposure (RTECS, 1998).	150 (N)	Rats, diet, lesions in GI tract (BASF, 1987; Mori, 1953; Harrison et al., 1991; Rodrigues et al., 1986).

[a] Only non-proprietary chemicals with available data are listed.
[b] (N) = NOAEL; (L) = LOAEL. When more than one NOAEL and/or LOAEL was available, only the lowest available NOAEL or LOAEL was used and is listed here. If both NOAEL and LOAEL data are available, the NOAEL is used and is listed here. If a chronic NOAEL or LOAEL was not available, other values (e.g., from shorter-term studies) were used as noted.
[c] Comments may include exposure route, test animal, duration of test, effects, and source of data.
[d] Although health effects have been noted in workers and laboratory tests from inhalation exposure to acetic acid, no appropriate chronic inhalation toxicity value is available.
[e] Conversion factors are used in the risk calculations based on molecular weights of cupric chloride, copper ion, and copper sulfate pentahydrate.
[f] A conversion factor is used in the risk calculations based on molecular weights of copper and copper sulfate pentahydrate.
[g] Not considered a "chronic" value because the study duration was less than 90 days. The value was used, however, as the best available value, rather than leaving a data gap for a chemical where adverse health effects have been noted.
[h] In the absence of other data, this value will be used as a LOAEL.
[i] More information on lead is presented in Section 3.4.5 of the Risk Characterization.
[j] TClo = The lowest dose of a chemical that is expected to cause a defined toxic effect. In the absence of other data, this is used as a LOAEL.
ND: No Data. A NOAEL or LOAEL was not available for this chemical.
NA: Not applicable. A NOAEL or LOAEL is not required because an RfC or RfD is available for this chemical.

Table 3-24. Developmental Toxicity Values Used in Risk Characterization for Non-Proprietary Ingredients

Chemical [a]	Developmental Inhalation NOAEL / LOAEL (mg/m^3) [b]	Comments [c] (Inhalation)	Developmental Oral/Dermal NOAEL / LOAEL [b] (mg/kg-day)	Comments [c] (Oral/Dermal)
Ammonium chloride	ND		1,691 (N)	Mice, drinking water, after gd [d] 7, no congenital effects (Shepard, 1986).
Copper ion, Copper sulfate pentahydrate	ND		3 (L) [e]	Copper: mink, diet, increased mortality (Aulerich et al., 1982; ATSDR, 1990a).
Ethylenediamine	ND		470 (L)	Rats, gd 6-15 diet, resorption, impaired growth, missing or shortened innominate arteries, and delayed ossification of cervical vertebrae or phalanges (DePass et al., 1987).
Ethylene glycol	150 (N)	Rats and mice, 6 hr/day, gd 6-15, fetal malformations in mice (exencephaly, cleft palate, and abnormal rib and facial bones) (Shell Oil, 1992; Union Carbide, 1991).	500 (N)	Rats, gd 6-15, gavage, teratogenic effects at higher dose levels. NOAEL based on developmental effects (Bushy Run, 1995).
Ethylene glycol monobutyl ether	ND		100 (N)	Rats, gd 9-11, oral gavage, developmental toxicity (Sleet et al., 1989).

[a] Only those chemicals with available data are listed.
[b] (N) = NOAEL; (L) = LOAEL. When more than one NOAEL and/or LOAEL was available, only the lowest available NOAEL or LOAEL was used and is listed here. If both NOAEL and LOAEL data are available, the NOAEL is used and is listed here.
[c] Comments may include test effects, test animal, duration during time of gestation, exposure route, and source of data.
[d] gd = gestation day.
[e] Conversion factors are in the risk calculations based on molecular weights of copper ion and copper sulfate pentahydrate.
ND: No data available.

Table 3-25. Summary of Health Effects Information
(from Structure-Activity Team Reports)

Chemical	SAT Health Effects Pertaining to Dermal or Inhalation Exposure	Overall Concern Level
1,4-Butenediol	Expect good absorption via all routes of exposure. The primary alcohols will oxidize to the corresponding acids (fumaric or maleic) via aldehydes. There is concern for mutagenicity as an unsaturated aldehyde. This compound is expected to be irritating to the lungs and other mucous membranes. Effects on the liver and kidney and neurotoxicity (sedation) are also expected.	Low moderate
Aliphatic acid B	Expect no absorption by skin, but expect absorption by lungs and GI tract. Related compound is reported to be positive in a dominant lethal assay. Uncertain concerns for developmental toxicity and kidney toxicity. Some concern for irritation.	Moderate
Aliphatic dicarboxylic acid A	Absorption is expected to be poor through the skin and good through the lungs and GI tract. As a free acid, this compound is expected to be irritating to all exposed tissues. A mixture of acids containing this compound was tested in rats. The mixture was negative for mutagenicity but caused signs of neurotoxicity. A mixture containing the dimethyl ester of this compound was tested in acute inhalation and dermal studies because blurring of vision had been reported in humans. An increase in the anterior chamber depth in the eye was seen following inhalation and dermal exposure. This could be an indication of changes in circulation in the eye which could lead to glaucoma. A mixture of the same compounds was tested in a 1-generation reproduction study in rats via inhalation, showing a decrease in postnatal pup weight and irritation of the respiratory tract in parental animals.	Low moderate
Alkylalkyne diol	Expect poor absorption via all routes of exposure. This compound may be irritating to the eyes, lungs, and mucous membranes and cause defatting of the skin which can lead to skin irritation. There is uncertain concern for neurotoxicity and liver and kidney effects.	Low
Alkylamino acid A	Absorption is expected to be poor through the skin and good through the lungs and GI tract. This compound is expected to chelate metals such as calcium, magnesium, and zinc. Based on its potential to chelate calcium, there is concern for developmental toxicity, inhibition of blood clotting, and effects on the nervous system and muscles including effects on the heart. Chelation of zinc may cause immunotoxicity (retardation of wound healing). This compound is expected to be irritating to all exposed tissues and may be a dermal sensitizer. A salt of this compound caused developmental effects in rats. There is concern for oncogenicity and kidney toxicity. There is also a potential for male reproductive effects. This compound may be mutagenic.	Low moderate

Chemical	SAT Health Effects Pertaining to Dermal or Inhalation Exposure	Overall Concern Level
Alkylaryl imidazole	Expect good absorption via the lungs and GI tract. Absorption of the neat material is expected to be nil through the skin; however, absorption is expected to be moderate through the skin when in solution. There is concern for developmental toxicity and neurotoxicity.	Low moderate
Alkylaryl sulfonate	Absorption is expected to be nil through the skin and poor through the lungs and GI tract. There is uncertain concern for irritation to mucous membranes.	Low
Alkylimine dialkanol	Absorption is expected to be poor through the skin, moderate through the GI tract, and good through the lungs. This compound is a moderate to severe skin irritation and a severe eye irritant. It has low acute toxicity. Another analog was tested in a subchronic gavage study in rats and dogs. Cataracts were noted in rats, stomach and lung lesions consistent with irritation were seen, and liver effects were seen in female dogs. There is concern for developmental toxicity. There is little concern for mutagenicity by analogy to a similar compound.	Moderate
Amino acid salt	Absorption is expected to be nil through the skin and good through the lungs and GI tract. There is uncertain concern for developmental toxicity. This compound is an amino acid analog and may be an antimetabolite. This chemical is also expected to be an irritant to moist tissues such as the lungs and respiratory tract.	Low moderate
Ammonia compound B	Absorption is expected to be nil through the skin and good through the lungs and GI tract. This material will be irritating and/or corrosive to all exposed tissues. The degree of irritation is a function of the concentration. Fluoride causes dental fluorosis (pitting and discoloration of the teeth) and crippling skeletal malformations. Additional concerns for this compound are neurotoxicity, mutagenicity, and possibly developmental toxicity. The uncertain concern for developmental toxicity is by analogy to ammonium chloride.	Moderate high
Aryl phenol	Expect moderate absorption by all routes. Moderate concerns for oncogenicity due to positive data; low moderate concerns for mutagenicity due to positive Ames and mouse lymphoma assays; low moderate concerns for renal effects and developmental and reproductive toxicity due to presence of phenolic moiety.	Moderate
Bismuth compound	Absorption is expected to be nil through the skin and good through the lungs and GI tract. In water, this compound will cause irritation of all moist tissues. There is also concern for neurotoxicity and possibly developmental toxicity. There is no concern for mutagenicity based on negative results for DNA damage. This compound has a relatively high oral LD50. [a]	Moderate, based on irritation
Citric acid	Expect poor absorption by skin, but expect absorption by lungs and GI tract. No health concerns identified.	Low

Chemical	SAT Health Effects Pertaining to Dermal or Inhalation Exposure	Overall Concern Level
Ethoxylated alkylphenol	Absorption is expected to be poor through the skin, moderate through the GI tract, and good through the lungs. As a surfactant, this compound may cause lung effects if inhaled. This compound is expected to be a severe and persistent eye irritant. Eye irritation is of particular concern because this type of compound can anesthetize the eye so an individual will not feel pain and rinse the material out of the eye. It is also expected to be irritating to the lungs. Possible signs of lung irritation (lung discoloration) were noted with a similar chemical tested in an acute inhalation study in rats. There is uncertain concern for reproductive effects and immunotoxicity. By analogy to a related compound, this chemical may be an endocrine disrupter. Liver and kidney effects were noted in rats with a structural analog. Myocardial degeneration has also been noted in several species with related compounds. Developmental toxicity as demonstrated by skeletal changes has been noted with dermal and oral exposure.	Low moderate
Fatty amine	Absorption is expected to be poor through the skin, moderate through the GI tract, and good through the lungs. This compound is expected to be a strong irritant and/or corrosive to exposed tissues. A similar compound was reported to be a moderate skin irritant and a severe eye irritant. Oleyl amine is a severe irritant. There is also concern for lung effects if inhaled. Another analog was tested in a subchronic gavage study in rats and dogs. Cataracts were noted in rats, stomach and lung lesions consistent with irritation were seen, and liver effects were seen in female dogs. There is concern for developmental toxicity. There is little concern for mutagenicity by analogy to a similar compound.	Moderate
Hydroxyaryl acid	Absorption is expected to be poor through the skin and good through the lungs and GI tract. There is concern for developmental toxicity and uncertain concern for effects on blood clotting (slower time for clotting). This compound is expected to have estrogenic activity. It has low acute toxicity. It may also cause neurotoxicity and hypersensitivity. There is some concern for mutagenicity.	Moderate
Hydroxyaryl sulfonate	Absorption is expected to be nil through the skin and good through the lungs and GI tract. There is concern for developmental toxicity. This compound is also expected to be an irritant (the free acid is corrosive to the eyes) and may cause neurotoxicity.	Low moderate
Maleic acid	Expect no absorption by skin, but expect absorption by lungs and GI tract. Maleic acid is reported to be negative in a NTP Ames assay. According to Merck this chemical is strongly irritating to corrosive.	Moderate

Chemical	SAT Health Effects Pertaining to Dermal or Inhalation Exposure	Overall Concern Level
Malic acid	Expect no absorption by skin, but expect absorption by lungs and GI tract. Concerns for mild irritation to skin and eyes.	Low moderate
Potassium compound	Absorption/corrosion by all routes. Concentrated form is corrosive to all tissues. Dilute form may be irritating. No other health concerns identified.	High for concentrated form only, otherwise low
Potassium peroxymonosulfate	Absorption is expected to be nil through the skin and good through the lungs and GI tract. The peroxymonosulfate moiety is reactive with moisture (oxidizing agent). This material will be an irritant as a concentrated solution.	Moderate
Quaternary alkylammonium chlorides	Absorption is expected to be poor through the skin, moderate through the GI tract, and good through the lungs. This chemical is expected to be a strong irritant and/or corrosive to all exposed tissues. It is also expected to be neurotoxic. There is also concern for lung effects if inhaled. There is concern for developmental toxicity as an ethanolamine derivative. This compound is expected to be in the moderately toxic range for acute toxicity.	Moderate
Sodium benzene sulfonate	Absorption is expected to be nil through the skin and good through the lungs and GI tract. There is concern for methemoglobinemia, neurotoxicity, and developmental toxicity. Serious brain damage was noted in a 2-week inhalation study with a related compound. There is uncertain concern for oncogenicity. This compound is reported to be negative in the Ames assay. It is expected to be irritating to mucous membranes and the upper respiratory tract.	Moderate concern
Sodium hypophosphite; Sodium hypophosphite monohydrate	Absorption is expected to be nil through the skin and good through the lungs and GI tract. This compound has low acute toxicity. It is irritating to mucous membranes and may cause dermal sensitization. There is uncertain concern for mutagenicity. It is reported to be effective in inhibiting the growth of selected Gram-positive pathogenic bacteria.	Low moderate concern
Substituted amine hydrochloride	Absorption is expected to be nil through the skin and good through the lungs and GI tract. This chemical has fairly high acute toxicity. It is a severe skin irritant in guinea pigs and a weak to moderate dermal sensitizer. In a repeated dose dietary study in rats, the primary effects were on the red blood cells (through methemoglobin production) and the spleen. This compound is reported to be positive in a variety of mutagenicity assays, although there are also some negative responses. There is concern for oncogenicity based on the mutagenicity results. There is uncertain concern for developmental toxicity.	Moderate concern

Chemical	SAT Health Effects Pertaining to Dermal or Inhalation Exposure	Overall Concern Level
Transition metal salt	Absorption is expected to nil through the skin and good through the lungs and GI tract. This compound is expected to be an irritant because it is hydroscopic. There is concern for mutagenicity. There is also concern for neurotoxicity and uncertain concern for allergic reactions.	Moderate concern

[a] LD50: Lethal dose to 50 percent of the test population.

Table 3-26. Overview of Available Toxicity Data

Chemical	Cancer: Slope Factor (SF), Weight-of-Evidence (WOE) Classification	Inhalation: RfC, NOAEL, or LOAEL [a]	Oral/Dermal: RfD, NOAEL, or LOAEL [a]	SAT Rank
1,4-Butenediol				X
Acetic acid			NOAEL	
Aliphatic acid A			Yes	
Aliphatic acid B				X
Aliphatic acid D		Yes	Yes	
Aliphatic acid E				
Aliphatic dicarboxylic acid A				X
Aliphatic dicarboxylic acid C			Yes	
Alkylalkyne diol				X
Alkylamino acid A				X
Alkylamino acid B				
Alkylaryl imidazole				X
Alkylaryl sulfonate				X
Alkyldiol		Yes	Yes	
Alkylimine dialkanol				X
Alkylphenol ethoxylate				X
Alkylphenol polyethoxyethanol				X
Alkylpolyol			Yes	
Amino acid salt				X
Amino carboxylic acid			Yes	
Ammonium chloride		RfC (for ammonia)	D-NOAEL RfD (for ammonium sulfamate)	
Ammonia compound A		RfC (for ammonia)	Yes	
Ammonia compound B		RfC (for ammonia)	Yes	X
Ammonium hydroxide		RfC (for ammonia)	RfD (for ammonium sulfamate)	

Chemical	Cancer: Slope Factor (SF), Weight-of-Evidence (WOE) Classification	Inhalation: RfC, NOAEL, or LOAEL [a]	Oral/Dermal: RfD, NOAEL, or LOAEL [a]	SAT Rank
Aromatic imidizole product	Not enough information to identify a specific chemical.			
Arylphenol			Yes	X
Bismuth compound				X
Citric acid [b]				X
Copper ion	WOE (for copper)	LOAEL	LOAEL; D-LOAEL	
Copper salt C	WOE (for copper)	Yes	Yes; D-LOAEL	
Copper sulfate pentahydrate	WOE (for copper)	LOAEL	LOAEL; D-LOAEL	
Cyclic amide		Yes	Yes	X
Ethoxylated alkylphenol				X
Ethylenediamine		NOAEL	RfD; D-LOAEL	
Ethylene glycol		LOAEL; D-NOAEL	RfD; D-NOAEL	
Ethylene glycol monobutyl ether		RfC	RfD; D-NOAEL	
Fatty amine				X
Fluoboric acid				X
Gum			Yes	
Hydrochloric acid	WOE	RfC		
Hydrogen peroxide	WOE	Other [b]	LOAEL	
Hydroxy carboxylic acid		Yes	Yes	X
Hydroxyaryl acid				X
Hydroxyaryl sulfonate				X
Inorganic metallic salt A	SF, WOE	Yes	Yes	
Inorganic metallic salt B		Yes	Yes	
Inorganic metallic salt C		Yes	Yes	
Lead	WOE	Other [b]	Other [b]	
Maleic acid				X
Malic acid [c]				X
Methane sulfonic acid				
Nickel sulfate	WOE (for nickel dust)	MRL [d]	RfD	
Nitrogen acid				
Nonionic surfactant	Not enough information to identify specific chemical.			
Palladium chloride	Some data (for Pd)			
Palladium salt	Some data (for Pd)			
Phosphoric acid		RfC	ADI [e]	
Potassium compound				X
Potassium gold cyanide			RfD [f]	
Potassium peroxymonosulfate				X

Chemical	Cancer: Slope Factor (SF), Weight-of-Evidence (WOE) Classification	Inhalation: RfC, NOAEL, or LOAEL [a]	Oral/Dermal: RfD, NOAEL, or LOAEL [a]	SAT Rank
Propionic acid	Some data	Other [c]	NOAEL	
Quantenary alkylammonium chlorides				X
Silver salt	WOE (for silver)		Yes	
Silver nitrate	WOE (for silver)		RfD (for silver)	
Sodium benzene sulfonate				X
Sodium hydroxide				
Sodium hypophosphite				X
Sodium hypophosphite mono hydrate				X
Sodium phosphorus salt				X
Sodium salt [g]				
Stannous methane sulfonic acid	WOE		RfD (for tin)	
Substituted amine hydrochloride				X
Sulfuric acid	WOE	Other [c]		
Surfactant	Not enough information to identify specific chemical.			
Thiourea	WOE			
Tin			RfD	
Tin chloride	WOE		RfD	
Transition metal salt				X
Unspecified tartrate			Yes	
Urea				
Urea compound B	WOE			
Urea compound C			Yes	
Vinyl polymer	WOE		Yes	

[a] "Yes" indicates a value is available (RfC or RfD, NOAEL or LOAEL) but the type of toxicity measure is not specified in order to protect confidential ingredient identity. D-NOAEL/or D-LOAEL: Developmental NOAEL or LOAEL available.
[b] Toxicity data other than RfD, NOAEL or LOAEL were used; see Tables 3-22 and 3-23 for details.
[c] Generally recognized as safe (GRAS) by the U.S. Food & Drug Administration (HSDB, 1995).
[d] MRL = minimal risk level.
[e] ADI = allowable daily intake.
[f] These values are only relevant to the oral route; potassium gold cyanide is expected to be chemically stable except under highly acidic conditions such as those found in the stomach (pH 1-2).
[g] Not generally considered poisonous to humans or animals.

3.3.3 Ecological Hazard Summary

Ecological hazards data are presented in two ways: through a CC and an aquatic hazard concern level, each derived separately from aquatic toxicity data (fish, invertebrates, and algae). Hazards to terrestrial species were not assessed because sufficient toxicity data were not available. CCs are based on the most sensitive endpoint, modified by an assessment factor, which reflects the amount and quality of toxicity data available for that chemical. CCs are compared to estimated surface water concentrations as part of the Risk Characterization (Section 3.4). Aquatic hazard concern levels are based on where the lowest available toxicity value (i.e., the most sensitive endpoint) fits into pre-defined ranges of values, indicating relative toxicity when compared to other chemicals.

Concern Concentration

Table 3-27 presents a summary of the available ecological hazards information. CCs were determined for aquatic species (e.g., *Daphnia*, algae, and/or fish) using standard EPA methodology. The method for determining CCs is summarized below and presented in more detail in Appendix H.

Table 3-27. Estimated (Lowest) Aquatic Toxicity Values and Concern Concentrations for PWB Surface Finishing Chemicals, Based on Measured Test Data or SAR Analysis

Chemical	Acute (a) Toxicity (mg/L)			Chronic (c) Toxicity (mg/L)			Concern Concentration (mg/L)
	Fish	Invert	Algae	Fish	Invert	Algae	
1,4-Butenediol	0.5			0.08			0.008 (c)
Acetic acid	79	65					0.65 (a)
Aliphatic acid A	data omitted [a]						0.5 - 1 (a)
Aliphatic acid B	data omitted [a]						1- 5 (c)
Aliphatic acid D	data omitted [a]						5 - 10 (c)
Aliphatic acid E	data omitted [a]						>1 (c)
Aliphatic dicarboxylic acid A	data omitted [a]						>1 (c)
Aliphatic dicarboxylic acid C	data omitted [a]						>10
Alkylalkyne diol	data omitted [a]						0.1 - 0.5 (c)
Alkylamino acid A	data omitted [a]						500 - 1,000 (c)
Alkylamino acid B	data omitted [a]						0.1 - 5 (c)
Alkylaryl imidazole	data omitted [a]						0.001 - 0.005 (c)
Alkylaryl sulfonate	data omitted [a]						0.001 - 0.005 (c)
Alkyldiol	data omitted [a]						10 - 50 (c)
Alkylimine dialkanol	data omitted [a]						0.001 - 0.005 (c)
Alkylphenol ethoxylate	data omitted [a]						0.1 - 0.5 (c)
Alkylphenol polyethoxyethanol	16	16	20	2	2	5	0.2 (c)
Alkylpolyol	data omitted [a]						5 - 10 (c)

Chemical	Acute (a) Toxicity (mg/L)			Chronic (c) Toxicity (mg/L)			Concern Concentration (mg/L)
	Fish	Invert	Algae	Fish	Invert	Algae	
Amino acid salt	data omitted [a]						0.5 - 1 (c)
Amino carboxylic acid	data omitted [a]						5 - 10 (c)
Ammonia compound A	data omitted [a]						1 - 5 (a)
Ammonia compound B	data omitted [a]						0.01 - 0.05 (c)
Ammonium chloride	725	161					1.6 (a)
Ammonium hydroxide	12	32	>30	1	3	>3	0.1 (c)
Arylphenol	data omitted [a]						0.01 - 0.05 (c)
Bismuth compound	data omitted [a]						0.1 - 0.5 (c)
Citric acid In soft water In hard water	>100	>100	5 100	>10	>10	1 30	0.1 (c) 3.0 (c)
Copper ion	0.14	12.8					0.001 (a)
Copper salt C	data omitted [a]						0.005 - 0.01(c)
Copper sulfate pentahydrate	0.34	0.3	0.00002	0.022	0.0014	0.062	0.01 (c)
Cyclic amide	data omitted [a]						10 - 50 (c)
Ethoxylated alkylphenol	data omitted [a]						0.1 - 0.5 (c)
Ethylenediamine	220	26.5	>100		0.16	8.3	0.02 (c)
Ethylene glycol	10,000	6,900	31,000	5,400	710	440	44 (c)
Ethylene glycol monobutyl ether [b]	116	89	620	10	3.9	32	0.04 (c)
Fatty amine	data omitted [a]						0.001 - 0.005 (c)
Fluoboric acid	>1,000	560	160	20	70	1.4	0.14 (c)
Gum	data omitted [a]						0.5 - 1 (c)
Hydrochloric acid	70	100	345	63	16	15	1.5 (c)
Hydrogen peroxide	5.9	4.3	1.7				0.02 (a)
Hydroxyaryl acid	data omitted [a]						0.1 - 0.5 (c)
Hydroxyaryl sulfonate	data omitted [a]						1 - 5 (c)
Hydroxy carboxylic acid	data omitted [a]						1 - 5 (c)
Inorganic metallic salt A	data omitted [a]						0.0001-0.0005 (c)
Inorganic metallic salt B	data omitted [a]						0.001 - 0.005 (c)
Inorganic metallic salt C	data omitted [a]						0.001 - 0.005 (c)
Lead	315	143	500	4.1	30		0.41 (c)
Maleic acid	5,227	1,199	30,654			993	99.3 (c)
Malic acid	2,860 g/L	2,380 g/L	1,200 g/L	204,000	24,378	14,339	1,434 (c)
Methane sulfonic acid	>1,000	>1,000	>1,000	>100	>100	>100	10 (c)
Nickel sulfate	1.28	2.58	1.9				0.01 (a)
Nitrogen acid	data omitted [a]						1 - 5 (c)
Palladium chloride	1,584	1,567	917	170	49	47	4.7 (c)

Chemical	Acute (a) Toxicity (mg/L)			Chronic (c) Toxicity (mg/L)			Concern Concentration (mg/L)
	Fish	Invert	Algae	Fish	Invert	Algae	
Palladium salt	data omitted [a]						1 - 5 (c)
Phosphoric acid	1,751	25,817	13,761	2,405	394	278	27.8 (c)
Potassium compound	data omitted [a]						1,000 - 1,500 (c)
Potassium gold cyanide	≥0.6	≥2	≥0.4	≥0.06	≥0.03	≥0.1	0.003 (c)
Potassium peroxymonosulfate	≤1	≤3	≤3	≤0.1	≤0.3	≤1	0.01 (c)
Propionic acid	1,369	587	6,644	1,216	318	292	29.2 (c)
Quantenary alkylammonium chlorides	data omitted [a]						0.01 - 0.05 (c)
Silver nitrate	0.007	0.0007	0.13	0.001	0.005		0.0001 (c)
Silver salt	data omitted [a]						0.0001 - 0.0005 (c)
Sodium benzene sulfonate	data omitted [a]						>1 (c)
Sodium hydroxide	133,000	191,000 g/L	3,180 g/L	498,000	22,658	10,616	1,062 (c)
Sodium hypophosphite and Sodium hypophosphite monohydrate	199,000 g/L	1,330 g/L	55,700 g/L	8,430 g/L	331,000	103,000	10,300 (c)
Sodium phosphorus salt	data omitted [a]						10,000 - 50,000 (c)
Sodium salt	data omitted [a]						50 - 100 (c)
Stannous methane sulfonic acid	7	140	≤ 8	0.2	0.9	≤ 0.8	0.02 (c)
Substituted amine hydrochloride	data omitted [a]						0.01 - 0.05 (c)
Sulfuric acid	42	5,200 g/L	250,000	600,000	4,222	2,241	224 (c)
Thiourea	>100	9	4.8	≥60	0.9	0.3	0.03(c)
Tin	2.7	55	≤3	0.07	0.35	≤0.3	0.007 (c)
Tin chloride	1.89	19.5	0.2	0.4	42		0.04 (c)
Transition metal salt	data omitted [a]						≤1 - 5 (c)
Unspecified tartrate	data omitted [a]						1 - 5 (c)
Urea	>1,000	>1,000	>1,000	>100	>100	>100	>10 (c)
Urea compound B	data omitted [a]						0.01 - 0.05 (c)
Urea compound C	data omitted [a]						0.01 - 0.05 (c)
Vinyl polymer	data omitted [a]						≥1 - 5

[a] Data omitted from table and a range reported for CC in order to protect identity of confidential ingredients.
[b] Diethylene glycol monobutyl ether reviewed instead; both chemicals are very similar.

The CC for each chemical in water was calculated using the general equation:

$$CC = \text{acute or chronic toxicity value} \div UF$$

where,

CC = aquatic toxicity concern concentration, the concentration of a chemical in the aquatic environment below which no significant risk to aquatic organisms is expected

UF = uncertainty factor, the adjustment value used in the calculation of a CC that incorporates the uncertainties associated with: 1) toxicity data (e.g., laboratory test versus field test, measured versus estimated data); 2) acute exposures versus chronic exposures; and 3) species sensitivity. This factor is expressed as an order of magnitude or as a power of ten (U.S. EPA, 1984).

If several acute or chronic toxicity values are available, the lowest one is used (most sensitive tested species), unless poor or uncertain data quality disqualify one or more of the values. UFs are dependent on the amount and type of toxicity data contained in a toxicity profile and reflect the amount of uncertainty about the potential effects associated with a toxicity value. In general, the more complete the toxicity profile and the greater the quality of the toxicity data, the smaller the UF used.

The following approach was used, depending on availability and type of data:

- If the toxicity profile only contained one or two acute toxicity values (no chronic values), UF = 1,000 and the CC was calculated by using the lower acute value.
- If the toxicity profile contained three or more acute values (no chronic values), UF = 100 and the CC was calculated by using the lowest acute value.
- If the toxicity profile contained at least one chronic value, and the value was for the most sensitive species, UF = 10 and the CC was calculated by using the lowest chronic value; otherwise, UF = 100 and the CC was calculated with the acute value for the most sensitive species.

Hazard Concern Levels

Table 3-28 presents aquatic hazard concern levels; chemicals were assigned to aquatic toxicity concern levels according to the following EPA criteria:

For chronic values:

≤ 0.1 mg/L.....High concern
> 0.1 to # 10 mg/L.....Moderate concern
> 10 mg/L.....Low concern

For acute values:

≤ 1 mg/L.....High concern
> 1 to # 100 mg/L.....Moderate concern
> 100 mg/L.....Low concern

Chronic toxicity ranking takes precedence over the acute ranking.

Most surface finishing chemicals can theoretically be subject to spills and releases. Also, PWB facilities routinely release wastewater to POTWs. Different geographic regions and different POTWs have different levels of acceptability for such wastes, and the acceptable levels can change over time. Discontinuing use of chemicals in Table 3-28 with Medium to High hazard concern levels can help avoid potential problems.

Table 3-28. Environmental Hazard Ranking of PWB Finishing Chemicals

Chemical	Lowest Acute (a) or Chronic (c) Value (mg/L)	Hazard Rank [a]
1,4-Butenediol	0.08 (c)	H
Acetic acid	65 (a)	L
Aliphatic acid A	NR	L
Aliphatic acid B	NR	L
Aliphatic acid D	NR	L
Aliphatic acid E	NR	L
Aliphatic dicarboxylic acid A	NR	L
Aliphatic dicarboxylic acid C	NR	L
Alkylalkyne diol	NR	M
Alkylamino acid A	NR	L
Alkylamino acid B	NR	M
Alkylaryl imidazole	NR	H
Alkylaryl sulfonate	NR	H
Alkyldiol	NR	L
Alkylimine dialkanol	NR	H
Alkylphenol ethoxylate	NR	M to H [b]
Alkylphenol polyethoxyethanol	0.008 (c) to 2 (c)	M to H [b]
Alkylpolyol	NR	L
Amino acid salt	NR	L
Amino carboxylic acid	NR	L
Ammonia compound A	NR	L
Ammonia compound B	NR	H
Ammonium chloride	161(a)	L
Ammonium hydroxide	1 (c)	M
Arylphenol	NR	M
Bismuth compound	NR	M
Citric acid	1 (c)	M
Copper ion	0.14 (a)	H
Copper salt C	NR	H
Copper sulfate pentahydrate	0.001(c)	H
Cyclic amide	NR	L
Ethoxylated alkylphenol	NR	M to H [b]

Chemical	Lowest Acute (a) or Chronic (c) Value (mg/L)	Hazard Rank [a]
Ethylenediamine	0.16 (c)	M
Ethylene glycol	440 (c)	L
Ethylene glycol monobutyl ether [c]	3.9 (c)	M
Fatty amine	NR	H
Fluoboric acid	1.4 (c)	M
Gum	NR	L
Hydrochloric acid	15 (c)	M
Hydrogen peroxide	1.7 (a)	M
Hydroxyaryl acid	NR	M
Hydroxy aryl sulfonate	NR	L
Hydroxy carboxylic acid	NR	L
Inorganic metallic salt A	NR	H
Inorganic metallic salt B	NR	H
Inorganic metallic salt C	NR	H
Lead	4.1 (c)	M
Maleic acid	993 (c)	L
Malic acid	14,339 (c)	L
Methane sulfonic acid	>100 (c)	L
Nickel sulfate	1.3 (a)	M
Nitrogen acid	NR	L
Palladium chloride	47 (c)	L
Palladium salt	NR	L
Phosphoric acid	278 (c)	L
Potassium compound	NR	L
Potassium gold cyanide	≥0.03 (c)	H
Potassium peroxymonosulfate	≤0.1 (c)	H
Propionic acid	292 (c)	L
Quantenary alkylammonium chlorides	NR	M
Silver nitrate	0.001 (c)	H
Silver salt	NR	H
Sodium benzene sulfonate	NR	L
Sodium hydroxide	10,616 (c)	L
Sodium hypophosphite and Sodium hypophosphite monohydrate	103,000 (c)	L
Sodium phosphorus salt	NR	L
Sodium salt	NR	L
Stannous methane sulfonic acid	0.2 (c)	M
Substituted amine hydrochloride	NR	M
Sulfuric acid	2,241 (c)	L

Chemical	Lowest Acute (a) or Chronic (c) Value (mg/L)	Hazard Rank [a]
Thiourea	0.3 (c)	M
Tin	0.07 (c)	H
Tin chloride	0.4 (c)	M
Transition metal salt	NR	M
Unspecified tartrate	NR	L
Urea	>100 (c)	L
Urea compound B	NR	M
Urea compound C	NR	M
Vinyl polymer	NR	L

[a] Ranking based on the lowest estimated acute or chronic value; H = high, M = medium, L = low.
[b] Toxicity of breakdown product results in high hazard rank.
[c] Diethylene glycol monobutyl ether reviewed instead; both chemicals are very similar.
NR: Not reported in order to protect confidential ingredient identity.

3.3.4 Summary

For human health hazards, toxicity data in the form of RfDs, RfCs, NOAELs, LOAELs, and cancer slope (cancer potency) factors were compiled for inhalation and dermal pathways. Inorganic metallic salt A (a confidential ingredient used in the nickel/gold process) was the only chemical with an established cancer slope (cancer potency) factor. Other chemicals in the surface finishing processes are carcinogens or suspected carcinogens, but do not have established slope factors. Strong inorganic acid mist of sulfuric acid has been determined by IARC to be a human carcinogen (IARC Group 1). Sulfuric acid is used in every surface finishing process in this evaluation. It is not expected, however, to be present as a strong acid mist because it is greatly diluted in the aqueous baths. Lead and thiourea have been determined by IARC to be possible human carcinogens (IARC Group 2B) and lead has also been classified by EPA as a probable human carcinogen (EPA Class B2). Lead is used in tin-lead solder in the HASL process. Thiourea is used in the immersion tin process. Urea compound B, a confidential ingredient in the nickel/gold and nickel/palladium/gold processes, is possibly carcinogenic to humans.

A total of 83 chemicals are considered as part of the surface finishing use cluster. For non-cancer health effects, eight surface finishing chemicals have inhalation RfCs available from which to calculate hazard quotient (HQ) in the risk characterization. For the remaining chemicals, 12 have an inhalation NOAEL or LOAEL from which to calculate margin of exposure (MOE). Pertaining to dermal exposure, 12 surface finishing chemicals have RfDs from which to calculate HQs; of the remaining chemicals, 19 have an oral NOAEL or LOAEL from which to calculate MOE. For a number of chemicals, no quantitative risk indicator could be calculated for direct comparison of risk among alternatives. A qualitative assessment was done for 33 chemicals, based on chemical structure, for which no quantitative non-cancer health effects measures were available.

An ecological hazards assessment was performed based on chemical toxicity to aquatic organisms. CCs were estimated for surface finishing chemicals using an established EPA method. A CC is an acute or chronic toxicity value divided by a UF. UFs are dependent on the amount and type of toxicity data contained in a toxicity profile and reflect the amount of uncertainty about the potential effects associated with a toxicity value. CCs were determined for aquatic species (e.g., *Daphnia*, algae, and/or fish). CCs are compared to estimated surface water concentrations modeled from PWB wastewater releases in Section 3.4.

Chemicals were also ranked for aquatic toxicity concern levels using established EPA criteria (high, moderate, and low concern) based on the available toxicity data. The number of chemicals with a high aquatic hazard concern level include eight in the HASL process, nine in nickel/gold, five in nickel/palladium/gold, five in OSP, three in immersion silver, and six in the immersion tin process.

3.4 RISK CHARACTERIZATION

Risk characterization integrates the hazard and exposure components of a risk evaluation and presents overall conclusions. Risk characterization typically includes a description of the assumptions, scientific judgments, and uncertainties that are part of this process. The focus of this risk characterization is on chronic (long-term) exposure to chemicals that may cause cancer or other toxic effects, rather than on acute toxicity from brief exposures to chemicals. The focus is also on those health effects from chronic exposures that could be used to measure risk. From an ecological risk standpoint, the focus is on chronic exposure to chemicals that cause sublethal effects (e.g., effects on growth and reproduction). The Process Safety Assessment (Section 3.5) includes further information on chemical safety concerns for workers.

The goals of the PWB project risk characterization are to:

- present conclusions and uncertainties associated with a screening-level health risk assessment of chemicals used in the surface finishing process of PWB manufacture;
- integrate chemical hazard and exposure information to assess potential risks from ambient environment and occupational exposures from the surface finishing process;
- use reasonable and consistent assumptions across alternatives, so potential health risks associated with one alternative can be compared to the potential health risks associated with other alternatives; and
- identify the areas of concern that differ among the substitutes in a manner that facilitates decision-making.

This section contains a summary of the exposure assessment (Section 3.4.1), a summary of the human health hazards assessment (Section 3.4.2), and the ecological hazards assessment (Section 3.4.3), a description of methods used to calculate risk indicators (Section 3.4.4), potential human health risk results (Section 3.4.5), an evaluation of lead risks from tin-lead solder used in the HASL process (Section 3.4.6), ecological (aquatic) risk results (Section 3.4.7), a discussion of uncertainties (Section 3.4.8), and conclusions (Section 3.4.9). Detailed exposure and hazard data are presented separately in the Exposure Assessment (Section 3.2) and Human Health and Ecological Hazards Summary (Section 3.3), respectively.

3.4.1 Summary of Exposure Assessment

The exposure assessment uses a “model facility” approach where, as much as possible, reasonable and consistent assumptions are used across alternatives. Data to characterize the model facility and exposure patterns for each process alternative were aggregated from a number of sources, including PWB shops in the U.S. and abroad, supplier data, and input from PWB manufacturers at project meetings. Thus, the model facility is not entirely representative of any one facility, and actual exposure (and risk) could vary substantially, depending on site-specific operating conditions and other factors.

Chemical exposures to PWB workers and the general population were estimated by combining information gathered from industry (PWB Workplace Practices Questionnaire and Performance Demonstration data, MSDSs, other information provided by product suppliers, and other available information) with standard EPA exposure assumptions (e.g., for inhalation rate, surface area of dermal contact, and other parameters). The pathways for which potential exposure from surface finishing process baths was quantified include inhalation and dermal contact for workers, inhalation for the general population living near a PWB facility, and contact with aquatic organisms living in a stream that receives treated wastewater originating from a PWB facility. Acute impacts, such as impacts from chemical spills, are not addressed due to the pre-defined scope of this assessment.

Inhalation exposure could occur by breathing air containing vapor or aerosol-phase chemicals from the surface finishing process line. Inhalation exposures to workers from non-conveyorized lines are estimated in the exposure assessment. Inhalation exposure to workers from conveyorized surface finishing lines is much lower than for non-conveyorized lines because the lines are typically enclosed and vented to the outside.[15] The model used to estimate daily inhalation exposure is from the EPA *Chemical Engineering Branch Manual for the Preparation of Engineering Assessments* (U.S. EPA, 1991a):

$$I = (Cm)(b)(h)$$

where,

I	=	daily inhalation potential dose rate (mg/day)
Cm	=	airborne concentration of substance (mg/m^3)
b	=	inhalation rate (m^3/hr)
h	=	duration (hr/day)

Daily exposures are then averaged over a lifetime (70 years) for carcinogens, and over the exposure duration (e.g., 25 years working in a facility) for non-carcinogens,[16] using the following equations:

For carcinogens:

---

[15] Inhalation exposures for conveyorized process configurations were initially assumed to be negligible, and are not presented separately here. Some inhalation exposure is possible, however, during sampling and bath replacement, when the baths are opened for a short period of time. After characterizing risks from inhalation for non-conveyorized lines, inhalation exposures and risks were estimated for the subset of inhalation chemicals of concern for conveyorized lines. No chemical exposures from inhalation resulted in risks above concern levels for conveyorized lines.

[16] Different averaging times are used for characterizing risk for carcinogenic and non-carcinogenic effects. For carcinogenic agents, because even a single incidence of exposure is assumed to have the potential to cause cancer throughout an individual's lifetime, the length of exposure to that agent is averaged over a lifetime. An additional factor is that the cancer latency period may extend beyond the period of working years before it is discernible. For chemicals exhibiting non-cancer health effects from chronic (longer-term) exposure, where there is an exposure threshold (a level below which effects are not expected to occur), only the time period when exposure is occurring is assumed to be relevant and is used as the averaging time.

$$LADD = (I)(EF)(ED)/[(BW)(AT_{CAR})]$$

For non-carcinogens:

$$ADD = (I)(EF)(ED)/[(BW)(AT_{NC})]$$

where,

LADD	=	lifetime average daily dose (mg/kg-day)
ADD	=	average daily dose (mg/kg-day)
EF	=	exposure frequency (days/year)
ED	=	exposure duration (years)
BW	=	body weight (kg)
AT_{CAR}	=	averaging time for carcinogenic effects (days)
AT_{NC}	=	averaging time for non-carcinogenic chronic effects (days)

The daily intake for inhalation exposure to workers was calculated by first modeling chemical emissions from surface finishing baths with three air-transport mechanisms: liquid surface diffusion (desorption), bubble desorption, and aerosol generation and ejection. This modeled chemical emission rate was combined with data from the PWB Workplace Practices Questionnaire and Performance Demonstration Data Sheets regarding process room size and air turnover rate to estimate an average indoor air concentration for the process area.

Modeled air concentrations were used to evaluate inhalation exposure to a nearby population. This outdoor air modeling used the air emission rates that were estimated for the process baths, assuming they are vented outside at the same rate they are emitted from the baths. The Industrial Source Complex - Long Term (ISCLT) air dispersion model[17] was used to estimate air concentrations resulting from dispersion in the outdoor air. The modeled air concentrations of each contaminant were determined at 100 meters radially from a PWB facility. The highest estimated air concentration was used to estimate inhalation exposure to a hypothetical population located near a model PWB facility. Inhalation exposures estimated for the public living 100 meters away from a PWB facility were very low (approximately 10,000 times lower than occupational exposures).

Dermal exposure could occur when skin comes in contact with the bath solution while dipping boards, adding bath replacement chemicals, etc. Although the data suggest that most surface finishing line operators wear gloves for many activities, it was assumed in this evaluation that workers do not wear gloves, to account for the fraction that do not. Otherwise, dermal exposure is expected to be negligible. For dermal exposures, the flux of a material through the skin was estimated based on U.S. EPA, 1992a:

$$D = (S)(C)(f)(h)(0.001)$$

[17] This version of the ISCLT model is provided as part of the Risk*Assistant™ 2.0 software package (Hampshire Research Institute, 1995).

where,

D	=	dermal potential dose rate (mg/day)
S	=	surface area of contact (cm^2)
C	=	concentration of chemical in the bath (mg/L)
f	=	flux through skin (cm/hour)
h	=	duration (hours/day) with a conversion factor of 0.001 (L/cm^3)

It should be noted that the above equation was developed for exposures with an infinite volume of liquid or boundary layer contacting the skin, such as swimming or bathing. Occupational conditions of dermal contact are likely to be more finite in comparison, resulting in possible overestimates of flux through the skin when using the above equation.

Similar to inhalation, daily dermal exposures were then averaged over the exposure duration for non-carcinogens (cancer risk was not quantified because none of the surface finishing chemicals have an oral or dermal cancer slope factor) using the following equation:

$$ADD = (D)(EF)(ED)/[(BW)(AT_{NC})]$$

For dermal exposure, the concentration of chemical in the bath and duration of contact for workers was obtained from publicly-available bath chemistry data, disclosed proprietary chemical information, supplier data sheets, and PWB Workplace Practices Questionnaire information. A permeability coefficient (rate of penetration through skin) was estimated for organic compounds and a default rate assumption was used for inorganic chemicals. Reliance on such estimates in the absence of data is a source of uncertainty in the exposure assessment.

Key assumptions in the exposure assessment include the following:

- The exposure frequency (i.e., days/year of line operation) was based on the time required to manufacture 260,000 ssf of PWB.
- For dermal exposure, it was assumed that line operators do not wear gloves. Although the data suggest that many surface finishing line operators do wear gloves for various activities, it was assumed for this evaluation that workers do not wear gloves, to account for the subset of workers who do not wear proper personal protective equipment.
- For dermal exposure, it was assumed that all non-conveyorized lines are manual hoist.
- The worker on a non-conveyorized line is assumed to potentially have dermal contact for the entire time spent in the surface finishing process area, and the contact time is assumed to be divided equally among the baths over an 8-hour workday. This does not mean that a worker has both hands immersed in a bath for that entire time but that the skin is in contact with bath solution (i.e., the hands may remain wet from contact). This assumption may result in an overestimate of dermal exposure.
- For estimating ambient (outdoor) air concentrations, it was assumed that no air pollution control technologies are used to remove airborne chemicals from facility air prior to venting it to the outside.

- For inhalation exposure to workers, it was assumed that chemical emissions to air in the process room from conveyorized lines are negligible, and that no vapor control devices (e.g., bath covers) are used on baths in non-conveyorized lines.
- For air concentrations, the model assumes complete mixing in the process room and that concentrations do not change with time (i.e., steady state).
- For all exposures, it was assumed that there is one surface finishing process line and one line operator per shift in a process area.
- For characterizing the chemical constituents in the surface finishing process baths, it was assumed that the form (speciation) and concentration of all chemicals in the baths are constant over time.

Chemical concentrations in baths are based on publicly-available chemistry data, including MSDSs, proprietary chemical information, and supplier Product Data Sheets that describe how to mix and maintain chemical baths. Many MSDSs provided concentration ranges for chemical constituents instead of absolute concentrations, in which case it was assumed that a chemical is present at the mid-point of the reported concentration range. This assumption may either overestimate or underestimate risk for chemicals, depending on their actual concentrations.

Assumptions and parameter values used in these equations, and results of the exposure calculations, are presented in the Exposure Assessment (Section 3.2). In order to provide information about the position an exposure estimate has in the distribution of possible outcomes, exposure (or risk) descriptors are used following EPA's *Guidelines for Exposure Assessment* (U.S. EPA, 1992b). For this risk characterization, whenever possible the exposure assessment uses a combination of central tendency (either an average or median estimate) and high-end (90th percentile)[18] assumptions, as would be used for an overall high-end exposure estimate. The 90th percentile is used for:

- hours per day of workplace exposure;
- exposure frequency;
- exposure duration in years (90th percentile for occupational and 95th percentile for residential exposures);
- time required for chemical bath replacement;
- time and frequency of filter replacements, conveyor equipment cleaning, and chemical bath sampling (minutes per occurrence and number of occurrences per year); and
- estimated workplace air concentrations.

Average values are used for:

- body weight;
- concentration of chemical in bath;

[18] For exposure data from the PWB Workplace Practices Questionnaire, this means that 90 percent of the facilities reported a lower value, and ten percent reported a higher value.

- frequency of chemical bath replacements;
- number of baths in a given process; and
- bath size.

Some values used in the exposure calculations, however, are better characterized as "what-if," especially pertaining to use of gloves, process area ventilation rates, and production times (days/year) required to manufacture 260,000 ssf of PWB for the model facility. ("What-if" represents an exposure estimate based on postulated questions, making assumptions based on limited data where the distribution is unknown.) Because some part of the exposure assessment for both inhalation and dermal exposures qualifies as a "what-if" descriptor, the entire assessment should be considered "what-if."

3.4.2 Summary of Human Health Hazards Assessment

For human health hazards, toxicity data in the form of RfDs, RfCs, NOAELs, LOAELs, and cancer slope (cancer potency) factors were compiled for inhalation and dermal pathways. Inorganic metallic salt A (a confidential ingredient used in the nickel/gold process) was the only chemical with an established cancer slope (cancer potency) factor. Other chemicals in the surface finishing processes are known or suspected carcinogens, but do not have established slope factors. Strong inorganic acid mist of sulfuric acid has been determined by IARC to be a human carcinogen (IARC Group 1). Sulfuric acid is used in every surface finishing process in this evaluation. It is not expected, however, to be present as a strong acid mist because it is greatly diluted in the aqueous baths. Lead and thiourea have been determined by IARC to be possible human carcinogens (IARC Group 2B) and lead has also been classified by EPA as a probable human carcinogen (EPA Class B2). Lead is used in tin-lead solder in the HASL process. Thiourea is used in the immersion tin process. Urea compound B, a confidential ingredient in the nickel/gold and nickel/palladium/gold processes, is possibly carcinogenic to humans.

3.4.3 Summary of Ecological Hazards Assessment

An ecological hazard assessment was performed based on chemical toxicity to aquatic organisms. CCs were estimated for surface finishing chemicals using an established EPA method (see Table 3-27 and Appendix H). A CC is an acute or chronic toxicity value divided by a UF. UFs are dependent on the amount and type of toxicity data contained in a toxicity profile, and reflect the amount of uncertainty about the potential effects associated with a toxicity value. Concern concentrations were determined for aquatic species (e.g., *Daphnia*, algae, and/or fish) for each chemical. The lowest CCs are for inorganic metallic salt A, silver nitrate, and silver salt. Chemicals also were ranked for aquatic toxicity concern levels using established EPA criteria (high, moderate, and low concern) based on the available toxicity data (see Table 3-28). The number of chemicals with a high aquatic hazard concern level include eight in the HASL process, nine in nickel/gold, five in nickel/palladium/gold, five in OSP, three in immersion silver, and six in the immersion tin process.

3.4.4 Methods Used to Calculate Human Health Risks

Estimates of potential human health risk from chemical exposure are characterized here in terms of excess lifetime cancer risk, HQ, and MOE. This section defines these risk indicators and discusses the methods for calculating each of them.

Cancer Risk

Cancer risks are expressed as the excess probability of an individual developing cancer over a lifetime from chemical exposure. For chemicals classified as carcinogens, an upper bound excess lifetime cancer risk, expressed as a unitless probability, was estimated by the following equation:

$$\text{Cancer Risk} = \text{LADD} \times \text{slope factor}$$

where,

Cancer Risk = the excess probability of developing cancer over a lifetime as a result of exposure to a potential carcinogen. The estimated risks are the upper bound excess lifetime cancer risks for an individual. (*Upper bound* refers to the method of determining a slope factor, where the upper bound value for the slope of the dose-response curve is used. *Excess* means the estimated cancer risk is in addition to the already-existing background risk of an individual contracting cancer from all other causes.)

LADD = the lifetime average daily dose, the estimated potential daily dose rate received during the exposure duration, averaged over a 70-year lifetime (in mg/kg-day). LADDs were calculated in the Exposure Assessment (Section 3.2).

Slope factor (q_1 *) is defined in Section 3.3.1.

Non-Cancer Risk Indicators

Non-cancer risk estimates are expressed either as an HQ or as an MOE, depending on whether or not RfDs and RfCs are available. There is a higher level of confidence in the HQ than the MOE, especially when the HQ is based on an RfD or RfC that has been peer-reviewed by EPA (as with data from the EPA IRIS database). If an RfD or RfC is available, the HQ is calculated to estimate risk from chemicals that exhibit chronic, non-cancer toxicity. (RfDs and RfCs are defined in Section 3.3.2.) The HQ is the unitless ratio of the RfD (or RfC) to the potential dose rate. For surface finishing chemicals that exhibit non-cancer toxicity, the HQ was calculated by:

$$\text{HQ} = \text{ADD}/\text{RfD}$$

where,

ADD = average daily dose rate, the amount of a chemical ingested, inhaled, or applied to the skin per unit time, averaged over the exposure duration (in mg/kg-day)

ADDs were calculated in the Exposure Assessment (Section 3.2).

The HQ is based on the assumption that there is a level of exposure (i.e., the RfD or RfC) below which it is unlikely, even for sensitive subgroups, to experience adverse health effects. Unlike cancer risk, the HQ does not express *probability* and is not necessarily linear; that is, an HQ of ten does not mean that adverse health effects are ten times more likely to occur than for an HQ of one. However, the ratio of estimated dose to RfD/RfC reflects the level of concern.

For chemicals where an RfD or RfC was not available, an MOE was calculated by:

$$MOE = NOAEL/ADD \text{ or } LOAEL/ADD$$

As with the HQ, the MOE is not a probabilistic statement of risk. The ratio for calculating MOE is the inverse of the HQ, so that a high HQ (exceeding one) indicates a potential concern, whereas a high MOE (exceeding 100 for a NOAEL-based MOE or 1,000 for a LOAEL-based MOE) indicates a low concern level. (NOAELS and LOAELs are defined in Section 3.3.2.) As the MOE increases, the level of concern decreases. (As the HQ increases, the level of concern also increases.) In general, there is a higher level of confidence for HQs than for MOEs because the toxicity data on which RfDs and RfCs are based have passed a more thorough level of review, and test-specific uncertainty factors have been included.

Both the exposure estimates and toxicity data are specific to the route of exposure (i.e., inhalation, oral, or dermal). Very few RfDs, NOAELs, or LOAELs are available for dermal exposure. If oral data were available, the following adjustments were made to calculate dermal values based on EPA (1989) guidance:

$$RfD_{DER} = (RfD_{ORAL})\ (\text{GI absorption})$$
$$NOAEL/LOAEL_{DER} = (NOAEL \text{ or } LOAEL_{ORAL})\ (\text{GI absorption})$$
$$SF_{DER} = (SF_{ORAL})/(\text{GI absorption})$$

where,

RfD_{DER} = reference dose adjusted for dermal exposure (mg/kg-day)
$NOAEL/LOAEL_{DER}$ = NOAEL or LOAEL adjusted for dermal exposure (mg/kg-day)
SF_{DER} = cancer slope factor adjusted for dermal exposure $(mg/kg\text{-}day)^{-1}$
GI absorption = gastrointestinal absorption efficiency

This adjustment is made to account for the fact that the oral RfDs, NOAELs, and LOAELs are based on an applied dose, while dermal exposure represents an estimated absorbed dose. The oral RfDs, NOAELs, and LOAELs used to assess dermal risks therefore were adjusted using GI absorption to reflect an absorbed dose. Table 3-29 lists the GI absorption data for chemicals used in calculating risk from dermal exposure. (Data for some proprietary ingredients are not presented in order to protect confidential chemical identities.)

Table 3-29. Gastrointestinal (GI) Absorption Factors

Chemicals [a]	GI Absorption Factor	Source
Acetic acid	0.9	chemical profile [b]
Aliphatic acid A	0.9	chemical profile [b]
Aliphatic acid D	0.5	NR
Aliphatic dicarboxylic acid C	0.2	assumption [c]
Alkyldiol	NR	NR
Alkylpolyol	0.2	assumption [c]
Amino carboxylic acid	0.2	assumption [c]
Ammonia compound A	0.9	chemical profile [b]
Ammonia compound B	0.9	chemical profile [b]
Ammonium chloride	0.9	chemical profile [b]
Ammonium hydroxide	0.9	chemical profile [b]
Aryl phenol	0.5	chemical profile [b]
Copper ion, Copper salt C, and Copper sulfate pentahydrate	0.6	midpoint of range, 0.15 - 0.97; U.S. EPA, 1984
Cyclic amide	0.5	chemical profile [b]
Ethylene glycol	0.5	midpoint of range; HSDB, 1998
Ethylene glycol monobutyl ether	0.5	ATSDR, 1998
Ethylenediamine	0.78	midpoint of range, 0.6 - 0.95 U.S. EPA, 1988b
Hydroxy carboxylic acid	0.2	assumption [c]
Hydrogen peroxide	0.2	assumption [c]
Inorganic metallic salt A	NR	NR
Inorganic metallic salt B	0.15	NR
Inorganic metallic salt C	0.15	NR
Nickel sulfate	0.05	midpoint of range, 0.01 - 0.1, chemical profile
Phosphoric acid	0.2	U.S. EPA, 1995
Potassium gold cyanide	0.2	assumption [c]
Propionic acid	0.2	assumption [c]
Silver nitrate	0.08	midpoint of range, 0.05 - 0.1 (U.S. EPA, 1991c; ATSDR, 1990b)
Silver salt	NR	NR
Stannous methane sulfonic acid	0.2	assumption [c]
Tin chloride	0.5	Johnson and Greger, 1982
Unspecified tartrate	0.5	chemical profile [b]

Chemicals [a]	GI Absorption Factor	Source
Urea compound C	0.2	assumption [c]
Vinyl polymer	0.1	chemical profile [b]

[a] Includes only chemicals for which dermal HQs or MOEs could be calculated.
[b] Good, moderate, and low GI absorption, as reported in EPA chemical profiles, were translated to assumed GI absorption fractions of 0.9, 0.5, and 0.1, respectively.
[c] An assumption of 20 percent GI absorption was made for chemicals with no available GI absorption data.
NR: Not reported; data for some proprietary ingredients are not presented in order to protect confidential chemical identities.

Lead

Methods used to evaluate potential lead risks from tin-lead solder used in the HASL process are described in Section 3.4.6.

3.4.5 Results of Calculating Human Health Risk Indicators

This section presents the results of calculating risk indicators for both the occupational setting and the ambient (outdoor) environment. When considering these risk characterization results, it should be remembered that the results are intended for use in comparing relative potential risk between processes, based on a model PWB facility, and should not be used as absolute indicators of actual health risks to surface finishing line workers or to the public.

Occupational Setting

Estimated cancer risks and non-cancer risk indicators from occupational exposure to surface finishing chemicals are presented below. It should be noted that no epidemiological studies of health effects among PWB workers were located.

Inhalation Cancer Risk. Nickel/gold is the only process containing a chemical for which a cancer slope (cancer potency) factor is available. Inorganic metallic salt A, in the nickel/gold process, is the only chemical for which an inhalation cancer risk has been estimated. This metal compound is considered a human carcinogen.[19]

Inhalation exposure estimates are based on the assumptions that emissions to indoor air from conveyorized lines are negligible, that the air in the process room is completely mixed and chemical concentrations are constant over time, and that no vapor control devices (e.g., bath covers) are used in non-conveyorized lines. The exposure estimates use 90th percentile modeled air concentrations, which means that, based on the PWB Workplace Practices Questionnaire data and available information on bath concentrations, approximately 90 percent of the facilities are

[19] A cancer classification of known human carcinogen has been assigned by either the EPA, IARC, and/or the National Toxicology Program (NTP). Further details about the carcinogen classification are not provided in order to protect the confidential chemical's identity.

expected to have lower air concentrations and, therefore, lower risks. Using 90th percentile data is consistent with EPA policy for estimating upper-bound exposures.

The upper bound maximum individual cancer risk over a lifetime is 2×10^{-7} based on a workplace concentration of 2.4×10^{-6} milligrams inorganic metallic salt A per cubic meter of air, over an 8 hour-day, for line operators using the non-conveyorized nickel/gold process. Cancer risks less than 1×10^{-6} (one in one million) are generally considered to be of low concern. The use of modeled, steady state, workplace air concentrations instead of actual monitoring data of average and peak concentrations thus emerges as a significant source of uncertainty in estimating cancer risk to workers exposed to inorganic metallic salt A in this industry. The available toxicological data do not indicate that dermal exposure to inorganic metallic salt A increases cancer risk, but no dermal cancer studies were located.

Risks to other workers would be proportional to the amount of time spent in the process area. The exposure from inhalation for a typical line operator is based on spending 8 hr/day in the surface finishing process area. Exposure times (i.e., time spent in the process area) for various worker types from the workplace practices database are listed below. The number in parentheses is the ratio of average time for that worker type to the 8 hr/day exposure time for a line operator.

- laboratory technician: 2.8 hr/day (0.35);
- maintenance worker: 1.6 hr/day (0.2);
- supervisor: 5.5 hr/day (0.69); and
- wastewater treatment operator: 1 hr/day (0.12).

(Other types of workers may be in the process area for shorter or longer times.)

Other Potential Cancer Risk. Slope factors (cancer potency values) are needed to calculate estimates of cancer risk. In addition to the chemical discussed above, lead and thiourea have been determined by IARC to be possible human carcinogens (IARC Group 2B); lead has also been classified by EPA as a probable human carcinogen (EPA Class B2). Lead is used in tin-lead solder in the HASL process. Thiourea is used in the immersion tin process. Urea compound B, a confidential ingredient in the nickel/gold and nickel/palladium/gold processes, is possibly carcinogenic to humans. There are potential cancer risks to workers from these chemicals, and workplace exposures have been estimated, but cancer potency and cancer risks are unknown. Additionally, strong inorganic acid mists of sulfuric acid have been determined by IARC to be a human carcinogen (IARC Group 1). Sulfuric acid is used in every surface finishing process in this evaluation. It is not expected, however, to be present as a strong acid mist because it used in diluted form in the aqueous baths.

Non-Cancer Risk. HQs and MOEs were calculated for line operators and laboratory technicians from workplace exposures. An HQ exceeding one indicates a potential concern. Unlike cancer risk, the HQ does not express probability, only the ratio of the estimated dose to

the RfD or RfC, and it is not necessarily linear (an HQ of ten does not mean that adverse health effects are ten times more likely than an HQ of one).

EPA considers high MOE values, such as values greater than 100 for a NOAEL-based MOE or 1,000 for a LOAEL-based MOE, to pose a low level of concern (Barnes and Dourson, 1988). As the MOE decreases, the level of concern increases. Chemicals are noted here to be of potential concern if a NOAEL-based MOE is lower than 100, a LOAEL-based MOE is lower than 1,000, or an MOE based on an effect level that was not specified as a LOAEL (used in the absence of other data) is less than 1,000. As with the HQ, it is important to remember that the MOE is not a probabilistic statement of risk.

Inhalation risk indicators of concern are presented in Table 3-30. This includes chemicals of potential concern based on MOE and/or HQ results, as well as cancer risk results for the one chemical with a cancer slope factor. Inhalation exposure estimates are based on the assumptions that emissions to air from conveyorized lines are negligible, that the air in the process room is completely mixed and chemical concentrations are constant over time, and that no vapor control devices (e.g., bath covers) are used in non-conveyorized lines.

Dermal risk indicators of concern are presented in Table 3-31. This includes chemicals of potential concern based on MOE and/or HQ. Dermal exposure estimates are based on the assumption that both hands are routinely immersed in the bath, the worker does not wear gloves, and all non-conveyorized lines are operated by manual hoist.

Table 3-32 provides a summary of the potential health effects for the chemicals of concern listed in Tables 3-30 and 3-31. It should be noted that Tables 3-30 and 3-31 do not include chemicals for which toxicity data were unavailable. Table 3-33 lists chemicals where inhalation or dermal exposure is expected to occur, but appropriate toxicity values are not available. (Table 3-25 provides qualitative structure-activity information pertaining to chemical toxicity for those chemicals without available measured toxicity data.)

Table 3-30. Summary of Human Health Risks From Occupational Inhalation Exposure for Selected Chemicals

Chemical of Concern	Human Health Risk Indicator [a]			
	HASL (NC)	Nickel/Gold (NC)	Nickel/Palladium/Gold (NC)	OSP (NC)
Alkyldiol	NA	line operator	line operator	NA
Ethylene glycol	MOE (3, 9) 550, line operator LOAEL	NA	NA	MOE (3, 9) 370, line operator LOAEL
Hydrochloric acid	NA	HQ (1, 2, 3) 29, line operator	HQ (2, 12) 41, line operator	NA
Hydrogen peroxide	NA	MOE (9) 940, line operator LOAEL	MOE (9) 730, line operator LOAEL	NA
Inorganic metallic salt A	NA	cancer risk $< 1 \times 10^{-6}$, line operator	NA	NA
Nickel sulfate	NA	HQ (4) 23, line operator	HQ (4) 50, line operator	NA
Phosphoric acid	NA	HQ (3) 2.7, line operator	HQ (3) 3.5, line operator	NA
Propionic acid	NA	NA	MOE (5) 31, line operator LOAEL	NA

[a] This table includes results for chemicals and pathways with an MOE less than 1,000 if based on a LOAEL (or less than 100 if based on a NOAEL), an HQ greater than one, or cancer risk. It does not include chemicals for which toxicity data were unavailable. Specific results are not presented for confidential ingredients in order to protect proprietary ingredient identity.

[b] How to read this table:

A	(B)
C,D	
E	

A: Type of risk indicator for which results are reported (HQ, MOE, or cancer risk).
B: Process bath(s) in which the chemical is used. These are only shown for non-proprietary chemicals. Numbers in parentheses indicate the process bath(s) in which the chemical is used:

(1) acid dip	(2) catalyst
(3) cleaner	(4) electroless nickel
(5) electroless palladium	(6) immersion gold
(7) immersion silver	(8) immersion tin
(9) microetch	(10) OSP
(11) predip	(12) preinitiator

C: Value calculated for risk indicator (cancer risk, HQ, or MOE).
D: Type of worker for which risk results are presented (line operator or laboratory technician).
E: Type of toxicity data used for MOE: NOAEL, LOAEL, or data from human exposures, which do not provide a range of exposures but identify levels that have adverse effects on humans.
NA: Not applicable.

Table 3-31. Summary of Human Health Risks Results From Occupational Dermal Exposure for Selected Chemicals

Chemical of Concern [a]	Human Health Risk Indicator [a, b]						
	HASL (NC)	HASL (C)	Nickel/Gold (NC)	Nickel/ Palladium/Gold (NC)	OSP (NC)	OSP (C)	Immersion Tin (NC)
Ammonia compound A	NA	NA	NA	line operator	NA	NA	NA
Ammonium chloride	NA	NA	HQ (6) 2.3, line operator	NA	NA	NA	NA
Ammonium hydroxide	NA	NA	HQ (6) 2.5, line operator	HQ (6) 3.5, line operator	NA	NA	NA
Copper ion	NA	NA	NA	NA	MOE (10) 0.68, line operator 10, lab tech LOAEL	MOE (10) 14, line operator 48, lab tech LOAEL	NA
Copper salt C	NA	NA	NA	NA	line operator	NA	NA
Copper sulfate pentahydrate	MOE (9) 2.7, line operator 190, lab tech LOAEL	MOE (9) 64, line operator 860, lab tech LOAEL	MOE (9) 0.77, line operator 12, lab tech LOAEL	MOE (9) 0.92, line operator 37, lab tech LOAEL	MOE (9) 3.0, line operator 46, lab tech LOAEL	MOE (9) 59, line operator 210, lab tech LOAEL	NA
Hydrogen peroxide	NA	NA	MOE (9) 430, line operator LOAEL	MOE (9) 510, line operator LOAEL	NA	NA	NA
Inorganic metallic salt B	NA	NA	line operator, lab tech	line operator, lab tech	NA	NA	NA
Nickel sulfate	NA	NA	HQ (4) 140, line operator 9.2, lab tech	HQ (4) 190, line operator 4.6, lab tech	NA	NA	NA
Urea compound C	NA	NA	NA	NA	NA	NA	line operator

[a] This table includes results for chemicals and pathways with an MOE less than 1,000 if based on LOAELs (or less than 100 based on NOAELs), an HQ greater than one, or cancer risk above $1x10^{-6}$. It does not include chemicals for which toxicity data were unavailable. Specific results are not presented for confidential ingredients in order to protect proprietary ingredient identity.

[b] How to read this table:

A (B)
C,D
E

A: Type of risk indicator for which results are reported (HQ, MOE, or cancer risk).
B: Process bath(s) in which the chemical is used. Numbers in parentheses indicate the process bath(s) in which the chemical is used:

(1) acid dip	(2) catalyst
(3) cleaner	(4) electroless nickel
(5) electroless palladium	(6) immersion gold
(7) immersion silver	(8) immersion tin
(9) microetch	(10) OSP
(11) predip	(12) preinitiator

C: Value calculated for risk indicator (cancer risk, HQ, or MOE).
D: Type of worker for which risk results are presented (line operator or laboratory technician).
E: Type of toxicity data used for MOE: NOAEL, LOAEL, or data from human exposures, which do not provide a range of exposures but identify levels that have adverse effects on humans.
NA: Not applicable.

For inhalation exposure to workers, the following chemicals result in an HQ greater than one or an MOE below the concern levels:

- ethylene glycol in non-conveyorized HASL;
- alkyldiol, hydrochloric acid, hydrogen peroxide, nickel sulfate, and phosphoric acid in non-conveyorized nickel/gold;
- alkyldiol, hydrochloric acid, hydrogen peroxide, nickel sulfate, phosphoric acid, and propionic acid in non-conveyorized nickel/palladium/gold; and
- ethylene glycol in non-conveyorized OSP.

Chemicals with HQs from dermal exposure greater than one, NOAEL-based MOEs lower than 100, or LOAEL-based MOEs lower than 1,000, include:

- copper sulfate pentahydrate in non-conveyorized and conveyorized HASL;
- ammonium chloride, ammonium hydroxide, copper sulfate pentahydrate, hydrogen peroxide, inorganic metallic salt B, and nickel sulfate in non-conveyorized nickel/gold;
- ammonia compound A, ammonium hydroxide, copper sulfate pentahydrate, hydrogen peroxide, inorganic metallic salt B, and nickel sulfate in non-conveyorized nickel/palladium/gold;
- copper ion, copper salt C, and copper sulfate pentahydrate in non-conveyorized OSP;
- copper ion and copper sulfate pentahydrate in conveyorized OSP; and
- urea compound C in non-conveyorized immersion tin.

Table 3-32. Summary of Potential Human Health Effects for Chemicals of Concern

Chemical of Concern	Potential Health Effects
Ammonia compound A, Ammonium chloride, and Ammonium hydroxide	Contact with ammonium chloride solution or fumes irritate the eyes. Large doses of ammonium chloride may cause nausea, vomiting, thirst, headache, hyperventilation, drowsiness, and altered blood chemistry. Ammonia fumes are extremely irritating to skin, eyes, and respiratory passages. The severity of effects depends on the amount of dose and duration of exposure.
Alkyldiol	Can affect the respiratory system if inhaled, and kidneys if absorbed into the body.
Copper ion, Copper sulfate pentahydrate, and Copper salt C	Long-term exposure to high levels of copper may cause liver damage. Copper is not known to cause cancer. The seriousness of the effects of copper can be expected to increase with both level and length of exposure.
Ethylene glycol	In humans, low levels of vapors produce throat and upper respiratory irritation. When ethylene glycol breaks down in the body, it forms chemicals that crystallize and can collect in the body, which prevent kidneys from working. The seriousness of the effects can be expected to increase with both level and length of exposure.
Hydrochloric acid	Hydrochloric acid in the air can be corrosive to the skin, eyes, nose, mucous membranes, respiratory tract, and gastrointestinal tract.
Hydrogen peroxide	Hydrogen peroxide in the air can irritate the skin, nose, and eyes. Ingestion can damage the liver, kidneys, and gastrointestinal tract.
Inorganic metallic salt A	Exposure can cause flu-like symptoms, weakness and coughing, and has been linked to lung cancer and kidney disease.
Inorganic metallic salt B	Exposure to this material can damage the nervous system, kidneys, and immune system.
Nickel sulfate	Skin effects are the most common effects in people who are sensitive to nickel. Workers who breath very large amounts of nickel compounds have developed lung and nasal sinus cancers.
Phosphoric acid	Inhaling phosphoric acid can damage the respiratory tract.
Propionic acid	No data were located for health effects of propionic acid exposure in humans, although some respiratory effects were seen in laboratory mice.
Urea compound C	Dermal exposure to urea compound C has resulted in allergic contact dermatitis in workers, and exposure has caused weight loss in mice.

Table 3-33. Data Gaps for Chronic Non-Cancer Health Effects for Workers

Chemical	Inhalation [a] or Dermal [b] Exposure Potential	SAT Rank (if available)
HASL		
1,4-Butenediol	Inhalation and Dermal	Low-moderate
Alkylaryl sulfonate	Inhalation	Low
Arylphenol	Inhalation	Moderate
Fluoboric acid	Dermal	
Hydrochloric acid	Dermal	
Sodium hydroxide	Dermal	
Sulfuric acid	Dermal	
Tin	Dermal	
Nickel/Gold		
Aliphatic acid A	Inhalation	
Aliphatic acid B	Inhalation	Moderate
Aliphatic acid E	Inhalation and Dermal	
Aliphatic dicarboxylic acid A	Inhalation	Low-moderate
Aliphatic dicarboxylic acid C	Inhalation	
Alkylamino acid B	Dermal	
Ammonia compound B	Inhalation	Moderate-high
Hydrochloric acid	Dermal	
Malic acid	Inhalation	Low-moderate
Palladium chloride	Dermal	
Potassium compound	Inhalation and Dermal	Low
Sodium hydroxide	Dermal	
Sodium hypophosphite	Inhalation	Low-moderate
Sulfuric acid	Dermal	
Urea compound B	Inhalation and Dermal	
Nickel/Palladium/Gold		
Aliphatic acid B	Inhalation	Moderate
Aliphatic acid E	Inhalation and Dermal	
Aliphatic dicarboxylic acid A	Inhalation	Low-moderate
Aliphatic dicarboxylic acid C	Inhalation	
Ammonia compound B	Inhalation	Moderate-high
Hydrochloric acid	Dermal	
Malic acid	Inhalation	Low-moderate
Palladium salt	Dermal	
Potassium compound	Inhalation and Dermal	Low
Sodium hydroxide	Dermal	

Chemical	Inhalation [a] or Dermal [b] Exposure Potential	SAT Rank (if available)
Sodium hypophosphite monohydrate	Inhalation	Low-moderate
Sulfuric acid	Dermal	
Urea compound B	Inhalation and Dermal	
OSP		
Acetic acid	Inhalation	
Alkylaryl imidazole	Dermal	Low-moderate
Aromatic imidazole product	Dermal	
Arylphenol	Inhalation	Moderate
Hydrochloric acid	Dermal	
Sodium hydroxide	Dermal	
Sulfuric acid	Dermal	
Immersion Silver		
1,4-Butenediol	Dermal	Low-moderate
Nitrogen acid	Dermal	
Sodium hydroxide	Dermal	
Sulfuric acid	Dermal	
Immersion Tin		
Alkylaryl sulfonate	Inhalation	Low
Fluoboric acid	Dermal	
Hydrochloric acid	Dermal	
Methane sulfonic acid	Dermal	
Sulfuric acid	Dermal	
Thiourea	Dermal	
Urea compound C	Inhalation	

[a] Applies only to the non-conveyorized process configuration.
[b] Applies to either process configuration.

Lead

Risk results for workers from lead in the HASL process are presented in Section 3.4.6.

Ambient (Outdoor) Environment

Potential risks are evaluated from exposure to chemicals released to outdoor air from a PWB facility. Inhalation is the only exposure route to be quantified for people living nearby a model PWB facility.

Cancer Risk. As with the occupational setting, the nickel/gold process is the only process for which cancer risk to humans in the ambient (outdoor) environment has been estimated. These results for the non-conveyorized nickel/gold process, assuming that emissions are vented to the outside, are an upper bound excess[20] individual lifetime cancer risk for nearby residents of 2×10^{-11}. Inorganic metallic salt A is a human carcinogen.[21] These estimates indicate low concern and are interpreted to mean that, over a lifetime, an individual resident is expected to have no more than one chance in 50 billion of developing cancer from exposure to inorganic metallic salt A from a nearby facility using the non-conveyorized process.

None of the other process alternatives use chemicals for which cancer slope factors were available, so no other cancer risks were estimated. Other identified chemicals in the surface finishing processes are suspected carcinogens, but do not have established slope factors. Lead and thiourea have been determined by IARC to be possible human carcinogens (IARC Group 2B); lead has also been classified by EPA as a probable human carcinogen (EPA Class B2). Lead is used in tin-lead solder in the HASL process. Thiourea is used in the immersion tin process. Urea compound B, a confidential ingredient in the nickel/gold and nickel/palladium/gold processes, is possibly carcinogenic to humans. Exposure for nearby residents from these chemicals has been estimated, but cancer potency and cancer risks are unknown. Additionally, strong inorganic and acid mists of sulfuric acid have been determined by IARC to be a human carcinogen (IARC Group 1). Sulfuric acid is used in diluted form in every surface finishing process in this evaluation. It is not expected, however, to be released to the environment as a strong acid mist.

Non-Cancer Risk. All HQs are less than one for ambient exposure to the general population, indicating low concern from the estimated air concentrations. An MOE was calculated for chemicals if an inhalation LOAEL or NOAEL was available and an RfC was not. All MOEs for ambient exposure are greater than 1,000 for all processes, indicating low concern.

These results suggest there is low risk to nearby residents, based on incomplete but best available data. Data limitations include the use of modeled air concentrations using data compiled for a model facility rather than site-specific, measured concentrations. For estimating ambient (outdoor) air concentrations, one key assumption is that no air pollution control technologies are used to remove airborne chemicals from facility air prior to venting it to the outside. Other data limitations are the lack of solid waste data to characterize exposure routes in addition to inhalation, and lack of toxicity data for many chemicals.

---

[20] *Upper bound* refers to the method of determining a slope factor, where the upper bound value (generated from a certain probability statement) for the slope of the dose-response curve is used. *Excess* means the estimated cancer risk is in addition to the already-existing background risk of an individual contracting cancer from all other causes.

[21] A cancer classification of known human carcinogen has been assigned by either the EPA, IARC, and/or NTP. Further details about the carcinogen classification are not provided in order to protect the confidential chemical's identity.

Lead. Risk results for people living near a PWB facility from lead in the HASL process are presented below in Section 3.4.6.

3.4.6 Evaluation of Lead Risks from Tin-Lead Solder Used in the HASL Process

Although classified as a probable carcinogen by EPA, and known to cause other serious health effects from chronic exposure, EPA has not derived a cancer slope factor, an RfD, or an RfC for lead. Therefore, it is not possible to calculate a cancer risk, and the standard approach of calculating an HQ to assess non-cancer health risks is not used for lead. Instead, lead exposure is estimated using one of two exposure-biokinetic models, the Interim Adult Lead Methodology (U.S. EPA, 1996a) and the Integrated Exposure Uptake Biokinetic Model for Lead in Children (U.S. EPA, 1994). Both of these models relate estimated exposure levels to a lead concentration in blood, which can then be compared to blood-lead levels at which health effects are known to occur. These models are described further in Section 3.2.4 of the Exposure Assessment.

Table 3-34 presents federal (and other) regulations and guidelines for lead. This table also presents comparable lead exposure values for workers and the ambient environment potentially resulting from the lead in tin-lead solder used in the HASL process. For workers, the lowest federal target or action levels are from OSHA and ACGIH, at 30 µg/dL in blood. By comparison, the 5 to 12 µg/dL blood-lead levels from actual facility monitoring data for HASL line operators are below this level. These monitoring data are limited to one facility, however.

We also modeled worker blood-lead levels using EPA's Adult Lead Methodology. Estimated adult worker blood-lead levels (central estimate) from the model range from 2 to 63 µg/dL, depending on the worker's lead intake rate. This estimate is higher than the limited available monitoring data, with workers' measured blood-lead levels from 5 to 12 µg/dL. Estimated lead exposure using this model are very uncertain and could vary greatly depending on worker activities. The ALM model was run based on the assumption that a worker gets lead on his/her hands from handling solder, and then accidentally ingests some of that lead (e.g., by eating or smoking without thoroughly washing their hands). The amount of lead ingested this way is highly uncertain. Results from the model are based on a "conservative overestimate" from surface wipe samples in hand soldering operations of 0.03 mg/day (Monsalve, 1984) and on a range of soil ingestion rates of 10 to 50 mg/day for an adult in contact with soil (Stanek et al., 1997 and U.S. EPA 1997a), respectively.[22] (Ingestion data are not available specifically for a HASL worker handling solder.) However, these results do indicate that there may be risk from lead exposure via the ingestion route from poor hygiene practices.

[22] 10 mg/day is an average estimate; 50 mg/day is a central tendency estimate.

Table 3-34. Risk Evaluation Summary for Lead

Federal Regulations and Guidelines for Lead			Lowest Federal Level	Comparable Lead Exposure Values	
Workplace					
Worker blood-lead target/action levels	OSHA, adults "who wish to bear children"	30 µg/100g	30 µg/dL	Occupational blood-lead monitoring data.	5 - 12 µg/dL
	OSHA, blood-lead level of concern	40 µg/dL		Modeled (ALM) blood-lead data for an adult worker.	2 - 63 µg/dL (depending on intake rate)
	OSHA, medical removal	50 µg/dL			
	ACGIH (ACGIH, 1998)	30 µg/dL			
	NIOSH, level to be maintained through air concentrations	60 µg/100 g			
Pregnant worker: fetal blood-lead target/action levels	OSHA	30 µg/100g	10 µg/dL	Modeled (ALM) fetal blood-lead level.	3 - 102 µg/dL (depending on maternal intake rate)
	CDC	10 µg/dL [a]			
Workplace air exposure limit	OSHA PEL (8 hr TWA)	50 µg/m^3	50 µg/m^3	Workplace air monitoring data (average of HASL process area monitoring data provided by one PWB manufacturer).	3 µg/m^3
	NIOSH REL (NIOSH, 1994)	100 µg/m^3			
	ACGIH TLV TWA (ACGIH, 1998)	50 µg/m^3			
Ambient Environment					
Ambient air concentration	National Ambient Air Quality Standard, (U.S. EPA, 1987b)	1.5 µg/m^3 (averaged over 3 mo.)	1.5 µg/m^3	Ambient air concentrations near a PWB facility based on HASL workplace air monitoring data and air dispersion model.	0.00009 µg/m^3
Blood-lead target/action levels for child	CDC	10 µg/m^3	10 µg/m^3	Not determined. The IEUBK model estimates blood- lead levels for children age 0 through 6 years. However, estimated ambient air concentration from a HASL process are 1,000 times lower than the default value for air in the model. IEUBK model results using default values range from 2.7 to 4.5 µg/dL.	
	OSHA	30 µg/100g			
	International: WHO blood lead level of concern (WHO, 1986)	20 µg/dL			

[a] CDC considers children to have an elevated level of lead if the amount of lead in the blood is at least 10 µg/dL. Medical evaluation and environmental remediation should be done for all children with blood levels > 20 µg/dL. Medical treatment may be necessary in children if the blood lead concentration is > 45 µg/dL (RTI, 1999).

NOTES:
ACGIH: American Conference of Governmental Industrial Hygienists, Inc.
CDC: Centers for Disease Control and Prevention.
EPA: U.S. Environmental Protection Agency.
NIOSH: National Institute for Occupational Safety and Health.
OSHA: Occupational Safety and Health Administration.
WHO: World Health Organization.
PEL: Permissible Exposure Limit.
REL: Recommended Exposure Level.
TWA: Time-weighted average.
TLV: Threshold limit value.
ALM: Adult Lead Methodology.
IEUBK: Integrated Exposure Uptake Biokinetic Model for Lead in Children.
About units: µg/dL = micrograms of elemental lead per deciliter (100 mL) of blood; 100 g blood is approximately equal to 100 mL or 1 dL.

In addition to an adult worker, we used the ALM to model potential fetal blood-lead levels, assuming a pregnant HASL line operator is exposed to lead through incidental ingestion. Estimated 95th percentile fetal blood-lead levels of from 3.2 to 100 µg/dL can be compared to the guidance level from CDC and EPA of 10 µg/dL for children.[23] Again, these estimates are based on uncertain ingestion rates.

Estimated workplace and ambient air concentration of lead also can be compared directly to air regulations and guidelines for airborne lead from federal agencies (e.g., U.S. EPA, OSHA) and the World Health Organization (WHO). For the workplace, an average of air monitoring data from one PWB manufacturer[24] of 3 µg/m^3 can be compared to the lowest federal regulatory level of 50 µg/m^3 (an OSHA, 8-hour, time-weighted average permissible exposure limit). For ambient air near a facility, an estimated air concentration of 0.0001 µg/m^3 is well below the EPA air regulation of 1.5 µg/m. (Ambient air modeling from a PWB facility is described further in Section 3.2.3 of the Exposure Assessment.) It should be noted that these air monitoring data are also limited to only one PWB manufacturer, and may vary from facility to facility.

The recommended approach for evaluating lead exposure to nearby residents is to apply the IEUBK model to estimate blood-lead levels in children who may be exposed. (This is discussed further in Section 3.2.4.) The default air concentration set in the model, based on average 1990 U.S. urban air levels, is 1,000 times higher than the ambient air concentration estimated from a HASL process. The IEUBK model could not discern any difference in children's blood-lead levels based on such a small incremental increase in background air concentrations. Based on these results, risks from lead exposure to nearby residents is expected to be below concern levels.

3.4.7 Results of Calculating Ecological (Aquatic) Risk Indicators

We calculated ecological risk indicators (RI_{ECO}) for aquatic organisms as a unitless ratio:

$$RI_{ECO} = C_{SW} / CC$$

where,

C_{SW} = estimated surface water concentration following treatment in a POTW (mg/l)
CC = concern concentration (mg/l)

The method for estimating surface water concentrations is described in Section 3.2.3 of the Exposure Assessment. Exposure concentrations below the CC are assumed to present low risk to aquatic species. An ecological risk indicator greater than one indicates that the estimated

---

[23] CDC considers children to have an elevated level of lead if the amount of lead in the blood is at least 10 µg/dL. Medical evaluation and environmental remediation should be done for all children with blood-lead levels $20 µg/dL. Medical treatment may be necessary in children if the blood-lead concentration is > 45 µg/dL (RTI, 1999).

[24] Results from both personal monitoring for HASL line operators and air samples from the HASL process area were averaged.

chemical concentration exceeds the concentration of concern for the aquatic environment based on chemical toxicity to aquatic organisms. The level of concern increases as the ratio of exposure concentration to CC increases. the derivation of CCs is described in Section 3.3.3 of the Human Health and Ecological Hazards Summary and in Appendix H.

The results for non-metal surface finishing chemicals are summarized in Table 3-35. Estimated surface water concentrations of several non-metals exceed the CC, as follows:

- alkylaryl sulfonate, 1,4-butenediol, hydrogen peroxide, and potassium peroxymonosulfate in the non-conveyorized HASL process;
- alkylaryl sulfonate, hydrogen peroxide, and potassium peroxymonosulfate in the conveyorized HASL process;
- alkylaryl imidazole in non-conveyorized and conveyorized configurations of the OSP process;
- hydrogen peroxide in the conveyorized immersion silver process; and
- potassium peroxymonosulfate in the non-conveyorized the immersion tin process (the estimated surface water concentration per thiourea is equal to the CC).

Table 3-35. Summary of Aquatic Risk Indicators for Non-Metal Chemicals of Concern

Chemical	CC (mg/L)	Aquatic Risk Indicator (RI_{ECO})					
		HASL (NC)	HASL (C)	OSP (NC)	OSP (C)	Imm. Silver (C)	Imm. Tin (NC)
1,4-Butenediol	0.008	1.3	NA	NA	NA	NA	NA
Alkylaryl imidazole	0.001 - 0.005	NA	NA	6.6 - 33	3.6 - 18	NA	NA
Alkylaryl sulfonate	0.001 - 0.005	1 - 5	0.7 - 3.5	NA	NA	NA	NA
Hydrogen peroxide	0.02	2.0	1.5	NA	NA	1.3	NA
Potassium peroxymonosulfate	0.01	8.2	6.1	NA	NA	NA	3.6
Thiourea	0.03	NA	NA	NA	NA	NA	1.0 [a]

[a] Estimated surface water concentration is equal to the CC; this is not counted as an exceedance.
NA: Not applicable; estimated surface water concentration is less than CC or the chemical is not an ingredient of that process configuration.
NC: Non-conveyorized.
C: Conveyorized.

It is assumed that on-site treatment is targeted to remove metals so that permitted concentrations are not exceeded. If on-site treatment is not used to remove metals, high aquatic risk indicators are possible. The ratio of estimated surface water concentration to CC for metals is presented in Table 3-36. These data are presented to highlight the importance of on-site treatment for toxic metals; because on-site treatment is expected to be performed to meet water discharge permit requirements, these results are not used in comparing potential aquatic risks among surface finishing alternatives.

Table 3-36. Summary of Aquatic Risk Indicators for Metals Assuming No On-Site Treatment

Chemical	CC (mg/L)	Aquatic Risk Indicator (RI_{ECO})					
		HASL (NC)	HASL (C)	Nickel/ Gold	Nickel/ Palladium/ Gold	OSP (NC)	OSP (C)
Copper ion	0.001	NA	NA	NA	NA	46	25
Copper sulfate pentahydrate	0.01	5.1	3.8	NA	NA	6.3	5.1
Nickel sulfate	0.01	NA	NA	5.1	5.5	NA	NA
Potassium gold cyanide	0.003	NA	NA	1.5	NA	NA	NA

NA: Not applicable; estimated surface water concentration is less than CC or the chemical is not an ingredient of that process configuration.
NC: Non-conveyorized.
C: Conveyorized.

3.4.8 Uncertainties

An important component of any risk characterization is the identification and discussion of uncertainties. There are uncertainties involved in the measurement and selection of hazard data, and in the data, models, and scenarios used in the Exposure Assessment. Any use of the risk characterization should include consideration of these uncertainties.

Uncertainties in the Exposure Assessment include the following:

- accuracy of the description of exposure setting: how well the model facility used in the assessment characterizes an actual facility; the likelihood of exposure pathways actually occurring (scenario uncertainty);
- missing data and limitations of workplace practices data: this includes possible effects of any chemicals that may not have been included (e.g., minor ingredients in the formulations); possible effects of side reactions in the baths which were not considered; and questionnaire data with limited facility responses;
- estimating exposure levels from averaged data and modeling in the absence of measured, site-specific data;
- data limitations in the Source Release Assessment: releases to land could not be characterized quantitatively;
- chemical fate and transport model applicability and assumptions: how well the models and assumptions represent the situation being assessed and the extent to which the models have been validated or verified (model uncertainty);
- parameter value uncertainty, including measurement error, sampling (or survey) error, parameter variability, and professional judgement; and
- uncertainties in estimating exposure to lead, especially with assumptions made about hand-to-mouth lead intake rates for workers.

Key assumptions made in the Exposure Assessment are discussed in Section 3.4.1.

Uncertainties in the human health hazard data (as typically encountered in a hazard assessment) include the following:

- using dose-response data from high dose studies to predict effects that may occur at low levels;
- using data from short-term studies to predict the effects of long-term exposures;
- using dose-response data from laboratory animals to predict effects in humans;
- using data from homogeneous populations of laboratory animals or healthy human populations to predict the effects on the general human population, with a wide range of sensitivities (uncertainty due to natural variations in human populations);
- using LOAELs and NOAELs in the absence of peer-reviewed RfDs and RfCs;
- possible increased or decreased toxicity resulting from chemical interactions;
- assuming a linear dose-response relationship for cancer risk (in this case for inorganic metallic salt A);
- effects of chemical mixtures not included in toxicity testing (effects may be independent, additive, synergistic, or antagonistic); and
- possible effects of substances not evaluated because of a lack of chronic/subchronic toxicity data.

Uncertainties in the ecological hazards data and ecological risk characterization, which attempt to evaluate potential ecotoxicity impacts to aquatic organisms from long-term (chronic) exposure in a receiving stream, include the following:

- use of laboratory toxicity data to evaluate the effects of exposure in a stream;
- use of estimated toxicity data in the absence of measured data;
- use of data from acute exposure to evaluate the effect of chronic exposures;
- variation in species sensitivity; and
- uncertainties in estimating surface water concentrations from the drag-out model and predicted POTW treatment efficiencies; also, surface water concentrations are based on estimated releases to a modeled stream flow for the electronics industrial sector.

Another source of uncertainty comes from use of structure-activity relationships (SARs) for estimating human health hazards in the absence of experimental toxicity data. Specifically, this was done for: aliphatic acid B, aliphatic dicarboxylic acid A, alkylalkyne diol, alkylamino acid A, alkylaryl imidazole, alkylaryl sulfonate, alkylimine dialkanol, amino acid salt, ammonia compound B, aryl phenol, bismuth compound, 1,4-butenediol, citric acid, ethoxylated alkylphenol, fatty amine, hydroxyaryl acid, hydroxyaryl sulfonate, maleic acid, malic acid, potassium compound, potassium peroxymonosulfate, quaternary alkylammonium chlorides, sodium benzene sulfonate, sodium hypophosphite, sodium hypophosphite monohydrate, substituted amine hydrochloride, and transition metal salt.

Uncertainties in assessing risk from dermal exposure come from the use of toxicological potency factors from studies with a different route of exposure than the one under evaluation (i.e., using oral toxicity measures to estimate dermal risk). This was done for chemicals with oral RfDs and chemicals with oral NOAELs or LOAELs (as noted in Tables 3-25 and 3-26).

Uncertainties in dermal risk estimates also stem from the use of default values for missing gastrointestinal absorption data. Specifically, this was done for: aliphatic acid E, aliphatic dicarboxylic acid C, alkylamino acid B, alkylpolyol, amino carboxylic acid, fluoboric acid, gum, hydrogen peroxide, hydroxy carboxylic acid, nitrogen acid, potassium gold cyanide, propionic acid, stannous methane sulfonic acid, and sulfuric acid, and urea compound C.

Finally, the risk characterization does not address the potential adverse health effects associated with acute exposure to peak levels of chemicals. This type of exposure is especially important when evaluating developmental risks associated with exposure.

3.4.9 Conclusions

This risk characterization uses a health-hazard based framework and a model facility approach to compare the potential health risks of one surface finishing process technology to the potential risks associated with switching to an alternative technology. As much as possible, reasonable and consistent assumptions are used across alternatives. Data to characterize the model facility and exposure patterns for each process alternative were aggregated from a number of sources, including PWB shops in the U.S., supplier data, and input from PWB manufacturers at project meetings. Thus, the model facility is not entirely representative of any one facility, and actual risk could vary substantially, depending on site-specific operating conditions and other factors.

When using the results of this risk characterization to compare potential health effects among alternatives, it is important to remember that this is a screening level rather than a comprehensive risk characterization, both because of the predefined scope of the assessment and because of exposure and hazard data limitations. It should also be noted that this approach does not result in any absolute estimates or measurements of risk, and even for comparative purposes, there are several important uncertainties associated with this assessment.

Another significant source of uncertainty is the limited data available for dermal toxicity and the use of oral to dermal extrapolation when dermal toxicity data were unavailable. There is high uncertainty in using oral data for dermal exposure and in estimating dermal absorption rates, which could result in either over- or under-estimates of exposure and risk.

A third significant source of uncertainty is from the use of SARs to estimate toxicity in the absence of measured toxicity data, and the lack of peer-reviewed toxicity data for many surface finishing chemicals. Other uncertainties associated with the toxicity data include the possible effects of chemical interactions on health risks, and extrapolation of animal data to estimate human health risks from exposure to inorganic metallic salt A and other PWB chemicals.

Another major source of uncertainty in estimating exposure is the reliance on modeled data (i.e., modeled air concentrations) to estimate worker and ambient exposure. It should also be noted that there is no comparative evaluation of the severity of effects for which HQs and MOEs are reported.

The Exposure Assessment for this risk characterization, whenever possible, used a combination of central tendency and high-end assumptions, as would be used for an overall high-end exposure estimate. Some values used in the exposure calculations, however, are better characterized as "what-if," especially pertaining to exposure frequency, bath concentrations, use of gloves, and process area ventilation rates for a model facility. Because some part of the exposure assessment for both inhalation and dermal exposures qualifies as a "what-if" descriptor, the entire assessment should be considered "what-if."

Occupational Exposures and Risks

Health risks to workers were estimated for inhalation exposure to vapors and aerosols from surface finishing baths and for dermal exposure to surface finishing bath chemicals. Inhalation exposure estimates are based on the assumptions that emissions to indoor air from conveyorized lines are negligible, that the air in the process room is completely mixed and chemical concentrations are constant over time, and that no vapor control devices (e.g., bath covers) are used in non-conveyorized lines. Dermal exposure estimates are based on the assumption that workers do not wear gloves and that all non-conveyorized lines are operated by manual hoist. Dermal exposure to line operators on non-conveyorized lines is estimated for routine line operation and maintenance (e.g., bath replacement, filter replacement), and on conveyorized lines for bath maintenance activities alone.

Based on the number of chemicals with risk results above concern levels, some alternatives to the non-conveyorized HASL process appear to pose lower occupational risks (i.e., conveyorized immersion silver, conveyorized and non-conveyorized immersion tin, and conveyorized HASL), some may pose similar levels of risk (i.e., conveyorized and non-conveyorized OSP), and some may pose higher risk (i.e., non-conveyorized nickel/gold and nickel/palladium/gold). There are occupational inhalation risk concerns for chemicals in the non-conveyorized HASL, nickel/gold, nickel/palladium/gold, and OSP processes. There are also occupational risk concerns for dermal contact with chemicals in the non-conveyorized HASL, nickel/gold, nickel/palladium/gold, OSP, and immersion tin processes, and the conveyorized HASL and OSP processes.

Cancer Risk. The non-conveyorized nickel/gold process contains the only chemical for which an occupational cancer risk has been estimated (inorganic metallic salt A). The line operator inhalation exposure estimate for inorganic metallic salt A results in an estimated upper bound excess individual life time cancer risk of 2×10^{-7} (one in five million) based on high end exposure. Cancer risks less than 1×10^{-6} (one in one million) are generally considered to be of low concern. Risks to other types of workers[25] were assumed to be proportional to the average amount of time spent in the process area, which ranged from 12 to 69 percent of the risk for a line operator.

[25] These include laboratory technicians, maintenance workers, supervisors, and wastewater treatment operators. Other types of workers may be present for shorter or longer times.

Other identified chemicals in the surface finishing processes are suspected or known carcinogens. Lead and thiourea have been determined by IARC to be possible human carcinogens (IARC Group 2B); lead has also been classified by EPA as a probable human carcinogen (EPA Class B2). Lead is used in tin-lead solder in the HASL process. Thiourea is used in the immersion tin process. Urea compound B, a confidential ingredient in the nickel/gold and nickel/palladium/gold processes, is possibly carcinogenic to humans. Exposure for workers from these chemicals has been estimated, but cancer potency and cancer risks are unknown. Additionally, strong inorganic and acid mists of sulfuric acid have been determined by IARC to be a human carcinogen (IARC Group 1). Sulfuric acid is used in diluted form in every surface finishing process in this evaluation. It is not expected, however, to be released to the air as a strong acid mist. There are potential cancer risks to workers from these chemicals, but because there are no slope factors, the risks cannot be quantified.

Non-Cancer Risk. For non-cancer risk, HQs greater than one, NOAEL-based MOEs lower than 100, or LOAEL-based MOEs lower than 1,000 were estimated for occupational exposures to chemicals in the non-conveyorized and conveyorized HASL processes, non-conveyorized nickel/gold process, non-conveyorized nickel/palladium/gold process, non-conveyorized and conveyorized OSP processes, and the non-conveyorized immersion tin process.

Based on calculated occupational exposure levels, there may be adverse health effects to workers exposed to chemicals with an HQ exceeding 1.0 or an MOE less than 100 or 1,000. However, it should be emphasized that these conclusions are based on screening level estimates. These numbers are used here for relative risk comparisons between processes, and should not be used as absolute indicators for actual health risks to surface finishing line workers.

Lead. Worker blood-lead levels measured at one PWB manufacturing facility were below any federal regulation or guideline for workplace exposure. Modeling data, however, indicate that blood-lead levels could exceed recommended levels for an adult and fetus, given high incidental ingestion rates of lead from handling solder. These results are highly uncertain; ingestion rates are based on surface wipe samples from hand soldering operations and on incidental soil ingestion rates for adults in contact with soil. However, this indicates the need for good personal hygiene for HASL line operators, especially wearing gloves and washing hands to prevent accidental hand-to-mouth ingestion of lead.

Public Health Risks

Potential public health risk was estimated for inhalation exposure for the general public living near a PWB facility. Public exposure estimates are based on the assumption that emissions from both conveyorized and non-conveyorized process configurations are vented to the outside. The risk indicators for ambient exposures to humans, although limited to airborne releases, indicate low concern for nearby residents. The upper bound excess individual cancer risk for nearby residents from inorganic metallic salt A in the non-conveyorized nickel/gold process was estimated to be from approaching zero to 2×10^{-11} (one in 50 billion). This chemical has been

classified as a human carcinogen.[26] All hazard quotients are less than one for ambient exposure to the general population, and all MOEs for ambient exposure are greater than 1,000 for all processes, indicating low concern from the estimated air concentrations for chronic non-cancer effects.

Estimated ambient air concentrations of lead from a HASL process are well below EPA air regulatory limits for lead, and risks to the nearby population from airborne lead are expected to be below concern levels.

Ecological Risks

We calculated ecological risk indicators (RI_{ECO}) for non-metal surface finishing chemicals that may be released to surface water. Risk indicators for metals are not used for comparing alternatives because it is assumed that on-site treatment is targeted to remove metals so that permitted concentrations are not exceeded. Estimated surface water concentrations for non-metals exceeded the CC in the following processes: four in the non-conveyorized HASL process, three in the conveyorized HASL process, one in the non-conveyorized OSP process, one in the conveyorized OSP process, one in the conveyorized immersion silver process, and one in the non-conveyorized immersion tin process.

Overall Risk Screening and Comparison Summary

Table 3-37 presents an overall comparison of potential human health and ecological risks for the baseline (non-conveyorized HASL) and the alternative process configurations.

[26] A cancer classification of known human carcinogen has been assigned by either the EPA, IARC, and/or NTP. Further details about the carcinogen classification are not provided in order to protect the confidential chemical identity.

Table 3-37. Overall Comparison of Potential Human Health and Ecological Risks for the Non-Conveyorized HASL and Alternative Processes

Process	Number of Chemicals					
	Potential Carcinogen [a]	Inhalation Concern [b]	Dermal Concern [c]	Inhalation Data Gaps [d]	Dermal Data Gaps [e]	Aquatic Concern [f]
HASL (NC) (Baseline)	2	1	1+ lead	3	6	4
HASL (C)	2	0	1+ lead	0	6	3
Nickel/Gold (NC)	3	5	6	10	8	0
Nickel/Palladium/Gold (NC)	1	6	6	9	7	0
OSP (NC)	1	1	3	2	5	1
OSP (C)	1	0	2	0	5	1
Immersion Silver (C)	1	0	0	0	4	1
Immersion Tin (NC)	1	0	1	2	5	1
Immersion Tin (C)	1	0	0	0	5	0

[a] The number of chemicals with an EPA cancer WOE of A, B1, or B2, or an IARC WOE of 1, 2A, or 2B (see Table 3-21).
[b] The number of chemicals for which the HQ for worker inhalation exceeds 1, the NOAEL-based MOE is less than 100, or the LOAEL-based MOE is less than 1,000. See Table 3-30 for detailed results.
[c] The number of chemicals for which the HQ for dermal contact by workers exceeds 1, the NOAEL-based MOE is less than 100, or the LOAEL-based MOE is less than 1,000. See Table 3-30 for detailed results.
[d] The number of chemicals for which worker inhalation exposure is possible, but appropriate toxicity data are not available for calculating a risk indicator (see Table 3-33).
[e] The number of chemicals for which worker dermal contact is possible but appropriate toxicity data are not available for calculating a risk indicator (see Table 3-33).
[f] The number of chemicals for which the ecological risk indicators exceeds the concern level (i.e., $RI_{eco} > 1.0$). See Table 3-35 for detailed results.

3.5 PROCESS SAFETY ASSESSMENT

Process safety is a concern and responsibility of employers and employees alike. Each company has the obligation to provide its employees with a safe and healthy work environment, while each employee is responsible for his/her own safe personal work habits. In the surface finishing process of PWB manufacturing, hazards may be either chemical or process hazards. Chemicals used in the surface finishing process can be hazardous to worker health and, therefore, must be handled and stored properly, using appropriate personal protective equipment and safe operating practices. Automated equipment can be hazardous to employees if safe procedures for cleaning, maintaining, and operating the equipment are not established and regularly performed. These hazards can result in serious injury and health problems to employees, and potential damage to equipment.

The U.S. Department of Labor and the Occupational Safety and Health Administration (OSHA) have established safety standards and regulations to assist employers in creating a safe working environment and protecting workers from potential workplace hazards. In addition, individual states may also have safety standards regulating chemical and physical workplace hazards for many industries. Federal safety standards and regulations affecting the PWB industry can be found in the Code of Federal Regulations (CFR) Title 29, Part 1910, and are available by contacting your local OSHA field office. State and local regulations are available from the appropriate state office.

An effective process safety program identifies potential workplace hazards and, if possible, seeks to eliminate or at least reduce their potential for harm. Some companies have successfully integrated the process safety program into their ISO 14000 certification plan, often establishing process safety practices that go beyond OSHA regulations. This section of the CTSA presents chemical and process safety concerns associated with the surface finishing baseline technology and substitutes, as well as OSHA requirements to mitigate these concerns.

3.5.1 Chemical Safety Concerns

As part of its mission, OSHA's Hazard Communication Standard (29 CFR 1910.1200) requires that chemical containers be labeled properly with chemical name and warning information [.1200(f)], that employees be trained in chemical handling and safety procedures [.1200(h)], and that a MSDS be created and made available to employees for every chemical or chemical formulation used in the workplace [.1200(g)]. Each MSDS must be in English and include information regarding the specific chemical identity and common name of the hazardous chemical ingredients. In addition, information must be provided on the physical and chemical characteristics of the hazardous chemical(s), known acute and chronic health effects and related health information, exposure limits, whether the chemical is a carcinogen, emergency and first-aid procedures, and the identification of the organization preparing the data sheet. Copies of MSDSs for all of the chemicals/chemical formulations used must be kept and made available to workers who may come into contact with the process chemicals during their regular work shift.

In order to evaluate the chemical safety concerns of the various surface finishing processes, MSDSs for 37 chemical products comprising six surface finishing technology categories were collected and reviewed for potential hazards to worker safety. MSDSs were not received for five confidential chemical products. Chemical safety data for pure chemical compounds not sold as products were obtained from the Merck Index (Budavari, 1989).

Evaluating the chemical safety concerns specific to the HASL process baths was not possible because there are no suppliers of microetch or cleaner baths made specifically for the HASL process. Manufacturers will typically use the same microetch and cleaner formulation that is used as part of another process line (e.g., the microetch and cleaner used in the making holes conductive line). The chemical safety hazards for the HASL baths are similar to those reported by the other processes for the same bath type. Therefore, the worse case bath from another process was selected and reported for the HASL process to indicate the maximum safety hazard which could be associated with the HASL process bath. Actual safety hazards for the bath will depend greatly on the bath chemistry selected, and so may be less than the stated values.

Alternative processes with more than one product line submitted for evaluation were treated in a similar manner to the HASL process. For each bath category, the actual bath which posed the greatest hazard for each chemical hazard category was listed. For example, the microetch bath which posed the greatest hazard, out of the two microetch baths submitted for OSP, was listed for the OSP process

The results of that review are summarized and discussed in the sections below. General information on OSHA storage and handling requirements for chemicals is located in Section 3.5.3. For a more detailed description of OSHA storage and handling requirements for surface finishing chemical products, contact your area OSHA field office or state technical assistance program.

Flammable, Combustible, and Explosive Surface Finishing Chemical Products

Table 3-38 presents a breakdown of surface finishing chemical products that, when in concentrated form, are flammable, combustible, explosive, or pose a fire hazard. The following lists OSHA definitions for chemicals in these categories, and discusses the data presented in the table.

Table 3-38. Flammable, Combustible, Explosive, and Fire Hazard Possibilities for Surface Finishing Processes

Surface Finishing Process	Bath Type	Hazardous Property [a, b]			
		Flammable	Combustible	Explosive	Fire Hazard
HASL [c]	Cleaner Microetch	 1(3)		1(1)	1(1) 2(3)
OSP [d] (2 product lines)	Microetch	1(3)			2(3)
Immersion Silver	Cleaner			1(1)	1(1)
Immersion Tin [d] (2 product lines)	Immersion Tin			1(4)	

[a] Table entries are made in the following format - # of products meeting OSHA definition for the given hazardous property, as reported in the products' MSDSs (Total # of products in the process bath). A **blank** entry means that none of the products for the specific process bath meet the OSHA reporting criteria for the given property. Example: For the immersion tin bath, 1 (4) means that one of the four products in the bath were classified as explosive per OSHA criteria, as reported on the products' MSDSs.
[b] Data for pure chemicals (e.g., sulfuric acid) not sold as products were obtained from the Merck Index (Budavari, 1989) and included in category totals.
[c] Formulations for HASL process baths were unavailable because cleaner and microetch bath chemistries are not made specifically for the HASL process. Hazards reported for HASL bath types were reported as the worst case of the results of similar baths from other processes.
[d] For alternative processes with more than one product line, the hazard data reported represents the most hazardous bath of each type for the two product lines (e.g., of the microetch baths from the two product lines, the one with the most hazardous chemicals is reported).

Flammable - A flammable chemical is defined by OSHA [29 CFR 1910.1200(c)] as one of the following:

- An aerosol that, when tested by the method described in 16 CFR 1500.45, yields a flame projection exceeding 18 inches at full valve opening, or a flashback at any degree of valve opening.
- A gas that: 1) at ambient temperature and pressure, forms a flammable mixture with air at a concentration of 13 percent by volume or less; or 2) when it, at ambient temperature and pressure, forms a range of flammable mixtures with air wider than 12 percent by volume, regardless of the lower limit.
- A liquid that has a flashpoint below 100 °F (37.8 °C), except any mixture having components with flashpoints of 100 °F (37.8 °C) or higher, the total of which make up 99 percent or more of the total volume of the mixture.
- A solid, other than a blasting agent or explosive as defined in 29 CFR 1910.109(a), that is liable to cause fire through friction, absorption of moisture, spontaneous chemical change, or retained heat from manufacturing or processing, or which can be ignited readily and when ignited burns so vigorously and persistently as to create a serious hazard.

Two chemical products are reported as flammable according to MSDS data. Although the chemicals are flammable in their concentrated form, none of the chemical baths in the surface finishing line contain flammable aqueous solutions.

Combustible Liquid - As defined by OSHA [29 CFR 1910.1200(c)], a liquid that is considered combustible has a flashpoint at or above 100 °F (37.8 °C), but below 200 °F (93.3 °C), except any mixture having components with flashpoints of 200 °F (93.3 °C), or higher, the total volume of which make up 99 percent or more of the total volume of the mixture. None of the chemical products have been reported as combustible by their MSDSs.

Explosive - As defined by OSHA [29 CFR 1910.1200(c)], a chemical is considered explosive if it causes a sudden, almost instantaneous release of pressure, gas, and heat when subjected to sudden shock, pressure, or high temperature. Three chemical products are reported as explosive by their MSDSs.

Fire Hazard - A chemical product that is a potential fire hazard is required by OSHA to be reported on the product's MSDS. According to MSDS data, six chemical products are reported as potential fire hazards.

Corrosive, Oxidizer, and Reactive Surface Finishing Chemical Products

A breakdown of surface finishing chemical baths containing chemical products that are corrosive, oxidizers, or reactive in their concentrated form is presented in Table 3-39. The table also lists process baths that contain chemical products that may cause a sudden release of pressure when opened. The following lists OSHA definitions for chemicals in these categories and discusses the data presented in the table.

Corrosive - As defined by OSHA (29 CFR 1910.1200 [Appendix A]), a chemical is considered corrosive if it causes visible destruction of, or irreversible alterations in, living tissue by chemical action at the site of contact following an exposure period of four hours, as determined by the test method described by the U.S. Department of Transportation, 49 CFR Part 173, Appendix A. This term does not apply to chemical action on inanimate surfaces. A review of MSDS data found that 37 surface finishing chemical products are reported as corrosive in their concentrated form. Some surface finishing baths may also be corrosive, but MSDSs do not provide data for the process chemical baths once they are prepared.

Oxidizer - As defined by OSHA (29 CFR 1910.1200[c]), an oxidizer is a chemical other than a blasting agent or explosive as defined by OSHA [29 CFR 1910.109(a)], that initiates or promotes combustion in other materials, thereby causing fire either of itself or through the release of oxygen or other gases. Five chemical products are reported as oxidizers, according to MSDS data.

Table 3-39. Corrosive, Oxidizer, Reactive, Unstable, and Sudden Release of Pressure Possibilities for Surface Finishing Processes

Surface Finishing Process	Bath Type	Hazardous Property [a, b]				
		Corrosive	Oxidizer	Reactive	Unstable	Sudden Release of Pressure
HASL [c]	Cleaner	1(1)				
	Microetch	3(4)	1(3)		1(3)	1(4)
Nickel/Gold [d] (2 product lines)	Cleaner	1(1)				
	Microetch	3(4)	1(4)			1(4)
	Catalyst	3(3)				
	Acid Dip	1(1)				
Nickel/Palladium/Gold	Cleaner	1(1)				
	Microetch	3(4)	1(4)			1(4)
	Catalyst	3(3)				
	Activator	1(4)				
	Electroless Nickel	3(3)				
	Electroless Palladium	1(3)				
OSP [d] (2 product lines)	Cleaner	1(1)				
	Microetch	3(4)	1(3)			1(4)
Immersion Silver	Cleaner	1(1)				
	Microetch	1(3)	1(3)		1(3)	
Immersion Tin [d] (2 product lines)	Cleaner [c]	1(2)				
	Microetch	2(2)				
	Predip	1(1)				
	Immersion Tin	3(4)				

[a] Table entries are made in the following format - # of products meeting OSHA definition for the given hazardous property, as reported in the products' MSDSs (Total # of products in the process bath). A **blank** entry means that none of the products for the specific process bath meet the OSHA reporting criteria for the given property. Example: For the immersion tin bath, 3(4) means that four of the five products in the bath were classified as corrosive per OSHA criteria, as reported by the products' MSDSs.

[b] Data for pure chemicals (e.g., sulfuric acid) not sold as products were obtained from the Merck Index (Budavari, 1989) and included in category totals.

[c] Formulations for HASL process baths were unavailable because cleaner and microetch bath chemistries are not made specifically for the HASL process. Hazards reported for HASL bath types were reported as the worst case of the results of similar baths from other processes.

[d] For alternative processes with more than one product line, the hazard data reported represents the most hazardous bath of each type for the two product lines (e.g., of the microetch baths from the two product lines, the one with the most hazardous chemicals is reported).

Reactive - A chemical is considered reactive if it is readily susceptible to change and the possible release of energy. EPA gives a more precise definition of reactivity for solid wastes. As defined by EPA (40 CFR 261.23), a solid waste is considered reactive if a representative sample of the waste exhibits any of the following properties: 1) is normally unstable and readily undergoes violent change without detonating; 2) reacts violently or forms potentially explosive mixtures with water; 3) when mixed with water, generates toxic gases, vapors, or fumes in a quantity sufficient to present a danger to human health or the environment (for a cyanide or sulfide bearing waste, this includes exposure to a pH between 2 and 12.5); 4) is capable of detonation or explosive reaction if subjected to a strong initiated source or if heated under confinement; or 5) is

explosive reaction if subjected to a strong initiated source or if heated under confinement; or 5) is readily capable of detonation or explosive decomposition or reaction at standard temperature and pressure. A review of MSDS data shows that none of the chemical products used in the surface finishing processes are considered reactive.

Unstable - As defined by OSHA (29 CFR 1910.1200[c]), a chemical is unstable if in the pure state, or as produced or transported, it will vigorously polymerize, decompose, condense, or will become self-reactive under conditions of shock, pressure, or temperature. Only two of the chemical products are reported as unstable, according to MSDS data.

Sudden Release of Pressure - OSHA requires the reporting of chemical products that, while stored in a container subjected to sudden shock or high temperature, causes a pressure increase within the container that is released upon opening. MSDS data indicates four chemical products that are potential sudden release of pressure hazards.

Surface Finishing Chemical Product Health Hazards

A breakdown of surface finishing process baths that contain chemical products that are sensitizers, acute or chronic health hazards, or irreversible eye damage hazards in their concentrated form is presented in Table 3-40. Also discussed in this section are surface finishing chemical products that are potential eye or dermal irritants and suspected carcinogens. The following presents OSHA definitions for chemicals in these categories and discusses the data in Table 3-40, where appropriate.

Sensitizer - A sensitizer is defined by OSHA [29 CFR 1910.1200 Appendix A (mandatory)] as a chemical that causes a substantial proportion of exposed people or animals to develop an allergic reaction in normal tissue after repeated exposure to the chemical. Sixteen chemical products are reported as sensitizers by MSDS data.

Acute and Chronic Health Hazards - As defined by OSHA (29 CFR 1910.1200 Appendix A), a chemical is considered a health hazard if there is statistically significant evidence based on at least one study conducted in accordance with established scientific principles that acute or chronic health effects may occur in exposed employees. Health hazards are classified using the criteria below:

- acute health hazards are those whose effects occur rapidly as a result of short-term exposures, and are usually of short duration; and
- chronic health hazards are those whose effects occur as a result of long-term exposure, and are of long duration.

Chemicals that are considered a health hazard include carcinogens, toxic or highly toxic agents, reproductive toxins, irritants, corrosives, sensitizers, hepatotoxins, nephrotoxins, neurotoxins, agents that act on the hematopoietic system, and agents which damage the lungs, skin, eyes, or mucous membranes.

Table 3-40. Sensitizer, Acute and Chronic Health Hazards, and Irreversible Eye Damage Possibilities for Surface Finishing Processes

Surface Finishing Process	Bath Type	Hazardous Property [a, b]				
		Sensitizer	Acute Health Hazard	Chronic Health Hazard	Carcinogen	Irreversible Eye Damage
HASL [c]	Cleaner	1(2)	1(1)	1(1)	1(1)	1(1)
	Microetch	2(3)	3(4)	3(3)		3(4)
Nickel/Gold [d] (2 product lines)	Cleaner		1(1)	1(1)	1(1)	1(1)
	Microetch	1(2)	3(4)	2(2)		3(4)
	Catalyst	1(2)	2(3)	1(2)		1(2)
	Acid Dip	1(1)	1(1)	1(1)		1(1)
	Electroless Nickel		2(2)	2(2)	1(2)	
	Immersion Gold		2(2)	2(2)		1(2)
Nickel/Palladium/Gold	Cleaner		1(1)	1(1)		
	Microetch	1(4)	3(4)	1(4)		3(4)
	Catalyst	1(3)	2(3)	1(3)		1(3)
	Activator		4(4)	2(4)	2(4)	1(4)
	Electroless Nickel	1(3)	3(3)	2(3)		2(3)
	Electroless Palladium		2(3)	1(3)	1(3)	3(3)
	Immersion Gold		1(2)	1(2)		
OSP [d] (2 product lines)	Cleaner		1(1)	1(1)		1(1)
	Microetch	2(3)	3(3)	3(3)		3(4)
Immersion Silver	Cleaner		1(1)	1(1)		1(1)
	Microetch	1(3)	2(3)	2(3)		2(3)
Immersion Tin [d] (2 product lines)	Cleaner	1(2)	1(2)	1(2)		1(2)
	Microetch	1(2)	1(2)	1(2)		2(2)
	Predip					1(1)
	Immersion Tin	2(4)	1(4)	1(4)	1(1)	2(4)

[a] Table entries are made in the following format - # of products meeting OSHA definition for the given hazardous property, as reported in the products' MSDSs (Total # of products in the process bath). A **blank** entry means that none of the products for the specific process bath meet the OSHA reporting criteria for the given property. Example: For the immersion tin bath, 2(4) means that three of the five products in the bath were classified as sensitizers per OSHA criteria, as reported by the products' MSDSs.

[b] Data for pure chemicals (e.g., sulfuric acid) not sold as products were obtained from the Merck Index (Budavari, 1989) and included in category totals.

[c] Formulations for HASL process baths were unavailable because cleaner and microetch bath chemistries are not made specifically for the HASL process. Hazards reported for HASL bath types were reported as the worst case of the results of similar baths from other processes.

[d] For alternative processes with more than one product line, the hazard data reported represents the most hazardous bath of each type for the two product lines (e.g., of the microetch baths from the two product lines, the one with the most hazardous chemicals is reported).

A review of MSDS data shows that 41 chemical products are reported as potentially posing acute health hazards, and 32 chemical products potentially pose chronic health hazards. OSHA does not require reporting of environmental hazards such as aquatic toxicity data, nor are toxicity data on MSDSs as comprehensive as the toxicity data collected for the CTSA. OSHA health hazard data are presented here for reference purposes only, and are not used in the risk characterization component of the CTSA.

Carcinogen - As defined by OSHA (29 CFR 1910.1200 Appendix A), a chemical is considered to be a carcinogen if: 1) it has been evaluated by the IARC, and found to be a carcinogen or potential carcinogen; 2) it is listed as a carcinogen or potential carcinogen in the Annual Report on Carcinogens published by the National Toxicology Program (NTP); or 3) it is regulated by OSHA as a carcinogen. A review of MSDS data indicates that seven chemical products are reported as potential carcinogens, by either NTP, IARC, or EPA WOE Classifications. Suspected carcinogens include nickel sulfate, thiourea, and various lead compounds that are commonly used in several processes. Suspected carcinogens are discussed in more detail in the human health and ecological hazards summary, Section 3.3.

Dermal or Eye Irritant - An irritant is defined by OSHA [29 CFR 1910.1200 Appendix A (mandatory)] as a chemical, that is not corrosive, but which causes a reversible inflammatory effect on living tissue by chemical action at the site of contact. A chemical is considered a dermal or eye irritant if it is so determined under the testing procedures detailed in 16 CFR 1500.41- 42 for four hours exposure. Table 3-40 does not include this term, because all of the surface finishing chemical products are reported as either dermal or eye irritants.

Irreversible Eye Damage - Chemical products that, upon coming in contact with eye tissue, can cause irreversible damage to the eye are required by OSHA to be identified as such on the product's MSDS. A review of MSDS data shows that 34 chemical products are reported as having the potential to cause irreversible eye damage.

Other Chemical Hazards

Surface finishing chemical products that have the potential to form hazardous decomposition products are presented below. In addition, chemical product incompatibilities with other chemicals or materials are described, and other chemical hazard categories are presented. The following lists OSHA definitions for chemicals in these categories and summarizes the MSDS data, where appropriate.

Hazardous Decomposition - A chemical product, under specific conditions, may decompose to form chemicals that are considered hazardous. The MSDS data for the chemical products in the surface finishing process indicate that over half of the products have the possibility of decomposing to form potentially hazardous chemicals. Each chemical product should be examined to determine its decomposition products so that potentially dangerous reactions and exposures can be avoided. The following are examples of hazardous decomposition of chemical products that are employed in the surface finishing alternatives:

- products used in the predip and immersion tin baths of the immersion tin process, or in the microetch and OSP baths of the OSP process, may decompose to release carbon monoxide and carbon dioxide gas;
- oxygen gas may be generated by some of the microetch baths from the nickel/gold process, posing a potential combustion hazard;
- thermal decomposition under fire conditions of certain chemical bath constituents in the nickel/gold or the nickel/palladium/gold process can result in releases of toxic oxide gases such as nitrogen, sulfur, or chlorine;
- some chemical products used in the nickel/gold and nickel/palladium/gold processes will release toxic chlorine fumes if they are allowed to react with persulfate compounds; and
- one product present in the cleaner bath of the immersion silver process will react with reactive metals to release flammable hydrogen gas.

Incompatibilities - Chemical products are often incompatible with other chemicals or materials with which they may come into contact. A review of MSDS data shows that over 80 percent of the surface finishing chemical products have incompatibilities that can pose a threat to worker safety if the proper care is not taken to prevent such occurrences. Reported incompatibilities range from specific chemicals or chemical products, such as acids or cyanides, to other environmental conditions, such as direct heat or sunlight. Chemical incompatibilities that are common to products from all the surface finishing processes include acids, bases, alkalies, oxidizing and reducing agents, metals, and combustible materials. Incompatibilities were also found to exist between chemical products used on the same process line. Individual chemical products for each process bath should be closely examined to determine specific incompatibilities, and care should be taken to avoid contact between incompatible chemicals and chemical products, textiles, and storage containers.

The following are examples of chemical incompatibilities that exist for chemical products used in the surface finishing alternatives:

- some products in the catalyst baths of both the nickel/gold and nickel/palladium/gold processes are incompatible with strong bases, alkalies, and oxidizing agents;
- organic materials, combustible materials, and oxidizing and reducing agents should be kept away from the microetch bath of the OSP process, and strong alkaline materials should be avoided in the microetch baths for all of the processes; and
- persulfate should be avoided in the electroless palladium bath of the nickel/palladium/gold process, because it will react with the chemicals in the bath to release chlorine gas.

Other Chemical Hazard Categories - OSHA requires the reporting of several other hazard categories on the MSDSs for chemicals or chemical products that have not already been discussed above. These additional categories include chemical products that are:

- water-reactive (react with water to release a gas that presents a health hazard);
- pyrophoric (will ignite spontaneously in air at temperatures below 130 °F);
- stored as a compressed gas;

- classified as an organic peroxide; or
- chemicals that have the potential for hazardous polymerization.

A review of MSDS data indicates that none of the chemical products are reported as being water-reactive, pyrophoric, a compressed gas, an organic peroxide, or as having the potential for hazardous polymerization.

3.5.2 Hot Air Solder Leveling (HASL) Process Safety Concerns

Several unique process safety concerns arise from the operation of the HASL process, due to differences in the way the final surface finish is applied. Although the cleaning and microetch baths are similar to those used by the other alternatives, the solder finish is applied by the physical process of manually contacting the PWB with molten solder, rather than applying the surface finish through a chemical plating or coating process. The molten solder bath, which is typically operated at a temperature of up to 500 °F, poses several safety concerns, such as accidental contact with the molten metal by workers, exposure to acids in the flux, and the potential for fire.

Solder eruptions often occur during process startup as the solid solder is heated. Solder melts from bottom to top, and pressure may build up from thermal expansion causing the solder to erupt. Splattering of the melted solder onto workers could cause serious burns. Caution should be exercised during process startup to avoid worker injury. Heat resistant clothing, face shields, protective aprons, long sleeve gloves, and shoes should be required when working around the solder bath.

Fire is possible at the solder bath and the exhaust/ventilation system, although it does not occur frequently. When fire occurs, small amounts of hazardous gases, such as hydrogen chloride and carbon dioxide, can be released. Causes of fire include the build-up of carbon residual from the use of oil-based flux and other flammable materials kept too close to the process. Isolating flammable materials from the process area and regular cleaning of the HASL machine will prevent a fire from occurring.

Other safety concerns include workers exposed to small amounts of acid in the flux, lead in the solder bath, and to process chemicals in the cleaner and microetch baths. Risk from exposure to process chemicals is addressed in detail in Section 3.4, Risk Characterization. Like other surface finishing processes, federal safety standards and regulations concerning the HASL process can be found in CFR Title 29, Part 1910, and are available from the appropriate state office.

3.5.3 Process Safety Concerns

Exposure to chemicals is just one of the safety issues that PWB manufacturers may have to address during their daily activities. Preventing worker injuries should be a primary concern for employers and employees alike. Work-related injuries may result from faulty equipment, improper use of equipment, bypassing equipment safety features, failure to use personal protective equipment, and physical stresses that may appear gradually as a result of repetitive

motions (i.e., ergonomic stresses). Any or all of these types of injuries may occur if proper safeguards or practices are not in place and adhered to. An effective worker safety program includes:

- an employee training program;
- employee use of personal protective equipment;
- proper chemical storage and handling; and
- safe equipment operating procedures;

The implementation of an effective worker safety program can have a substantial impact on business, not only in terms of direct worker safety, but also in reduced operating costs as a result of fewer days of absenteeism, reduced accidents and injuries, and lower insurance costs. Maintaining a safe and efficient workplace requires that both employers and employees recognize and understand the importance of worker safety and dedicate themselves to making it happen.

Employee Training

A critical element of workplace safety is a well-educated workforce. To help achieve this goal, the OSHA Hazard Communication Standard requires that all employees at PWB manufacturing facilities (regardless of the size of the facility) be trained in the use of hazardous chemicals to which they are exposed. A training program should be instituted for workers, especially those operating the surface finishing process, who may come into contact with, or be exposed to, potentially hazardous chemicals. Training may be conducted by either facility staff or outside parties who are familiar with the PWB manufacturing process and the pertinent safety concerns. The training should be held for each new employee, as well as periodic retraining sessions when necessary (e.g., when a new surface finishing process is instituted), or on a regular schedule. The training program should inform the workers about the types of chemicals with which they work and the precautions to be used when handling or storing them, when and how personal protection equipment should be worn, and how to operate and maintain equipment properly.

Storing and Using Chemicals Properly

Because the surface finishing process requires handling a variety of chemicals, it is important that workers know and follow the correct procedures for the use and storage of the chemicals. Much of the use, disposal, and storage information about surface finishing process chemicals may be obtained from the MSDSs provided by the manufacturer or supplier of each chemical or formulation. Safe chemical storage and handling involves keeping chemicals in their proper place, protected from adverse environmental conditions, as well as from other chemicals with which they may react. Examples of supplier recommended storage procedures found on the MSDSs for surface finishing chemicals are listed below.

- store chemical containers in a cool, dry place away from direct sunlight and other sources of heat;
- chemical products should only be stored in their properly sealed original containers and labeled with the common name of the chemical contents;

- incompatible chemical products should never be stored together; and
- store flammable liquids separately in a segregated area away from potential ignition sources or in a flammable liquid storage cabinet.

Some products have special storage requirements and precautions listed on their MSDSs (e.g., relieving the internal pressure of the container periodically). Each chemical product should be stored in a manner consistent with the recommendation on the MSDS. In addition, chemical storage facilities must be designed to meet any local, state, and federal requirements that may apply.

Not only must chemicals be stored correctly, but they must also be handled and transported in a manner that protects worker safety. Examples of chemical handling recommendations from suppliers include:

- wear appropriate protective equipment when handling chemicals;
- open containers should not be used to transport chemicals;
- use only spark-proof tools when handling flammable chemicals; and
- transfer chemicals using only approved manual or electrical pumps to prevent spills created from lifting and pouring.

Proper chemical handling procedures should be a part of the training program given to every worker. Workers should also be trained in chemical spill containment procedures and emergency medical treatment procedures in case of chemical exposure to a worker.

Use of Personal Protective Equipment

OSHA has developed several personal protective equipment standards that are applicable to the PWB manufacturing industry. These standards address general safety and certification requirements (29 CFR Part 1910.132), the use of eye and face protection (Part 1910.133), head protection (Part 1910.135), foot protection (Part 1910.136), and hand protection (Part 1910.138). The standards for eye, face, and hand protection are particularly important for the workers operating the surface finishing process where there is close contact with a variety of chemicals, of which nearly all irritate or otherwise harm the skin and eyes. In order to prevent or minimize exposure to such chemicals, workers should be trained in the proper use of personal safety equipment.

The recommended personal protective equipment for a worker handling chemicals is also indicated on the MSDS. For the majority of surface finishing chemicals, the appropriate protective equipment indicated by the MSDS includes:

- goggles to prevent the splashing of chemical into the eyes;
- chemical aprons or other impervious clothing to prevent splashing of chemicals on clothing;
- gloves to prevent dermal exposure while operating the process; and
- boots to protect against chemical spills.

Additional personal protective equipment recommended for workers operating the HASL process includes:

- heat resistant gloves to prevent burns by accidental contact with molten solder; and
- face shield to protect face and eyes from solder splatter.

Other items less frequently suggested include chemically resistant coveralls and hats. In addition to the personal protective equipment listed above, some MSDSs recommend that other safety equipment be readily available. This equipment includes first aid kits, oxygen supplies (SCBA), fire extinguishers, ventilation equipment, and respirators.

Other personal safety considerations are the responsibility of the worker. Workers should be prohibited from eating or keeping food near the surface finishing process. Because automated processes contain moving parts, workers should also be prohibited from wearing jewelry or loose clothing, such as ties, that may become caught in the machinery and cause injury to the worker or the machinery itself. In particular, the wearing of rings or necklaces may lead to injury. Workers with long hair that may also be caught in the machinery should be required to securely pull their hair back or wear a hair net.

Use of Equipment Safeguards

In addition to the use of proper personal protection equipment for all workers, OSHA has developed safety standards (29 CFR Part 1910.212) that apply to the equipment used in a PWB surface finishing process. Among the safeguards recommended by OSHA that may be used for conveyorized equipment are barrier guards, two-hand trip devices, and electrical safety devices. Safeguards for the normal operation of conveyor equipment are included in the standards for mechanical power-transmission apparatus (29 CFR Part 1910.219) and include belts, gears, chains, sprockets, and shafts. PWB manufacturers should be familiar with the safety requirements included in these standards and should contact their local OSHA office or state technical assistance program for assistance in determining how to comply with them.

In addition to normal equipment operation standards, OSHA also has a lockout/tagout standard (29 CFR Part 1910.147). This standard is designed to prevent the accidental start-up of electric machinery during cleaning or maintenance operations, and apply to the cleaning of conveyorized equipment as well as other operations. OSHA has granted an exemption for minor servicing of machinery, provided the equipment has other appropriate safeguards, such as a stop/safe/ready button that overrides all other controls and is under the exclusive control of the worker performing the servicing. Such minor servicing of conveyorized equipment can include clearing fluid heads, removing jammed panels, lubricating, removing rollers, minor cleaning, adjustment operations, and adding chemicals. Rigid finger guards should also extend across the rolls, above and below the area to be cleaned. Proper training of workers is required under the standard whether lockout/tagout is employed or not. For further information on the applicability of the OSHA lockout/tagout standard to surface finishing process operations, contact the local OSHA field office.

Occupational Noise Exposure

OSHA has also developed standards (29 CFR Part 1910.95) that apply to occupational noise exposure. These standards require protection against the effects of noise exposure when the sound levels exceed certain levels specified in the standard. No data were collected on actual noise levels from surface finishing process lines.

REFERENCES

American Conference of Governmental Industrial Hygienists (ACGIH). 1998. 1998 TLVs and BEIs. Threshold Limit Values for Chemical Substances and Physical Agents. Biological Exposure Indices. Cincinnati, OH.

Agency for Toxic Substances and Disease Registry (ATSDR). 1990a. "Toxicological Profile for Copper." ATSDR, U.S. Department of Health and Human Services, Public Health Service. Atlanta, GA.

Agency for Toxic Substances and Disease Registry (ATSDR). 1990b. "Toxicological Profile for Silver." ATDSR, U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA.

Agency for Toxic Substances and Disease Registry (ATDSR). 1997a. "Toxicological Profile for Nickel (Update)." ATSDR, U.S. Department of Health and Human Services, Public Health Service, Atlanta.

Agency for Toxic Substances and Disease Registry (ATDSR). 1997b. "Technical Report for Ethylene Glycol/Propylene Glycol." Draft for Public Comment. ATSDR, U.S. Department of Health and Human Services, Public Health Service, Atlanta.

Agency for Toxic Substances and Disease Registry (ATDSR). 1998. "Toxicological Profile for 2-Butoxyethanol and 2-Butoxyethanol Acetate." ATSDR, U.S. Department of Health and Human Services, Public Health Service, Atlanta.

Alexander, F.W. and H.T. Delves. 1981. "Blood Lead Levels during Pregnancy." Int. Arch. Occup. Environ. Health. Vol. 48, pp.35-39.

Aulerich, R.J., R.K. Ringer, M.R. Bleavins, et al. 1982. "Effects of Supplemental Dietary Copper on Growth, Reproductive Performance and Kit Survival of Standard Dark Mink and the Acute Toxicity of Copper to Mink." J. Animal Sci. Vol. 55 pp.337-343 (as cited in ATSDR, 1990).

Barnes, D.G. and M. Dourson. 1988. "Reference Dose (RfD): Descriptions and Uses in Health Risk Assessments." Regulatory Toxicology and Pharmacology. Vol. 8, pp. 471-486.

BASF Corporation. 1987. Results of several investigations with propionic acid with cover letter. October 6. Submission to EPA under TSCA, section FYI.

Bayes, Martin. 1996. Shipley Company. Personal communication to Jack Geibig, UT Center for Clean Products and Clean Technologies. January.

Berglund, R. and E. Lindh. 1987. "Prediction of the Mist Emission Rate from Plating Baths." Proc. Am. Electroplaters and Surface Finishers Soc. Ammu. Tech. Conf.

Budavari, S. (Ed.). 1989. The Merck Index, 11th ed. Rahway: Merck & Co., Inc.

Bureau of Labor Statistics. 1990. "Statistical Summary: Tenure with Current Employer as of January 1987." As cited in EPA, 1991b.

Bureau of Labor Statistics. 1997. Job Tenure Summary. Labor Force Statistics from the current Population Survey. Website: http://stats.bls.gov/news.release/tenure.nws.htm. Information downloaded on March 24.

Bushy Run Research Center (Bushy Run). 1995. Developmental Toxicity Evaluation of Ethylene Glycol Administered by Gavage to CD Rats: Determination of a No Observable Effect Level with Cover Letter. TSCATS data submissions retrieved from TOXLINE, December 5. FYI-OTS-0790-0692; FYI-OTS-0990-0323.

Centers for Disease Control and Prevention (CDC). 1991. "Preventing Lead Poisoning in Young Children." U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA.

Clayson, D.B., F. Iverson, E.A. Nera and E. Lok. 1991. Title not available. Mutat Res. Vol. 248, p.321 (cited in Katz and Guest, 1994, HSDB, 1998).

Decisioneering, Inc. 1993. Crystal Ball® software.

DePass, L.R., R.S.H. Yang and M.D. Woodside. 1987. "Evaluation of the Teratogenicity of Ethylenediamine Dihydrochloride in Fischer 344 Rats by Conventional and Pair-Feeding Studies." Fund. Appl. Toxicol. Vol.9, pp.687-697 (cited in U.S. EPA, 1988).

Franklin, C.A., M.J. Inskip, C.L. Baccanale, E.J. O'Flaherty, W.I. Manton, D.L. Schanzer, J. Blenkinsop and C.M. Edwards. 1995. "Transplacental Transfer of Lead in Non-Human Primates (Macaca fascicularis): Use of Serially Administered Stable Isotope Tracers in Lead to Elicit Contribution of Maternal Bone Lead to Blood Lead and the Fetus." Poster presented at the 1995 meeting of the Society of Toxicology, Baltimore, MD. The Toxicologist Vol.15, p.194.

Froiman, Gail. 1996. U.S. Environmental Protection Agency (EPA). Personal communication to Debbie Boger. April.

Gaul, L.E. and A.H. Staud. 1935. "Clinical spectroscopy. Seventy Cases of Generalized Argyrosis Following Organic and Colloidal Silver Medication." J. Am. Med. Assoc. Vol.104, pp.1387-1390. Cited in IRIS, 1998 and U.S. EPA, 1991.

Goyer, R.A. 1990. "Transplacental Transport of Lead." Environmental Health Perspectives Vol. 89, pp.101-105.

Graziano, J.H., D. Popovac, P. Factor-Litvak, P. Shrout, J. Kline, M.J. Murphy, Y. Zhao, A. Mehmeti, X. Ahmedi, B. Rajovic, Z. Zvicer, D. Nenezic, N. Lolacono and Z. Stein. 1990. "Determinants of Elevated Blood Lead Levels during Pregnancy in a Population Surrounding a Lead Smelter Kosovo, Yugoslavia." Environmental Health Perspectives Vol. 89, pp.95-100.

Gupta, B.N., R.N. Khanna and K.K. Datta. 1979. "Toxicological Studies of Ammonium Sulfamate in Rat after Repeated Oral Administration." Toxicology Vol.13, pp.45-49.

Hampshire Research Institute. 1995. Risk*Assistant™ Version 2.0 software.

Harrison, P.T., P. Grasso and V. Badescu. 1991. Title not available. Food Chem. Toxicio.
Vol. 29, p.367 (cited in Katz & Guest, 1994).

Howard, P.H., R.S. Boethling, W.F. Jarvis, W.M. Meylan and E.M. Michalenko. 1991. Handbook of Environmental Degradation Rates. Lewis Publishers, Chelsea, MI.

Hazardous Substance Data Bank (HSDB). 1995. MEDLARS Online Information Retrieval System, National Library of Medicine, National Toxicology Program (via TOXNET), Bethesda, MD.

Hazardous Substance Data Bank (HSDB). 1998. MEDLARS Online Information Retrieval System, National Library of Medicine, National Toxicology Program (via TOXNET), Bethesda, MD. June.

International Agency for Research on Cancer (IARC). 1974. IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans Vol.7, pp.95-109. IARC, Lyon, France.

International Agency for Research on Cancer (IARC). 1985. Hydrogen Peroxide. In: IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans. Allyl Compounds, Aldehydes, Epoxides and Peroxides, Vol. 36, pp. 285-314. IARC, Lyon, France.

International Agency for Research on Cancer (IACR). 1987. IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Man. Overall evaluations of carcinogenicity. An updating of Vols. 1- 42, p.64. IARC, Lyon, France.

International Agency for Research on Cancer (IARC). 1990. "Nickel and Nickel Compounds." Monographs on the Evaluation of the Carcinogenic Risks to Humans. Vol.49, pp.257-445. IARC, Lyon, France.

International Agency for Research on Cancer (IARC). 1992. "Occupational Exposures to Mists and Vapours from Sulfuric Acid and Other Strong Inorganic Acids." IARC Monograph on the Evaluation of the Carcinogenic Risks to Humans. Occupational Exposures to Mists and Vapours from Sulfuric Acid; and Other Industrial Chemicals. Vol. 54, pp. 41-119. IARC, Lyon, France.

International Agency for Research on Cancer (IARC). 1993. "Cadmium and Cadmium Compounds." IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans. Vol. 58, pp.119-237. IARC, Lyon, France.

IRIS. Integrated Risk Information System. 1998. U.S. EPA, Office of Health and Environmental Assessment, Cincinnati, OH.

IRIS. Integrated Risk Information System. 1999. U.S. EPA, Office of Health and Environmental Assessment, Cincinnati, OH.

IRIS. Integrated Risk Information System. 2000. U.S. EPA, Office of Health and Environmental Assessment, Cincinnati, OH.

Ito, A., H. Watanabe, M. Naito and Y. Naito. 1981. "Induction of Duodenal Tumors in Mice by Oral Administration of Hydrogen Peroxide. Gann. Vol. 72, pp.174-175 (cited in IARC, 1985).

Johnson, M.A. and J.L. Greger. 1982. "Effects of Dietary Tin on Tin and Calcium Metabolism of Adult Males. Am. J. Clin. Nutr. Vol. 35, pp.655-660.

Monsalve, E.R. 1984. "Lead Ingestion Hazard in Hand Soldering Environments." Presentation for the Eighth Annual Seminar, Solder Technology and Product Assurance. February 22-24. Soldering Technology Branch, Product Assurance Division, Engineering Department, Naval Weapons Center, China Lake, CA.

Mori, K. 1953. "Production of Gastric Lesions in the Rat by the Diet Containing Fatty Acids." Gann. Vol. 44, pp.421-427 (cited in FDA, 1979).

National Institute for Occupational Safety and Health (NIOSH). 1976. A Guide to Industrial Respiratory Protection. Cincinnati, OH: NIOSH, U.S. Department of Health and Human Services. NEW Pub. 76-189.

National Institute for Occupational Safety and Health (NIOSH). 1994. NIOSH Manual of Analytical Methods, 4th edition. Methods 7082 (Lead by Flame AAS), 7105 (Lead by HGAAS), 7505 (Lead Sulfide), 8003 (Lead in Blood and Urine), 9100 (Lead in Surface Wipe Samples). U.S. Department of Health and Human Services, Centers for Disease Control, Cincinnati, OH.

National Institute for Occupational Safety and Health (NIOSH). 1999. NIOSH Pocket Guide to Chemical Hazards and Other Databases. (CD-ROM). NIOSH, Cincinnati, OH. DHHS (NIOSH) Publication No. 99-115.

Perry, W.G., F.A. Smith and M.B. Kent. 1994. "The Halogens." In: Clayton, G.D. and F.E. Clayton. Patty's Industrial Hygiene and Toxicology, 4th ed., Vol. II, Part F, pp. 4487-4505. John Wiley and Sons, New York.

Pocock, S.J., A.G. Shaper, M. Walker, C.J. Wale, B. Clayton, T. Delves, R.F. Lacey, R.F. Packham and P. Powell. 1983. "Effects of Tap Water Lead, Water Hardness, Alcohol, and Cigarettes on Blood Lead Concentrations." J. Epi. Comm. Health. Vol. 37, pp.1-7.

Pozzani, U.C. and C.P. Carpenter. 1954. "Response of Rats to Repeated Inhalation of Ethylenediamine Vapors." Arch. Ind. Hyg. Occup. Med. Vol. 9, pp.223-226. (cited in U.S. EPA, 1998).

RTECS. Registry of Toxic Effects of Chemical Substances. 1998. MEDLARS Online Information Retrieval System, National Library of Medicine.

Robinson, R.B., C.D. Cox, N.D. Jackson and M.B. Swanson. 1997. "Estimating Worker Inhalation Exposure to Chemicals From Plating Baths at Printed Wiring Board Facilities." Presented at the 1997 Canadian Society of Civil Engineers - American Society of Civil Engineers Environmental Engineering conference, Edmonton, Alberto, Canada. July.

Robinson, R.B., C.D. Cox and J. Drucker. 1999. Prediction of Water Quality From Printed Wiring Board Processes. Final report to the University of Tennessee Center for Clean Products and Clean Technologies and to the U.S. Environmental Protection Agency. Part of the Verification of Finishing Technologies Project, EPA Grant X825373-01-2 (Amendment No. 2). August.

Rodrigues, C., E. Lok, E. Nera, F. Iverson, D. Page, K. Karpinski and D.B. Clayson. 1986. Title not available. Toxicology 38:103 (cited in Katz & Guest, 1994).

Research Triangle Institute (RTI). 1999. Toxicological Profile for Lead (Update). Prepared for the U.S. Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry, Atlanta, GA.

Schroeder, H.A. and M. Mitchener. 1971. "Scandium, Chromium (VI), Gallium, Yttrium, Rhodium, Palladium, Indium in Mice: Effects on Growth and Life Span." J Nutr. Vol. 101, pp.1431-1438.

Sharp, John. 1999. Teradyne, Inc. Personal communication to Dipti Singh at U.S. Environmental Protection Agency (EPA). September.

Shell Oil (Shell Oil Company). 1992. Final Report Teratologic Evaluation of Ethylene Glycol (CAS No. 107-21-1) Administered to CD Rats on Gestational Days 6 through 15. Cover letter dated March 5. HSE-84-0072 (002334). 8EHQ-0492-3402 Init.

Shepard, T.H. 1986. Catalog of Teratogenic Agents, 5th ed. The Johns Hopkins University Press, Baltimore, p. 38 (cited in HSDB, 1998).

Sherlock, J.C., D. Ashby, H.T. Delves, G.I. Forbes, M.R. Moore, W.J. Patterson, S.J. Pocock, M.J. Quinn, W.N. Richards and T.S. Wilson. 1984. "Reduction in Exposure to Lead from Drinking Water and its Effect on Blood Lead Concentrations." Human Toxicol. Vol. 3, pp.383-192.

Sleet, R.B. et al. 1989. National Toxicology Program, Report NTP 89-058. NTIS PB89-165849 (cited in Gingell et al., 1994).

Sollmann, T. 1921. Title not available. J. Pharmacol. Exp. Ther.. Vol. 16, pp.463-474 (cited in Katz, Guest and Astill, 1982).

Stanek, Edward J., Edward J. Calabrese, Ramon Barnes and Penelope Pekow. 1997. "Soil Ingestion in Adults." Ecotoxicology and Environmental Safety. Vol. 36, pp.249-257.

Syracuse Research Corporation (SRC). Updated periodically. Environmental Fate Database (EFDB©). Syracuse, NY.

Union Carbide (Union Carbide Chemicals and Plastics Company, Inc.). 1991. Evaluation of the Teratogenic Potential of Ethylene Glycol Aerosol in the CD Rat and the CD-1 Mouse. Cover letter dated November 7. 8EHQ-1191-1508 Init.

U.S. Air Force. 1990. "Copper - Elemental Copper." In: The Installation Restoration Toxicology Guide. Wright-Patterson Air Force Base, OH. Vol. 5, pp. 77-1 - 77-44.

U.S. Environmental Protection Agency (EPA). 1984. Health Effects Assessment for Copper. Office of Research and Development, Office of Emergency and Remedial Response, Washington, D.C., Office of Health and Environmental Assessment, Environmental Criteria and Assessment Office, Cincinnati, OH.

U.S. Environmental Protection Agency (EPA). 1987a. Health Effects Assessment for Tin. Prepared for Office of Solid Waste and Emergency Response by Environmental Criteria and Assessment Office, Cincinnati, OH.

U.S. Environmental Protection Agency (EPA). 1987b. Code of Federal Regulations. 40 CFR 50.12.

U.S. Environmental Protection Agency (EPA). 1988a. Reportable Quantity Document for Hydrogen Peroxide. EPA Office of Solid Waste and Emergency Response, Environmental Criteria and Assessment Office, Cincinnati, OH, 9 p.

U.S. Environmental Protection Agency (EPA). 1988b. Health and Environmental Effects Document for Ethylenediamine. Prepared by Environmental Criteria and Assessment Office, Office of Health and Assessment, Cincinnati, OH, for the Office of Solid Waste and Emergency Response.

U.S. Environmental Protection Agency (EPA). 1989. Risk Assessment Guidance for Superfund, Volume 1: Human Health Evaluation Manual (Part A). Interim Final. Office of Emergency and Remedial Response. Washington, D.C. EPA/540/1-89/002. (Appendix A).

U.S. Environmental Protection Agency (EPA). 1990. Supplement to the 1986 EPA Air Quality Criteria Document for Lead - Volume 1 Addendum. Office of Research and Development, Office of Health and Environmental Assessment, Washington, D.C. EPA-600/8-89/049A.

U.S. Environmental Protection Agency (EPA). 1991a. Chemical Engineering Branch Manual for the Preparation of Engineering Assessments. EPA Office of Toxic Substances, Washington, D.C.

U.S. Environmental Protection Agency (EPA). 1991b. Human Health Evaluation Manual, Supplemental Guidance: Standard Default Exposure Factors. EPA Office of Solid Waste and Emergency Response, Washington D.C.

U.S. Environmental Protection Agency (EPA). 1991c. Drinking Water Health Advisory for Silver. Office of Water, Washington, D.C. NTIS No. PB92-135516.

U.S. Environmental Protection Agency (EPA). 1992a. Dermal Exposure Assessment: Principles and Applications, Interim Repot. EPA Office of Research and Development, Washington, D.C. EPA/600/18-91/011B.

U.S. Environmental Protection Agency (EPA). 1992b. Guidelines for Exposure Assessment. Washington, D.C. EPA 600-2-92-001.

U.S. Environmental Protection Agency (EPA). 1994. Guidance Manual for the Integrated Exposure Uptake Biokinetic Model for Lead in Children. EPA/540/R-93/081, and IEUBK Model, version 0.99D.

U.S. Environmental Protection Agency (EPA). 1995. Supplemental Guidance to RAGS: Region 4 Bulletins, Human Health Risk Assessment (Interim Guidance). Waste Management Division, Office of Health Assessment.

U.S. Environmental Protection Agency (EPA). 1996a. "Recommendations of the Technical Workgroup for Lead for an Interim Approach to Assessing Risks Associated with Adult Exposures to Lead in Soil." US EPA Technical Workgroup for Lead, December.

U.S. Environmental Protection Agency (EPA). 1996b. "Proposed Guidelines for Carcinogen Risk Assessment." EPA Office of Research and Development, Washington, D.C. EPA/600/P-92/1003C.

U.S. Environmental Protection Agency (EPA). 1997a. Exposure Factors Handbook. EPA Office of Research and Development, Washington, D.C. EPA/600/p-95/1002Fa.

U.S. Environmental Protection Agency (EPA). 1997b. "Health Effects Assessment Summary Tables. FY_1997." Office of Research and Development, Office of Energy and Remedial Response.

U.S. Environmental Protection Agency (EPA). 1997c. Toxic Release Inventory Relative Risk-Based Environmental Indicators: Interim Toxicity Weighting Summary Document. Office of Pollution, Prevention and Toxics (MS 7406), Washington, D.C. June.

U.S. Environmental Protection Agency (EPA). 1998a. Printed Wiring Board Pollution Prevention and Control Technology: Analysis of Updated Survey Results. EPA Office of Pollution Prevention and Toxics, Washington, D.C. EPA 744-R-98-003. August.

U.S. Environmental Protection Agency (EPA). 1998b. Printed Wiring Board Cleaner Technologies Substitutes Assessment: Making Holes Conductive. Design for the Environment Printed Wiring Board Project. EPA Environmental Technology Initiative Program, Washington, D.C. EPA 744-R-97/002a. June.

World Health Organization (WHO). 1974. Toxicological Evaluation of Certain Food Additives with a Review of General Principles and of Specifications. Seventeenth Report of the Joint FAO/WHO Expert Committee on Food Additives. WHO Technical Report Series No. 539 (cited in U.S. EPA, 1997 [HEAST]).

World Health Organization (WHO). 1986. Regional Office for Europe: Air Quality Guidelines. Vol. 11, 1-34. Geneva, Switzerland: World Health Organization.

Chapter 4
Competitiveness

4.1 PERFORMANCE DEMONSTRATION RESULTS

4.1.1 Background

This section of the Cleaner Technologies Substitutes Assessment (CTSA) summarizes the performance testing of the surface finishing technologies. To conduct the performance evaluation, a test board was designed and fabricated, then 16 different surface finishes were applied at 13 volunteer printed wiring board (PWB) manufacturing sites, in the U.S. and England, during "performance demonstrations" between May and July, 1998. The performance of the alternative surface finishes, taken in conjunction with risk, cost, and other information in this document, provides a more comprehensive assessment of alternative technologies.

In a joint and collaborative effort, Design for the Environment (DfE) project partners organized and conducted the performance demonstrations. The demonstrations were open to any supplier of surface finishing technologies who chose to submit product line information and nominate appropriate demonstration sites. Prior to the start of the demonstrations, DfE project partners advertised the project and requested participation from all interested suppliers through trade shows, conferences, and direct telephone calls.

A summary of the methodologies used and key results are presented in this chapter. Additional results, details on testing and analysis methodologies, and more information on the test board design, can be found in Appendix F.

The assembled PWBs used in the performance demonstration provided electrical responses for 23 individual circuits that fall into seven major circuit groups. The first four circuit groups had both plated through hole (PTH) and surface mount technology (SMT) components.

- high current low voltage (HCLV),
- high voltage low current (HVLC),
- high speed digital (HSD),
- high frequency low pass filter (HF LPF),
- high frequency transmission line coupler (HF TLC),
- leakage networks, and
- stranded wire (SW).

The design of the assembled PWB made it an excellent discriminating test vehicle to discover problem areas associated with new technologies, materials, and processes. Test boards were exposed to the following test conditions ("environmental testing") to accelerate the discovery process:

- 85/85: 85°C and 85% relative humidity for three weeks),
- thermal shock (TS): 200 cycles between -50°C and 125°C, and
- mechanical shock (MS): dropped 25 times from a height of three meters onto a concrete surface)

In general, each of the surface finishes applied during the performance demonstrations were very robust under the conditions of the three tests. Some problem areas did develop, however, during the testing. In particular, a problem area with HF LPF circuits related to open PTHs was identified. The number of HF LPF anomalies was compared to the amount that would be expected under a hypothesis that anomalies are independent of surface finish. This analysis led to the following summary statements about the HF LPF circuits with respect to each surface finish:

- Hot air solder leveling (HASL) anomalies were close to the expected values throughout the three tests.
- Nickel/gold had far fewer anomalies than expected for all circuits.
- Nickel/palladium/gold had far fewer anomalies than expected for all circuits.
- Organic solderability preservative (OSP) anomalies were close to expected values, except for one HF LPF SMT circuit where there were more anomalies than expected.
- Immersion silver had many more anomalies than expected for all circuits.
- Immersion tin anomalies were close to expected for PTH circuits, but were higher than expected for SMT circuits.

The number of open PTH anomalies in the HF LPF circuit may have been related to the inherent strength of the metals, as well as to board design (i.e., the small diameter vias in this circuit). Product designers should be aware of these phenomena when considering a change of surface finishes.

Other notable anomalies were in the HCLV SMT and HVLC SMT circuits in the mechanical test, during which SMT components across all surface finishes fell off the board.

A failure analysis was conducted on the test boards that failed the 85/85 test and on a control group not subjected to the test, in order to determine if any links existed between board contamination from fabrication and assembly process residues and the electrical anomalies. In addition, the boards were inspected visually to identify any obvious anomalies or defects. The results indicated that the failures were not a result of residue, and that solder cracking was the most common visual defect. HASL had more solder cracks than the other finishes.

4.1.2 Performance Demonstration Methodology

The general plan for the performance demonstration was to collect data on alternative surface finishing processes, during actual production runs, at sites where the processes were already in use. These demonstration sites were production facilities, customer testing facilities (beta sites), or supplier testing facilities. Whenever possible, production facilities were used. Each demonstration site received standardized test boards, which were run through the surface

finishing operation during their normal production. The information collected through the demonstrations was intended to provide a "snapshot" of the way the technology was performing at that particular site at that particular time. This methodology was developed by consensus with the technical workgroup, which included suppliers, trade association representatives, EPA, and PWB manufacturers. A detailed performance demonstration methodology is included in Appendix F.

Each supplier was asked to submit the names of up to two facilities at which the demonstrations of their technology were to be conducted. This selection process encouraged the suppliers to nominate the facilities where the technology was performing at its best. This, in turn, provided for more consistent comparisons across technologies. The demonstration sites included 13 facilities, at which 16 different demonstrations were run.

To minimize differences in performance due to processes other than surface finishing, the panels used for testing were all manufactured at one facility, Network Circuits, in Irving, Texas. After fabrication, the panels were numerically coded for tracking purposes, and six panels (containing four boards per panel) were shipped to each demonstration site, where the appropriate surface finish was applied.

An observer from the DfE project team was present at each demonstration site to monitor the processing of the test panels. Observers were present to confirm that the processing was completed according to the methodology and to record data. Surface finish application at each demonstration site was completed within one day, while performance processing at all sites was completed over a three-month period.

When the processing was completed, the panels were put into sealed bags and shipped to a single facility, which acted as a collection point for all performance demonstration panels. Completed panels were then shipped back to Network Circuits, where the panels were cut into boards. All coded boards were then shipped to a single facility (EMPF/American Competitiveness Institute) for assembly. One subgroup was assembled using low-residue (LR) flux and the other with water soluble (WS) flux.

Following assembly, the boards were sent to Raytheon Systems Inc. in McKinney, Texas, where the performance characteristics of the assembled boards were tested. Testing included Circuit Electrical Performance and Circuit Reliability testing. The Electrical Performance testing assessed the circuit performance of the printed wiring assemblies (PWAs), or assembled PWBs, before and after exposure to 85°C temperatures at 85% relative humidity for 3 weeks. For the Circuit Reliability testing, the same PWAs were tested after being subject to thermal shock and mechanical shock conditions.

Limitations of the Performance Demonstration Methodology

The performance demonstration was designed to provide a snapshot of the performance of different surface finishing technologies. Because the demonstration sites were not chosen

randomly, the sample may not be representative of all PWB manufacturing facilities in the U.S. (However, there is no specific reason to believe that they are not representative.)

4.1.3 Test Vehicle Design

The test vehicle design was based on a test board designed by the Sandia National Laboratory Low-Residue Soldering Task Force (LRSTF). This test vehicle was used by the Circuit Card Assembly and Materials Task Force (CCAMTF), a joint industry and military program evaluating several alternative surface finishing technologies. The design is a functional PWA designed to test process effects resulting from changing materials and processes. The PWA and the test/data analysis methodology are considered excellent discriminators in comparing processes fluxes, surface finishes, or other process technologies. It should be noted that circuit technology continues to change rapidly; the PWA design is based on 1994 technology and does not incorporate some more recent, state-of-the-art, circuitry. It is unknown whether the results might have differed with newer circuit technology. However, the test PWA was designed to contain approximately 80 percent of the circuitry used in military and commercial electronics. In addition, use of this test vehicle by the DfE PWB Project provided great savings in cost and time that would be required to develop a new test vehicle, and allows for some comparison with CCAMTF results.

The test vehicle was designed to be representative of a variety of extreme circuits: high voltage, high current, HSD, low-leakage current, and high frequency (HF) circuits. A designer can use the resulting measurements to make some analytical judgments about the *process* being tested. The test PWA was not intended to be a “production” board, which would typically be too narrow in breadth to represent a wide variety of these circuit extremes. Even though some technology complexities/advancements are not duplicated, the basic types are represented, and comparison of baseline technologies can be extrapolated, in some cases, to more current technology by analysis. The performance results are assessed based on the acceptance criteria developed by the CCAMTF project, which are described in Table 4-1.

The test PWA measures 6.05" x 5.8" x 0.062". See Appendix F for more details on the design of the test PWA. The PWA is divided into six sections, each containing one of the following types of electronic circuits:

- HCLV;
- HVLC;
- HSD,
- HF;
- SW; and
- other networks.

The components in the HCLV, HVLC, HSD, and HF circuits represent two principal types of soldering technology:

- PTH: Leaded components are soldered through vias in the circuit board by means of a wave soldering operation.

- SMT: Leadless components are soldered to pads on the circuit board by passing the circuit board through a reflow oven

The other networks used for current leakage measurements are 10-mil pads, a socket for a pin grid array (PGA), and a gull wing. The two stranded wires (SW) are hand soldered.

The test vehicle provides 23 separate electrical responses as shown in Table 4-1. The criteria for 17 of the 23 circuits require a comparison to the pre-test measurements (i.e., before exposure to test environments), while the criteria for the remaining six circuits are based on absolute responses. The CCAMTF project conducted baseline testing for 480 test PWAs, which were used as the basis of the acceptance criteria that were published in their Joint Test Protocol. These criteria are also shown in Table 4-1.

It should be noted that these acceptance criteria are not absolutes, but rather guidelines based on engineering judgement and experience with the particular circuit. Therefore, in some cases when values that are just outside the acceptance criterion, they may be considered "not of practical significance." This would be the case when a single observation is close to the acceptance criterion. For example, if the criterion specifies an acceptable increase of 10dB and the increase for one board was measured at 10.2dB, it would be difficult to make any conclusion from a single observation so close to the acceptance criterion. However, if all HASL boards, for example, measured 10.2dB while all other surface finishes were below 10dB, it would be reasonably clear that there is an effect due to the surface finish.

The test PWAs were manufactured with the following six surface finishes for the DfE PWB Project:

- HASL;
- nickel/gold;
- nickel/palladium/gold;
- OSP;
- immersion silver; and
- immersion tin.

Additional information about each technology, including a process flow diagram and a description of each process step, is presented in Section 2.1, Chemistry of Use and Process Description.

Table 4-1. Electrical Responses for the Test PWA and Acceptance Criteria

Electrical Response	Circuitry	Acceptance Criteria
High Current Low Voltage		
1	HCLV PTH	Change in voltage from pre-test < 0.50V
2	HCLV SMT	Change in voltage from pre-test < 0.50V
High Voltage Low Current		
3	HVLC PTH	4µA < x < 6µA
4	HVLC SMT	4µA < x < 6µA
High Speed Digital		
5	HSD PTH Propagation Delay	< 20% increase from pre-test
6	HSD SMT Propagation Delay	< 20% increase from pre-test
High Frequency Low Pass Filter		
7	HF PTH 50MHz	Within ± 5dB of pre-test
8	HF PTH f (-3dB)	Within ± 50MHz of pre-test
9	HF PTH f (-40dB)	Within ± 50MHz of pre-test
10	HF SMT 50MHz	Within ± 5dB of pre-test
11	HF SMT f (-3dB)	Within ± 50MHz of pre-test
12	HF SMT f (-40dB)	Within ± 50MHz of pre-test
High Frequency Transmission Line Coupler		
13	HF TLC 500MHz Forward Response	Within + **[±?]** 5dB of pre-test
14	HF TLC 500MHz Forward Response	Within ± 5dB of pre-test
15	HF TLC 1GHz Forward Response	Within ± 5dB of pre-test
16	HF TLC Reverse Null Frequency	Within ± 50MHz of pre-test
17	HF TLC Reverse Null Response	< 10dB increase over pre-test
Other Networks: Leakage		
18	10-mil Pads	Resistance > 7.7 $\log_{10}$ ohms
19	PGA-A	Resistance > 7.7 $\log_{10}$ ohms
20	PGA-B	Resistance > 7.7 $\log_{10}$ ohms
21	Gull Wing	Resistance > 7.7 $\log_{10}$ ohms
Stranded Wire		
22	Stranded Wire 1	Change in voltage from pre-test< 0.356V
23	Stranded Wire 2	Change in voltage from pre-test < 0.356V

Abbreviations and Definitions:
HCLV - high current low voltage
HF - high frequency
HSD - high speed digital
HVLC - high voltage low current
PGA - pin grid array
PTH - plated through hole
SMT - surface mount technology
TLC - transmission line coupler

These surface finishes were applied at one or more of the different demonstration sites. Table 4-2 provides a summary of the 164 PWAs that were subjected to environmental testing by surface finish, manufacturing site, and flux type. Table 4-2 also shows that both fluxes were not used with all demonstration sites, and that 84 PWAs were processed with low residue flux, while 80 PWAs were processed with water soluble flux.

Table 4-2. Distribution of the Number of LRSTF PWAs by Surface Finish, Site, and Flux

Surface Finish	Site	Low Residue Flux	Water Soluble Flux
HASL	1	8	8
	2	8	—
	3	—	8
Nickel/Gold	13	4	8
	14	8	—
	15	—	8
Nickel/Palladium/Gold	16	8	4
OSP	4	4	—
	5	8	8
	6	8	8
Immersion Silver	11	8	4
	12	—	8
Immersion Tin	7	4	8
	8	8	—
	9	8	—
	10	—	8
	Total No. of Boards:	84	80

Due to the uneven distribution of fluxes during assembly, the number of PWAs are different for each surface finish, as follows:

Surface Finish	No. of PWAs (Percent of total)
HASL	32 (19.5%)
Nickel/Gold	28 (17.1%)
Nickel/Palladium/Gold	12 (7.7%)
OSP	36 (22.0%)
Immersion Silver	20 (12.2%)
Immersion Tin	36 (22.0%)
Total	**164**

4.1.4 Environmental Testing Methodology

Each of the 164 PWAs summarized in Table 4-2 was exposed to the following environmental test sequence:

- Exposure to three weeks of 85°C and 85% relative humidity.
- 200 cycles of thermal shock with the PWAs rotated between chambers at -50°C and 125°C with 30 minute dwells at each temperature.
- Mechanical shock where the PWA is mounted in a rectangular fixture and dropped 25 times on a concrete surface from a height of 1 meter.

The PWAs were functionally tested prior to exposure to these environments and after each environment. Although the sequential nature of the tests may affect the results (i.e., the PWAs may be weakened in the mechanical test because of the previous two tests), the testing sequence was planned to minimize any carryover effect. The 85/85 environment was the first test because it is relatively benign with respect to impacts on the functionality of the PWA. In contrast, the mechanical shock test was performed last because it can cause separation of SMT components and therefore permanent damage to the PWA.

4.1.5 Analysis of the Test Results

General Linear Models

General linear models (GLMs) were used to analyze the test data for each of the 23 electrical circuits in Table 4-1 at each test time. The GLM analysis determines which experimental factors or combinations of factors (interactions) explain a statistically significant portion of the observed variation in the test results, and in quantifying their contribution.

Analysis of Variance and Multiple Comparisons of Means

Another statistical approach can be used to determine which groups of site/flux *means* are significantly different from one another for a given electrical response from the test PWA. This procedure begins with an analysis of variance (ANOVA) of the test results (Iman, 1994) for a given circuit. An ANOVA is perhaps best explained via an example.

An ANOVA performed on the 164 pre-test measurements for HCLV PTH produced the following:

Source	DF	Sum of Squares	Mean Square	F-Statistic	P-Value
Site/Flux	22	0.2908	0.0132	0.70	0.838
Error	141	2.6796	0.0190		
Total	163	2.9704			

The meaning of the terms in each of the columns of the ANOVA table is now given.

Source. The entries in this column represent the following:

- Site/Flux refers to the 23 site/flux combinations listed in Table 4-3.
- Error refers to the random/unexplained variation in the HCLV PTH voltage measurements.
- Total refers to the total variation in the data.

Degrees of Freedom. The numbers in this column represent a statistical term known as the degrees of freedom (DF). The degrees of freedom associated with each source are calculated as follows:

Site/Flux	23 - 1 (the number of site/flux combinations - 1) = 22
Error	Total DF - Site/Flux DF = (164 - 1) - (23 -1) = 163 - 22 = 141
Total	164 - 1 (the number of test measurements -1) = 163

Sum of Squares. The entries in this column are the sums of squares associated with each source of variation. The Total Sum of Squares is calculated by summing the squares of the deviations of the 164 data points from the sample mean. If this number were divided by 164 - 1, the result would be the usual sample variance (i.e., $s^2 = 2.9704/163 = 0.0182$). The other sums of squares in this column represent a partitioning of the total sum of squares. Note that they sum to the total sum of squares:

$$0.2908 + 2.6796 = 2.9704$$

The calculations for these other sums of squares are somewhat more involved than the total sum of squares and will not be discussed here. The interested reader can find details of these calculations in Iman, 1994.

Mean Square. The values in this column are obtained by dividing the sum of squares in each row by their respective degrees of freedom:

$$\text{Mean Square for Site/Flux} = 0.2908/22 = 0.0132$$
$$\text{Mean Square for Error} = 2.6796/141 = 0.0190$$

The Mean Square Error calculation is an estimate of the standard error for the experiment. Note that this estimate (0.0190) differs from the sample variance (0.0182), as the standard error is computed after the other source of variation in the data (Site/Flux) has been taken into account. Note that these two variance estimates are close in this particular example, but they can differ greatly.

F-Statistic. This column contains the f-statistic that is used to determine if Site/Flux makes a statistically significant contribution to the total variation. The f-statistic is the ratio of the Mean Square for Site/Flux and Mean Square Error:

F-statistic = (Mean Square Site/Flux)/(Mean Square Error) = 0.0132/0.0190 = 0.70

In the surface finishes analysis, when the f-statistic was significant, the Least Significant Difference (LSD) procedure (described below) was used to compare the means of the 23 site/flux combinations given in Table 4-3, and results are displayed in boxplots (also described below).

P-Value. The statistical significance of the f-statistic (the p-value) is given in the last column of the ANOVA table. This value is determined by comparing the f-statistic to its probability distributions (the larger the f-statistic, the more significant the contribution). Probability distributions for f-statistics are indexed by two parameters known as degrees of freedom. The degrees of freedom for the f-statistic are Site/Flux DF = 22 and Error DF = 141. The p-value is computed as the tail probability for the f-statistic as:

$$\text{P-Value} = \text{Prob}(F_{22,141} > F_{\text{site/Flux}}) = \text{Prob}(F_{22,141} > 0.70) = 0.838$$

Whenever a p-value in this analysis is less than 0.01, the corresponding source of variation can be regarded as making a significant contribution to the overall variation. In this example the p-value is quite large, which signifies that Site/Flux does not make a significant contribution to the overall variation in the data. Thus, there is no need to check for differences in the means of the site/flux combinations. In statistical analyses, the level of significance frequently is a p-value less than 0.05. The more stringent 0.01 is used in this report because of the relatively small cell sizes (4 or 8 samples per circuit per site/flux combination) and the potentially important decisions that may be made based on these test results.

Least Significant Difference. In the event that the p-values associated with the F-statistics are less than 0.01, the sample means can be incorporated into a test statistic for determining which population means are significantly different from one another. The "measuring stick" used to compare the sample means is known as Fisher's LSD. In particular, two population means are declared significantly different from one another if the absolute difference of the corresponding sample means exceeds LSD_a, which is defined as:

$$LSD_{\alpha} = t_{\alpha/2,\, n-k} \sqrt{MSE} \sqrt{\frac{1}{n_i} + \frac{1}{n_j}}$$

where,

α	=	level of significance
t	=	the $\alpha/2$ quantile from a Student's t distribution with *n-k* degrees of freedom
MSE	=	mean square error for the model
n_i and n_j	=	sample sizes for the means being compared

When the F-statistic is significant, the LSD procedure will be used to compare the means of the 23 site/flux combinations given in Table 4-3. Results of the multiple comparisons will be displayed in boxplots (described below).

Table 4-3. Listing of 23 Site/Flux Combinations Used in the Multiple Comparisons Analyses

Site/Flux Combination	Surface Finish	Flux Type	Site No.	No. of Observations
1	HASL	LR	1	8
2	HASL	WS	1	8
3	HASL	LR	2	8
4	HASL	WS	3	8
5	OSP	LR	4	4
6	OSP	WS	4	8
7	OSP	LR	5	8
8	OSP	WS	5	8
9	OSP	LR	6	8
10	Immersion Tin	LR	7	4
11	Immersion Tin	WS	7	8
12	Immersion Tin	LR	8	8
13	Immersion Tin	LR	9	8
14	Immersion Tin	WS	10	8
15	Immersion Silver	LR	11	8
16	Immersion Silver	WS	11	4
17	Immersion Silver	WS	12	8
18	Nickel/Gold	LR	13	4
19	Nickel/Gold	WS	13	8
20	Nickel/Gold	LR	14	8
21	Nickel/Gold	WS	15	8
22	Nickel/Palladium/Gold	LR	16	8
23	Nickel/Palladium/Gold	WS	16	4

Abbreviations and Definitions:
LR - low residue
WS - water soluble

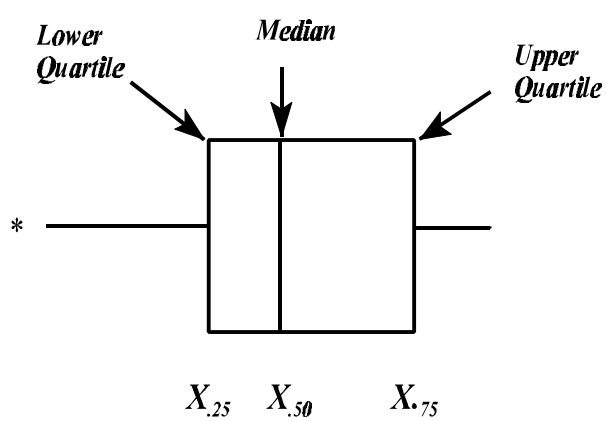
Boxplot Displays

A boxplot is simply a rectangular box with lines extending from the left-hand and right-hand sides of the box as shown below. The left-hand side of the box represents the lower quartile ($X_{.25}$) or lower 25 percent of the sample data. The right-hand side of the box represents the upper quartile ($X_{.75}$), or upper 25 percent of the sample data (or lower 75 percent). Thus, the box covers the middle 50 percent of the sample data. A vertical line inside the box connecting the top and bottom sides represents the sample median ($X_{.50}$).

The interquartile range (IQR) is the difference between the upper quartile and the lower quartile. A horizontal line at the right-hand side of the box extends to the maximum observation in the interval from $X_{.75}$ to $X_{.75}$ + 1.5 IQR. This line never extends beyond $X_{.75}$ + 1.5 IQR. A horizontal line on the left-hand side extends to the smallest observation between $X_{.25}$ and $X_{.25}$ - 1.5 IQR. This line never extends below $X_{.25}$ - 1.5 IQR. Any observations outside of these limits are regarded as outliers and are marked with an asterisk or other symbols. A heavy dot is frequently added to a boxplot to identify the sample mean.

Boxplots can be constructed in either a horizontal or vertical position. When the boxplot is constructed vertically, the top side of the box represents the upper quartile and the bottom side represents the lower quartile.

Boxplot displays have advantages over traditional plots of means, such as: 1) the median is not heavily influenced by outlying or unusual observations that can be misleading; and 2) the information about the variability in the data, captured in a boxplot, is lost in a plot of the means. Boxplots will be used as the basis for graphical displays of the multiple comparisons results for each electrical response for each test.



A Boxplot Used to Display Test Results

4.1.6 Overview of Test Results

The 164 PWAs as summarized in Table 4-2 were functionally tested at the following four times:

- Pre-test;
- Post-85/85;
- Post-TS; and
- Post-MS.

At each of these test times, 3,772 electrical test measurements were recorded (164 PWAs × 23 individual circuits). An overall summary of success rates based on 3,608 measurements[1] at each test time is shown in Table 4-4.

Table 4-4. Number of Anomalies Observed at Each Test Time

Test Time	Anomalies	Success Rate
Pre-test	2	99.9%
Post-85/85	17	99.6%
Post-TS	113	96.9%
Post-MS	527	85.4%

Abbreviations and Definitions:
MS - mechanical shock
TS - thermal shock

An overview of the test results at each test time is discussed in this section. A discussion of the results for each test time for each major circuit group is presented in Sections 4.1.7 through 4.1.13. An overview of the circuits meeting the acceptance criteria after each testing sequence is summarized in Table 4-5 for each major circuit group.

[1] Since HF TLC RNF gave a constant response of 50MHz throughout, there is no variability to analyze.

Table 4-5. Percentage of Circuits Meeting Acceptance Criteria at Each Test Time [2]

Circuitry	85/85	Thermal Shock	Mechanical Shock
HCLV	100%	100%	48.2% (7.1% SMT)
HVLC	99.7%	99.7%	50.0% (0.0% SMT)
HSD	99.7%	98.8%	99.1% (99.3% SMT)
HF LPF	98.7%	89.4%	82.6% (74.8% SMT)
HF TLC	99.8%	99.5%	97.9%
Other Networks	99.8%	100%	100%
SW	100%	99.7%	98.5%
Totals	**99.5%**	**96.9%**	**85.4%**

Abbreviations and Definitions:
HCLV - high current low voltage
HF LPF - high frequency low pass filter
HF TLC - high frequency transmission line coupler
HSD - high speed digital
HVLC - high voltage low current
SMT - surface mount technology
SW - stranded wire

Overview of Pre-Test Results

The electrical measurements were compared to the acceptance criteria given in Table 4-1 at each test time. Note that the acceptance criteria require a comparison to pre-test results for all but six of the 23 electrical circuits (#'s 3, 4, 18-21 in Table 4-1). Hence, pre-test comparisons to the acceptable criteria can only be made for those six circuits. There were no pre-test anomalies observed for those six circuits. Pre-test measurements for the remaining 17 circuits were compared to CCAMTF pre-test results. Table 4-6 presents this comparison of the ranges of the measurements for each of the 23 circuits with pre-test measurements for the PWAs used in the CCAMTF 85/85 testing.

Table 4-6 shows that the two sets of ranges for circuits 5 through 12 and 16 do not even overlap. The lack of overlap in the ranges for the HSD PTH and HSD SMT circuits (#'s 5 and 6) is due to different components being used on the DfE PWAs than were used in processing the PWAs in the CCAMTF program. The differences in the HF LPF circuits 7 through 12 are more difficult to pinpoint. The most likely explanation lies in the fact that the actual boards used in the DfE program and those in the CCAMTF PWAs were produced by two different manufacturers. FR-4 epoxy was used for the board laminate material. HF LPF responses are sensitive to the dielectric constant of the board laminate material. Differences in FR-4 epoxy at the two manufacturing locations used by the DfE program and the CCAMTF program could have affected the dielectric constant and hence the HF LPF responses. Another possibility is that the board

[2] The total number of measurements, rather than the number of measurements meeting the acceptance criteria after the previous test, is used to calculate these percentages. While it is possible to adjust for anomalies resulting from the previous test, doing so: 1) would make the calculation conditional on the previous test and therefore would require a very careful interpretation ; and 2) would not reflect the "curing" that can occur with a circuit that is an anomaly in one test but meets the acceptance criteria in the subsequent test.

layers manufactured at the two locations might not be the same thickness. A microsection was required to make this determination, which was beyond the scope of this analysis. A final possibility is that the two sets of boards might have used a different lot of ceramic capacitors, but this is not likely, as all the parts for the DfE and CCAMTF boards were ordered at the same time.

Table 4-6. Comparison of CCAMTF Pre-Test Ranges with DfE Pre-Test Measurements

Circuit [units]	CCAMTF Pre-Test		DfE Pre-Test	
	Min	Max	Min	Max
1 HCLV PTH [V]	6.60	7.20	6.80	7.52
2 HCLV SMT [V]	6.96	7.44	7.00	7.44
3 HVLC PTH [μA]	5.00	5.25	5.00	5.25
4 HVLC SMT [μA]	4.92	4.97	4.81	5.39
5 HSD PTH Propagation Delay [μ sec]	12.66	13.50	16.76	18.20
6 HSD SMT Propagation Delay [μ sec]	4.28	5.45	8.89	9.52
7 HF PTH 50MHz [dB]	-0.320	0.094	-1.176	-0.365
8 HF PTH f (-3dB) [MHZ]	239.4	262.6	274.4	287.5
9 HF PTH f (-40dB) [MHZ]	425.3	454.9	456.7	485.2
10 HF PTH 50MHz [dB]	-0.296	0.081	-0.901	-0.617
11 HF SMT f (-3dB) [MHZ]	275.0	283.3	313.0	338.0
12 HF SMT f (-40dB) [MHZ]	642.6	674.0	811.2	951.9
13 HF TLC 50MHz Forward Response [dB]	-49.74	-36.48	-50.87	-42.66
14 HF TLC 500MHz Forward Response [dB]	-21.47	-17.54	-19.91	-15.28
15 HF TLC 1GHz Forward Response [dB]	-16.91	-12.08	-15.01	-12.89
16 HF TLC Reverse Null Frequency [MHZ]	624.2	659.8	50.0	79.7
17 HF TLC Reverse Null Response [dB]	-74.53	-38.22	-43.67	-32.08
18 10-mil Pads [$\log_{10}$ ohms]	10.01	15.00	10.10	15.00
19 PGA-A [$\log_{10}$ ohms]	8.94	15.00	10.38	14.00
20 PGA-B [$\log_{10}$ ohms]	8.72	15.00	10.07	13.70
21 Gull Wing [$\log_{10}$ ohms]	9.71	14.00	9.01	13.70
22 SW 1 [mV]	5	19	7	19
23 SW 2 [mV]	19	28	19	28

Abbreviations and Definitions:
HCLV - high current low voltage
HF - high frequency
HSD - high speed digital
HVLC - high voltage low current
PGA - pin grid array
PTH - plated through hole
SMT - surface mount technology
SW - stranded wire
TLC - transmission line coupler

The reverse response function (#16 in Table 4-6) provides a range of responses from 50MHz to 1GHz. The low point of this curve is referred to as the null point. The coordinates of the null point are the HF TLC Reverse Null Frequency (in MHZ) and HF TLC Reverse Null Response (in dB). The HF TLC Reverse Null Frequency ranged from approximately 624MHz to 660MHz in the CCAMTF program, while the HF TLC Reverse Null Response ranged from approximately -75dB to -38dB. However, the null point of the reverse response function for the DfE PWAs occurred at the beginning of the curve, which is approximately 50MHz. In fact, all but two of the HF Reverse Null Frequency measurements were 50MHz with the others being 77.3MHz and 79.7MHz. The Reverse Null Response ranged from -43.7dB to -32.1dB. The nearly constant value of HF Reverse Null Frequency relegates any subsequent analysis of the uncertainty to a moot point. As discussed further in subsequent sections, none of the discrepancies could be attributed to the performance of the surface finishes.

Overview of 85/85 Results

At the conclusion of the 85/85 test, 99.5% of the electrical measurements met the acceptance criteria given in Table 4-1. There were 17 anomalies distributed across 10 PWAs, as shown in Table 4-7. Among the PWAs with anomalies, five were assembled with the low-residue flux and five were assembled with the water-soluble flux. The anomalies are summarized in Appendix F, Table F-1. Table F-1 also contains observations made by the testing technician that are useful in identifying the source of the anomaly for those cases where a problem was obvious, such as an open PTH, a burnt etch, or a failed device.

Table 4-7. Frequency Distribution of Post-85/85 Anomalies per PWA by Surface Finish
(Sample sizes are given in parentheses)

Number of Anomalies per PWA	HASL (32)	Nickel/Gold (28)	Nickel/Palladium/Gold (12)	OSP (36)	Immersion Silver (20)	Immersion Tin (36)
None	31	26	12	35	18	32
1		2			1	3
2						1
3	1			1	1	
Total Anomalies	**3**	**2**	**0**	**3**	**4**	**5**

Overview of Thermal Shock Results

The number of anomalies increased from 17 at the post-85/85 test to 113 at the post-TS test, so that 96.9% of the electrical measurements met the acceptance criteria given in Table 4-1. Of the 17 anomalies at post-85/85, 16 carried over to post-TS, so that the thermal shock test introduced 97 new anomalies. 91% of the post-TS anomalies occurred for HF LPF circuits. As shown in Table 4-8, the 113 anomalies affected 42 PWAs, with 19 PWAs accounting for 88 of the anomalies. Of the PWAs with anomalies, 16 were assembled with low residue flux and 26 were assembled with water soluble flux. The anomalies are summarized by surface finish in Appendix F, Table F-2. This summary includes several observations made by the testing technician that are useful in identifying the source of the anomaly.

A chi-square test of independence (Iman, 1994) indicates that the anomalies are not uniformly distributed over the surface finishes, with immersion silver and immersion tin having more than expected. The p-value for this test is 0.025. The chi-square test does not indicate a difference in anomalies with respect to flux type.

Table 4-8. Frequency Distribution of Post-Thermal Shock Anomalies per PWA by Surface Finish
(Sample sizes are given in parentheses)

Number of Anomalies per PWA	HASL (32)	Nickel/Gold (28)	Nickel/Palladium/ Gold (12)	OSP (36)	Immersion Silver (20)	Immersion Tin (36)
None	25	25	11	28	11	22
1	4	1	1	2	2	3
2				3		3
3	2	2		2	3	5
4					1	3
5						
6	1			1	3	
Total Anomalies	**16**	**7**	**1**	**20**	**33**	**36**

Overview of Mechanical Shock Results

The number of anomalies increased greatly from 113 at post-TS to 527 at post-MS. 85% of the electrical measurements met the acceptance criteria given in Table 4-1. Of the 113 anomalies at post-TS, 97 carried over to post-MS, hence the mechanical shock test introduced 430 new anomalies. These new anomalies included 157 from HCLV SMT — in contrast, there was only one HVLC SMT anomaly at post-TS. In addition, there were 163 new anomalies from the HVLC SMT circuits. Thus, these two circuits accounted for 320 of the 430 new anomalies. The anomalies for these two SMT circuits were attributable to SMT components coming off the board during the execution of the mechanical shock test. This affected every board and has no relation to site, surface finish, or flux.

All anomalies, except for those associated with HCLV SMT and HVLC SMT (since these affected every PWA), are summarized in Appendix F, Table F-3. In addition, this table includes comments made by the test technician. There were five minor stranded wire anomalies that are not listed in Table F-3.

At post-MS, every PWA had at least one anomaly. Table 4-9 provides a breakdown of the number of anomalies per PWA for each surface finish. The last row in this table gives the median number of anomalies per PWA for each surface finish. The hypothesis that the mean number of anomalies is the same for all surface finishes is easily rejected with a p-value of 0.000 based on the Kruskal-Wallis test (Iman, 1994). Immersion silver has the most anomalies per PWA with nickel/gold and nickel/palladium/gold having the least. HASL and OSP had approximately the same number of anomalies, with immersion tin slightly higher than these two.

The following section provides insight on the source of the anomaly disparities relative to surface finish.

Table 4-9. Frequency Distribution of Post-Mechanical Shock Anomalies per PWA by Surface Finish
(Sample sizes are given in parentheses)

Number of Anomalies per PWA	HASL (32)	Nickel/Gold (28)	Nickel/Palladium/Gold (12)	OSP (36)	Immersion Silver (20)	Immersion Tin (36)
none						
1	1	1				
2	16	20	11	14	5	12
3	8	5	1	14	5	11
4		1		3		2
5	5	1		3	3	3
6					2	6
7					2	1
8	2			2		1
9					1	
10					2	
Total Anomalies	**98**	**65**	**25**	**113**	**95**	**131**
Median	**2**	**2**	**2**	**3**	**4**	**3**

4.1.7 High Current Low Voltage (HCLV) Circuitry Performance Results

Pre-test measurements and deltas were analyzed with GLM for the main effects of site and flux and their interactions, where the base case was defined as HASL at Site l and processed with low residue flux. These data were also subjected to a second GLM analysis for the main effects of surface finish and flux, where the base case was defined as HASL processed with low residue flux. The specific equations used for these two analyses are given in Appendix F as Equation F-1 and F-2, respectively.

The results of the GLM analyses indicate that the experimental parameters surface finish, site, and flux do not significantly affect the HCLV voltage measurements at pre-test, nor do they affect the changes in the voltage after exposure to each of the three test environments. That is, the HCLV measurements are robust with respect to surface finish, site, and flux. The results for the two GLMs used in the analysis are examined in more detail in Appendix F.

Multiple comparison procedures for comparing the means of the 23 site/flux combinations given in Table 4-3 were explained previously. The overall ANOVA that precedes the use of multiple comparisons produced a significant f-statistic only at post-MS for HCLV PTH. The HCLV SMT was close to significance at post-TS with a p-value of 0.018, as shown in Table 4-10 (non-significant values > 0.0 l have been shaded).

Table 4-10. P-Values for HCLV Test Results

Test Time	P-Value for HCLV PTH	P-Value for HCLV SMT
Pre-test	0.838	0.442
Post-85/85	0.953	0.109
Post-TS	0.496	0.018
Post-MS	0.001	0.861

Abbreviations and Definitions:
HCLV - high current low voltage
MS - mechanical shock
PTH - plated through hole
SMT - surface mount technology
TS - thermal shock

Boxplot Displays of Multiple Comparison Results. Boxplot displays provide a convenient way to display multiple comparison results. Multiple comparison procedures are only justified for HCLV PTH at post-MS since the other f-statistics were not significant. However, boxplot displays are given in Figure 4-1 to 4-8 for all HCLV circuits for purposes of comparison. Figures 4-1 to 4-4 display the test results at each test time for HCLV PTH circuits and Figures 4-5 to 4-8 do the same for HCLV SMT circuits. For improved readability, all boxplots referenced in this chapter can be found in Section 4.1.16 at the end of the performance results discussion. Additional boxplots, where findings were not significant, can be found in Appendix F.

Some explanation of the contents of each graph of boxplots should facilitate understanding. The test time and circuit type are labeled in the upper left-hand corner of each boxplot display. The numbers (1 to 23) on the horizontal axis in each figure correspond respectively to the 23 site/flux combinations listed in Table 4-3. The label WS on the horizontal axis signifies those demonstration sites for which water soluble flux was used; otherwise, the flux type was low residue (LR). The boxplots are grouped by surface finish, which are identified with labels across the top of each graph. At pre-test, the vertical axis corresponds to the absolute test measurement. After pre-test, the vertical axis either corresponds to the absolute test measurement or the difference from the pre-test measurement as specified in the acceptance criteria. The sample mean is identified in each boxplot with a solid circle

Note that there is a lot of overlap in all boxplots in Figure 4-1, which is consistent with the lack of significance in the f-statistics for equality of means and in the results for the GLMs. Also note that the total variation in the boxplots is approximately 0.3V, which most likely is not of concern. Figures 4-2 to 4-4 display the differences between the current HCLV PTH measurements and those obtained at pre-test. Note that all differences in Figures 4-2 and 4-3 are well below the acceptance criteria of $\Delta V < 0.5V$. However, several of the differences are well above the acceptance criteria following mechanical shock, as illustrated in Figure 4-4. The significant difference in means in Figure 4-4 at post-MS is attributable mostly to immersion silver at Site 17 processed with a water soluble flux. It should be noted, however, that the other two immersion silver sites showed no anomalies. This may indicate a site-specific problem and not a surface finish problem. Additional failure analysis would be needed to draw further conclusions.

Figures 4-5 to 4-8 are similar to those for HCLV PTH. Figure 4-8 for the HCLV SMT circuit is especially worthy of note as it reflects the increase in voltage due to the loss of one or two resistors (as illustrated in detail in Equations 2.1 to 2.3 in Appendix F). The loss of resistors has caused an increase in voltage of 2V to 3V, which exceeds the acceptance criteria.

Comparison to Acceptance Criteria. The acceptance criteria for HCLV PTH and HCLV SMT (responses 1 and 2 in Table 4-1) are based on the following differences between test measurements:

Delta 1 = 85/85 - pre-test
Delta 2 = thermal shock - pre-test
Delta 3 = mechanical shock - pre-test

Specifically, these differences are not to exceed 0.50V.

None of the HCLV PTH or HCLV SMT voltage measurements exceeded the acceptance criterion of $\Delta V < 0.50V$ after exposure to 85/85 or thermal shock. However, following mechanical shock there were 12 HCLV PTH anomalies and 158 HCLV SMT anomalies. Whereas the HCLV SMT anomalies affected almost every PWA, the HCLV PTH anomalies were distributed unevenly among surface finishes, as shown in Table 4-11.

Table 4-11. Number of HCLV PTH Anomalies at Post-Mechanical Shock by Surface Finish

Surface Finish	Anomalies	No. of PWAs
HASL	1	32
Nickel/Gold	0	28
Nickel/Palladium/Gold	0	12
OSP	3	36
Immersion Silver	5	20
Immersion Tin	3	36

4.1.8 High Voltage Low Current (HVLC) Circuitry Performance Results

Results of the GLM analyses for HVLC PTH and HVLC SMT circuits are given in Tables F-6 and F-7, respectively. The GLM analyses show no practical significance relative to the acceptance criteria, which indicates that site, flux, and surface finish parameters do not influence the HVLC measurements.

Unlike the resistors in the HCLV circuit that were in a parallel design, the HVLC resistors were in a series circuit design. Thus, when one resistor is missing the circuit is open.

Boxplot Displays of Multiple Comparison Results. The overall ANOVA that precedes the use of multiple comparisons did not produce significant f-statistics for HVLC PTH (level of significance = 0.01). However, it did produce significant f-statistics for the first three test times for the HVLC SMT circuit, as shown in Table 4-12 (shaded entries are > 0.01).

Table 4-12. P-Values for HVLC Test Results

Test Time	P-Value for HVLC PTH	P-Value for HVLC SMT
Pre-test	0.046	0.000
Post-85/85	0.028	0.000
Post-TS	0.625	0.000
Post-MS	0.274	0.742

Abbreviations and Definitions:
HCLV - high current low voltage
MS - mechanical shock
PTH - plated through hole
SMT - surface mount technology
TS - thermal shock

Figures F-1 to F-8 give boxplots for the HVLC PTH and SMT circuits. It is important to keep the vertical scale in mind relative to the acceptance criteria when viewing these boxplots. That is, the acceptance criteria indicates that the current should be between 4µA and 6µA. These boxplots are centered close to 5µA, and the total spread is on the order of 0.02µA for the PTH circuits and approximately 0.5µA for SMT circuits. Hence, even though there are some statistically significantly differences, they are not likely to be of practical concern. Note the boxplots in Figure F-8 for HCLV SMT at post-MS. These values are all either 0µA, or very close to it, reflecting the fact that the resistors came off the PWA during the mechanical shock test. This loss of components occurred on every PWA and was not related to the site, surface finish, or flux.

Comparison to Acceptance Criterion. The acceptance criteria for HVLC PTH and HVLC SMT are listed in Table 4-1 (responses 3 and 4). All HVLC PTH circuits met the acceptance criteria of 4µA and 6µA for the entire sequence of tests. Only one HVLC SMT current measurement failed to meet the acceptance criterion after exposure to 85/85 (see Table F-1). In turn, this same PWA also was the only one that did not meet the acceptance criteria after thermal shock. The test technician noted that this PWA exhibited a burnt edge after 85/85. However, after the mechanical shock test all HVLC SMT circuits failed to meet the acceptance criteria due to resistors coming off the PWA resulting in an open circuit.

4.1.9 High Speed Digital (HSD) Circuitry Performance Results

The pre-test measurements for HSD PTH and HSD SMT circuits were subjected to GLM analyses, as were the deltas after 85/85, thermal shock, and mechanical shock. The complete results of the GLM analyses are given in Tables F-8 and F-9, respectively. The GLM analyses indicate that the experimental parameters under evaluation do not influence the HSD total propagation delay measurements.

Boxplot Displays of Multiple Comparison Results. The overall ANOVA that precedes the use of multiple comparisons did not produce significant f-statistics for either HSD PTH or HSD SMT circuitry. The p-values for the respective f-statistics are given in Table 4-13 (shaded entries are > 0.01).

Table 4-13. P-Values for HSD Test Results

Test Time	P-Value for HSD PTH	P-Value for HSD SMT
Pre-test	0.442	0.585
Post-85/85	0.443	0.359
Post-TS	0.491	0.954
Post-MS	0.487	0.760

Abbreviations and Definitions:
HSD - high speed digital
MS - mechanical shock
PTH - plated through hole
SMT - surface mount technology
TS - thermal shock

Figures F-9 and F-10 give boxplots of pre-test measurements of total propagation delay for the HSD PTH and HSD SMT circuits, respectively. Note that most total propagation delays in Figure F-9 for HSD PTH are a little over 17 nanoseconds (ns) with a range of about 1ns. Figure F-10 shows that the total propagation delays for HSD SMT have a range of about 0.4ns and are centered about 9.2ns. The percentage changes in the total propagation delay measurements were small and well within the acceptance criteria so boxplot displays of these measurements are not presented.

Comparison to Acceptance Criterion. The acceptance criteria for HSD PTH and HSD SMT are listed in Table 4-1 (responses 5 and 6). One HSD SMT did not give a response after exposure to 85/85 (see Table F-1). This same circuit also failed to give a response after thermal shock, as did one additional HSD SMT circuit and two HSD PTH circuits. At post-MS, two HSD PTH circuits and one HSD SMT circuit did not give a response. The testing technician indicated that the HSD device had failed. Previous testing with the test PWA in other programs has indicated a failure of the HSD components, which is independent of the experimental parameters under evaluation in the DfE program. All other HSD circuits were well within the acceptance criterion.

4.1.10 High Frequency Low Pass Filter (HF LPF) Circuitry Performance Results

Pre-test measurements for all HF LPF circuits were subjected to GLM analyses, as were the deltas after 85/85, thermal shock, and mechanical shock. The results of the GLM analyses are given in Tables F-10 to F-15. The GLM analyses indicate that the parameters under evaluation (site, surface finish, or flux) do not influence the HF LPF measurements. The same is true at post-85/85, post-TS and post-MS. However, the test measurements contained many extreme outlying observations at both of these later two test times, which greatly increases the sample variance and in turn hinders the interpretation of the GLM results. As indicated in Tables F-1, F-2, and F-3 there were many anomalous HF LPF test measurements (171 at post-MS). The principal source of these outliers was open PTHs, is discussed in more detail under *Comparison to Acceptance Criteria.*

Boxplot Displays of Multiple Comparison Results

The ANOVA that precedes the use of multiple comparisons produced significant f-statistics for HF LPF PTH 50MHz at all test times and for three other HF LPF circuits at post-TS. The p-values for the respective f-statistics are given in Table 4-14 (all p-values > 0.01 are shaded).

Table 4-14. P-Values for HF LPF Test Results

Test Time	P-Value for HF PTH 50MHz	P-Value for HF PTH f(-3dB)	P-Value for HF PTH f(-40dB)	P-Value for HF SMT 50MHz	P-Value for HF SMT f(-3dB)	P-Value for HF SMT f (-40dB)
Pre-test	0.002	0.052	0.024	0.241	0.092	0.057
Post-85/85	0.000	0.484	0.487	0.227	0.258	0.970
Post-TS	0.004	0.578	0.594	0.016	0.074	0.023
Post-MS	0.002	0.001	0.028	0.000	0.112	0.000

Abbreviations and Definitions:
HF - high frequency
LPF - low pass filter
MS - mechanical shock
PTH - plated through hole
SMT - surface mount technology
TS - thermal shock

These results are discussed separately for each of the six HF LPF circuits. Boxplot displays of all test results for HF LPF circuits have been created to aid in the interpretation. Only the boxplots showing statistical and practical significance are shown here (Figures 4-9 to 4-15); the rest are in Appendix F.

HF LPF PTH 50MHz. While the p-values for the associated f-statistic were highly significant at all test times, Figure 4-9 identifies the source of this significance at pre-test, where the responses for nickel/gold applied at Site 18 and subsequently processed with low residue flux are much lower than the others. Post-85/85 and post-TS results indicate just the opposite for this demonstration site (see Figures F-11 and F-12). What occurred is that the problem circuit returned to normal at post-85/85 and post-TS, but those measurements were then compared to their low pre-test measurements, which caused the differences to be large in the positive direction. Hence, the large values at post-85/85 and post-TS are an artifact of the pre-test measurements and should most likely be ignored as the circuit performance was in line with all others. More importantly, the significant differences at pre-test are too small to be of practical concern. The range depicted in Figure 4-9 is approximately 0.7dB and the acceptance criterion allows a change of $\pm$5dB. On the other hand, Figure 4-10 is of concern as several of the surface finishes have measurements well below the lower bound acceptance criterion of -5dB. In particular, one of the five OSP PWAs, two of the three immersion silver PWAs, and one of the five immersion tin PWAs. This circuit had 15 anomalies at post-MS.

HF LPF PTH f(-3dB). Figure 4-11 shows the boxplot for the HF LPF PTH f(-3dB) circuit at the post-MS test time. Boxplots for the other three test times can be found in Appendix

F, since the p-values for the associated F-statistic were not significant, except for post-MS. Figure 4-11 shows notable variation in the magnitude of the differences — note the vertical scale. Several cases are well outside the acceptance criterion. In particular, one of four nickel/gold PWAs, two of the three immersion silver PWAs, and one of five immersion tin PWAs are quite low. This circuit had 18 anomalies at post-MS.

HF LPF PTH f(-40dB). Figure 4-12 shows the boxplot for the HF LPF PTH f(-40dB) circuit at the post-MS test time. Boxplots for the other three test times can be found in Appendix F. While the p-values for the associated f-statistic were not significant at any of the test times, Figure 4-12 shows notable variation in the magnitude of the differences (note the vertical scale). Several cases are well outside the acceptance criterion of ±50MHz. In particular, two of the three immersion silver PWAs and one of five immersion tin PWAs are quite low. This circuit had 14 anomalies at post-MS.

HF LPF SMT 50MHz. Figure 4-13 shows the boxplot for the HF LPF SMT 50MHz circuit at the post-MS test time. Boxplots for the other three test times can be found in Appendix F, since the p-values for the associated f-statistic were not significant, except for post-MS. The magnitude of the changes at post-85/85 and post-TS are too small to be of practical concern relative to the acceptance criteria of ±5dB. On the other hand, the post-MS results are of serious concern, as nine of 23 cases are well below the lower acceptance bound of -5dB. It is noteworthy that neither nickel/gold or nickel/palladium/gold had any anomalies. This circuit had 30 anomalies at post-MS.

HF LPF SMT f(-3dB). Figure 4-14 shows the boxplot for the HF LPF SMT f(-3dB) circuit at the post-MS test time. Boxplots for the other three test times can be found in Appendix F. While the p-values for the associated F-statistic were not significant at any of the test times, Figure 4-14 shows notable variation in the magnitude of the differences (note the vertical scale). Several cases are well outside the acceptance criterion of ±50MHz. It is noteworthy that neither nickel/gold or nickel/palladium/gold had any anomalies. This circuit had 29 anomalies at post-MS.

HF LPF SMT f(-40dB). Figure 4-15 shows the boxplot for the HF LPF SMT f(-40dB) circuit at the post-MS test time. Boxplots for the other three test times can be found in Appendix F, since the p-values for the associated f-statistic were not significant, except at post-MS. This circuit had the most anomalies (65) at post-MS. Some of the anomalies may be due to the high variability in the frequency when measured at -40dB. Figure 4-15 shows notable variation in the magnitude of the differences (note the vertical scale). Most cases are well outside the acceptance criterion of ±50MHz. Nickel/gold and nickel/palladium gold are again noteworthy as they have very few anomalies.

Comparison to Acceptance Criteria

The acceptance criteria for the six HF LPF circuits are shown in Table 4-1 (responses 7 through 12). Thirteen of 984 HF LPF test measurements did not meet the acceptance criterion after exposure to 85/85 (see Table F-1). These 13 responses occurred on six PWAs, with 12 of the 13 occurring with PTH components. After exposure to thermal shock, the number of HF LPF anomalies increased to 104 (see Table F-2). Thirteen of these 103 HF LPF anomalies carried over

from the 85/85 test. At post-MS, the number of anomalies increased to 171 with 97 carrying over from thermal shock.

PWAs with HF LPF anomalies generally have multiple anomalies. This can be seen in Table 4-15, which shows the frequency distribution of the number of HF LPF anomalies per PWA at post-MS (see Tables F-1 to F-3).

Table 4-15. Frequency Distribution of HF LPF Anomalies at Post-Mechanical Shock per PWA

No. of HF LPF Anomalies per PWA at Post-Mechanical Shock	Frequency
None	90
1	36
2	5
3	20
4	4
5	5
6	4

The test technician comments indicate that most of the HF LPF anomalies were due to an open PTH, which affects both PTH and SMT. To explain further, a circuit board consists of alternating layers of epoxy and copper through which a hole is drilled during fabrication. This via is plated with a very thin layer of electroless copper to provide a “seed bed” for the primary coatings. Copper is then electroplated over the electroless copper strike. The final surface finish (HASL, OSP, etc.) is then applied. Failure to make an electrical connection between the copper etches on the opposite sides of the board is known as an open PTH. The opens occurred in very small vias in the HF LPF circuit. Small vias can be very difficult to plate. Opens were present during in-circuit testing and at pre-test. In some cases, a z-wire was inserted through the via to make an electrical connection between the etches on the opposite side of the board. It appears that test conditions may accelerate the problem.

Although an open PTH is a fabrication issue, there does appear to be a relationship with surface finish. The HF LPF anomalies are summarized by surface finish in Table 4-17 for each of the six HF LPF circuits. Under the assumption that the anomalies occur independent of surface finish, the expected number of anomalies can be calculated for each cell. For example, consider Table 4-16, which summarizes the observed and expected anomalies for the HF LPF PTH 50MHz circuit.

Table 4-16. Comparison of the Observed and Expected Number of Anomalies for the HF LPF PTH 50MHz Circuit by Surface Finish

Surface Finish	Observed Anomalies (Expected)	Observed Non-Anomalies (Expected)	Row Total
HASL	1 (2.9)	31 (29.1)	32
Nickel/Gold	2 (2.6)	26 (25.4)	28
Nickel/Palladium/Gold	0 (1.1)	12 (10.9)	12
OSP	2 (3.3)	34 (32.7)	36
Immersion Silver	6 (1.8)	14 (18.2)	20
Immersion Tin	4 (3.3)	32 (32.7)	36
Column Total	**15**	**149**	**164**

Abbreviations and Definitions:
HF - high frequency
LPF - low pass filter
PTH - plated through hole

Under the hypothesis of independence of row and column classifications, the expected number of observations in each cell is the product of the cell's row and column totals divided by the grand total. For example, the expected number of anomalies for HASL is computed as (32)(15)/164 = 2.9. The expected values for all cells are shown in parentheses in the example. A chi-square statistic is calculated on the differences of the observed and expected number in each cell (Iman, 1994). The chi-square distribution is used to approximate the p-value for the chi-square statistic. For the above example, the p-value is 0.016, which is not significant at the 0.01 level. With this level of significance, the hypothesis of independence is not rejected for the HF LPF PTH 50MHz circuit. That is, there are no significant differences in the number of anomalies among the surface finishes for the HF LPF PTH 50MHz circuit.

Table 4-17. Comparison of the Observed and Expected Number of Anomalies Under the Hypothesis of Independence of Surface Finishes

	No. of PWAs	50MHz	HF LPF PTH f(-3dB)	f(-40dB)	50MHz	HF LPF SMT f(-3dB)	f(-40dB)
HASL	32	1 (2.9)	2 (4.1)	1 (2.9)	6 (5.9)	7 (5.9)	15 (13.1)
Nickel/Gold	28	2 (2.6)	3 (3.6)	2 (2.6)	0 (5.1)	0 (5.1)	1 (11.4)
Nickel/Palladium/Gold	12	0 (1.1)	0 (1.5)	0 (1.1)	0 (2.2)	0 (2.2)	1 (4.9)
OSP	36	2 (3.3)	2 (4.6)	1 (3.3)	6 (6.6)	5 (6.6)	20 (14.7)
Immersion Silver	20	6 (1.8)	6 (2.6)	7 (1.8)	7 (3.7)	6 (3.7)	11 (8.2
Immersion Tin	36	4 (3.3)	5 (4.6)	3 (3.3)	11 (6.6)	11 (6.6)	17 (14.7)
Totals	**164**	**15**	**18**	**14**	**30**	**29**	**65**
	p-value	0.016	0.051	0.001	0.006	0.008	0.000

Abbreviations and Definitions:
HF - high frequency
LPF - low pass filter
PTH - plated through hole
SMT - surface mount technology

Such is not the case for the last four HF LPF circuits listed in Table 4-17, where the p-values at the bottom of the table indicate that the anomalies are not independent of surface finish. The expected values for anomalies appear in parenthesis in each cell in that table. These comparisons show:

- HASL anomalies are close to the expected values throughout.
- Nickel/gold has far fewer anomalies than expected.
- Nickel/palladium/gold has far fewer anomalies than expected.
- OSP anomalies are close to expected, except for the last column, where they have more anomalies than expected.
- Immersion silver has many more anomalies that expected for all circuits.
- Immersion tin anomalies are close to expected for PTH circuits, but are higher than expected for SMT circuits.

The number of open PTH anomalies may be related to the inherent strength of the metals. Tin and silver are relatively weak; OSP has no metal, while nickel makes the PTH stronger. To determine the relevancy of metal strength to the open PTH anomalies, the HF LPF circuits would need to be subjected to failure analysis to check for copper plating thickness and PTH voids in the vias, as both of these may be problems in small vias. In addition, the chemical removal of copper from the via may be much greater in immersion tin and immersion silver, depending on how they were processed.

4.1.11 High Frequency Transmission Line Coupler (HF TLC) Circuitry Performance Results

Pre-test measurements for all HF TLC circuits except Reverse Null Frequency were subjected to GLM analyses, as were the deltas after 85/85, thermal shock, and mechanical shock. The results of the GLM analyses are given in Tables F-16 to F-20. The GLM analyses indicate that the experimental parameters do not influence the pre-test HF TLC measurements, except for those at 50 MHZ. The results for the 50MHz case are examined in further detail.

The predicted response at pre-test for HF TLC 50MHz for the base case (HASL at Site 1 processed with low residue flux) based on the Site & Flux GLM was -47.43dB. The predicted differences from the base case are given in Appendix F in Table F-21. The results show that the demonstration sites that produced nickel/gold and nickel/palladium/gold (# 13 - 16) have predicted increases of less than 3dB. While statistically significant, this change is rather small compared to the base case value and is probably not of practical utility. Overall, some of the demonstration sites differ from the base case by approximately -1.5dB to 2.9dB. These changes again may not have any practical significance, since the important concept is not so much the magnitude of the response, but rather its stability when subject to environmental stress conditions, which is the basis for the acceptance criteria.

The predicted response at pre-test for HF TLC 50MHz for the base case (HASL processed with low residue flux) based on the Surface Finish & Flux GLM was -46.73dB, which is almost identical to that for the Site & Flux GLM. The predicted differences from the base case are given in Appendix F in Table F-22. These predictions are consistent with those in

Table F-21, and show that immersion tin and immersion silver are approximately 1.0dB lower than the base case, and nickel/gold and nickel/palladium/gold are approximately 1 to 2dB higher than the base case. Again, these differences are most likely not of practical utility.

Boxplot Displays of Multiple Comparison Results. The ANOVA that precedes the use of multiple comparisons produced a significant f-statistic for only the HF TLC 50MHz circuit at pre-test. The p-values for the respective f-statistics are given in Table 4-18 (all p-values > 0.01 are shaded).

Table 4-18. P-Values for HF TLC Test Results

Test Time	P-Value for HF TLC 50MHz	P-Value for HF TLC 500MHz	P-Value for HF TLC 1GHz	P-Value for HF TLC RNR
Pre-test	0.000	0.070	0.250	0.418
Post-85/85	0.285	0.111	0.299	0.201
Post-TS	0.344	0.560	0.650	0.770
Post-MS	0.313	0.390	0.568	0.359

Abbreviations and Definitions:
HF TLC - high frequency transmission line coupler
MS - mechanical shock
TS - thermal shock

Boxplot displays of the test results for HF TLC 50MHz are given in Appendix F. While the F-statistic is significant at pre-test, the post-85/85 results show that the changes from the base case are centered about 0dB and well within the acceptance criteria of ±5dB. Thus, while the magnitude of the individual responses at pre-test may or may not be of practical concern in a particular application, the acceptance criteria is focused on the stability of the response when the circuit is subsequently subjected to environmental stress. The post-85/85 and post-TS results confirm that changes in the responses are all acceptable. However, post-MS shows several anomalies (seven by count), as shown in Figure 4-16. Five of these seven anomalies were for immersion silver, while HASL and immersion tin each had one anomaly.

Figure 4-17 displays the boxplot of the test results for HF TLC 500MHz post-MS. The HF TLC 500MHz results for the other test times are quite similar to those for HF TLC 50MHz, and boxplots of these results can also be found in Appendix F. Post-MS results for HF TLC 500MHz had only one slight anomaly compared to seven for HF TLC 50MHz. This anomaly was only -5.22dB, compared to the lower bound of -5dB, so it is of no concern. Boxplots displays for HF TLC 1GHz are not given to conserve space. The total variation at pre-test for HF TLC 1GHz was only 2dB, and there was only one slight anomaly of -5dB at post-MS, which is not of concern.

Figure 4-18 displays the boxplot of the test results for HF TLC RNR post-MS. None of the F-statistics were significant for testing equality of means; boxplots of results from the other three test times can be found in Appendix F. The reader should keep in mind that the decreases in the HF TLC RNR response in Figure 4-18 are favorable outcomes. The acceptance criterion only specifies an upper bound of either 5dBb or 10dB for the increase, depending on the magnitude of

the pre-test values. There were five slight anomalies at post-MS, with immersion tin having three, while HASL and immersion silver each had one.

Comparison to Acceptance Criteria. The acceptance criteria for HF TLC circuitry are listed in Table 4-1 (responses 13 to 17). Only one HF TLC RNR measurement failed to meet the acceptance criterion after exposure to 85/85 (see Table F-1). This measurement showed an increase of 10.2dB, which is only slightly above the acceptance criteria of 10dB and not of practical interest. At post-TS, this value was 10.02. One other HF TLC RNR measurement had an increase of 7.93dB at post-TS. All other changes were less than 5dB. One HF TLC 1GHz measurement was just below the lower limit of -5dB at -5.65dB. There were five anomalies at post-MS, none of which were of practical interest.

4.1.12 Leakage Measurements Performance Results

Four features were included in the design of the test PWA to check for current leakage: 10-mil pads, PGA socket (PGA-A, PGA-B), and a gull wing component (responses 18 to 21 in Table 4- l). The PGA hole pattern has four concentric squares that are electrically connected by traces on the top layer of the board. Two leakage current measurements were made: 1) between the two inner squares (PGA-A; and 2) between the two outer squares (PGA-B). Solder mask covers the pattern of the PGA-B, allowing a direct comparison of similar patterns with and without solder mask. Rather than an actual PGA device, a socket was used, because it provides the same soldering connections as a PGA device.

The leakage measurements were subjected to GLM analyses at pre-test and after 85/85, thermal shock, and mechanical shock. The results of the GLM analyses are given in Appendix F (Tables F-23 to F-26).

<u>10-Mil Pads</u>

Tables F-27 and F-28 give the predicted changes from their respective base cases for all leakage measurements at pre-test for the GLMs. Examination of the GLM results for 10-mil pad shows evidence of site-to-site variation and some interaction between site and flux that affects resistance either positively or negatively by up to an order of magnitude. Demonstration sites applying the OSP surface finish (Sites 6, 7, 8, and 9), as well as Sites 10 and 11 with immersion tin, do not differ from the base case when low residue flux is used. When sites are dropped from the GLM and replaced by surface finishes, the results show slight increases in resistance over the base case for OSP, immersion tin, and immersion silver.

The differences from the base case for both GLMs essentially disappear after exposure to the 85/85 test environment. This result is not unusual and may be due to a *cleansing effect* from the 85/85 test environment that removes residues resulting from board fabrication, assembly, and handling. This same phenomenon was observed for the other three leakage circuits.

Boxplot Displays of Multiple Comparison Results. As with the other circuits, an ANOVA was performed to determine if there was a significant difference in the mean leakage measurements for each of the four leakage circuits. The p-values for the respective f-statistics for

all four leakage measurements are given in the following summary (all p-values > 0.01 are shaded). Table 4-19 shows significant differences in the means at pre-test and post-85/85 for the 10-mil pads.

Table 4-19. P-Values for Leakage Test Results

Test Time	P-Value for 10-mil Pads	P-Value for PGA-A	P-Value for PGA-B	P-Value for Gull Wing
Pre-test	0.000	0.000	0.000	0.000
Post-85/85	0.000	0.510	0.198	0.551
Post-TS	0.047	0.048	0.026	0.432
Post-MS	0.213	0.125	0.093	0.243

Abbreviations and Definitions:
MS - mechanical shock
PGA - pin grid array
TS - thermal shock

Boxplot displays of the leakage measurements for 10-mil pads are given in Figures 4-19 and 4-20 for pre-test and post-85/85, respectively. Boxplots for post-TS and post-MS are in Appendix F. Figure 4-19 illustrates the impact of flux that was identified as significant in the GLM analyses. Every case with water soluble flux is higher (better) than the corresponding low residue analog. In Figure 4-20, the differences due to flux have disappeared. As mentioned above, this change is likely due to a cleansing effect from the 85/85 test environment, which removed residues resulting from board fabrication, assembly, and handling. The statistical significance of the F-statistic at post-85/85 is attributable to immersion tin produced at Site 13, which had lower resistance (i.e. higher current leakage). However, the resistance is still well above the acceptance criteria of 7.7.

Comparison to Acceptance Criterion. The acceptance criterion for the leakage measurements requires the resistance to be greater than 7.7 when expressed as log l0 ohms. There were no anomalies for the 10-mil pads at pre-test, post-85/85, post-TS, or post-MS.

<u>Pin Grid Array-A</u>

Examination of the GLM results in Table F-27 for PGA-A shows evidence of site-to-site variation and some interaction between site and flux that affects resistance either positively or negatively by up to an order of magnitude. Nine of the demonstration sites do not differ from the base case when low residue flux is used.

Table F-28 in Appendix F shows a flux effect of approximately 2.05 orders of magnitude as determined using GLM analyses surface finish, indicating there are no meaningful differences due to surface finishes. As was the case with the 10-mil pads, the differences from the base case for both GLMs essentially disappear after exposure to the 85/85 test environment.

Boxplot Displays of Multiple Comparison Results. The p-values for the ANOVA given above show the only test indicating a significant difference in mean leakage for the PGA-A circuit was the pre-test (shown in Figure 4-21). Boxplot displays of the other leakage

measurements for PGA-A are given in Appendix F. Figure 4-21 illustrates the impact of flux that was identified as significant in the GLM analyses. As was true with 10-mil pads, every case with water soluble flux is higher (better) than the corresponding low residue analog, although all test responses were above the acceptance criteria. In subsequent results, the differences due to flux disappear. As mentioned above, this change is likely due to a cleansing effect from the 85/85 test environment.

Comparison to Acceptance Criterion. There were no anomalies for PGA-A at pre-test, post-85/85, post-TS, or post-MS.

Pin Grid Array-B

Examination of the GLM results in Table F-27 for PGA-B shows a strong effect due to flux of approximately 2.77 orders of magnitude. Thirteen of the demonstration sites do not differ from the base case when low residue flux is used, and the other two only differ slightly. Table F-28 also shows a strong flux effect of approximately 2.71 orders of magnitude as determined in the GLM analyses surface finish, indicating there are no meaningful differences due to surface finishes. As was the case with the 10-mil pads and PGA-A, the differences from the base case for both GLMs essentially disappear after exposure to the 85/85 test environment.

Boxplot Displays of Multiple Comparison Results. The p-values for the ANOVA given above show the only test indicates a significant difference in mean leakage for the PGA-B circuit at pre-test. Figure 4-22 illustrates the impact of flux that was identified as significant in the GLM analyses. As was true with 10-mil pads and PGA-A, every case with water soluble flux is higher (better) than the corresponding low residue analog, though all test responses were above the acceptance criteria. In boxplots for the other test times, the differences due to flux disappear. As mentioned above, this change is likely due to a cleansing effect from the 85/85 test environment. Boxplot displays of the other leakage measurements for PGA-B are given in Appendix F.

Comparison to Acceptance Criterion. There were no anomalies for PGA-B at pre-test, post-85/85, post-TS, or at post-MS.

Gull Wing

Examination of the GLM results in Table F-27 for the Gull Wing shows a moderate effect due to flux of approximately 0.81 orders of magnitude. There is evidence of modest site-to-site variation and some interaction between site and flux. Eleven of the demonstration sites do not differ from the base case when low residue flux is used, and the other two only differ slightly. Table F-28 shows a flux effect of approximately 1.09 orders of magnitude as determined in the GLM analyses by surface finish, indicating there are no meaningful differences due to surface finishes. As was the case with the 10-mil pads, PGA-A, and PGA-B, the differences from the base case for both GLMs essentially disappear after exposure to the 85/85 test environment.

Boxplot Displays of Multiple Comparison Results. The p-values for the ANOVA given above show only the test time, with a significant difference in mean leakage for the gull wing circuit at pre-test, as illustrated in Figure 4-23. Boxplot displays of the leakage measurements for the gull wing at the other test times are given in Appendix F. Figure 4-23 illustrates the impact of flux that was identified as significant in the GLM analyses. As was true with 10-mil pads, PGA-A, and PGA-B, every case with water soluble flux is higher that the corresponding low residue analog, though all test responses were abofe the acceptance criteria. At subsequent test times, the differences due to flux disappear. As mentioned above, this change is likely due to a cleansing effect from the 85/85 test environment.

Comparison to Acceptance Criterion. There was one slight anomaly for the Gull Wing following 85/85. This value was 7.27 compared to the acceptance criteria of 7.7, so it is not of concern. There were no anomalies at post-TS or post-MS.

4.1.13 Stranded Wires

Two stranded wires were hand-soldered on the PWA (responses 22 and 23 in Table 4-1). One wire was soldered into PTHs, and the other was soldered to two terminals. Pre-test measurements for the stranded wire circuits were subjected to GLM analyses, as were the deltas after 85/85, thermal shock, and mechanical shock. The results of the GLM analyses are given in Tables F-29 and F-30. The GLM analyses indicate that the experimental parameters do not influence the stranded wire voltage measurements.

Boxplot Displays of Multiple Comparison Results. As with other circuits, an ANOVA was used to determine if there was a significant difference in the mean leakage measurements for the two stranded wire measurements. The p-values for the respective f-statistics for these two sets of voltage measurements are given in the following summary (all p-values > 0.01 are shaded). Table 4-20 shows no significant differences in the means at any test time. Boxplot displays of the pre-test voltage measurements (mV) can be found in Appendix F.

Table 4-20. P-Values for Stranded Wire Test Results

Test Time	P-Value for 10-mil Pads	P-Value for PGA-A
Pre-test	0.951	0.203
Post-85/85	0.410	0.407
Post-TS	0.537	0.440
Post-MS	0.396	0.408

Abbreviations and Definitions:
MS - mechanical shock
PGA - pin grid array
TS - thermal shock

Comparison to Acceptance Criterion. The acceptance criteria requires changes in voltage to be within 0.356V of their pre-test measurements. There were no anomalies for either Stranded Wire 1 or 2 at pre-test or following 85/85. There was one minor anomaly at post-TS for SW2 where the measured increase in voltage was 0.371V, compared to the upper acceptable limit of 0.356V. At post-MS, there was one minor anomaly for SW1 (0.375) and four minor

anomalies for SW2 (0.359, 0.37O, 0.365, and 0.357). All of these anomalies were right at the upper limit and are not of concern.

4.1.14 Failure Analysis

Following the analysis of the test boards, ion chromatography was used as a tool to analyze boards that failed 85˚C/85% relative humidity exposure. Contamination Studies Laboratories, Inc. (CSL) in Kokomo, Indiana, conducted this failure analysis. The purpose of the analysis was to determine if any links exist between board contamination from fabrication and assembly process residues and the electrical anomalies.

Test Sample Identification

Twenty boards were selected for the ion chromatography analysis including: 1) a test group of boards that failed after exposure to 85˚C/85% relative humidity; and 2) a control group of boards that were not subjected to the 85˚C/85% relative humidity environment. The test group consisted of 10 boards (identified in Table F-1) that exhibited various anomalies following 85˚C/85% relative humidity testing. For the control group, the 10 boards selected represented each of the six surface finishes and a variety of assembly processes and sites. Table 4-21 summarizes the 20 boards selected for ion chromatography analysis.

Visual Observations

The test group of boards was visually inspected to identify any obvious anomalies or defects. All 10 boards exhibited visual anomalies in varying degrees. The most common anomalies were solder cracking and discoloration of the surface metalization. Less common were pinholes and foreign material (e.g., solder balls). The following photographs show examples of the more prominent visual defects.

Table 4-21. Identification of Assemblies Selected for Ion Chromatography Analysis

Finish	Board #	Assembly Process	Site
Untested Board (Control Group)			
HASL	077-4	LR	1
HASL	096-2	WS	2
Nickel/Gold	068-4	WS	7
Nickel/Gold	017-4	LR	12
Nickel/Palladium/Gold	001-4	LR	15
OSP	061-2	WS	3
Immersion Silver	085-4	WS	8
Immersion Silver	074-3	LR	9
Immersion Tin	103-4	WS	4
Immersion Tin	034-4	LR	10
Post-85/85 Exposure (Anomaly Group)			
HASL	083-2	WS	1
Nickel/Gold	013-1	LR	13
Nickel/Gold	015-4	LR	14
OSP	056-4	LR	5
Immersion Silver	082-2	LR	11
Immersion Silver	094-4	WS	12
Immersion Tin	030-4	WS	9
Immersion Tin	032-4	LR	8
Immersion Tin	086-2	WS	7
Immersion Tin	102-4	WS	10

Abbreviations and Definitions:
LR - low residue flux
WS - water soluble flux

Test Method

The fundamental steps for conducting ion chromatography analysis per IPC-TM-650, method 2.3.28 are as follows:

1. The lab technician (LT) placed the test board(s) into clean KAPAK™ (heat-sealable polyester film) bag(s).
2. The LT introduced a mixture of isopropanol (75 percent volume) and deionized water (25 percent volume) into the bag(s), immersing the test board(s). NOTE: The heat-sealed bag(s) included an opening for ventilation.
3. The LT inserted the bag(s) into an 80 ºC water bath for one hour.
4. The LT removed the bag(s) from the water bath.
5. The LT separated the test board(s) from the bags.
6. The LT placed the test board(s) on a clean holding rack for air drying at room temperature.

7. The LT performed controls and blanks on the Dionex ion chromatography system before the test began. NOTE: NIST-traceable standards for system calibration were used.
8. The LT injected a 1.5 ml sample of each test sample's extract solution using a 5 mM sodium bicarbonate eluent.

Failure Analysis Results

The following tables show the ion chromatography data for each surface finish analyzed, reported as micrograms of the residue species per square inch of extracted surface (µg/in^2). NOTE: This measure should not be confused with micrograms of sodium chloride equivalent per square inch, which is the common measure for most ionic cleanliness test instruments.

Table 4-22. Ion Chromatography Anion $^{(-)}$ Data (HASL) [a]

Sample Description	Assembly Process	Site	Ion Chromatography Data		
			Cl^-	Br^-	WOA
Untested Boards (Control Group)					
Board #077-4	LR	1	5.87	3.82	154.33
Board #096-2	WS	2	14.53	10.01	3.01
Tested Boards (Anomaly Group)					
Board #083-2	WS	1	5.36	2.73	7.l5

[a] Test results reported as micrograms of the residue species per square inch of extracted surface (µg/in^2).
Br^- = bromide ion; Cl^- = chloride ion; LR = low residue flux; WOA = weak organic acids; WS = water soluble flux.

Table 4-23. Ion Chromatography Anion $^{(-)}$ Data (Immersion Tin) [a]

Sample Description	Assembly Process	Site	Ion Chromatography Data		
			Cl^-	Br^-	WOA
Untested Boards (Control Group)					
Board #034-4	LR	10	0.87	5.26	140.45
Board #103-4	WS	4	5.10	2.98	3.30
Tested Boards (Anomaly Group)					
Board #032-4	LR	8	1.75	4.12	15.78
Board # 030-4	WS	9	1.70	5.68	15.46
Board #086-2	WS	7	2.99	3.30	9.23
Board #102-4	WS	10	2.33	3.16	4.63

[a] Test results reported as micrograms of the residue species per square inch of extracted surface (µg/in^2).
Abbreviations and Definitions:
Br^- - bromide ion
Cl^- - chloride ion
LR - low residue flux
WOA - weak organic acids
WS - water soluble flux

Table 4-24. Ion Chromatography Anion $^{(-)}$ Data (Immersion Silver) [a]

Sample Description	Assembly Process	Site	Ion Chromatography Data		
			Cl^-	Br^-	WOA
Untested Boards (Control Group)					
Board #074-3	LR	9	0.60	6.53	159.48
Board #085-4	WS	8	4.77	2.64	5.22
Tested Boards (Anomaly Group)					
Board #082-2	LR	11	2.59	3.25	4.28
Board #094-4	WS	12	2.53	4.65	5.78

[a] Test results reported as micrograms of the residue species per square inch of extracted surface (µg/in^2).
Abbreviations and Definitions:
Br^- - bromide ion
Cl^- - chloride ion
LR - low residue flux
WOA - weak organic acids
WS - water soluble flux

Table 4-25. Ion Chromatography Anion $^{(-)}$ Data (Nickel/Gold) [a]

Sample Description	Assembly Process	Site	Ion Chromatography Data		
			Cl^-	Br -	WOA
Untested Boards (Control Group)					
Board #017-4	LR	12	1.01	5.34	150.81
Board #068-4	WS	7	4.57	1.78	3.08
Tested Boards (Anomaly Group)					
Board #013-1	LR	13	2.44	3.56	15.13
Board #015-4	LR	14	1.63	2.80	14.04

[a] Test results reported as micrograms of the residue species per square inch of extracted surface (µg/in^2).
Abbreviations and Definitions:
Br^- - bromide ion
Cl^- - chloride ion
LR - low residue flux
WOA - weak organic acids
WS - water soluble flux

Table 4-26. Ion Chromatography Anion $^{(-)}$ Data (OSP) [a]

Sample Description	Assembly Process	Site	Ion Chromatography Data		
			Cl^-	Br^-	WOA
Untested Boards (Control Group)					
Board #061-2	WS	3	3.57	3.45	2.57
Tested Boards (Anomaly Group)					
Board #056-4	LR	5	2.40	4.28	26.41

[a] Test results reported as micrograms of the residue species per square inch of extracted surface (µg/in^2).
Abbreviations and Definitions:
Br^- - bromide ion
Cl^- - chloride ion
LR - low residue flux
WOA - weak organic acids
WS - water soluble flux

Table 4-27. Ion Chromatography Anion $^{(-)}$ Data (Nickel/Palladium/Gold) [a]

Sample Description	Assembly Process	Site	Ion Chromatography Data		
			Cl^-	Br^-	WOA
Untested Boards (Control Group)					
Board #001-4	LR	15	0.84	5.15	151.18

[a] Test results reported as micrograms of the residue species per square inch of extracted surface (µg/in^2).
Abbreviations and Definitions:
Br^- - bromide ion
Cl^- - chloride ion
LR - low residue flux
WOA - weak organic acids

Chloride. Chloride ion (Cl^-) is one of the more detrimental materials found on printed circuit assemblies. Chloride, which can come from a variety of sources, is most often attributable to flux residues. Chloride will generally initiate and propagate electrochemical failure mechanisms, such as metal migration and electrolytic corrosion, when combined with water vapor and an electrical potential. The tolerance for chloride on an assembly depends on the flux chemistry that an assembler uses. An assembly processed with high-solids rosin fluxes (RA or RMA) can tolerate higher levels of chloride due to the encapsulating nature of the rosin. water soluble fluxes and no-clean fluxes, which flux manufacturers typically formulate using resins or very low levels of rosin, do not have this encapsulating protection. Therefore, they require lower levels of flux on final assemblies.

CSL recommends a maximum chloride level of no more than 4.5 to 5.0 µg/in^2 for finished assemblies processed with water-soluble fluxes, and no more than 2.5 µg/in^2 for finished assemblies processed with low solids (no-clean) fluxes. Although these recommended maximums do not presently appear in any nationally-accepted specifications or standards, years of failure analysis experience dealing with CSL's numerous customers serves as a basis or starting point.

With the exception of the HASL boards, all untested and tested assemblies exhibit levels at or below CSL's recommended guidelines. Therefore, the observed chloride levels are not considered to be detrimental from an electrochemical standpoint.

The two untested (control) boards with the HASL finish exhibit levels significantly above CSL's recommended limits and are therefore at risk for electrochemical failures. For the board processed with low residue (no clean) flux, CSL suspects that the high chloride is due mainly to the board fabricator's use of a chloride-activated HASL flux coupled with an ineffective post-HASL cleaning process. For the board processed with water-soluble flux, high chloride may be the result of both HASL residues and water soluble flux residues. In both cases, ineffective cleaning is the likely culprit.

The one tested HASL board with the reported anomaly exhibits a level only slightly above CSL's recommended limit. Although the chloride in the observed amount places the assembly at slight risk for electrochemical failures, CSL does not believe in this case that chloride contamination is the root cause for reported open PTH failures on Board #083-2.

Based on the fact the tested boards with known anomalies exhibit levels near or below CSL's recommended guidelines, there is reasonable confidence that the anomalies identified in the performance testing are not the result of chloride residues. The majority of the anomalies are either mechanical in nature (e.g., poor solder joint integrity) or component non-conformities (e.g., wrong value and device failures).

Bromide. Bromide ion (Br^-) is generally attributable to the bromide fire retardant added to epoxy-glass laminates to give fire resistance, and which is subsequently extracted in the ion chromatography analytical procedure. Bromide can also sometimes come from solder masks, marking inks, or fluxes that have a bromide activator material. Bromide, when from the fire retardant, is not a material that typically degrades the long-term reliability of electronic assemblies. If bromide comes from a flux residue, it can be corrosive, as other halides can be. The level of bromide varies depending on the porosity of the laminate and/or mask, the degree of over/under cure of the laminate or mask, or the number of exposures to reflow temperatures.

For epoxy-glass laminate, bromide levels typically fall within the range of 0 to 7 $\mu g/in^2$, depending upon the amount of fire retardant the laminate manufacturer has added. Exposure to reflow conditions tends to increase the porosity of the laminate and mask. With several exposures to reflow conditions, bromide can reach levels as high as 10 to 12 $\mu g/in^2$. The testing laboratory, CSL, does not presently consider bromide levels under 12 $\mu g/in^2$ to be detrimental on organic PWBs. However, CSL considers levels between 12 $\mu g/in^2$ to 20 $\mu g/in^2$ to be a borderline risk for failures if attributable to corrosive flux residues. Furthermore, levels above 20 $\mu g/in^2$ are considered to be a significant threat for failures if attributable to corrosive flux residues.

Based on CSL's guidelines, the bromide levels on the assemblies are acceptably low and as such do not pose a threat for electrochemical failures. CSL attributes these bromide levels to the fire retardant material in the FR-4 laminate.

Weak Organic Acids. Weak organic acids (WOAs), such as adipic or succinic acid, serve as activator compounds in many fluxes, especially no-clean fluxes. WOAs are typically

benign materials and are therefore not a threat to long term reliability. In order to avoid formulation disclosure difficulties with flux manufacturers, all detected WOA species were grouped together and referred to collectively as WOAs.

WOA levels vary greatly, depending on the delivery method (e.g., foam vs. spray) and the preheat dynamics. In general, water-soluble fluxes have a much lower WOA content than do low-solids (no clean) fluxes, and the amount of residual WOA is proportional to the amount of residual flux. Bare boards typically do not contain WOA residues.

Table 4-28. Acceptance Levels for Weak Organic Acids

Process	Level
Spray-applied, low solids solder paste deposition	0 - 20 µg/in^2
Foam-applied flux process w/air knife	20 - 120 µg/in^2
Spray-applied, low solids flux	250 - 400 µg/in^2

When WOA levels are under 400 µg/in^2, the residues are generally not detrimental. Excessive WOA amounts (appreciably greater than 400 µg/in^2) present a significant reliability threat for finished assemblies. Low levels of WOA can also create electrical performance problems in certain applications.

- An excessive amount of flux can produce the situation in which the thermal energy of preheat is spent driving off the solvent, therefore not allowing the flux to reach its full activation temperature. Unreacted flux residues readily absorb moisture that promotes the formation of corrosion and the potential for current leakage failures.
- Fully reacted and therefore benign WOAs act as insulators that, even at levels as low as 10 µg/in^2, can potentially create a high resistance contact-to-contact resistance problem on devices such as switches.

The observed levels of WOAs on all 20 boards are typical and therefore are not detrimental from an electrochemical standpoint. As expected, more WOA is evident on the boards processed with low residue fluxes than on those processed with water soluble fluxes.

4.1.15 Summary and Conclusions

The test PWA provides electrical responses for 23 individual circuits that fall into the following seven major circuit groups:

- high current low voltage (HCLV);
- high voltage low current (HVLC);
- high speed digital (HSD);
- high frequency low pass filter (HF LPF);
- high frequency transmission line coupler (HF TLC);
- leakage networks; and
- stranded wire (SW).

The first four circuit groups have both PTH and SMT components.

These characteristics make the test PWA an excellent discriminating test vehicle to discover problem areas associated with new circuit card technologies, materials, and processes. Exposure to environmental conditions such as the 85/85, thermal shock, and mechanical shock used in this test program can accelerate the discovery process. Table 4-29 illustrates how problem areas developed during the three tests.

Table 4-29 clearly identifies the HF LPF circuits as a problem area. The main problem was related to open PTHs, which were discussed previously in Section 4.1.10. The HF LPF anomalies resulted from a combination of board fabrication materials and processes and board design (i.e., the small diameter vias in the HF LPF circuit). Product designers should be aware of these phenomena when considering a change to the new surface finishes.

Table 4-29. Frequency of Anomalies by Individual Circuit Over Test Times

Circuitry		Post-85/85	Post-Thermal shock	Post-Mechanical Shock	Comments
HCLV					
1	HCLV PTH	0	0	12	Some should be subjected to failure analysis.
2	HCLV SMT	0	0	158	SMT components came off board during mechanical shock.
HVLC					
3	HVLC PTH	0	0	0	Excellent performance throughout.
4	HVLC SMT	1	1	164	SMT components came off board during mechanical shock.
HSD					
5	HSD PTH	0	2	2	Component problem.
6	HSD SMT	1	2	1	Component problem.
HF LPF					
7	HF PTH 50MHz	4	15	15	Perform failure analysis related to open PTH (see Section 4.1.10).
8	HF PTH f(-3dB)	4	15	18	Perform failure analysis related to open PTH (see Section 4.1.10).
9	HF PTH f(-40dB)	4	13	14	Perform failure analysis related to open PTH (see Section 4.1.10).
10	HF SMT 50MHz	0	18	30	Perform failure analysis related to open PTH (see Section 4.1.10).
11	HF SMT f(-3dB)	0	16	29	Perform failure analysis related to open PTH (see Section 4.1.10).
12	HF SMT f(-40dB)	1	27	65	Perform failure analysis related to open PTH (see Section 4.1.10).

Circuitry		Post-85/85	Post-Thermal shock	Post-Mechanical Shock	Comments
HFTLC					
13	HF TLC 50MHz	0	0	7	Minor anomalies.
14	HF TLC 500MHz	0	0	1	Minor anomalies.
15	HF TLC 1GHz	0	1	1	Minor anomalies.
16	HF TLC RNF				
17	HF TLC RNR	1	2	5	Minor anomalies.
Leakage					
18	10-mil Pads	0	0	0	Excellent performance throughout.
19	PGA-A	0	0	0	Excellent performance throughout.
20	PGA-B	0	0	0	Excellent performance throughout.
21	Gull Wing	1	0	0	Excellent performance throughout.
Stranded Wire					
22	SW 1	0	0	1	Excellent performance throughout.
23	SW 2	0	1	4	Minor anomalies.

Abbreviations and Definitions:
HCLV - high current low voltage
HF - high frequency
HSD - high speed digital
HVLC - high voltage low current
PGA - pin grid array
PTH - plated through hole
SMT - surface mount technology
SW - stranded wire
TLC - transmission line coupler

With the exception of the HCLV SMT and HVLC SMT circuits in the mechanical shock test, the surface finishes under study were very robust to the environmental exposures. When assessing the HCLV SMT and HVLC SMT results, product and process designers should consider the severity of the mechanical shock test (25 drops, five times on each edge excluding the connector edge and five times on each face, to a concrete surface from a height of one meter). Also, HCLV SMT and HVLC SMT anomalies due to SMT components coming off the board during the execution of the mechanical shock test were equally distributed across all surface finishes including the HASL baseline.

Based on the results of the Failure Analysis:

- Observed levels of bromide and WOA on all 20 assemblies are typical and therefore not detrimental from an electrochemical standpoint.
- Based on the fact the tested boards with known anomalies exhibit levels near or below CSL's recommended guidelines, there is reasonable confidence that the anomalies are not the result of chloride, bromide, or WOA contamination.

- From an overall contamination standpoint, the five non-HASL surface finishes tested in this analysis performed as well if not better against the HASL finish.
- Solder joint cracking failures were greater with the HASL finish than with the alternative finishes. The opens occurred along the interface of the component leads on these older PTH technology boards.

4.1.16 Boxplot Displays

Boxplot displays are presented here for selected results as discussed in this Chapter. Boxplots of the remaining test results are presented in Appendix F.

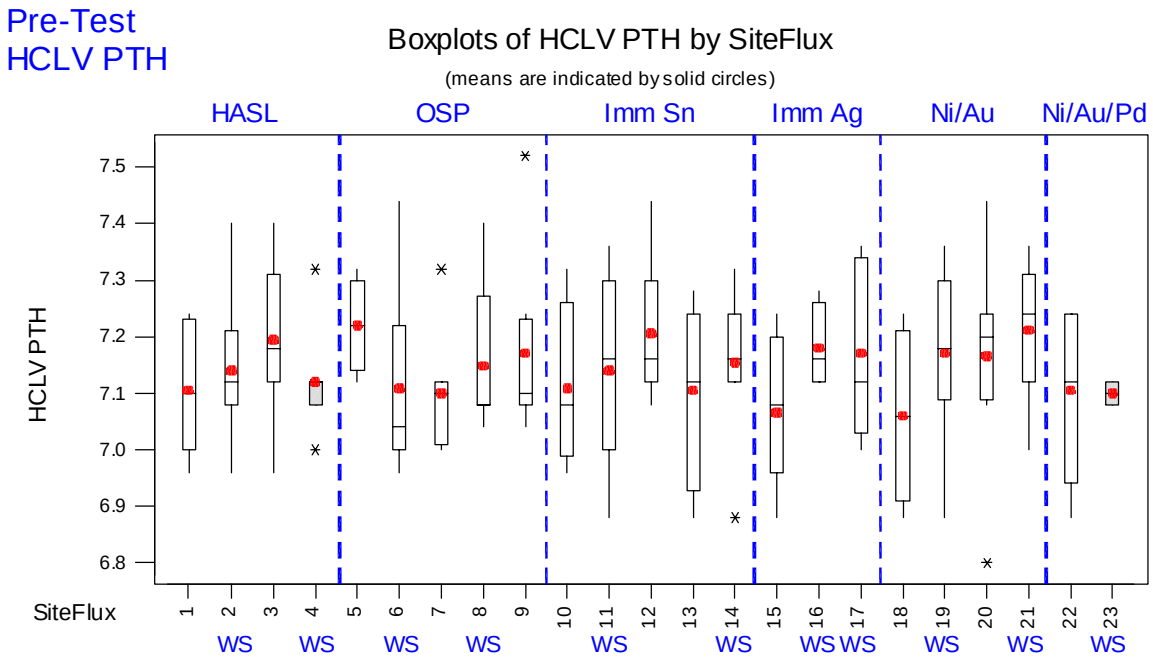


Figure 4-1. Boxplot Displays for HCLV PTH Measurements (volts) at Pre-test by Surface Finish

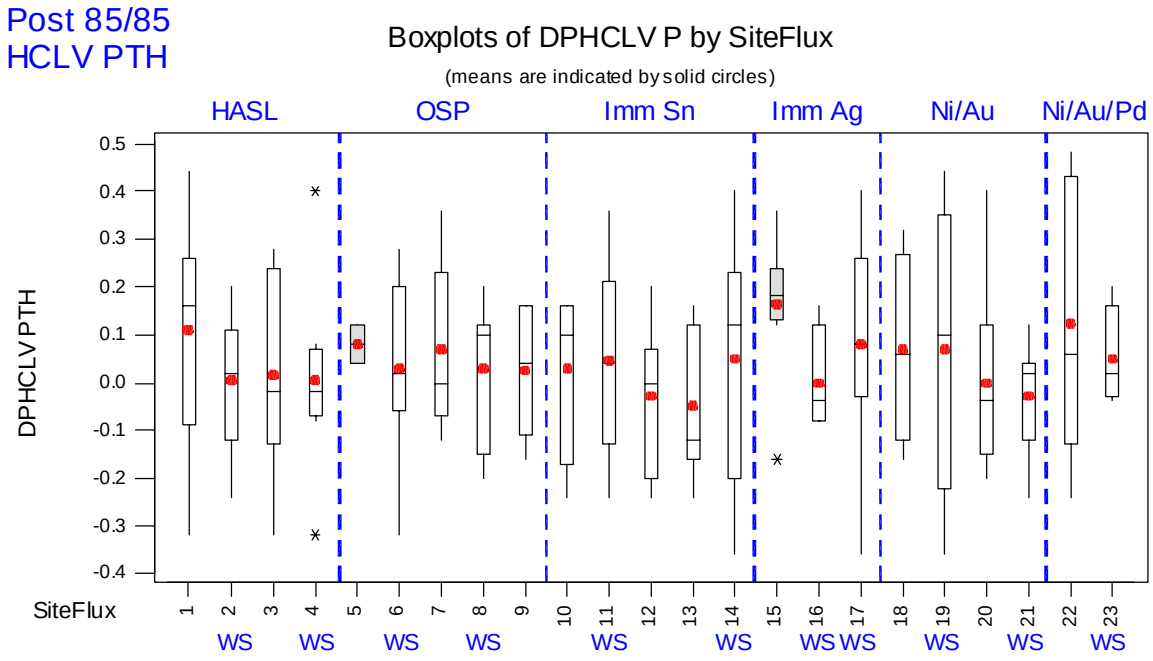


Figure 4-2. Boxplot Displays for HCLV PTH Post 85/85 – Pre-test Measurements (volts) by Surface Finish

(Acceptance Criterion = Δ<0.5V)

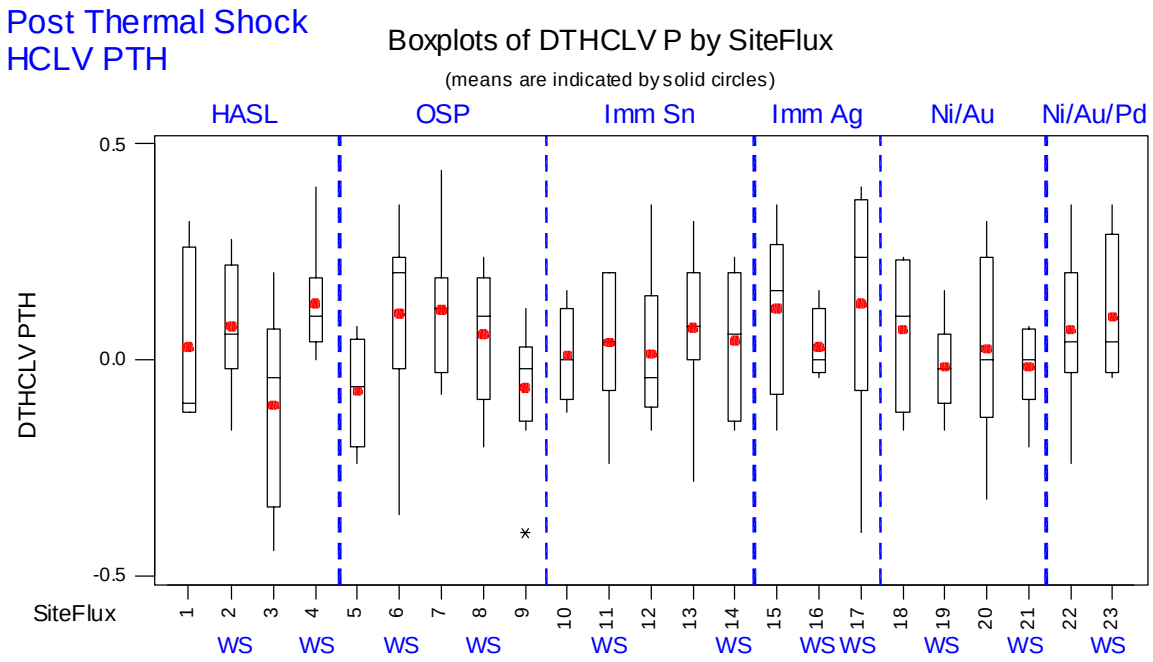


Figure 4-3. Boxplot Displays for HCLV PTH Post TS - Pre-Test Measurements (volts) by Surface Finish

(Acceptance Criterion = Δ<0.5V)

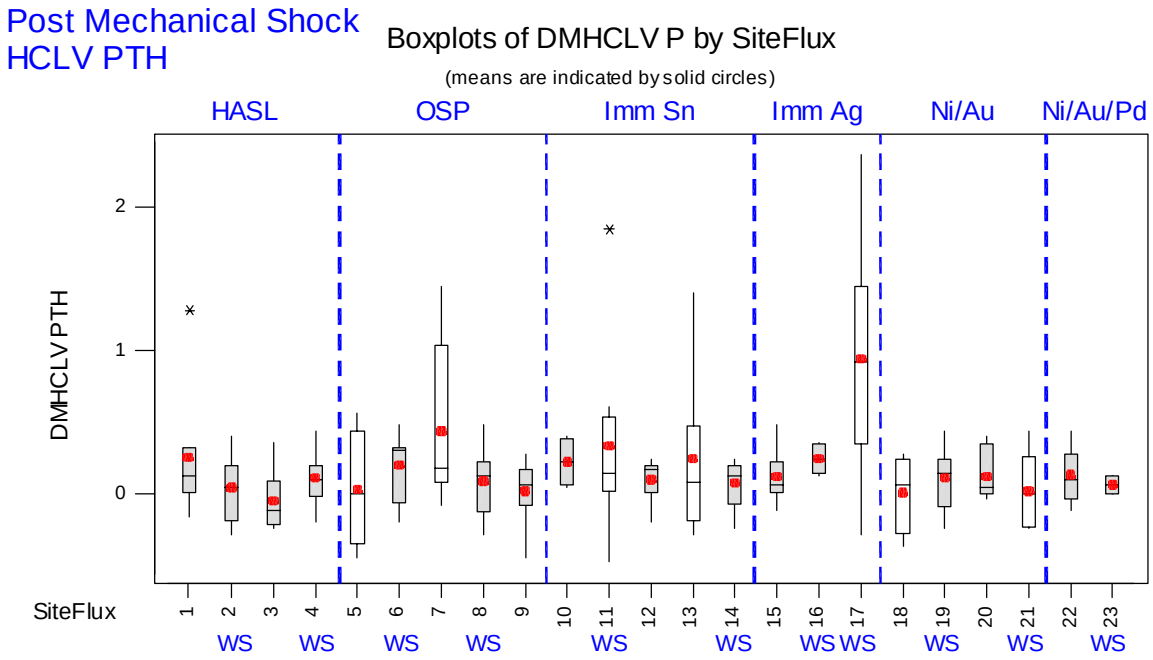


Figure 4-4. Boxplot Displays for HCLV PTH Post MS - Pre-Test Measurements (volts) by Surface Finish

(Acceptance Criterion = Δ<0.5V)

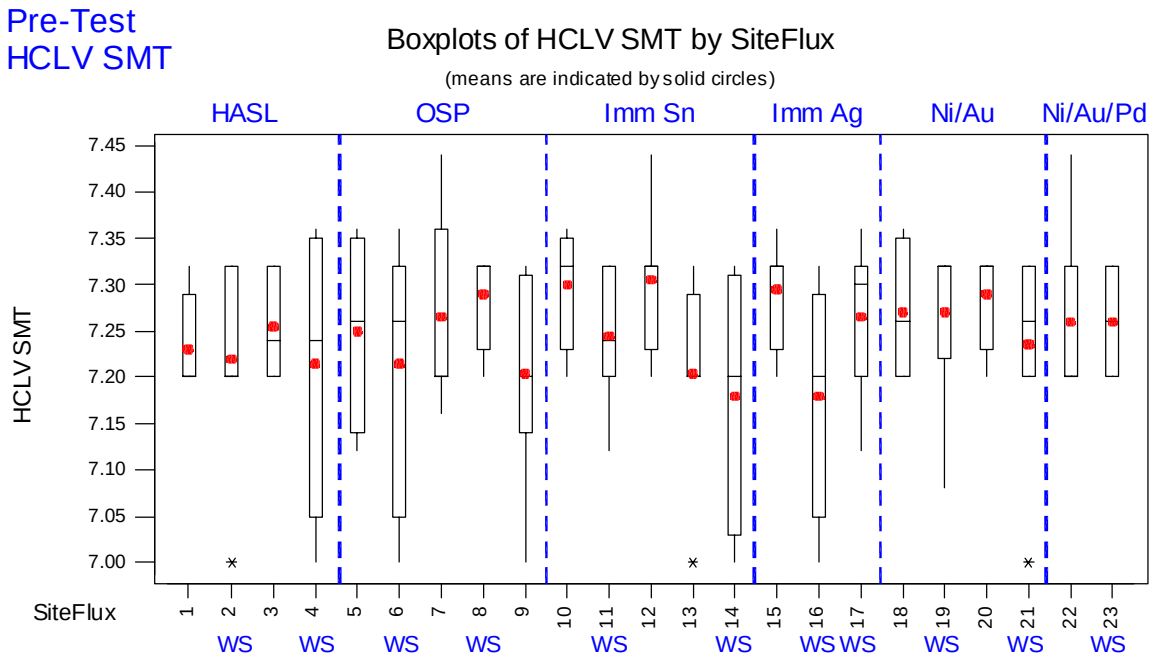


Figure 4-5. Boxplot Displays for HCLV SMT Measurements (volts) at Pre-Test by Surface Finish

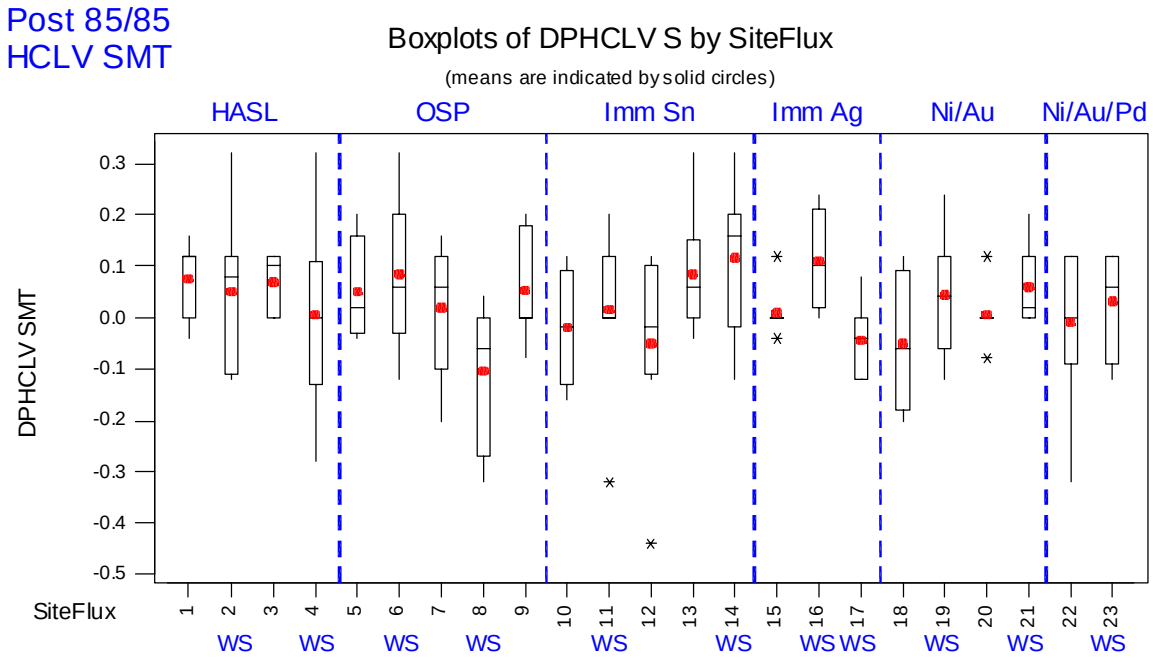


Figure 4-6. Boxplot Displays for HCLV PTH Post 85/85 - Pre-Test Measurements (volts) by Surface Finish

(Acceptance Criterion = Δ<0.5V)

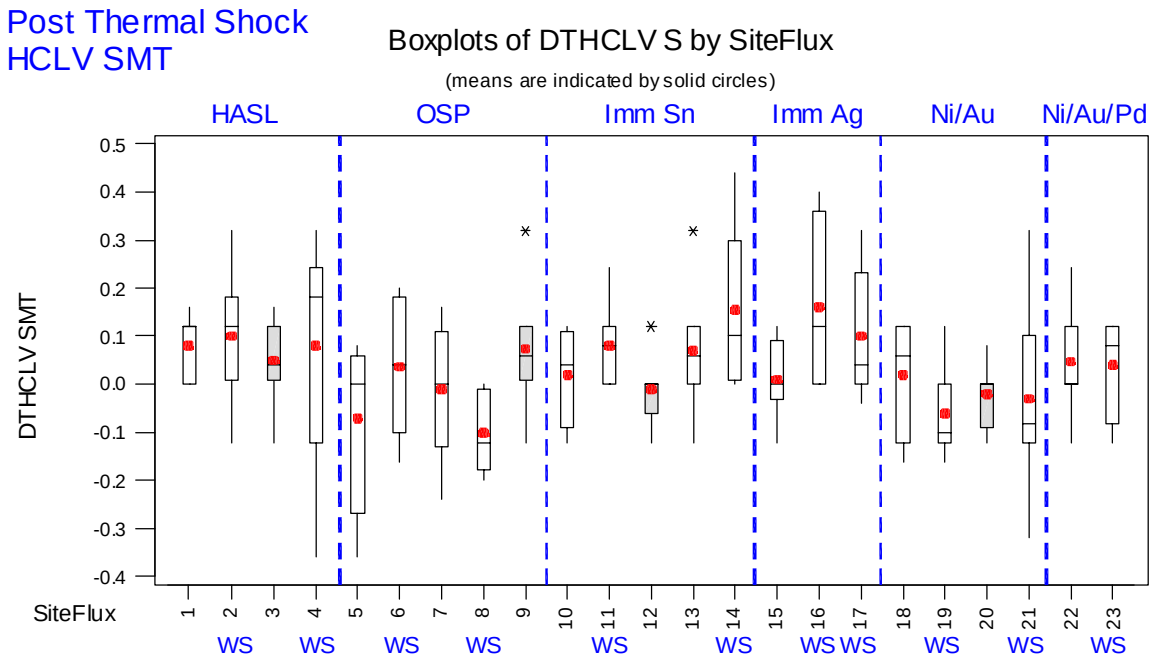


Figure 4-7. Boxplot Displays for HCLV PTH Post TS - Pre-Test Measurements (volts) by Surface Finish

(Acceptance Criterion = Δ<0.5V)

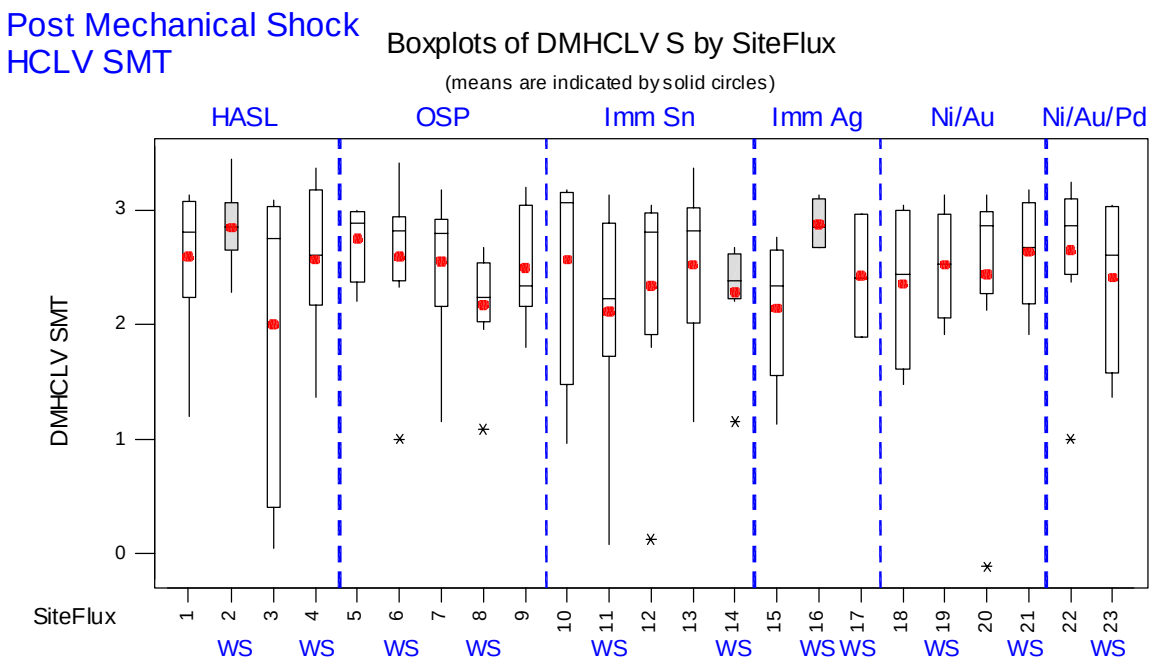


Figure 4-8. Boxplot Displays for HCLV PTH Post MS - Pre-Test Measurements (volts) by Surface Finish

(Acceptance Criterion = Δ<0.5V)

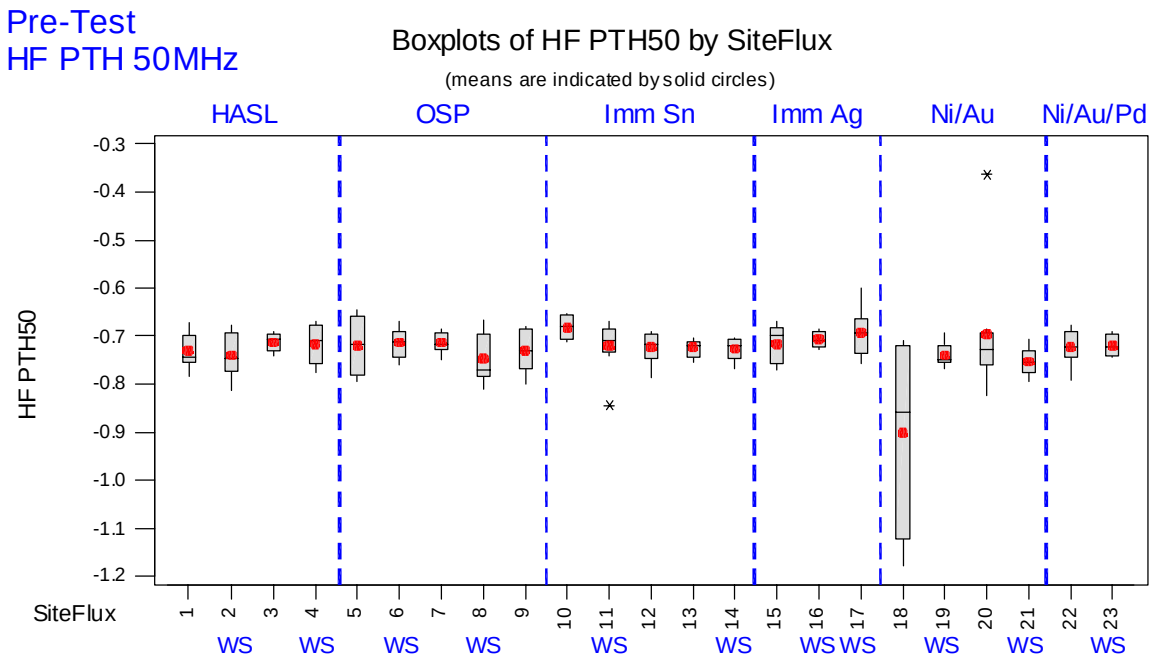


Figure 4-9. Boxplot Displays for HF PTH 50MHz Measurements at Pre-Test (dB) by Surface Finish

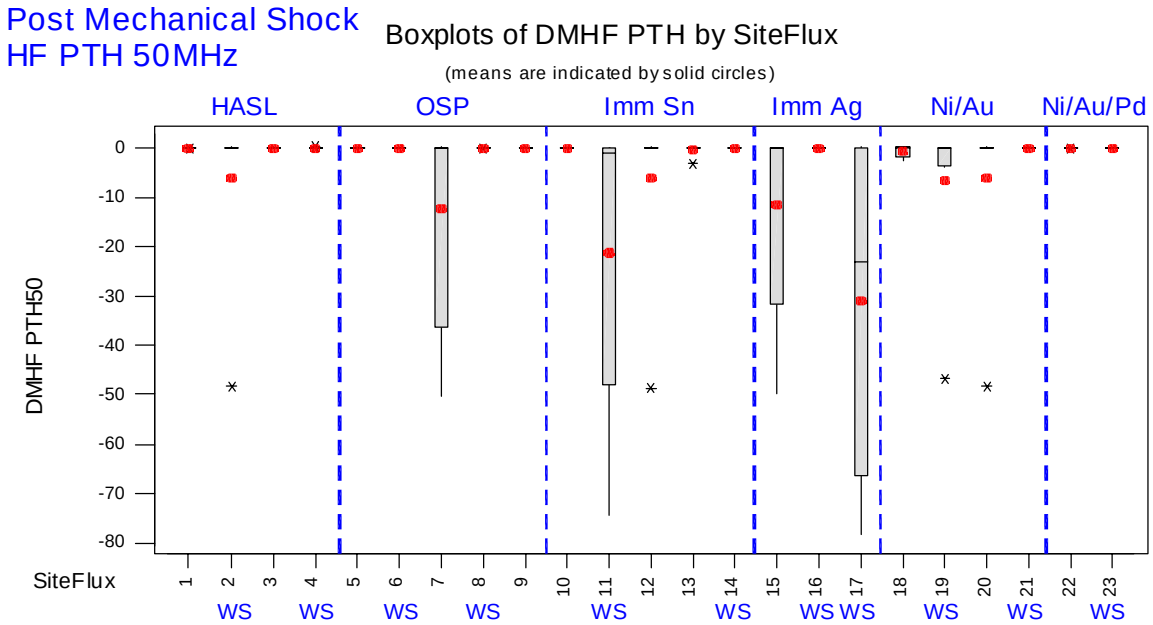


Figure 4-10. Boxplot Displays for HF PTH 50MHz Post MS - Pre-Test Measurements (dB) by Surface Finish

(Acceptance Criterion = ±5dB of Pre-test)

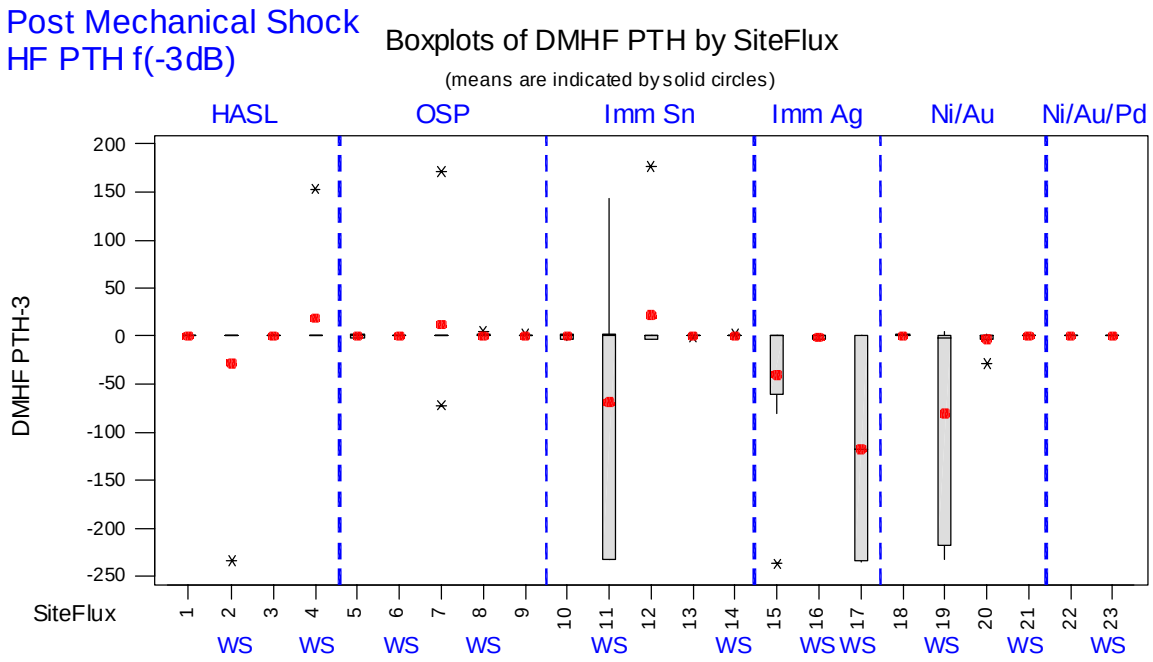


Figure 4-11. Boxplot Displays for HF PTH f(-3dB) Post MS - Pre-Test Measurements (MHz) by Surface Finish

(Acceptance Criterion = ±50MHz of Pre-test)

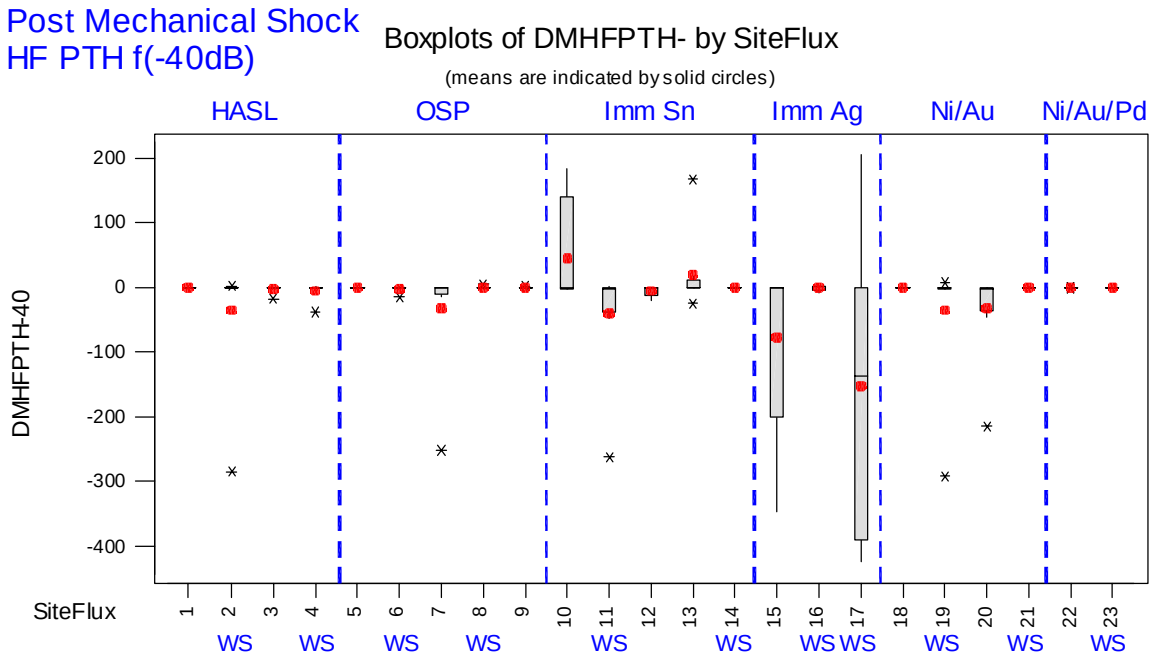


Figure 4-12. Boxplot Displays for HF PTH f(-40dB) Post MS - Pre-Test Measurements (MHz) by Surf. Finish

(Acceptance Criterion = ±50MHz of Pre-test)

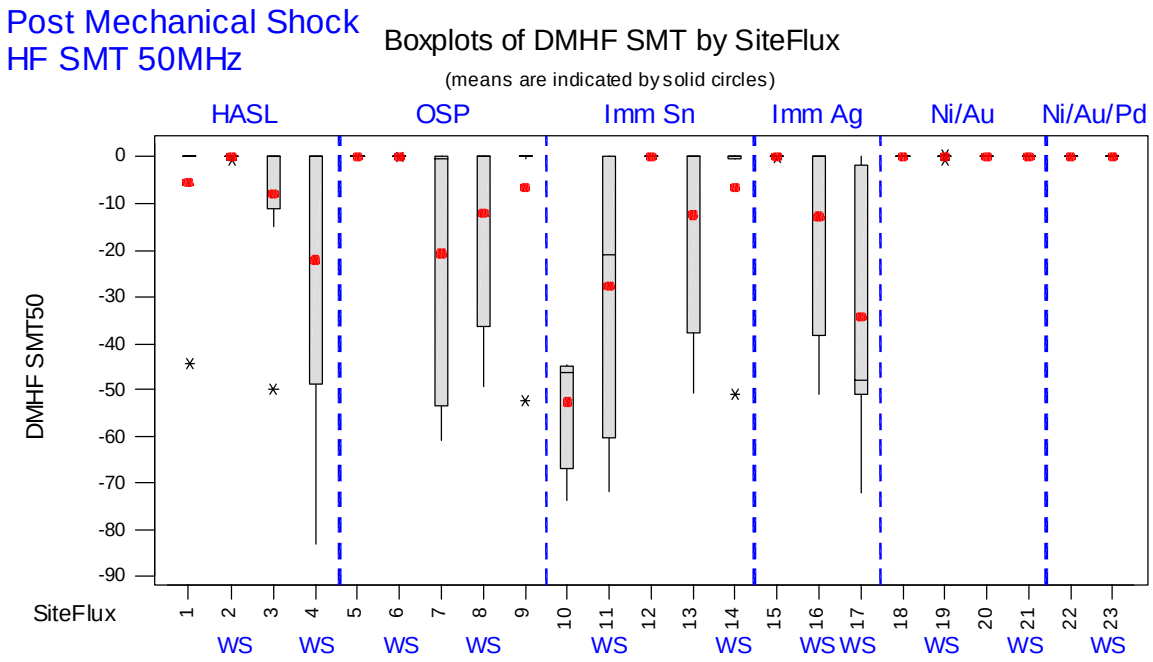


Figure 4-13. Boxplot Displays for HF SMT 50MHz Post MS - Pre-Test Measurements (dB) by Surface Finish

(Acceptance Criterion = ±5dB of Pre-test)

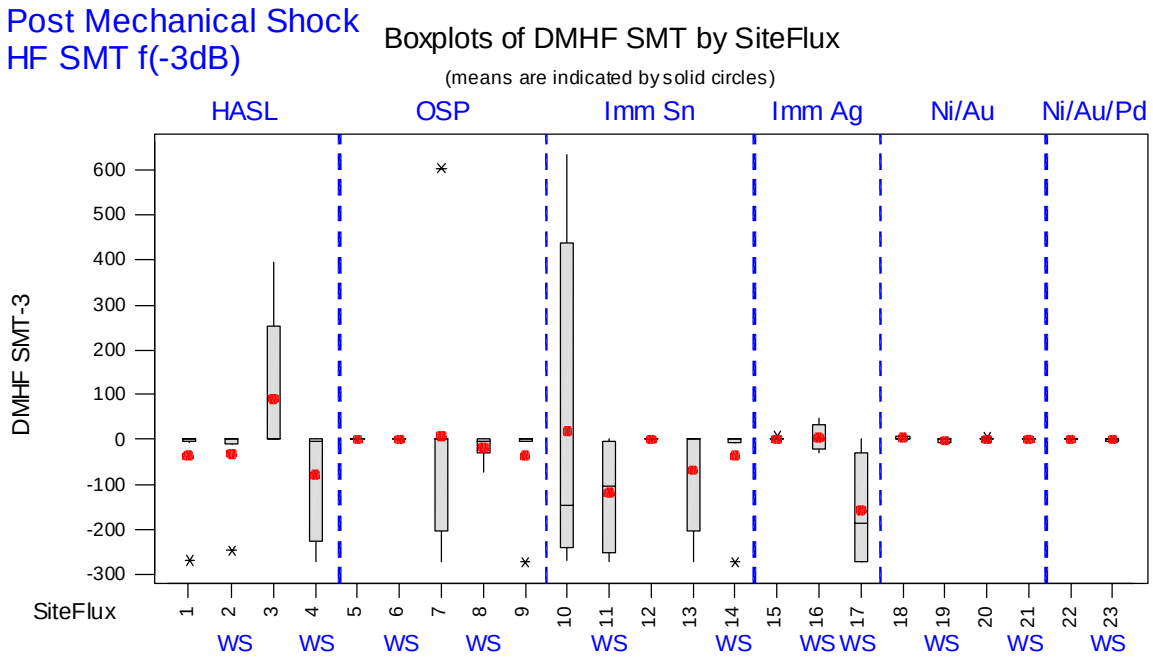


Figure 4-14. Boxplot Displays for HF SMT f(-3dB) Post MS - Pre-Test Measurements (MHz) by Surf. Finish

(Acceptance Criterion = ±50MHz of Pre-test)

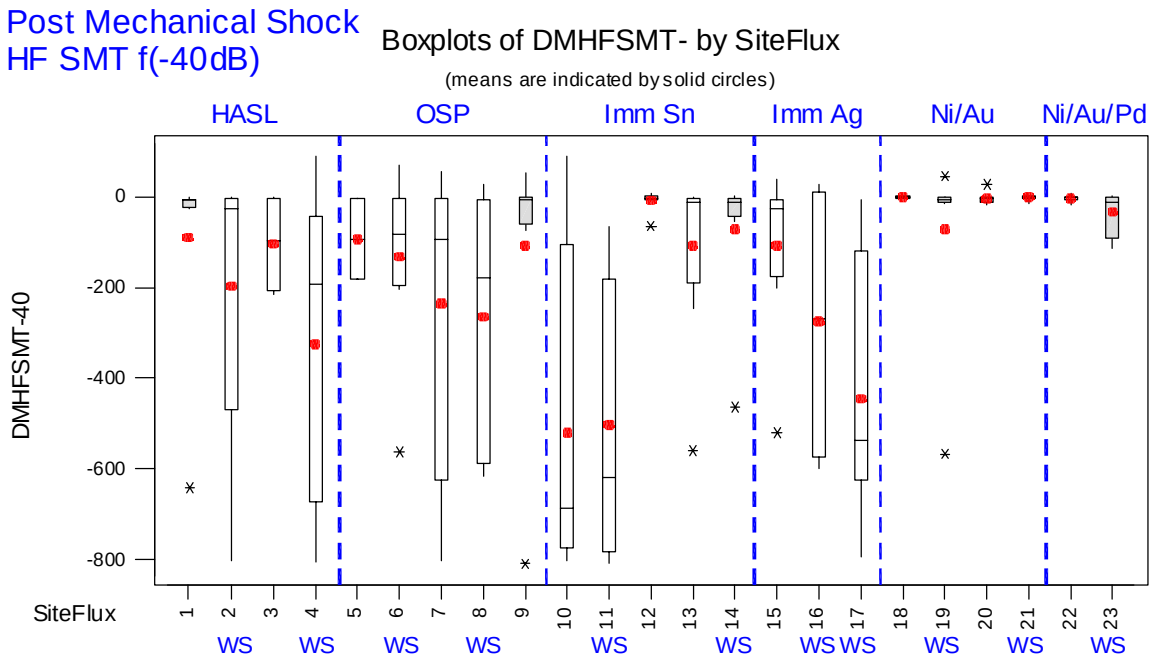


Figure 4-15. Boxplot Displays for HF SMT f(-40dB) Post MS - Pre-Test Measurements (MHz) by Surface Finish

(Acceptance Criterion = ±50MHz of Pre-test)

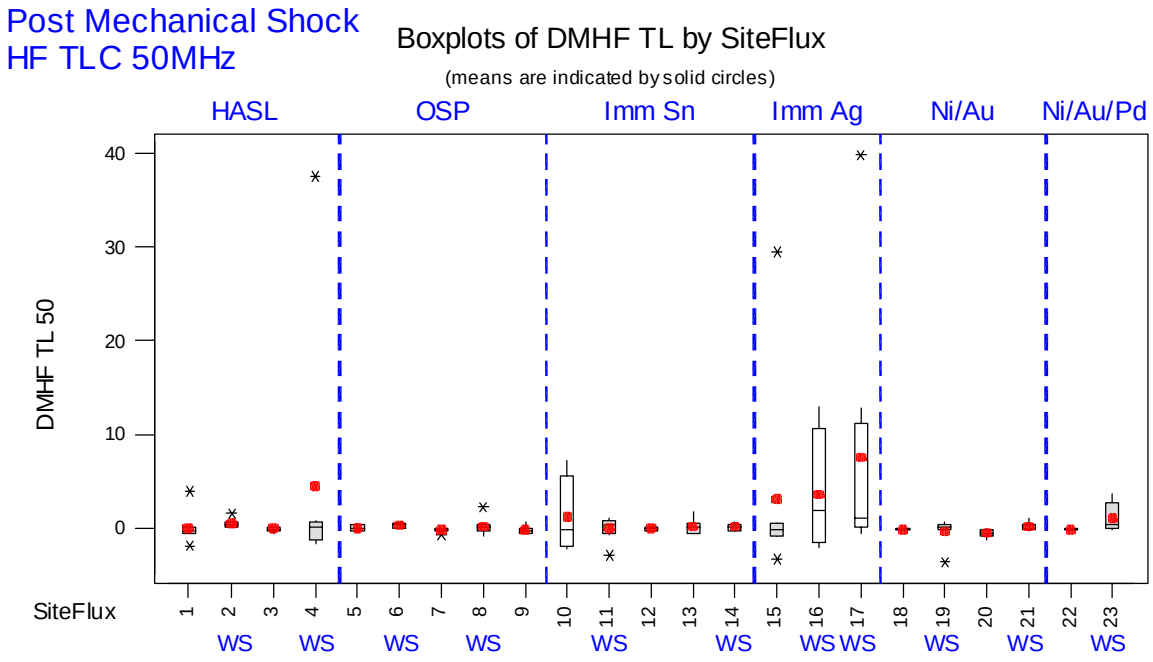


Figure 4-16. Boxplot Displays for HF TLC 50MHz Post MS - Pre-Test Measurements (dB) by Surface Finish

(Acceptance Criterion = ±5dB of Pre-test)

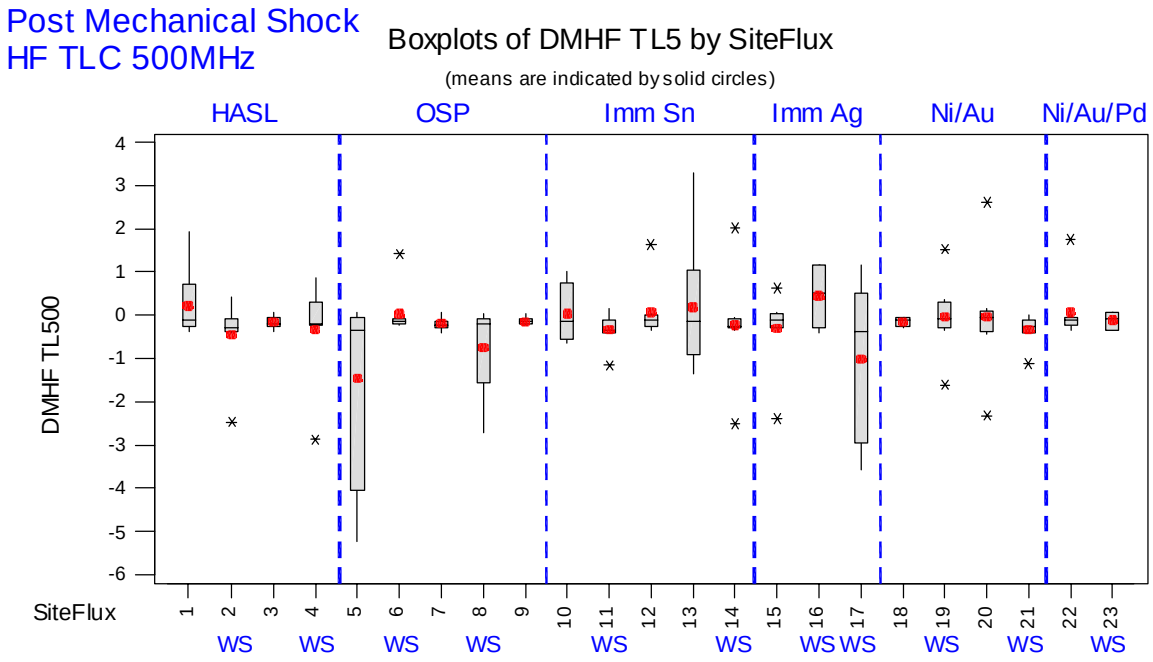


Figure 4-17. Boxplot Displays for HF TLC 500MHz Post MS - Pre-Test Measurements (dB) by Surface Finish

(Acceptance Criterion = ±5dB of Pre-test)

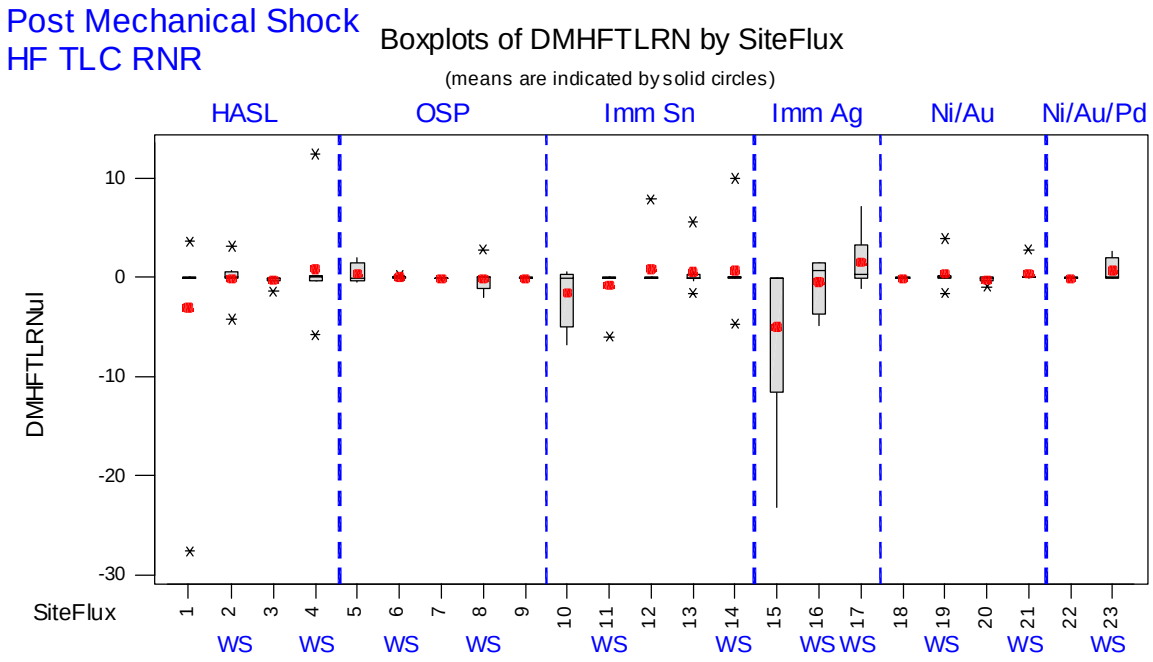


Figure 4-18. Boxplot Displays for HF TLC RNR Post MS - Pre-Test Measurements (dB) by Surface Finish

(Acceptance Criterion = <10dB increase over Pre-test)

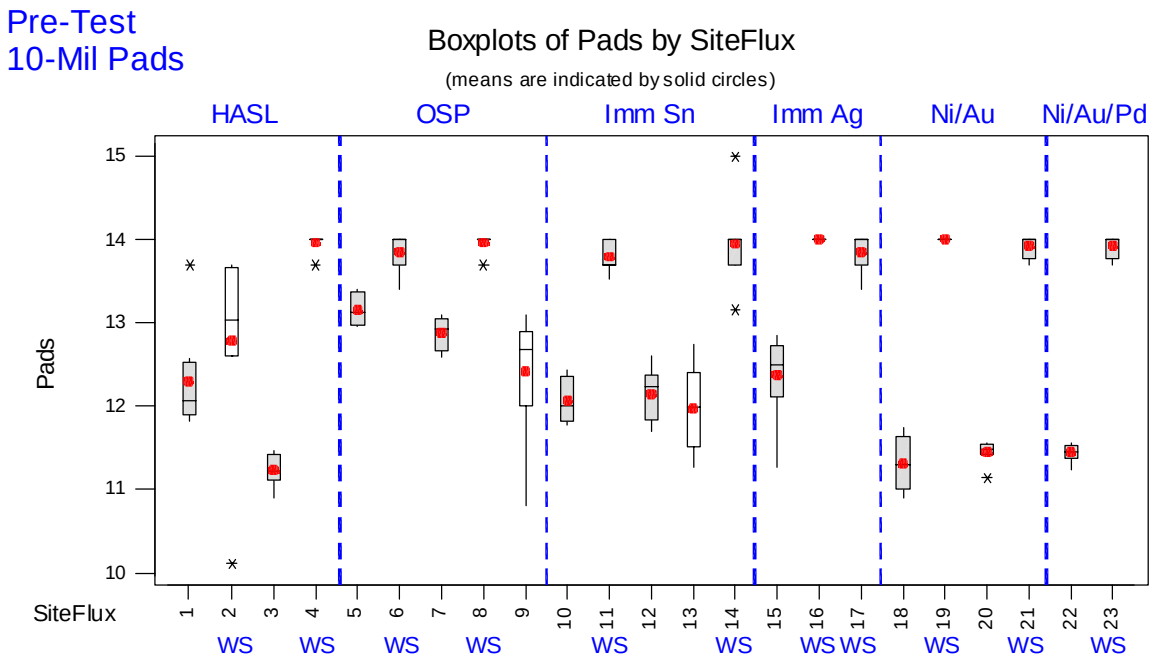


Figure 4-19. Boxplot Displays for 10-Mil Pad Measurements ($\log_{10}$ ohms) at Pre-Test by Surface Finish
(Acceptance Criterion = Resistance > 7.7 $\log_{10}$ ohms)

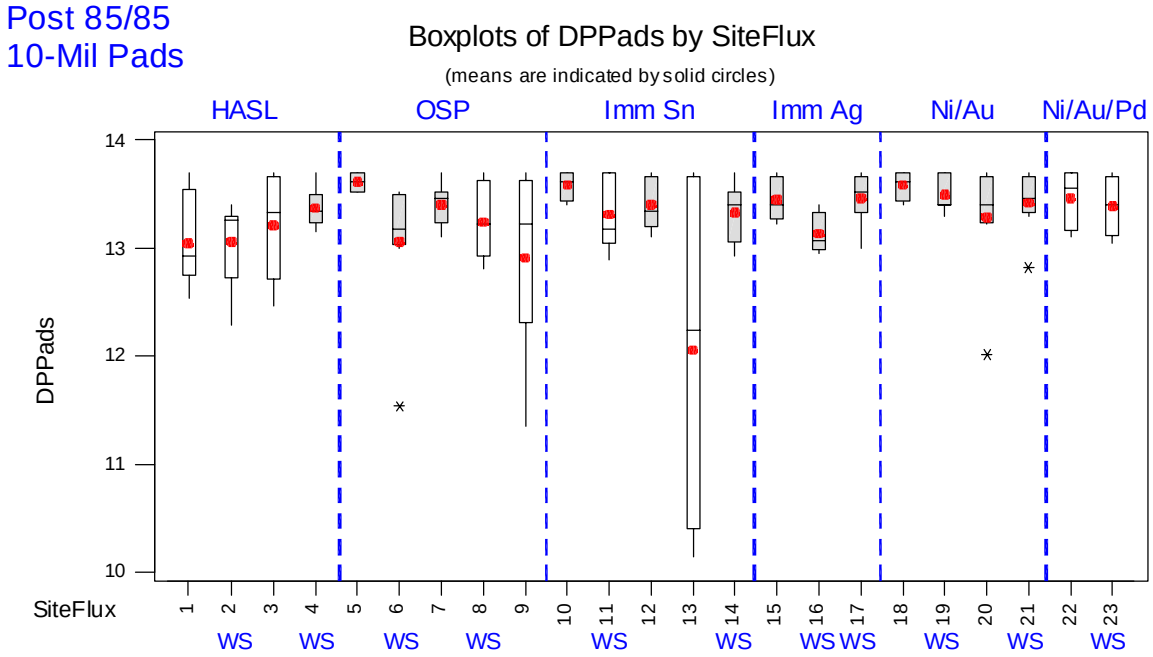


Figure 4-20. Boxplot Displays for 10-Mil Pad Post 85/85 - Pre-Test Measurements ($\log_{10}$ ohms) by Surface Finish
(Acceptance Criterion = Resistance > 7.7 $\log_{10}$ ohms)

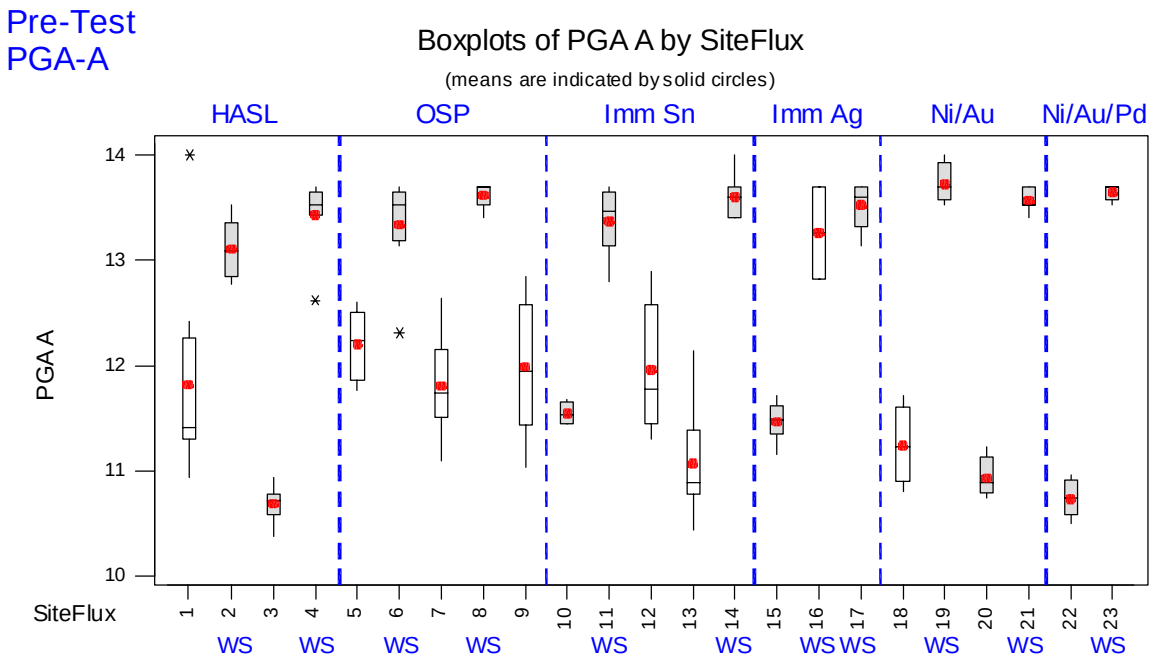


Figure 4-21. Boxplot Displays for PGA-A Measurements ($\log_{10}$ ohms) at Pre-Test by Surface Finish
(Acceptance Criterion = Resistance > 7.7 $\log_{10}$ ohms)

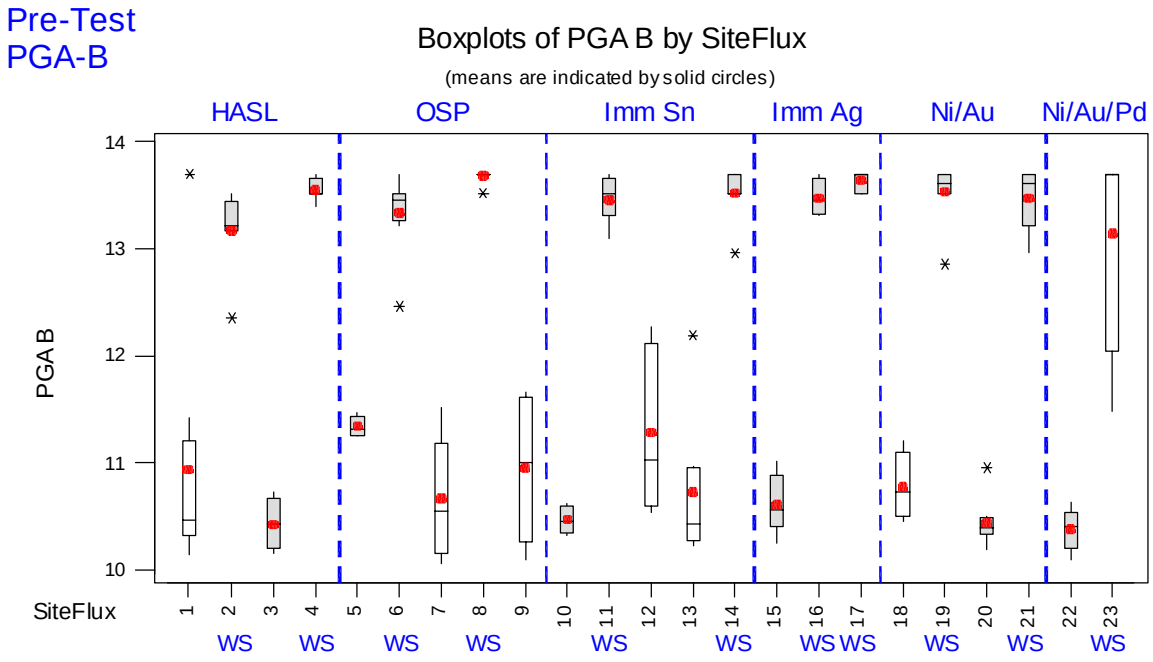


Figure 4-22. Boxplot Displays for PGA-B Measurements ($\log_{10}$ ohms) at Pre-Test by Surface Finish
(Acceptance Criterion = Resistance > 7.7 $\log_{10}$ ohms)

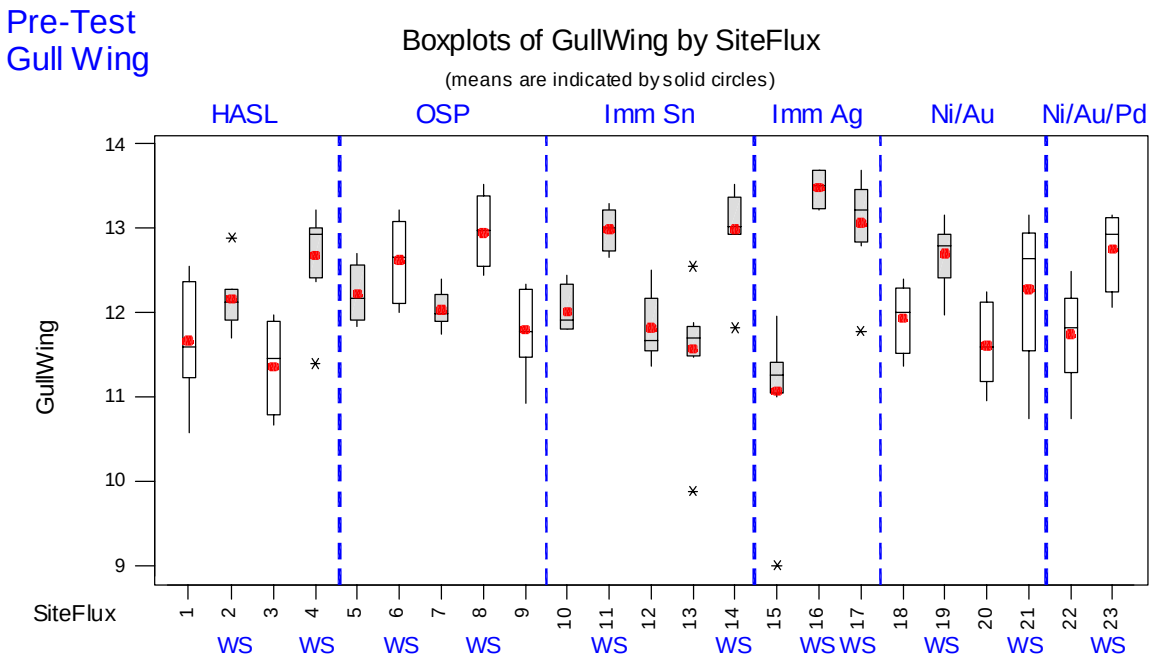


Figure 4-23. Boxplot Displays for the Gull Wing Measurements (log_{10} ohms) at Pre-Test by Surface Finish

(Acceptance Criterion = Resistance > 7.7 log_{10} ohms)

4.2 COST ANALYSIS

Operating an efficient and cost-effective manufacturing process with strict control of material and production costs is the goal of every successful company. Consumer demand for smaller and lighter electronics is fueling rapid and continuous advancements in circuit technology, such as higher aspect-ratio holes and tighter circuit patterns. This in turn forces manufacturers to evaluate and replace aging manufacturing processes in order to keep up with the ever-increasing technology threshold. These new processes represent a major capital investment to a company, and emphasize the importance of selecting an efficient, cost-effective process that will allow the company to remain competitive. As a result, manufacturers are seeking comprehensive and more detailed cost data before investing in alternative processes.

This section presents a comparative cost analysis of the surface finishing technologies. Costs were developed for each technology and equipment configuration (vertical, immersion-type equipment; or horizontal, conveyorized equipment) for which data were available from the PWB Workplace Practices Questionnaire and Performance Demonstration. Table 4-30 presents the processes (alternatives and equipment configurations) evaluated.

Table 4-30. Surface Finishing Processes Evaluated in the Cost Analysis

Surface Finishing Alternative	Non-Conveyorized	Conveyorized
HASL		
Nickel/Gold		
Nickel/Palladium/Gold		
OSP		
Immersion Silver		
Immersion Tin		

Costs were analyzed using a cost model developed by the University of Tennessee Department of Industrial Engineering. The model employs generic process steps and functional groups (see Section 2.1, Chemistry and Process Description of Surface Finishing Technologies) to form a typical bath sequence (see Section 3.1, Source Release Assessment) for each process alternative. To develop comparative costs on a $/surface square foot (ssf) basis, the cost model was formulated to calculate the cost of performing the surface finishing function on a job consisting of 260,000 ssf (value corresponds to the average annual throughput for facilities using HASL in the PWB Workplace Practices Questionnaire database).

Processes were also modeled at a throughput of 60,000 ssf, a number which corresponds to the average annual throughput for facilities using a non-HASL alternative. This additional modeling run was performed to examine the effects, if any, that operating throughput will have on the normalized cost for each process. Although the calculations presented in this section are based on the higher production operating conditions, similar calculations were performed using lower production level data and the results of the two runs are compared at the end of the cost analysis.

The overall objective of this analysis was to determine the comparative costs of the surface finishing technologies using a cost model that adheres to fundamental principles of cost analysis. Other objectives were to make the analysis flexible and to consider environmental costs. The cost model was designed to estimate the comparative costs of fully operational surface finishing process lines. It does not estimate start-up costs for a facility switching to an alternative surface finishing technology or the cost of other process changes that may be required to implement a new surface finishing line. Section 4.2.1 gives an overview of the cost methodology used in this analysis. Section 4.2.2 presents the cost categories defined for the analysis and discusses the categories that could not be quantified. Section 4.2.3 presents an overview of the simulation model purpose, approach and results, while Section 4.2.4 describes the activity-based costing techniques and results. Section 4.2.5 details of the individual cost formulations and presents sample cost calculations. Section 4.2.6 contains analysis results and conclusions.

4.2.1 Overview of the Cost Methodology

The costs of the surface finishing technologies were analyzed by identifying the steps in each process, breaking each step down into its cost components, and determining the cost of each component. Component costs were determined using a combination of traditional costing mechanisms, computer simulation, and activity-based costing (ABC). Figure 4-24 presents the hybrid cost formulation framework:

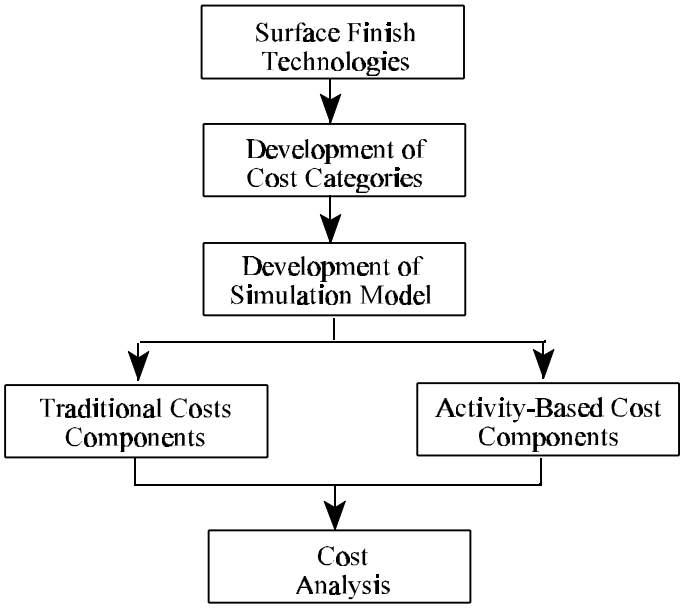


Figure 4-24. Hybrid Cost Analysis Framework

The generic process descriptions, chemical baths, typical bath sequences, and equipment configurations for each surface finishing process form the basis of the cost analysis and are presented in Table 4-30 and Figure 2-1 from Chapter 2, Profiling of the Surface Finishing Use Cluster. The process information was used to identify critical variables and to define the cost categories to be calculated by the cost analysis. The cost categories were analyzed to identify the data required to calculate the costs (e.g., unit costs; utilization or consumption rates; criteria for performing an activity, such as chemical bath replacement; the number of times an activity is performed). For each process, a computer simulation was developed using ARENA® computer simulation software. The simulation model then was used to model each process under similar operating conditions to determine operating data, such as overall production time, required by the cost analysis. Individual cost formulas were developed using traditional cost techniques, while costs typically allocated to overhead were quantified using ABC techniques. The costs were then calculated and compared to the cost of the baseline, non-conveyorized, HASL process. A more detailed description of each step is presented later in this chapter.

4.2.2 Cost Categories and Discussion of Unquantifiable Costs

Cost Categories

Table 4-31 summarizes the cost components considered in this analysis, gives a brief description of each cost component and key assumptions, and lists the primary sources of data for determining the costs. Section 4.2.5 gives a more detailed accounting of the cost components, including sample cost calculations for each component. In addition to traditional costs, such as capital, production, and maintenance costs, the cost formulation identifies and captures some environmental costs associated with the technologies. In this regard, both simulation and ABC assist in analyzing the impact of the surface finishing technologies on the environment. Specifically, the amounts of energy and water consumed, as well as the amount of wastewater generated, are determined for each surface finishing process.

Unquantifiable Cost Categories

The goal of this cost analysis was to perform a comparative cost analysis on the surface finishing alternatives in the evaluation. Although every effort was made to characterize each cost component listed in Table 4-31, data and/or process limitations prevented the quantification of every component. A qualitative discussion of each of these costs is presented below.

Table 4-31. Cost Component Categories

Cost Category	Component	Description of Cost Component	Sources of Cost Data
Capital Cost	Primary Equipment & Installation	Annualized cost of equipment with throughput capacity of 60 panels/hr x UR[a]; includes the cost of delivery and installation of equipment; assumes 10 year equipment life and straight-line depreciation.	Vendor quote for equipment and installation costs; time to complete job from simulation.
	Facility	Annualized cost of floor space required to operate surface finish process equipment x UR[a]; assumes 25 year facility life and straight-line depreciation.	Floor space requirements from IPC Workplace Practices Questionnaire; unit cost for industrial floor space from published sources.
Material Cost	Process Chemicals5858	Costs of chemicals used in initial bath setup, bath maintenance additions, and replacement of spent process baths.	Vendor quotes for chemical product cost; bath sizes from IPC Workplace Practices Questionnaire; bath replacement criteria from supplier data; number of bath replacements required for job from simulation.
Utility Cost	Water	Water consumption costs based on number of rinse stages per process line and normalized water flow rates per stage.	Number of rinse stages and normalized water flow rates per stage from Section 5.1, Resource Conservation; cost of water based on results reported by manufacturers from the Pollution Prevention and Control Survey.
	Electricity	Electricity costs based on daily electrical consumption of surface finish process equipment and days to complete job.	Daily electricity consumption from Section 5.2, Energy Impacts; days to complete job from simulation; cost of electricity based on national power grid from the Internal Energy Agency.
	Natural Gas	Natural gas consumption based on daily natural gas consumption from drying ovens and days to complete job.	Daily natural gas consumption from Section 5.2, Energy Impacts; days to complete job from simulation; cost of natural gas from the Knoxville Utilities Board (KUB).
Wastewater Cost	Publicly Owned Treatment Works (POTW) Permit	Cost for permit to discharge wastewater to POTW.	Not quantified; assumed to be the same for all alternatives.
	Wastewater Pretreatment Cost	Cost to pretreat wastewater prior to discharge to POTW.	Not quantified; pretreatment costs are expected to differ significantly among the alternatives, but inability to separate pretreatment of surface finish wastes from other process wastes made it impossible to reliably estimate these costs.
	Wastewater Discharge Costs	Fees for wastewater discharge assessed by local utility.	Quantity of wastewater discharged assumed equal to water usage; discharge fees based on fees charged by KUB.

Cost Category	Component	Description of Cost Component	Sources of Cost Data
Production Cost	Labor	Labor costs for line operator, excluding labor costs for maintenance activities (included under maintenance costs). Assumes one line operator per day per conveyorized process, 1.1 line operators per day per non-conveyorized process, to reflect the greater level of labor required.	Number of line operators based on IPC Workplace Practices Questionnaire data and site visits; days to produce job from simulation; labor rate based on published data.
	Transportation of Materials	Cost to transport chemicals required for bath replacement from storage to process line.	Cost of transporting materials from a bill of activity (BOA); number of bath replacements required from simulation.
Maintenance Cost	Bath Cleanup	Labor and material (excluding chemicals) costs to clean up a chemical tank during bath replacement.	Cost to clean up tank from BOA; number of bath cleanups (replacements) required from simulation.
	Bath Setup	Labor and equipment costs to set up a chemical tank after bath replacement.	Cost to set up bath from BOA; number of bath setups required from simulation.
	Sampling and Analysis	Labor and materials costs for sampling and analysis of chemical baths.	Assumes analytical work done in-house. Cost for one activity from BOA; annual number of samples from IPC Workplace Practices Questionnaire adjusted using UR[a].
	Filter Replacement	Labor costs for replacing bath filters.	Labor cost for one activity from BOA; annual number of filters replaced from IPC Workplace Practices Questionnaire adjusted using UR[a].
Waste Disposal Cost	Sludge Disposal	Disposal cost to recycle or disposal of sludge from wastewater treatment.	Not quantified; sludge disposal costs are expected to differ significantly among the alternatives, but insufficient data were available to reliably estimate these costs. Factors affecting sludge disposal cost include the characteristics of the sludge (e.g., type of metal content, percent solids, waste classification, etc.), the amount of sludge generated, and the type of disposal (e.g., reclaim, disposal to landfill, etc).
	Filter Disposal	Disposal cost to recycle or dispose of bath filters.	Not quantified; filter disposal costs are not expected to differ significantly among the alternatives, but insufficient data on the type and size of waste filters made it difficult to reliably estimate these costs. Factors affecting filter disposal cost include the waste classification of the filter, the size (weight and volume) of the filter, and the number of waste filters generated.
Quality Cost	Defective Boards	Costs of defective boards due to failure of the surface finish process line to apply an adequate finish to the surface of the PWB.	Not quantified; assumed equal among the alternatives. Performance Demonstration showed that all alternatives can work at least as well as the baseline process as long as they are operated according to supplier specifications.

[a] UR = utilization ratio = the time in days required to process 260,000 ssf ÷ one operating year (280 days).

Wastewater Treatment and Sludge Disposal Costs. PWB manufacturing consists of a number of process steps (see Section 1.2.3 for an overview of rigid multi-layer PWB manufacturing). In addition to the surface finishing process line, these steps include electroplating operations and other steps which consume large quantities of rinse water and, consequently, generate large quantities of wastewater. Most PWB manufacturers combine the effluents from various process lines into one wastewater stream which is treated on-site in a continuous process prior to discharge.

As part of the *Pollution Prevention and Control Survey* (U.S. EPA, 1998), PWB manufacturers were asked to provide the following about their on-site wastewater treatment facility:

a process flow diagram for wastewater treatment;
the quantity of sludge generated from wastewater treatment;
the percent solids of the sludge;
the costs of on-site wastewater treatment; and
the method and costs of sludge recycle and disposal.

Capital costs for wastewater treatment ranged from $1.2 million for a system purchased in 1980 with a capacity of 135 gallons per minute (gpm) to $4,000 for a system purchased in 1987 with a capacity of nine gpm. Costs for operating an on-site wastewater treatment system were as high as 3.1 percent of total annual sales. The median cost for wastewater treatment operation was 0.83 percent, and the average was 1.02 percent of annual sales.

Wastewater treatment sludges from PWB electroplating operations are classified as an F006 hazardous waste under the Resources Conservation and Recovery Act (RCRA); most facilities combine effluents from the electroplating line with other process wastewaters. Eighty-eight percent of respondents to the Pollution Prevention and Control Survey reported that wastewater treatment sludges are sent to an off-site recycling facility to recover the metals. The average and median costs for off-site recovery of sludge were $0.48/lb and $0.21/lb, respectively. In general, the lower costs experienced by some respondents compared to others were due to larger-size shipments and shorter distances to the recycling sites. In some cases, respondents whose sludge had a higher solids content also reported lower costs; dewatered sludge has a higher recovery value.

The PWB Workplace Practices Questionnaire attempted to characterize costs by collecting information about the percentage contribution of the surface finishing line to the overall wastewater and sludge generation rates. However, most manufacturers were unable to provide this information and the data that were reported were of variable to poor quality.

A drag-out model was developed to determine the extent of chemical contamination of the wastewater resulting from drag-out. The model was used to estimate quantities of the chemical constituents in the wastewater. Model results are presented in Section 3.2, Exposure Assessment and Appendix E. However, since the streams are co-mingled prior to treatment, industry sources explained that it would be difficult to reliably quantify the effect of the surface finishing wastewater stream on the treatment of the entire stream (e.g., a treatment chemical used to treat

the surface finishing wastewater may have a stronger affinity for another compound that may be present in the wastewater from another source, thus negatively affecting the treatment of the surface finishing wastewater).

Because the surface finishing line is only one of several process lines that discharge effluent to wastewater treatment, and because little or no information is available on the contribution of the surface finishing line to overall wastewater effluents, on-site wastewater treatment and sludge disposal costs could not be reliably estimated. However, costs of wastewater treatment and sludge disposal are expected to differ significantly among the alternatives, based on the compounds involved. For example, the presence of thiourea in the immersion tin process may require an additional treatment step to break down the compound prior to release. Silver is tightly regulated, thus the addition of an immersion silver process to a facility may require additional treatment to prevent exceeding the relatively low effluent limit. A detailed discussion of treatment concerns, systems, and options for each surface finishing process is presented in Section 6.2, Recycle, Recovery, and Control Technologies Assessment.

Other Solid Waste Disposal Costs. Two other types of solid wastes were identified among the technologies that could have significantly different waste disposal costs: filter disposal cost and defective boards disposal costs. Table 4-32 presents the number of filters that would be replaced in each process during a job of 260,000 ssf. This is based on data from the PWB Workplace Practices Questionnaire and a utilization ratio (UR) calculated for each process from simulation results (Simulation results are discussed further in Section 4.2.3). The UR is the percentage of time during the year required for the process to manufacture the required throughput. While these results illustrate that the number of waste filters generated by the processes differ significantly, no information is available on the characteristics of the filters used by the processes. For example, the volume or mass of the filters and waste classification of the filters (hazardous or non-hazardous) would significantly affect the unit cost for disposal. Therefore, filter disposal costs were not estimated.

The number of defective boards produced by a process has significance not only from the standpoint of quality costs, but also from the standpoint of waste disposal costs. Clearly, a higher defect rate leads to higher scrap and, therefore, waste of resources. However, the Performance Demonstration showed that each of the technologies can perform as well as the HASL process if operated according to specifications. Thus, for the purposes of this analysis, no differences would be expected in the defect rate or associated costs of the technologies.

Table 4-32. Number of Filter Replacements by Surface Finishing Process

Surface Finishing Process	Filter Replacements per Year [a]	Filter Replacements Required to Produce 260,000 ssf [b]
HASL, Non-conveyorized	**354**	**55**
HASL, Conveyorized	**354**	**28**
Nickel/Gold, Non-conveyorized	**119**	**90**
Nickel/Palladium/Gold, Non-conveyorized	**162**	**162**
OSP, Non-conveyorized	**150**	**19**
OSP, Conveyorized	**150**	**9**
Immersion Silver, Conveyorized	**19.5**	**4**
Immersion Tin, Non-conveyorized	**150**	**40**
Immersion Tin, Conveyorized	**150**	**57**

[a] 90th percentile data based on PWB Workplace Practices Questionnaire data. Data not adjusted for throughput or to account for differing maintenance policies at individual PWB manufacturing facilities.
[b] Values calculated by multiplying the filter replacements per year for a process by the utilization ratio for that process.

4.2.3 Simulation Modeling of Surface Finishing Processes

A computer simulation was developed using ARENA® computer simulation software for each surface finishing process. The purpose of the modeling is to simulate the operation of each process on the computer under identical conditions to predict a set of key metrics (e.g., overall production time, process down time, number of bath replacements) required to perform a comparative cost analysis. The model is necessary because the data collected from actual facilities, if available, would reflect the individual operating practices of each facility (e.g., bath maintenance frequencies, rise water flow rates, PWB feed rates) preventing a valid comparison of any process costs. Appendix G presents a graphic representation of the simulation models developed for each of the surface finishing technologies.

Simulation modeling provides a number of benefits to the cost analysis, including the following:

Simulation modeling replicates a production run on the computer screen, allowing the analyst to observe a process when the actual process does not exist: in this case, the generic surface finishing technologies, as defined in Figure 2-1, may not exist within any one facility.
Simulation allows for process-based modifications and variations, resulting in inherent flexibility within the system: models can be designed to vary the sequence of operations, add or delete operations, or change process times associated with operations, materials flows, and other variables.
Simulation modeling facilitates the comparison of technologies by modeling each technology operating under a single, consistently applied performance profile developed from data collected from industry.

Simulation enables a study of the sensitivity of critical performance measures to changes in underlying input variables (constant input variables may be modified in the sensitivity analysis to determine the uncertainty associated with these input variables).

Direct results of the simulation model and results derived from simulation outputs include the following:

the overall time the surface finishing line operates to produce the job;
the number of repetitions of an activity (e.g., bath replacements) over the course of the job;
consumption rates (e.g., water, energy, and chemical consumption); and
production rates (e.g., wastewater generation).

Simulation results were combined with traditional cost components to adjust these costs for the specified job. An example of this is the determination of equipment cost. Simulation results were used to calculate a UR, defined as the amount of time in days required to produce 260,000 ssf divided by one operating year. A 280-day operating year was selected to match the longest modeled operating time for any process (nickel/palladium/gold). Annualized equipment costs were determined using industry sources for equipment price and depreciation guidelines from the Internal Revenue Service. These costs were multiplied by the UR to determine the equipment costs for the job being evaluated.

Simulation Model Assumptions

Several assumptions used in the simulation model are based on the characteristics of a model facility presented in the Source Release Assessment and Exposure Assessment (Sections 3.1 and 3.2, respectively). Assumptions include the following:

The facility operates a surface finishing process line 280 days/year, one shift/day; [Note: many facilities operate two shifts, but the Exposure Assessment and this analysis use first shift data as representative. This assumption could tend to underestimate labor costs for companies that pay higher rates to second shift workers. Alternatively, it could tend to overestimate equipment costs for a company running two shifts and using equipment more efficiently. However, because this assumption is used consistently across technologies, the effects on the comparative cost results are expected to be minor.]
the surface finishing process line operates an average of 6.8 hr/shift;
the surface finishing line is down at least 1.2 hr/day for start-up time and for maintenance, including lubricating of equipment, sampling of baths, and filter replacement;
additional down time occurs when the surface finishing line is shut down to replace a spent or contaminated bath;
PWB panels that have been processed up to the surface finishing step are available whenever the surface finishing process line requires them;
if a chemical bath is replaced at the end of the day, and the amount of time required to replace the bath exceeds the time remaining in the shift hours, employees will stay after hours and have the bath ready by the beginning of the next shift;
the entire surface finishing process line is shut down whenever a bath requires replacing,

but partially processed racks or panels are finished before the line is shut down;
the surface finishing process only shuts down at the end of a shift and for bath replacement, when required; and
the process is empty of all panels or racks at the end of each shift, and starts the process empty at the beginning of a shift.

Further simulation assumptions have to be defined separately for conveyorized and non-conveyorized systems. Conveyorized surface finishing process assumptions are as follows:

the size of a panel is 17.5 x 23.1" (from PWB Workplace Practices Questionnaire data for conveyorized processes);
panels are placed on the conveyor whenever space on the conveyor is available, and each panel requires 18 inches (including space between panels);
conveyor speed is constant, thus, the volume (gallons) of chemicals in a bath varies by bath type (i.e., microetch, conditioner, etc.) and with the length of the process step (e.g., bath or rinse tank) to provide the necessary contact time (see Table 4-33 for bath volumes); and
the conveyor speed, cycle time, and process down time are critical factors that determine the time to complete a job.

Table 4-33. Bath Volumes Used for Conveyorized Processes

Chemical Bath	Bath Volume by Surface Finishing Alternative (gallons)			
	HASL	**OSP**	**Immersion Silver**	**Immersion Tin**
Cleaner	**66.5**	**66.5**	**66.5**	**66.5**
Microetch	**86.6**	**86.6**	**86.6**	**86.6**
Flux	**13.2**	NA	NA	NA
Solder	**17.4**	NA	NA	NA
OSP	NA	**125**	NA	NA
Predip	NA	NA	**46.2**	**46.2**
Immersion Silver	NA	NA	**142**	NA
Immersion Tin	NA	NA	NA	**140**

NA: Not applicable.

Non-conveyorized surface finishing process assumptions are as follows:

the average volume of a chemical bath is 51.1 gallons (from PWB Workplace Practices Questionnaire data for non-conveyorized processes);
only one rack of panels can be placed in a bath at any one time;
a rack contains 20 panels (based on PWB Workplace Practices Questionnaire data, including the dimensions of a bath, the size of a panel, and the average distance between panels in a rack);
the size of a panel is 4.22 ssf to give 84.4 ssf/rack;
the frequency at which racks are entered into the process is dependent upon the bottleneck

or rate limiting step; and
the duration of the rate limiting step, cycle time, and process down time are critical factors that determine the time to complete a job.

Simulation Model Input Values

Input values for the critical factors identified above (cycle time, down time, and conveyor speed for conveyorized processes, and cycle time, down time, and duration of rate limiting step for non-conveyorized processes) were developed from the PWB Workplace Practices Questionnaire data and Product Data Sheets (Product Data Sheets, which are prepared by suppliers, describe how to mix and maintain chemical baths). Tables 4-34 and 4-35 present time-related inputs to the simulation models for non-conveyorized and conveyorized processes, respectively.

Table 4-34. Time-Related Input Values for Non-Conveyorized Processes [a]

Non-Conveyorized Surface Finishing Technology	Time Required to Replace a Bath [b] (minutes)	Rate Limiting Bath	Time in Rate Limiting Bath [b] (minutes)	Process Cycle Time [b] (minutes)
HASL	136	Cleaner	3.47	7.94
Nickel/Gold	116	Electroless Nickel	18.3	86.8
Nickel/Palladium/Gold	113	Electroless Nickel	18.3	109
OSP	149	Cleaner	3.47	22.6
Immersion Tin	85	Immersion Tin	8.55	27.0

[a] Values may represent chemical products from more than one supplier. For example, two suppliers of nickel/gold chemical products participated in the project. Input values may underestimate or overestimate those of any one facility, depending on factors such as individual operating procedures, the chemical or equipment supplier, and the chemical product used.
[b] Average values from the PWB Workplace Practices Questionnaire and Performance Demonstration observer sheets.

Table 4-35. Time-Related Input Values for Conveyorized Processes [a]

Conveyorized Surface Finishing Technology	Time Required to Replace a Bath [b] (minutes)	Length of Conveyor [b] (feet)	Process Cycle Time [b] (minutes)	Conveyor Speed [c] (ft/min)
HASL	136	41.3	4.86	8.50
OSP	149	54.1	5.22	10.4
Immersion Silver	114	34.0	11.2	3.04
Immersion Tin	85	20.0	12.3	1.63

[a] Values may represent chemical products from more than one supplier. For example, two suppliers of OSP chemical products participated in the project. Input values may underestimate or overestimate those of any one facility, depending on factors such as individual operating procedures, the chemical or equipment supplier, and the chemical product used.
[b] Average values from PWB Workplace Practices Questionnaire and Performance Demonstration observer sheets.
[c] Conveyor speed was calculated by dividing the length of conveyor by the process cycle time.

The input values for the time required to replace a bath (in Tables 4-34 and 4-35) are used together with bath replacement criteria in the calculation of down time. Suppliers provide instructions with their products (called Product Data Sheets for the purposes of this project) that describe when a bath should be replaced because it is expected to be spent or too contaminated to be used. These replacement criteria are usually given in one of four forms:

as a bath production capacity in units of ssf per gallon of bath;
as a concentration-based criterion that specifies an upper concentration limit for contaminants in the bath, such as grams of copper per liter in the microetch bath;
as elapsed time since bath make-up; or
as a number of chemistry (or metal) turnovers before replacement.

Bath replacement criteria submitted by suppliers were supplemented with PWB Workplace Practices Questionnaire data and reviewed to determine average criteria for use in the simulation models. Criteria in units of ssf/gallon were preferred because these could be correlated directly to the volume of a bath. For baths with replacement criteria expressed in number of chemical turnovers, the ssf/gallon for that bath was adjusted by a factor equal to the number of metal turnovers (e.g., the replacement criteria for a 750 ssf/gal bath with two metal turnovers was considered to be 1500 ssf/gal of bath). Table 4-36 presents bath replacement criteria used to calculate input values for the nickel/gold processes, as an example. Appendix G presents the bath replacement criteria recommended by chemical suppliers, and the input values used in this analysis for the remaining surface finishing technologies.

Table 4-36. Bath Replacement Criteria for Nickel/Gold Processes

Chemical Bath	Bath Replacement Criteria [a] (ssf/gal)
Cleaner	**750**
Microetch	**570**
Catalyst	**830**
Acid Dip	**1500**
Electroless Nickel	**130**
Immersion Gold	**890**

[a] Values were selected from data provided by two nickel/gold suppliers. To convert to units of racks per bath replacement for non-conveyorized processes, multiply by 51.1 gallons (the average bath size) and divide by 84.4 ssf (ssf per rack). To convert to units of panels per bath replacement for conveyorized processes, multiply by the bath size in gallons and divide by 5.66 ssf/panel.

Simulation Model Results

Simulation models were run for each of the surface finishing processes. Simulation outputs used in the cost analysis include:

frequency and duration of bath replacements;
overall production time required for each process; and
down time incurred while producing 260,000 ssf.

For example, the frequency and duration of bath replacements for nickel/gold that were obtained from the simulation modeling are shown in Table 4-37. The frequency of bath replacements for each bath type was calculated by the simulation model using the bath replacement criteria presented for each bath in Table 4-36. Using the average time of bath replacement determined from the PWB Workplace Practices Questionnaire data, the total down time associated with the replacement of each bath type was determined. Summing over all baths, bath replacement consumed 36.7 hours (2,200 minutes) to produce 260,000 ssf when using the non-conveyorized nickel/gold process. Bath replacement simulation outputs for the other surface finishing processes are presented in Appendix G.

Table 4-37. Frequency and Duration of Bath Replacements for Non-Conveyorized Nickel/Gold Process

Chemical Bath	Frequency of Replacement	Avg. Time of Replacement (minutes)	Total Time of Replacement (minutes)
Cleaner	7	116	812
Microetch	9	116	1,044
Catalyst	6	116	696
Acid Dip	4	116	464
Electroless Nickel	40	116	4,640
Immersion Gold	6	116	696
Total	**72**	**116**	**8,352**

Table 4-38 presents the other simulation outputs: the total production time required and the down time incurred by the surface finishing processes while producing 260,000 ssf of PWB. Total production time is the sum of actual operating time and down time. The operating time is based on the process producing 260,000 ssf of PWB and operating 6.8 hr/day. The down time includes the remaining 1.2 hr/day that the line is assumed inactive, plus the time the process is down for bath replacements. The amount of process down time due to a bath replacement, shown in Table 4-37, may be adjusted by the model if the bath changeout occurs at the end of the day, when the replacement duration exceeds the time remaining in the day. (7,670 minutes of downtine are reported in Table 4-38, indicating that 680 minutes of the 8,352 reported in Table l4-37 occurred at the end of the day.) In this instance, the worker is considered to complete the bath replacement during the remaining 1.2 hours of the day set aside for process maintenance. The simulation model output reports for each process are presented in Appendix G.

Table 4-38. Production Time and Down Time for the Surface Finishing Processes to Produce 260,000 ssf of PWB

Surface Finishing Process	Total Production Time [a]		Total Down Time [a]	
	minutes	days	minutes	days
HASL, Non-conveyorized	17,830	43.7	2,330	5.7
HASL, Conveyorized	8,890	21.8	938	2.3
Nickel/Gold, Non-conveyorized	86,500	212	7,670	18.8
Nickel/Palladium/Gold, Non-conveyorized	114,240	280	11,380	27.9
OSP, Non-conveyorized	14,360	35.2	2,530	6.2
OSP, Conveyorized	6,570	16.1	1,020	2.5
Immersion Silver, Conveyorized	26,190	64.2	1,390	3.4
Immersion Tin, Non-conveyorized	30,680	75.2	1,880	4.6
Immersion Tin, Conveyorized	43,660	107	1,020	2.5

[a] To convert from minutes to days, divide by 6.8 hr/day (408 minutes).

4.2.4 Activity-Based Costing

ABC is a method of allocating indirect or overhead costs to the products or processes that actually incur those costs. ABC complements the traditional costing /modeling efforts of this assessment by allowing the cost of tasks that are difficult to quantify, or are just unknown by industry, to be determined. Activity-based costs are determined by developing a BOA for critical tasks, which are defined as tasks required to that support the operation of the surface finish process line. A BOA is a listing of the component activities involved in the performance of a certain task, together with the number of times each component activity is performed. The BOA determines the cost of a task by considering the sequence of actions and the resources utilized while performing that task. In this analysis, the costs of critical tasks determined by a BOA are combined with the number of times a critical task is performed, derived from simulation results to determine the total costs of that activity.

BOAs were developed for the following critical tasks performed during the operation of the surface finishing process:

chemical transport from storage to the surface finishing process;
tank cleaning;
bath setup;
bath sampling and analysis; and
filter replacement.

These BOAs were developed based on information developed for earlier projects involving similar tasks and on information gathered through site visits and general process knowledge. The following discussion uses the BOA for chemical transport, presented in Table 4-39, as an example of how BOAs were developed and used. Appendix G presents the BOAs for the remaining activities.

Key assumptions were developed to set the limits and to designate the critical activity's characteristics. For chemical transport, the assumptions were as follows:

- chemical costs are not included in the BOA, but are considered within material costs;
- labor costs considered are independent of those included within production costs;
- employee labor rate is $10.24 per hour, consistent with the rate for an operator-level job;
- multiple chemicals are required for each bath replacement;
- all chemicals for a bath replacement are transported on one forklift trip;
- chemicals are purchased in containers larger than the line containers used to move chemicals to the surface finishing process;
- all chemicals are stored in a central storage location;
- chemicals are maintained in central storage via inventory tracking and physical monitoring;
- forklift operation costs are $580/month or $0.06/minute, which includes leasing, maintenance, and fuel;
- forklifts are used to move all chemicals; and
- forklifts are parked in an assigned area when not in use.

Each critical task was broken down into primary and secondary activities. For example, chemical transport has six primary activities: paperwork associated with chemical transfer, moving forklift to chemical storage area, locating chemicals in storage area, preparation of chemicals for transfer, transporting chemicals to the surface finishing process, and transporting chemicals from the surface finishing process to the bath. The secondary activities for the primary activity of "transport chemicals to the surface finishing process" are: move forklift with chemicals, unload line containers, and park forklift in assigned parking area. For each secondary activity the labor, material, and forklift costs are calculated. The forklift costs are a function of the time that labor and the forklift are used. On a BOA, the sum of the costs of a set of secondary activities equals the cost of the primary activity.

Continuing the example, for a chemical transport activity that requires two minutes, the labor cost is $0.34 (based on a labor rate of $10.24/hour) and the forklift cost is $0.12 (based on $0.06/minute). Materials costs are determined for materials other than chemicals and tools required for an activity. The total of $9.28 shown in Table 4-39 represents the cost of a single act of transporting chemicals to the surface finishing line. The same BOAs are used for all surface finishing technologies because either the activities are similar over all technologies or information is unavailable to distinguish between them. However, individual facilities could modify a BOA to best represent their unique situations. Table 4-40 presents costs to perform each of the critical tasks one time.

Table 4-39. BOA for Transportation of Chemicals to the Surface Finishing Process Line

Activities	Time (min)	Resources			Cost ($/transport)
		Labor [a]	Materials [b]	Forklift [c]	
A. Paperwork and Maintenance					
1. Request for chemicals	2	$0.34	$0.10	$0.00	$0.44
2. Updating inventory logs	1	$0.17	$0.05	$0.00	$0.22
3. Safety and environmental record keeping	2	$0.34	$0.10	$0.00	$0.44
B. Move Forklift to Chemical Storage Area					
1. Move to forklift parking area	2	$0.34	$0.00	$0.12	$0.46
2. Prepare forklift to move chemicals	5	$0.85	$0.00	$0.30	$1.15
3. Move to line container storage area	2	$0.34	$0.00	$0.12	$0.46
4. Prepare forklift to move line container	3	$0.51	$0.00	$0.18	$0.69
5. Move forklift to chemical storage area	2	$0.34	$0.00	$0.12	$0.46
C. Locate Chemicals in Storage Area					
1. Move forklift to appropriate areas	1	$0.17	$0.00	$0.06	$0.23
2. Move chemical containers from storage to staging	2	$0.34	$0.00	$0.12	$0.46
3. Move containers from staging to storage	2	$0.34	$0.00	$0.12	$0.46
D. Preparation of Chemicals for Transfer					
1. Open chemical container(s)	1	$0.17	$0.05	$0.00	$0.22
2. Utilize correct tools to obtain chemicals	3	$0.51	$0.05	$0.00	$0.56
3. Place obtained chemicals in line container(s)	3	$0.51	$0.00	$0.00	$0.51
4. Close chemical container(s)	1.5	$0.26	$0.00	$0.00	$0.26
5. Place line container(s) on forklift	1	$0.17	$0.00	$0.06	$0.23
E. Transport Chemicals to Line					
1. Move forklift to line	2	$0.34	$0.00	$0.12	$0.46
2. Unload line container(s) at line	1	$0.17	$0.00	$0.06	$0.23
3. Move forklift to parking area	2	$0.34	$0.00	$0.12	$0.46
F. Transport Chemicals from Line to Bath					
1. Move line container(s) to bath	1	$0.17	$0.00	$0.00	$0.17
2. Clean line container(s)	2	$0.34	$0.20	$0.00	$0.54
3. Store line container(s) in appropriate area	1	$0.17	$0.00	$0.00	$0.17
Total Cost per Transport					**$9.28**

[a] Labor rate = $10.24 per hour.
[b] Materials do not include chemicals or tools.
[c] Forklift operating cost = $0.06 per minute.

Table 4-40. Costs of Critical Tasks

Task	Cost
Transportation of Chemicals	$9.28
Tank Cleaning	$67.00
Bath Setup	$15.10
Sampling and Analysis	$3.70
Filter Replacement	$17.50

4.2.5 Cost Formulation Details and Sample Calculations

This section develops and describes in detail the cost formulation used for evaluating the surface finishing process alternatives. The overall cost was calculated from individual cost categories that are common to, but expected to vary with, the individual process alternatives. The cost model was validated by cross-referencing the cost categories with Tellus Institute (White et al., 1992), and Pacific Northwest Pollution Prevention Research Center (Badgett et al., 1995).

The cost model for an alternative is as follows:

$$TC = C + M + U + WW + P + MA$$

where,

TC	=	total cost to produce 260,000 ssf
C	=	capital cost
M	=	material cost
U	=	utility cost
WW	=	wastewater cost
P	=	production cost
MA	=	maintenance cost

The unit cost of producing 260,000 ssf is then represented as follows:

$$\text{Unit Cost (\$/ssf)} = \text{TC (\$)} / 260{,}000 \text{ ssf}$$

The following sections present a detailed description of cost calculation methods together with sample calculations, using the non-conveyorized nickel/gold process as an example. Cost summary tables for all of the process alternatives are presented at the end of this section.

<u>Capital Costs</u>

This section presents methods and sample calculations for calculating capital costs. Capital costs are one-time or periodic costs incurred in the purchase of equipment or facilities. In this analysis, capital costs include the costs of primary equipment including equipment installation, and facility space utilized by the surface finishing process line. Primary equipment is the equipment vital to the operation of the surface finishing process without which the process would not be able to operate (i.e., bath tanks, heaters, rinse water system, etc.). Installation costs

include costs to install the process equipment and prepare it for production. Facility space is the floor space taken up by the actual process equipment plus an additional buffer area necessary for operation of the equipment by workers and access for maintenance and repair.

Total capital costs for the surface finishing processes were calculated as follows:

$$C = (E + I + F) \times UR$$

where,

E	=	annualized capital cost of equipment ($/yr)
I	=	annualized capital cost of installation ($/yr), which is sometimes included in the cost of the equipment
F	=	annualized capital cost of facility ($/yr)
UR	=	utilization ratio, defined as the time in days required to manufacture 260,000 ssf divided by one operating year (280 days)

The UR adjusts annualized costs for the amount of time required to process 260,000 ssf, determined from the simulation model for each process alternative. The components of capital costs are discussed further below followed by sample calculations of capital costs.

Equipment and Installation Costs. Primary equipment and installation cost estimates were provided by equipment suppliers and include delivery of equipment, installation, and sales tax. Equipment estimates were based on basic, no frills equipment capable of processing the modeled throughput rates determined by the simulation model, presented in Table 4-38. Equipment estimates did not include auxiliary equipment, such as statistical process control or automated sampling equipment sometimes found on surface finishing process lines.

Annual costs of the equipment (which includes installation) were determined assuming 5-year, straight-line depreciation and no salvage value. These annual costs were calculated using the following equation:

$$E = \text{equipment cost (\$)} \div 5 \text{ years}$$

Facility Costs. Facility costs are capital costs for the floor space required to operate the surface finishing line. Facility costs were calculated assuming industrial floor space costs $76/ft^2 and the facility is depreciated over 25 years using straight-line depreciation. The cost per square foot of floor space applies to Class A light manufacturing buildings with basements. This value was obtained from the Marshall Valuation Service (Vishanoff, 1995) and mean square foot costs (Ferguson, 1996). Facility costs were calculated using the following equation:

$$F = [\text{unit cost of facility utilized (\$/ft}^2\text{)} \times \text{footprint area/process step (ft}^2\text{/step)} \times \text{number of steps}] \div 25 \text{ years}$$

The “footprint area” is the area of floor space required by surface finishing equipment, plus a buffer zone to maneuver equipment or have room to work on the surface finishing process

line, and to maintain and repair it.[2] The footprint area per process step was calculated by determining the equipment dimensions of each process alternative, adjusting the dimensions for working space, and then determining the area per process step. Because the footprint area depends on the type of process automation, the average dimensions of both conveyorized (8' x 40') and non-conveyorized (5' x 23') equipment, irrespective of surface finish technology, were determined from the PWB Workplace Practices Questionnaire data. Because these dimensions account for the equipment only, an additional 8 ft was added to every dimension to allow space for line operation, maintenance, and chemical handling. The footprint area required by either equipment type, including the buffer zone, was calculated as 1,344 ft^2 for conveyorized processes and 819 ft^2 for non-conveyorized processes. The area required per process step was determined by first identifying the process alternative with the fewest process steps for each automation type, and then dividing the required floor space by that number of steps. This method conservatively estimated the amount of floor space required per process step for conveyorized processes as 168 ft^2/step, and for non-conveyorized processes as 91 ft^2/step. The overall area required for each process alternative was then calculated using the following equations:

Conveyorized:

$$F_C = [\$76/ft^2 \times 168\ ft^2/\text{step} \times \text{number of steps per process}] \div 25 \text{ years}$$

Non-conveyorized:

$$F_N = [\$76/ft^2 \times 91\ ft^2/\text{step} \times \text{number of steps per process}] \div 25 \text{ years}$$

Example Capital Cost Calculations. This section presents example capital costs calculations for the non-conveyorized nickel/gold process. From Figure 2-1, the non-conveyorized nickel/gold process consists of 14 chemical bath and rinse steps. Simulation outputs in Table 4-38 indicate this process takes 212 days to manufacture 260,000 ssf of PWB. Equipment vendors estimated equipment and installation costs at a combined $48,000 (Harbor, 2000). The components of capital costs are calculated as follows:

$$E = \$48{,}000 \div 5 \text{ yrs} = \$9{,}600/\text{yr}$$
$$F_N = (\$76/ft^2 \times 91\ ft^2/\text{step} \times 14 \text{ steps}) \div 25 \text{ yr} = \$3{,}870/\text{yr}$$
$$UR = 212 \text{ days} \div 280 \text{ days/yr} = 0.757 \text{ yr}$$

Thus, the capital costs for the non-conveyorized nickel/gold process to produce 260,000 ssf of PWB are as follows:

$$C = (\$9{,}600/\text{yr} + \$3{,}870/\text{yr}) \times 0.757 \text{ yr} = \$10{,}200$$

Material Costs

Materials costs were calculated for the chemical products consumed during the operation of the surface finishing process lines, through the initial setup and subsequent replacement of

[2] PWB manufacturers and their suppliers use the term “footprint” to refer to the dimensions of process equipment, such as the dimensions of the surface finishing process line.

process chemical baths. The following presents equations for calculating materials costs, along with some sample materials cost calculations.

Materials Cost Calculation Methods. Chemical suppliers were asked to provide estimates of chemical costs ($/ssf), along with the other process data required by the project. While some suppliers furnished estimates for one or more of their process alternatives, several suppliers did not provide chemical cost estimates for any of their surface finishing process lines being evaluated. Still others provided incomplete cost estimates, or did not provide any supporting documentation of assumptions used to estimate chemical costs. Therefore, these data could not be used in the comparative cost estimates. Instead, chemical costs were estimated using the methods detailed below.

Chemical baths are typically made up of one or more separate chemical products mixed together at specific concentrations to form a chemical solution. As PWBs are processed by the surface finishing line, the chemical baths become contaminated or depleted and require chemical additions or replacement. Baths are typically replaced according to analytical results or by supplier recommended replacement criteria specific to each bath. When the criteria are met or exceeded, the spent bath is removed and a new bath is created. The chemical cost to replace a specific bath one time is the sum of the costs of each chemical product in the bath, and is given by the following equation:

$$\text{Cost per bath replacement} = \sum_{I=1}^{n} [\text{chemical product I cost/bath (\$/gal)} \times \text{\% chemical product I in bath} \times \text{total volume of bath (gal)}]$$

where,

n = number of chemical products in a bath

Price quotes were obtained from chemical suppliers in $/gallon or $/lb for process chemical products. Chemical compositions of the individual process baths were determined from the corresponding Product Data Sheets submitted by the chemical suppliers of each process alternative. The average volume of a chemical bath for non-conveyorized processes was calculated to be 51.1 gallons from PWB Workplace Practices Questionnaire data. For conveyorized processes, however, conveyor speed is constant; thus, the volume of chemicals in a bath varies by bath type to provide the necessary contact time (see Table 4-33 for conveyorized process bath volumes). These data were used in the above equation to calculate the chemical cost per bath replacement for each product line. The bath replacement costs were then averaged across like product lines (e.g., chemical costs from various suppliers of the OSP were averaged by bath type) to determine an average chemical cost per replacement for each process bath.

To obtain the total materials cost, the chemical cost per bath replacement for each bath was multiplied by the number of bath replacements required (determined by simulation) and then summed over all the baths of an alternative process. The cost of chemical additions was not included, because no data were available to determine the amount and frequency of chemical additions. However, for process baths that are typically maintained rather than replaced (e.g.,

baths with expensive metal ions such as tin, gold, silver and palladium), the replacement criteria were adjusted to reflect the number of bath chemical turnovers that occur between bath replacements, thereby accounting for the additional chemical usage. A complete change of bath chemistry through bath maintenance, such as chemical additions, was considered one chemical turnover. The number of chemical turnovers for each bath is represented on Table 4-41 as the multiplying factor. Materials costs (M) are given by the following equation:

$$M = \sum_{j=1}^{m} [\text{chemical cost } j \text{ /bath replacement (\$) x number of replacements/bath}]$$

where,

m = number of baths in a process

The frequency of replacement for individual process baths was determined using supplier recommended criteria provided on Product Data Sheets and from PWB Workplace Practices Questionnaire data. Simulation models were used to determine the number of times a bath would be replaced during the production of 260,000 ssf of PWB by the surface finishing process. Appendix G presents bath replacement criteria used in this analysis and summaries of chemical product cost by supplier and by surface finishing technology.

Example Materials Cost Calculations. Table 4-42 presents an example of chemical costs per bath replacement for one of the two nickel/gold product lines that were submitted by chemical suppliers for evaluation. From the data in the table, the total cost of chemicals per bath was calculated by multiplying the average chemical cost for a bath (calculated by computing the chemical cost per bath of the second product line not shown in Table 4-42, then averaging the costs for a bath from both product lines) by the number of bath replacements required to process 260,000 ssf, as determined by the process simulation. The costs for each bath were then summed to give the total materials cost for the overall non-conveyorized nickel/gold product line. Data for each of the product lines submitted, including the other electroless nickel/immersion gold product line, are presented in Appendix G.

Table 4-41 presents the chemical cost per bath replacement, the number of bath replacements required, as determined by simulation, the total chemical cost per bath, and the total material cost for the non-conveyorized nickel/gold process. The chemical costs per process bath for both product lines were averaged to determine the average chemical cost per bath for the non-conveyorized nickel/gold process. Similar material cost calculations are presented in Appendix G for each of the surface finishing process alternatives.

Table 4-41. Materials Cost for the Non-Conveyorized Nickel/Gold Process

Bath	Chemical Cost/Bath Replacement [a]	Number of Bath Replacements [b]	Total Chemical Cost
Cleaner	$92.80	7	$649
Microetch	$386	9	$3,470
Catalyst	$1,640	6	$9,830
Acid Dip	$315	4	$1,260
Electroless Nickel	$890	40	$35,500
Immersion Gold	NA [c]	6	$57,900
Total Materials Cost			**$108,600**

[a] Reported data represents the chemical cost per bath replacement averaged from two nickel/gold product lines.
[b] Number of bath replacements required to process 260,000 ssf, as determined by process simulation.
[c] The immersion gold replacement cost was calculated differently than the other baths because of the wide disparity in costs and throughput between product lines. The overall cost for the gold bath was calculated for each product line and then averaged together to give the gold chemical cost for the process.

Table 4-42. Chemical Cost per Bath Replacement for One Product Line of the Non-Conveyorized Nickel/Gold Process

Bath	Chemical Product	Product Cost [a] ($)	Percentage of Chemical Product [b]	Multiplying Factor [c]	Chemical Cost/Bath Replacement [d] ($)
Cleaner	A	$25.0/gal	10	1	$128
Microetch	B	$5.66/gal	3	1	$266
	C	$9.39/gal	3	1	
	D	$27.3/kg	45 g/l	1	
	E	$1.20/gal	8.5	1	
Catalyst	F	$127/gal	30	1	$2,810
	G	$54.0/gal	20	1	
	H	$51.0/gal	12	1	
Acid Dip	I	$29.1/kg	2 g/l	1	$11.3
Electroless Nickel	J	$24.1/gal	6.6	6	$2,390
	K	$30.9/gal	15	6	
	L	$28.4/gal	6.6	5	
Immersion Gold	M	$21.4/gal	50	1	$70,200
	N	$40.0/g	3 g/l	3	

[a] Product cost from supplier of the chemical product.
[b] The percentage of a chemical product by volume in each process bath was determined from Product Data Sheets provided by the supplier of the chemical product.
[c] Multiplying factors reflect the number of chemical turnovers expected before the bath is replaced. A chemical turnover is considered to be a complete change of bath chemistry through bath maintenance such as chemical additions. Multiplying factors are used for baths that are typically maintained, rather than replaced.
[d] Cost per bath calculated assumes a bath volume of 51.1 gallons, as determined by PWB Workplace Practices Questionnaire data for non-conveyorized processes.

Utility Costs

Utility costs for the surface finishing process include water consumed by rinse tanks,[3] electricity used to power the panel transportation system, heaters and other process equipment, and natural gas consumed by drying ovens employed by some process alternatives. The following example presents utility costs calculation methods and utility costs for the nickel/gold process.

Utility Cost Calculation Methods. The rate of water consumption depends on both the number of distinct water rinse steps and the flow rate of the water used in those steps. The typical number of water rinse steps for each surface finishing alternative was determined using supplier- provided data together with data from the PWB Workplace Practices Questionnaire. Based on Questionnaire data, the average normalized water flow rate per rinse stage for individual rinse types was 0.176 gal/ssf for conveyorized processes, 0.258 gal/ssf for non-conveyorized processes, and 0.465 gal/ssf for high pressure rinse tanks, regardless of automation type. However, it was assumed that the rinse steps are shut off during periods of process down time. Therefore, daily water consumption rates were adjusted for the percentage of time the process was in operation. The total volume of water consumed was calculated by multiplying the number of each type of rinse tank occurring in the process by the appropriate water flow rates for each rinse. Water consumption rates for surface finishing technologies, along with a detailed description of the methodology used to calculate them, are presented in Section 5.1, Resource Conservation.

The cost of water was calculated by multiplying the water consumption rate of the entire surface finishing process by the unit cost factor for water. A unit cost of $2.19/1,000 gallons of water was obtained from the *Pollution Prevention and Control Survey* (U.S. EPA, 1998). The equation for calculating water cost (W) is:

$$W = \text{quantity of rinse water consumed (gal)} \times \$2.19/1{,}000 \text{ gal}$$

The rate of electricity consumption for each surface finishing alternative is dependent upon the equipment required to operate each alternative. Differences in required process equipment, such as the number of heaters, pumps, and type and extent of panel agitation, directly affect electricity consumption. The cost of electricity is calculated by multiplying the electricity consumption rate of the process alternative by the production time required to produce 260,000 ssf of PWB, and then applying a unit cost factor to the total. Electricity consumption rates for surface finishing alternatives are presented in Section 5.2, Energy Impacts, while the required production time was determined by the simulation model. A unit cost of $0.069/kW-hr was obtained from the International Energy Agency. The energy cost (E) was calculated using the following equation:

$$E = \text{hourly consumption rate (kW)} \times \text{required production time (hr)} \times \$0.069/\text{kW-hr}$$

Natural gas is used to fire the drying ovens required by many of the surface finishing processes. All processes with the exception of the nickel/gold and the nickel/palladium/gold

[3] Water is also used in surface finishing chemical baths to dilute chemical products to the appropriate concentration, but this use of water was assumed negligible compared to the water consumed in rinse tanks.

processes required gas-fired ovens for panel drying. The amount of gas consumed was determined by multiplying the natural gas consumption rate for the process alternative by the amount of operating time required by the process to produce 260,000 ssf of PWB, and then applying a unit cost to the result. Knoxville Utilities Board (KUB) charges $0.4028 per therm of natural gas consumed (KUB, 2000a), while the production time required to produce 260,000 ssf of PWB came from simulation results. Thus, the cost of natural gas consumption (G) was calculated by the following equation:

G = natural gas consumption rate (therm/hr) x required production time (hrs) x $0.4028/therm

The total utility cost (U) for a surface finishing process was determined as follows:

$$U = W + E + G$$

where,

W	=	cost of water consumed ($/ssf) to produce 260,000 ssf
E	=	cost of electricity consumed ($/ssf) to produce 260,000 ssf
G	=	cost of natural gas consumed ($/ssf) to produce 260,000 ssf

Example Utility Cost Calculations. The above methodology was used to calculate the utility costs for each of the surface finishing alternatives. This section presents example utility cost calculations for the non-conveyorized nickel/gold process.

Simulation results indicate the non-conveyorized nickel/gold process is down 18.8 days and takes 212 days overall (at 6.8 hrs/day) to produce 260,000 ssf. It is comprised of eight rinse steps which consume approximately 537,000 gallons of water during the course of the job (see Section 5.1, Resource Conservation). Electricity is consumed at a rate of 26.0 kW-hr of operation (see Section 5.2, Energy Impacts). The non-conveyorized nickel/gold process has no drying ovens and, therefore, does not consume natural gas. Based on this information, water, electricity, and gas costs were calculated as follows:

W = 537,000 gallons x $2.19/1,000 gal = $1,180
E = 26.0 kW x (212 days - 18.8 days) x 6.8 hr/day x $.069/kW-hr = $2,360
G = $0

Thus, the utility cost for the process was determined by the calculation:

U = $1,180 + $2,360 + $0 = $3,540

Wastewater Costs

Wastewater Cost Calculation Method. Wastewater costs for the surface finishing processes were only determined for the cost of discharging wastewater to a POTW. The analysis assumes that discharges are made in compliance with local allowable limits for chemical concentrations and other parameters so that no fines are incurred.

Wastewater quantities were assumed equal to the quantity of rinse water used. Rinse water usage was calculated in Section 5.1, Resource Conservation, and used to calculate water costs in the Utility Costs section. The unit costs for fees charged by a POTW for both city and non-city discharges of wastewater were obtained from KUB, and were averaged for use in calculating wastewater cost (KUB, 2000b). These average unit costs are not flat rates applied to the total wastewater discharge, but rather combine to form a tiered cost scale that applies an incremental unit cost to each level of discharge. The tiered cost scale for wastewater discharges to a POTW is presented in Table 4-43.

Table 4-43. Tiered Cost Scale for Monthly Wastewater Discharges to a POTW

Wastewater Discharge Quantity (ccf/month)	City Discharge Cost ($/ccf/month)	Non-City Discharge Cost ($/ccf/month)	Average Discharge Cost ($/ccf/month)
0 - 2	$6.30	$7.40	$6.85
3 - 10	$2.92	$3.21	$3.06
11 - 100	$2.59	$2.85	$2.72
101 - 400	$2.22	$2.44	$2.33
401 - 5,000	$1.85	$2.05	$1.95

Source: KUB, 2000b.
ccf: 100 cubic ft.

The unit costs displayed for each level of discharge are applied incrementally to the quantity of monthly discharge. For example, the first two cubic feet of wastewater discharged in a month are assessed a charge of $6.85, while the next eight cubic feet cost $3.06, and so on. The production time required to produce 260,000 ssf of PWB comes from the simulation models. Thus, wastewater costs (WW) were calculated as follows:

$$WW = \sum_{k=1}^{p} [\text{quantity of discharge in tier k (ccf/mo) x tier cost factor (\$/ccf)}] \times \text{required production time (months)}$$

where,
p = number of cost tiers
ccf = 100 cubic ft

Example Wastewater Cost Calculations. This section presents example wastewater calculations for the non-conveyorized nickel/gold process. Based on rinse water usage, the total wastewater release was approximately 537,000 gallons. The required production time in months was calculated using the required production time from Table 4-38 and an operating year of 280 days (212 days ÷ 280 days/year x 12 months/yr = 9.1 months). Thus, the monthly wastewater release was 78.9 ccf (537,000 gallons ÷ 9.1 months ÷ 748 gal/ccf). To calculate the wastewater cost for the non-conveyorized nickel/gold process, the tiered cost scale was applied to the quantity of discharge, and the resulting costs per tier were summed, as follows:

$6.85 x 2 ccf/month = $13.70 ccf/month
$3.06 x 8 ccf/month = $24.48 ccf/month
$2.72 x 68.9 ccf/month = $187.40 ccf/month

Monthly discharge cost = $13.70 + $24.48 + $187.40 = $226/month

The monthly cost was then multiplied by the number of months required to produce 260,000 ssf of PWB to calculate the overall wastewater treatment cost:

WW = $226/month x 9.1 month = $2,050

Production Costs

Production Cost Calculation Methods. Production costs for the surface finishing process include both the cost of labor required to operate the process and the cost of transporting chemicals to the production line from storage. Production costs (P) were calculated by the following equation:

$$P = LA + TR$$

where,
LA = production labor cost ($/ssf) to produce 260,000 ssf
TR = chemical transportation cost ($/ssf) to produce 260,000 ssf

Production labor cost is a function of the number and type of employees and the length of time required to complete a job. The calculation of production labor cost assumes that line operators perform all of the daily activities, excluding bath maintenance, vital to the operation of the surface finishing process. Labor costs associated with bath maintenance activities, such as sampling and analysis, are presented in the discussion of maintenance costs, below. An average number of line operators was determined for conveyorized (one line operator) from PWB Workplace Practices Questionnaire data and site visit observations. Although no significant difference in the number of line operators by automation type was reported in the data, the number of line operators for non-conveyorized processes was adjusted upward to 1.1 to reflect the greater level of labor content for these processes, as compared to conveyorized processes.

The labor time required to complete the specified job was calculated assuming an average shift time of eight hours per day, and using the number of days required to produce 260,000 ssf of PWB from simulation results. A labor wage of $10.24/hr was obtained from the American Wages

and Salary Survey (Fisher, 1999) and utilized for surface finishing line operators. Therefore, labor costs for process alternatives were calculated as follows:

LA = number of operators x $10.24/hr x 8 hr/day x required production time (days)

The production cost category of chemical transportation cost includes the cost of transporting chemicals from storage to the process line. A BOA, presented in Appendix G, was developed and used to calculate the unit cost per chemical transport. Because chemicals are consumed whenever a bath is replaced, the number of trips required to supply the process line with chemicals equals the number of bath replacements required to produce 260,000 ssf of PWB. Chemical transportation cost was calculated as follows:

TR = number of bath replacements x unit cost per chemical transport ($)

Example Production Cost Calculations. For the example of the non-conveyorized nickel/gold, production labor cost was calculated assuming 1.1 operators working for 212 days (see Table 4-38). Chemical transportation cost was calculated based on a cost per chemical transport of $9.28 (see Table 4-40 and Appendix G) and 72 bath replacements (see Table 4-37). Thus, the production cost was calculated as follows:

LA = 1.1 x $10.24 x 8 hr/day x 212 days = $19,100
TR = 72 x $9.28 = $668

thus,
P = $19,100 + $668 = $19,768

Maintenance Costs

Maintenance Cost Calculation Method. The maintenance costs for the surface finishing process include the costs associated with tank cleaning, bath setup, sampling and analysis of bath chemistries, and bath filter replacement. Maintenance costs were calculated as follows:

$$MA = TC + BS + FR + ST$$

where,

TC	=	tank cleanup cost ($/ssf) to produce 260,000 ssf
BS	=	bath setup cost ($/ssf) to produce 260,000 ssf
FR	=	filter replacement cost ($/ssf) to produce 260,000 ssf
ST	=	sampling cost ($/ssf) to produce 260,000 ssf

The maintenance costs listed above depend on the unit cost per repetition of the activity and the number of times the activity was performed. For each maintenance cost category, a BOA was developed to characterize the cost of labor, materials, and tools associated with a single repetition of that activity. The BOA and unit cost per repetition for each cost category are presented in Appendix G. It was assumed that the activities and costs characterized on the BOAs are the same, regardless of the surface finishing process or process baths. Unit costs per

repetition for both tank cleanup and bath setup were determined to be $67.00 and $15.10, respectively.

The number of tank cleanups and bath setups equals the number of bath replacements obtained from process simulation results (see Appendix G). Each time a bath is replaced, the tank is cleaned before a replacement bath is created. The costs of tank cleanup and bath setup are thus given by the following:

TC = number of tank cleanups x $67.00
BS = number of bath setups x $15.10

The PWB Workplace Practices Questionnaire data for both filter replacement and bath sampling and analysis were reported in occurrences per year, instead of as a function of throughput, and are represented in Section 3.2, the Exposure Assessment. These frequencies were adjusted for this analysis using the URs for the production time required to manufacture 260,000 ssf of PWB. Using the unit costs determined by the BOAs developed for filter replacement ($17.50 per replacement), and bath sampling and testing ($3.70 per test), the costs for these maintenance activities were calculated as follows:

ST = annual number of sampling & testing x UR x $3.70
FR = annual number of filter replacement x UR x $17.50

The total maintenance cost for each process alternative was determined by first calculating the individual bath maintenance costs using the above equations and then summing the results for all baths in that process.

Maintenance Costs Example Calculations. This section presents example maintenance costs calculations for the non-conveyorized nickel/gold process. From Table 4-38, this process has a production time of 212 days, which gives a UR of 0.76 (UR = 212 ÷ 280). The number of tank cleanups and bath setups equals the number of bath replacements reported in Table 4-37 (72 bath replacements). As reported in Section 3.2, Exposure Assessment, chemical baths are sampled and tested 1,260 times per year, and filters are replaced 119 times per year. Thus, the maintenance costs for the non-conveyorized nickel/gold process are:

TC = 72 x $67.00 = $4,820
BS = 72 x $15.10 = $1,090
ST = 1,260 x 0.76 x $3.70 = $3,530
FR = 119 x 0.76 x $17.50 = $1,580

Therefore, the overall maintenance cost for the process is:

MA = $4,820 + $1,090 + $3,530 + $1,580 = $11,000

Determination of Total Cost and Unit Cost

The total cost for surface finishing process alternatives was calculated by summing the totals of the individual costs categories. The cost per ssf of PWB produced, or unit cost (UC), can then be calculated by dividing the total cost by the amount of PWBs produced. Table 4-44 summarizes the total cost of manufacturing 260,000 ssf of PWB using the non-conveyorized nickel/gold process.

The UC for the non-conveyorized nickel/gold process was calculated as follows:

UC = total cost (TC) ÷ 260,000 ssf
= $156,000 ÷ 260,000 ssf
= $0.60/ssf

Table 4-44. Summary of Costs for the Non-Conveyorized Nickel/Gold Process

Cost Category	Component	Component Cost [a]	Totals [a]
Capital Cost	Primary Equipment & Installation	$7,260	
	Facility	$2,930	**$10,200**
Material Cost	Chemical(s)	$109,000	**$109,000**
Utility Cost	Water	$1,180	
	Electricity	$2,360	
	Natural Gas	$0	**$3,540**
Wastewater Cost	Wastewater Discharge	$2,050	**$2,050**
Production Cost	Transportation of Material	$668	
	Labor for Line Operation	$19,100	**$19,800**
Maintenance Cost	Tank Cleanup	$4,820	
	Bath Setup	$1,090	
	Sampling and Analysis	$3,530	
	Filter Replacement	$1,580	**$11,000**
Total Cost			**$156,000**

[a] Costs of producing 260,000 ssf of PWB by the process.

4.2.6 Results

Table 4-45 presents the costs for each of the surface finishing technologies. Table 4-46 presents unit costs ($/ssf). The total cost of producing 260,000 ssf ranged from a low of $26,300 for the conveyorized OSP process to a high of $399,000 for the non-conveyorized nickel/palladium/gold process, with the corresponding unit costs ranging from $0.10/ssf to $1.54/ssf for the same two processes. With the exception of the two technologies containing gold, all of the other surface finishing alternatives were less expensive than the baseline, non-conveyorized HASL process.

Total cost data in Table 4-45 illustrate that chemical cost is the largest cost for all of the surface finishing processes. Labor costs were the second largest cost component, though far smaller than the cost of process chemicals.

Table 4-45. Total Cost of Surface Finishing Technologies

Cost Category	Cost Components	HASL, NC	HASL, C	Nickel/Gold, NC
Capital Cost	Primary Equipment & Installation	$9,360	$11,000	$7,260
	Facility	$432	$398	$2,930
Material Cost	Chemical(s)	$74,800	$75,200	$109,000
Utility Cost	Water	$706	$565	$1,180
	Electricity	$669	$452	$2,360
	Natural Gas	$88	$45	$0
Wastewater Cost	Wastewater Discharge	$1,100	$851	$2,050
Production Cost	Transportation of Material	$167	$130	$668
	Labor for Normal Production	$3,940	$1,790	$19,100
Maintenance Cost	Tank Cleanup	$1,210	$938	$4,820
	Bath Setup	$272	$211	$1,090
	Sampling and Testing	$499	$249	$3,530
	Filter Replacement	$967	$482	$1,580
Total Cost		**$94,200**	**$92,400**	**$156,000**

Table 4-45. Total Cost of Surface Finishing Technologies (cont.)

Cost Category	Cost Components	Nickel/Palladium/Gold, NC	OSP, NC	OSP, C
Capital Cost	Primary Equipment & Installation	$15,400	$1,640	$2,880
	Facility	$6,090	$320	$264
Material Cost	Chemical(s)	$321,000	$18,500	$18,800
Utility Cost	Water	$2,060	$441	$301
	Electricity	$4,050	$313	$208
	Natural Gas	$0	$66	$31
Wastewater Cost	Wastewater Discharge	$3,530	$702	$463
Production Cost	Transportation of Material	$1,030	$159	$121
	Labor for Normal Production	$25,200	$3,170	$1,320
Maintenance Cost	Tank Cleanup	$7,430	$1,140	$871
	Bath Setup	$1,680	$257	$196
	Sampling and Testing	$8,900	$1,610	$738
	Filter Replacement	$2,840	$330	$151
Total Cost		**$399,000**	**$28,700**	**$26,300**

Table 4-45. Total Cost of Surface Finishing Technologies (cont.)

Cost Category	Cost Components	Immersion Silver, C	Immersion Tin, NC	Immersion Tin, C
Capital Cost	Primary Equipment & Installation	$10,540	$2,950	$16,800
	Facility	$937	$892	$2,340
Material Cost	Chemical(s)	$52,700	$29,000	$28,900
Utility Cost	Water	$301	$1,030	$702
	Electricity	$739	$494	$1,230
	Natural Gas	$140	$162	$240
Wastewater Cost	Wastewater Discharge	$529	$1,620	$1,220
Production Cost	Transportation of Material	$167	$204	$167
	Labor for Normal Production	$5,260	$6,780	$8,770
Maintenance Cost	Tank Cleanup	$1,210	$1,470	$1,210
	Bath Setup	$272	$332	$272
	Sampling and Testing	$937	$1,260	$1,800
	Filter Replacement	$80	$705	$1,000
Total Cost		**$73,800**	**$46,900**	**$64,700**

Table 4-46. Surface Finishing Alternative Unit Costs for Producing 260,000 ssf of PWB

Surface Finishing Alternative	Total Cost ($)	Unit Cost ($/ssf)	Cost Savings [a] (%)
HASL, Non-conveyorized	94,200	0.36	---
HASL, Conveyorized	92,400	0.35	**3**
Nickel/Gold, Non-conveyorized	156,000	0.60	**-67**
Nickel/Palladium/Gold, Non-conveyorized	399,000	1.54	**-327**
OSP, Non-conveyorized	28,700	0.11	**69**
OSP, Conveyorized	26,300	0.10	**72**
Immersion Silver, Conveyorized	73,800	0.28	**22**
Immersion Tin, Non-conveyorized	46,900	0.18	**50**
Immersion Tin, Conveyorized	64,700	0.25	**31**

[a] Cost savings measured by comparing cost of the surface finish to the cost of the baseline non-conveyorized HASL process. Positive results represent percent savings from the costs incurred had the baseline process been used, while negative results represent percent lost.

4.2.7 Conclusions

This analysis generated comparative costs for six surface finishing technologies, including HASL, nickel/gold, nickel/palladium/gold, OSP, immersion silver, and immersion tin processes. Costs were developed for each technology and equipment configuration for which data were available from the PWB Workplace Practices Questionnaire and Performance Demonstration, for a total of nine processes (five non-conveyorized processes and four conveyorized processes). Costs were estimated using a hybrid cost model that combines traditional costs with simulation modeling and activity-based costs. The cost model was designed to determine the total cost of processing a specific amount of PWBs through a fully operational surface finishing line, in this case 260,000 ssf. The cost model does not estimate start-up costs for a facility switching to a surface finishing alternative, which could factor significantly in the decision to implement a technology. Total costs were divided by the throughput (260,000 ssf) to determine a unit cost in $/ssf.

The cost components considered include capital costs (primary equipment and installation, and facility costs), materials costs (limited to chemical costs), utility costs (water, electricity, and natural gas costs), wastewater costs (limited to wastewater discharge cost), production costs (production labor and chemical transport costs), and maintenance costs (tank cleanup, bath setup, sampling and analysis, and filter replacement costs). Other cost components may contribute significantly to overall costs, but were not quantified because they could not be reliably estimated. These include wastewater treatment cost, sludge recycling and disposal cost, other solid waste disposal costs, and quality costs.

Overall, the costs ranged from $0.10/ssf for the conveyorized OSP process to $1.54/ssf for the non-conveyorized nickel/palladium/gold process. The cost of the baseline non-conveyorized HASL process was calculated to be $0.36/ssf.

Based on the results of this analysis, six of the eight alternative surface finishing processes are more economical than the baseline non-conveyorized HASL process. Three processes had a substantial cost savings of at least 50 percent of the cost per ssf over that of the baseline HASL process (conveyorized OSP at 72 percent cost savings, non-conveyorized OSP at 69 percent, and non-conveyorized immersion tin at 50 percent). Three other process alternatives realized a somewhat smaller cost savings over the baseline HASL process (conveyorized immersion tin at 31 percent, conveyorized immersion silver at 22 percent, and the conveyorized HASL process at 3 percent.)

Two processes were more expensive than the baseline. The exceptions were the electroless nickel/immersion gold process and the electroless nickel/palladium/immersion gold process, both of which had chemical costs exceeding the *entire* cost of the non-conveyorized HASL process, due to the precious metal content of the surface finish.

In general, conveyorized processes cost less than non-conveyorized processes of the same technology due to the cost savings associated with their higher throughput rates. The exception to this was immersion tin, which was more costly because the combination of process cycle time and conveyor length resulted in a lower throughput rate than its non-conveyorized version.

Chemical cost was the single largest component cost for all of the nine processes. Labor costs were the second largest cost component, though far smaller than the cost of process chemicals.

4.3 REGULATORY ASSESSMENT

This section describes the federal environmental regulations that may affect the use of chemicals in the surface finishing processes during PWB manufacturing. Discharges of these chemicals may be restricted by air, water, or solid waste regulations, and releases may be reportable under the federal Toxic Release Inventory (TRI) program. This section discusses and illustrates pertinent portions of federal environmental regulations that may be pertinent to surface finishing operations, including the Clean Water Act (Table 4-47), the Clean Air Act (Table 4-53), the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act (Table 4-54), the Superfund Amendments and Reauthorization Act and Emergency Planning and Community Right-To-Know Act (Table 4-55), and the Toxic Substances Control Act (Table 4-56). This section is intended to provide an overview of environmental regulations triggered by the use of the identified chemicals; it is not intended to be used as regulatory guidance.

The primary sources of information for this section were the EPA Register of Lists (U.S. EPA, 1998) and the EPA document, "Federal Environmental Regulations Affecting the Electronics Industry" (U.S. EPA, 1995). The former is a database of federal regulations applicable to specific chemicals that can be searched by chemical. The latter was prepared by the DfE PWB Project. Of the 83 chemicals reportedly used in one or more of the evaluated surface finishing technologies, no regulatory listings were found for 40 chemicals.

4.3.1 Clean Water Act

The Clean Water Act (CWA) is the basic federal law governing water pollution control in the U.S. today. The various surface finishing processes used by the PWB industry produce a number of pollutants that are regulated under the CWA. Applicable provisions, as related to specific chemicals, are presented in Table 4-47; these particular provisions and process-based regulations are discussed in greater detail below.

<u>CWA Hazardous Substances and Reportable Quantities</u>

Under Section 311(b)(2)(A) of the CWA, the Administrator designates hazardous substances which, when discharged to navigable waters or adjoining shorelines, present an imminent and substantial danger to the public health or welfare, including fish, shellfish, wildlife, shorelines, and beaches. 40 Code of Federal Regulations (CFR) Part 117 establishes the Reportable Quantity (RQ) for each substance listed in 40 CFR Part 116. When an amount equal to or in excess of the RQ is discharged, the facility must provide notice to the federal government of the discharge, following Department of Transportation requirements set forth in 33 CFR Section 153.203. Liability for cleanup can result from such discharges. This requirement does not apply to facilities that discharge the substance under a National Pollutant Discharge Elimination System (NPDES) Permit or a CWA Section 404 dredge and fill permit, or to a publicly owned treatment works (POTW), as long as any applicable effluent limitations or pretreatment standards have been met. Table 4-47 lists RQs of hazardous substances under the CWA that may apply to chemicals used in the surface finishing process.

Table 4-47. CWA Regulations that May Apply to Chemicals in the Surface Finishing Process

Chemical [a]	CWA 311 RQ (lbs)	CWA Priority Pollutant	CWA 307a	CWA 304(b)
Acetic acid	5,000			
Ammonium hydroxide	1,000			
Copper ion				
Copper sulfate pentahydrate				
Ethylenediamine	5,000			
Hydrochloric acid	5,000			
Nickel sulfate	100			
Nitric acid	1,000			
Phosphoric acid	5,000			
Propionic acid	5,000			
Silver nitrate	1			
Sodium hydroxide	1,000			
Sulfuric acid	1,000			
Urea				

[a] In addition to the chemicals listed, there are 29 confidential business information (CBI) chemicals that would fall under CWA regulations.
Abbreviations and Definitions:
CWA - Clean Water Act
CWA 304(b) - Effluent Limitations Guidelines
CWA 307(a) - Toxic Pollutants Pretreatment Standards
CWA 311 - Hazardous Substances
RQ - Reportable Quantity

The NPDES permit program (40 CFR Part 122) contains regulations governing the discharge of pollutants to waters of the U.S. Forty-three states and one territory are authorized to administer NPDES programs that are at least as stringent as the federal program; EPA administers the program in states or territories that are not authorized to do so, and on Native American lands. The following discussion covers federal NPDES requirements. Facilities may be required to comply with additional state requirements not covered in this document.

The NPDES program requires permits for the discharge of “pollutants” from any “point source” into “navigable waters” (except those covered by Section 404 dredge and fill permits). The CWA defines all of these terms broadly, and a source is required to obtain an NPDES permit if it discharges almost anything other than dredge and fill material directly to surface water. A source that sends its wastewater to a POTW is not required to obtain an NPDES permit, but may be required to obtain an industrial user permit from the POTW to cover its discharge.

CWA Priority Pollutant

In addition to other NPDES permit application requirements, facilities need to be aware of priority pollutants listed in 40 CFR Part 122, Appendix D; this list of 126 compounds was developed by EPA to define a specific list of chemicals to be given priority consideration in the development of effluent limitation guidelines. Each PWB applicant for an NPDES permit must provide quantitative data for those priority pollutants that the applicant knows or has reason to believe, will be discharged in greater than trace amounts. Each applicant also must indicate if it knows, or has reason to believe, it discharges any of the other hazardous substances or non-conventional pollutants listed at 40 CFR Part 122, Appendix D. In some cases, quantitative testing is required for these pollutants; in other cases, the applicant must describe why it expects the pollutant to be discharged and provide the results of any quantitative data about its discharge for that pollutant.

CWA Effluent Limitation Guidelines [CWA 301(b), 304(b)]

A principal means for attaining water quality objectives under the CWA is the establishment and enforcement of technology-based effluent limitations, which are based on the pollutant control capabilities of available technologies, taking into consideration the economic achievability of these limitations and a number of other factors. Because of differences in production processes, quantities, and composition of discharges, separate national standards are established for discharges associated with different industry categories. These standards are referred to as technology-based effluent limitation guidelines.

The effluent limitation to be applied to a particular pollutant in a particular case depends on the following:

whether the pollutant is conventional, non-conventional, or toxic;
whether the point source is a new or existing source; and
whether the point source discharges directly to the waters of the U.S. or to a POTW. (Facilities that discharge to POTWs must comply with the pretreatment standards.)

Existing sources must comply with either best practicable control technology currently available (BPT), best conventional pollution control technology (BCT), or best available control technology economically achievable (BAT) standards. New facilities must comply with New Source Performance Standards. NPDES permits also must contain any more stringent permit limitations based on state water quality standards.

In the absence of effluent limitation guidelines for a facility category, permit writers establish technology-based controls using their best professional judgement. In essence, the permit writer undertakes an effluent guideline-type analysis for a single facility. The permit writer will use information such as permit limits from similar facilities using similar treatment technology, performance data from actual operating facilities, and scientific literature. Best Professional Judgement may not be used in lieu of existing effluent guidelines. These guidelines apply only to direct dischargers of wastewater.

Pretreatment Standards

Only those facilities that discharge pollutants into waters of the U.S. need to obtain an NPDES permit. Facilities that discharge to POTWs, however, must comply with pretreatment requirements, as set out in Section 307(a) of CWA. These requirements were developed because of concern that dischargers' waste containing toxic, hazardous, or concentrated conventional industrial wastes might "pass through" POTWs, or that pollutants might interfere with the successful operation of the POTW. EPA has established national, technology-based "categorical pre-treatment standards" by facility category. In addition, or for industry categories without national standards, POTWs may establish "local limits" or individual industrial facilities.

Wastewater emission standards for the PWB industry can be found at 40 CFR Part 413 and 433, which include the Pretreatment Standards for Existing Sources (PSES) and Pretreatment Standards for New Sources (PSNS) that regulate PWB industry and wastewater, respectively. The major constituents of PWB wastewater are heavy metals and other cations.

The PSES and the PSNS establish maximum concentration levels of several metals that cannot be exceeded. They also regulate cyanide, which is used in some surface finishing alternatives. Generally speaking, PSNS puts more stringent regulations on pollutants than PSES. A summary of PSES for metals is included in Tables 4-48 and 4-49.

Table 4-48. Printed Circuit Board Facilities Discharging Less than 38,000 Liters per Day PSES Limitations (mg/L)

Pollutant or Pollutant Property	Max. Value for Any 1 Day (ppm)	Average Daily Values for 4 Consecutive Monitoring Days that Shall Not be Exceeded mg/L (ppm)
Cyanide (CN)	5.0	2.7
Lead (Pb)	0.6	0.4
Cadmium (Cd)	1.2	0.7

Table 4-49. Printed Circuit Board Facilities Discharging 38,000 Liters per Day or More PSES Limitations (mg/L)

Pollutant or Pollutant Property	Max. Value for Any 1 Day (ppm)	Average Daily Values for 4 Consecutive Monitoring Days that Shall Not be Exceeded mg/L (ppm)
Copper (Cu)	4.5	2.7
Nickel (Ni)	4.1	2.6
Lead (Pb)	0.6	0.4
Cadmium (Cd)	1.2	0.7
Silver (Ag)	1.2	0.7
Total Metals	10.5	6.8
Cyanide (CN)	1.9	1.0
PH	7.5 < pH < 10.0	7.5 < pH < 10.0

Both 40 CFR Part 433.17, PSNS, and Part 433.16, New Source Performance Standards (NSPS), have the same and more stringent regulated metal levels. Tables 4-50 and 4-51 summarize these sections.

Table 4-50. PSNS for Metal Finishing Facilities

Pollutant or Pollutant Property	Max. Value for Any 1 Day (ppm)	Average Daily Values for 4 Consecutive Monitoring Days that Shall Not be Exceeded mg/L (ppm)
Copper (Cu)	3.38	2.07
Nickel (Ni)	3.98	2.38
Lead (Pb)	0.69	0.43
Cadmium (Cd)	0.11	0.07
Silver (Ag)	0.43	0.24
Cyanide (CN)	1.20	0.65
PH	6.0 < pH < 9.0	6.5 < pH < 9.0

Table 4-51. Amenable Cyanide Limitation Upon Agreement

Pollutant or Pollutant Property	Max. Value for Any 1 Day (ppm)	Average Daily Values for 4 Consecutive Monitoring Days that Shall Not be Exceeded mg/L (ppm)
Cyanide (CN)	0.86	0.32

There is one table in 40 CFR Part 433.15 that shows a different set of PSES for all plants except job shops and independent printed circuit board manufacturers. Although most of the PWB companies participating in this project are independent manufacturers, Table 4-52 summarizes that section for reference purposes.

Table 4-52. PSES for All Plants Except Job Shops and Independent PWB Manufacturers

Pollutant or Pollutant Property	Max. Value for Any 1 Day (ppm)	Average Daily Values for 4 Consecutive Monitoring Days that Shall Not be Exceeded mg/L (ppm)
Copper (Cu)	3.38	2.07
Nickel (Ni)	3.98	2.38
Lead (Pb)	0.69	0.43
Cadmium (Cd)	0.69	0.26
Silver (Ag)	0.43	0.24
Cyanide (CN)	1.20	0.64

4.3.2 Clean Air Act

The Clean Air Act (CAA), with its 1990 amendments, sets the framework for air pollution control in the U.S. The various surface finishing processes produce a number of pollutants that are regulated under the CAA. Applicable provisions, as related to specific chemicals, are presented in Table 4-53; these particular provisions and process-based regulations are discussed below.

Table 4-53. CAA Regulations that May Apply to Chemicals in the Surface Finishing Process

Chemical [a]	CAA 111	CAA 112b	CAA 112r
Acetic acid			
Ethylene glycol			
Ethylenediamine			
Hydrochloric acid			
Malic acid			
Nickel sulfate			
Propionic acid			
Sulfuric acid			

[a] In addition to the chemicals listed, there are 16 CBI chemicals that have been identified as falling under the CAA regulations discussed.
Abbreviations and Definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program

<u>Hazardous Air Pollutants</u>

Section 112 of the CAA established a regulatory program for 188 hazardous air pollutants and directed EPA to add other pollutants to the list, as needed. EPA is required to establish Maximum Achievable Control Technology (MACT) standards for source categories that emit at least one of the pollutants on the list in major quantities. Chemicals listed in Section 112 (b) of the CAA that are used in surface finishing are shown in Table 4-53. EPA has identified categories of industrial facilities that emit substantial quantities of any of these 188 pollutants and plan to develop emissions limits for those industry categories between 1992 and 2000.

Section 112(r) of the CAA deals with sudden releases of, or accidents involving acutely toxic, explosive, or flammable chemicals. This provision, added by the CAA Amendments of 1990, establishes a list of substances which, if present in a process in a quantity exceeding a threshold, would require the facility to establish a Risk Management Program to prevent chemical accidents. This program must include preparation of a risk management plan, which is submitted to the state and local emergency planning organizations.

Minimum Standards for State Operating Permit Programs

The CAA and its implementing regulations (at 40 CFR Part 70) define the minimum standards and procedures required for state operating permit programs. The permit system is a new approach established by the 1990 Amendments that is designed to define each source's requirements and to facilitate enforcement. In addition, permit fees generate revenue to fund the program's implementation.

Any facility defined as a "major source" is required to secure a permit. Section 70.2 of the regulations defines a major source, in part, based upon if the source emits or has the potential to emit:

10 tons per year (TPY) or more of any hazardous air pollutant;
25 TPY or more of any combination of hazardous air pollutants; or
100 TPY of any air pollutant.

For ozone non-attainment areas, major sources are defined as sources with the potential to emit:

100 TPY or more of volatile organic compounds (VOCs) or oxides of nitrogen (NOx) in areas classified as marginal or moderate;
50 TPY or more of VOCs or NOx in areas classified as serious;
25 TPY or more of VOCs or NOx in areas classified as severe; and
10 TPY or more of VOCs or NOx in areas classified as extreme.

Section 70.2 also defines certain other major sources in ozone transport regions and serious non-attainment areas for carbon monoxide and particulate matter. In addition to major sources, all sources that are required to undergo New Source Review, sources that are subject to New Source Performance Standards or section 112 air toxics standards, and any affected source, must obtain a permit.

By November 15, 1993, each state was required to submit an operating permit program to EPA for approval. EPA was required to either approve or disapprove the state's program within one year after submission. Once approved, the state program went into effect.

Major sources, as well as other sources identified above, were to submit their permit applications to the state within one year of approval of the state program. Once a source submits a timely and complete application, it may continue to operate until the permit is issued. Permit issuance may take years because permit processing allows time for terms and conditions to be reviewed by the public and neighboring states as well as by EPA.

When issued, the permit includes all federal air requirements applicable to the facility, such as compliance schedules, emissions monitoring, emergency provisions, self-reporting responsibilities, and emissions limitations. States may also choose to include state air requirements in the permit. Five years is the maximum permit term.

As established in 40 CFR Part 70, the states are required to develop fee schedules to ensure the collection and retention of revenues sufficient to cover permit program costs. The CAA has set a presumptive minimum annual fee of $25 per ton for all regulated pollutants (except carbon monoxide), indexed for inflation, but states may set higher or lower fees as long as they collect sufficient revenues to cover program costs.

4.3.3 Resource Conservation and Recovery Act

One purpose of the Resource Conservation and Recovery Act (RCRA) of 1976 (as amended in 1984) is to set up a cradle-to-grave system for tracking and regulating hazardous waste. EPA has issued regulations, found in 40 CFR Parts 260-299, which implement the federal statute. These regulations are Federal requirements. Currently, 47 states have been authorized to implement the basic RCRA program and may include more stringent requirements in their authorized RCRA programs. In addition, non-RCRA-authorized states (Alaska, Hawaii, and Iowa) may have state laws establishing hazardous waste management requirements. A facility always should check with its state when analyzing which requirements apply to its activities.

To be an RCRA "hazardous waste", a material must first be a solid waste, which is defined broadly under RCRA and RCRA regulations. Assuming the material is a solid waste, the first evaluation to be made is whether or not it is also considered a hazardous waste. 40 CFR Part 261 addresses the identification and listing of hazardous waste. Waste generators are responsible for determining whether a waste is hazardous, and what classification, if any, may apply to the waste. Generators must undertake testing, or use their own knowledge and familiarity with the waste, to determine if it is hazardous. Generators may be subject to enforcement penalties for improperly determining that a waste is not hazardous.

RCRA Hazardous Waste Codes

Wastes can be classified as hazardous either because they are listed by EPA through regulation in 40 CFR Part 261, or because they exhibit certain characteristics; namely toxicity, corrosivity, reactivity, and ignitability. Listed hazardous wastes are specifically named (e.g., discarded commercial toluene, spent non-halogenated solvents). Characteristic hazardous wastes are solid waste which "fail" a characteristic test, such as the RCRA test for ignitability.

There are four separate lists of hazardous wastes in 40 CFR Part 261. If any waste from a PWB facility is on any of these lists, the facility is subject to regulation under RCRA (there are two CBI chemicals used in a surface finishing process that have been identified as "U" listed wastes). The listing is often defined by industrial processes, but all wastes are listed because they were determined to be hazardous (these hazardous constituents are listed in Appendix VII to Part 261). Section 261.31 lists wastes from non-specific sources and includes wastes generated by industrial processes that may occur in several different industries; the codes for such wastes always begin with the letter "F." The second category of listed wastes (40 CFR Section 261.32) includes hazardous wastes from specific sources; these wastes have codes that begin with the letter "K." The remaining lists (40 CFR Section 261.33) cover commercial chemical products that have been or are intended to be discarded; these have two letter designations, "P" and "U."

Waste codes beginning with "P" are considered acutely hazardous, while those beginning with "U" are simply considered hazardous.

Generator Status

A hazardous waste generator is defined as any person, by site, who creates a hazardous waste or makes a waste subject to RCRA Subtitle C. Generators are divided into three categories:

1. Large Quantity Generators—facilities that generate at least 1,000 kg (approximately 2,200 lbs) of hazardous waste per month, or greater than 1 kg (2.2 lbs) of acutely hazardous waste per month.
2. Small Quantity Generators—facilities that generate greater than 100 kg (approximately 220 lbs) but less than 1,000 kg of hazardous waste per month, and up to 1 kg (2.2 lbs) per month of acutely hazardous waste.
3. Conditionally Exempt Small Quantity Generators—facilities that generate no more than 100 kg (approximately 220 lbs) per month of hazardous waste and up to 1 kg (2.2 lbs) per month of acutely hazardous waste.

Large and small quantity generators must meet many similar requirements. 40 CFR Part 262 provides that small quality generators may accumulate up to 6,000 kg of hazardous waste on-site, at any one time, for up to 180 days without being regulated as a treatment, storage, or disposal facility (TSDF), which requires a TSDF permit. The provisions of 40 CFR 262.34(f) allow small quality generators to accumulate waste on-site for 270 days without having to apply for TSDF status, provided the waste must be transported over 200 miles. Large quantity generators have only a 90-day window to ship wastes off-site without needing a RCRA TSDF permit. Keep in mind that most provisions of 40 CFR Parts 264 and 265 (for hazardous waste treatment, storage and disposal facilities) do not apply to generators who send their wastes off-site within the 90- or 180-day window, whichever is applicable.

Hazardous waste generators that do not meet the conditions for being conditionally exempt, small quantity generators must (among other requirements such as record keeping and reporting):

obtain a generator identification number;
accumulate and ship hazardous waste in suitable containers or tanks (for accumulation only);
manifest the waste properly;
maintain copies of the manifest, a shipment log covering all hazardous waste shipments, and test records;
comply with applicable land disposal restriction requirements; and
report releases or threats of releases of hazardous waste.

TSDF Status

As mentioned above, Subtitle C of RCRA (40 CFR Parts 264 and 265) establishes substantive permit requirements for facilities that treat, store, or dispose of hazardous wastes. Generators (unless exempt, e.g., through the conditionally exempt, small quantity generators exemption [see 40 CFR Part 261.5(g)]), no matter what monthly waste output, with waste on site, for more than 90 days are classified as TSDFs. TSDFs must comply with 40 CFR Part 264-267 and Part 270, including permit requirements and stringent technical and financial responsibility requirements. Generators who discharge hazardous waste into a POTW, or from a point source regulated by an NPDES permit, are not required to comply with TSDF regulations.

4.3.4 Comprehensive Environmental Response, Compensation and Liability Act

The Comprehensive Environmental Response, Compensation and Liability Act (also known as CERCLA, or more commonly as "Superfund") was enacted in 1980. CERCLA is the Act that created the Superfund hazardous substance cleanup program and set up a variety of mechanisms to address risks to public health, welfare, and the environment caused by hazardous substance releases.

CERCLA RQs

Substances defined as hazardous under CERCLA are listed in 40 CFR Section 302.4. Under CERCLA, EPA has assigned a RQ to most hazardous substances; regulatory RQs are either 1, 10, 100, 1,000, or 5,000 pounds (except for radionuclides). If EPA has not assigned a regulatory RQ to a hazardous substance, typically its RQ is one pound (Section 102). Any person in charge of a facility (or vessel) must immediately notify the National Response Center as soon as a person has knowledge of a hazardous substance release in an amount that is equal to or greater than its RQ. There are some exceptions to this requirement, including the exceptions for federally permitted releases. There is also streamlined reporting for certain continuous releases (see 40 CFR 302.8). Table 4-54 lists RQs of substances under CERCLA that may apply to chemicals used in surface finishing processes.

Table 4-54. CERCLA RQs that May Apply to Chemicals in the Surface Finishing Process

Chemical [a]	CERCLA RQ (lbs)	Chemical [a]	CERCLA RQ (lbs)
Acetic acid	5,000	Phosphoric acid	5,000
Ammonium hydroxide	1,000	Propionic acid	5,000
Copper ion	1	Silver nitrate	1
Ethylene glycol	5,000	Sodium hydroxide	1,000
Ethylenediamine	5,000	Sulfuric acid	1,000
Hydrochloric acid	5,000	Thiourea	10
Nickel sulfate	100		

[a] In addition to the chemicals listed, there are 17 CBI chemicals with reportable quantities under CERCLA.
Abbreviations and Definitions:
CERCLA - Comprehensive Environmental Response, Compensation and Liability Act
RQ - Reportable Quantity

CERCLA Liability

CERCLA further makes a broad class of parties liable for the costs of removal or remediation of the release, or threatened release, of any hazardous substance at a facility. Section 107 specifies the parties liable for response costs, including the following: 1) current owners and operators of the facility; 2) owners and operators of a facility at the time hazardous substances were disposed; 3) persons who arranged for disposal, treatment, or transportation for disposal or treatment of such substances; and 4) persons who accepted such substances for transportation for disposal or treatment. These parties are liable for: 1) all costs of removal or remedial action incurred by the federal government, a state, or an Indian tribe not inconsistent with the National Contingency Plan (NCP); 2) any other necessary costs of response incurred by any person consistent with the NCP; 3) damages for injury to natural resources; and d) costs of health assessments.

4.3.5 Superfund Amendments and Reauthorization Act and Emergency Planning and Community Right-To-Know Act

CERCLA was amended in 1986 by the Superfund Amendments and Reauthorization Act (SARA). Title III of SARA is also known as the Emergency Planning and Community Right-To-Know Act (EPCRA). Certain sections of SARA and EPCRA may be applicable to surface finishing chemicals and PWB manufacturers. Table 4-55 lists applicable provisions as related to specific chemicals.

SARA Priority Contaminants

SARA Section 110 addresses Superfund site priority contaminants. This list contains the 275 highest-ranking substances of the approximately 700 prioritized substances. These chemical substances, found at Superfund sites, are prioritized based on their frequency of occurrence, toxicity rating, and potential human exposure. Once a substance has been listed, the Agency for Toxic Substances and Disease Registry must develop a toxicological profile containing general health/hazard assessments with effect levels, potential exposures, uses, regulatory actions, and further research needs.

EPCRA Extremely Hazardous Substances

Section 302(a) of EPCRA regulates extremely hazardous substances and is intended to facilitate emergency planning for response to sudden toxic chemical releases. Facilities must notify the State Emergency Response Commission (SERC) if these chemicals are present in quantities greater than their threshold planning quantities. These same substances also are subject to regulation under EPCRA Section 304, which requires accidental releases in excess of reportable quantities to be reported to the SERC and Local Emergency Planning Committee.

EPCRA Toxic Release Inventory

Under EPCRA Section 313, a facility in a covered Standard Industrial Code (SIC), that has 10 or more full-time employees, or the equivalent, and that manufactures, processes, or otherwise uses a toxic chemical listed in 40 CFR Section 372.65 above the applicable reporting threshold, must either file a toxic chemical release inventory reporting form (EPA Form R) covering release and other waste management activities, or if applicable, an annual certification statement (EPA Form A). The activity thresholds are 25,000 pounds per year for manufacturing (including importing) and processing, and 10,000 pounds per year for the otherwise use of a listed toxic chemical. Facilities that do not manufacture, process, or otherwise use more than one million pounds of a toxic chemical, and have a total annual reportable amount of no greater than 500 pounds for the chemical, may utilize the briefer Form A certification statement. The Form R, or form A if applicable, must be filed with the EPA and a state agency where the facility is located. Beginning in the 1991 reporting year, facilities must also report pollution prevention and recycling data for TRI chemicals on Form R pursuant to Section 6607 of the Pollution Prevention Act, 42 U.S.C. 13106. Table 4-55 lists chemicals used in surface finishing processes that are listed in the TRI.

Table 4-55. SARA and EPCRA Regulations that May Apply to Chemicals in the Surface Finishing Process

Chemical [a]	SARA 110	EPCRA 302a	EPCRA 313
Ammonium hydroxide			
Copper ion			
Copper sulfate pentahydrate			
Ethylene glycol			
Ethylenediamine			
Nickel sulfate			
Palladium chloride			
Phosphoric acid			
Sulfuric acid			

[a] In addition to the chemicals listed, there are 14 CBI chemicals identified as falling under the SARA and EPCRA regulations discussed.

Abbreviations and Definitions:
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
EPCRA - Emergency Planning & Community Right-To-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory

4.3.6 Toxic Substances Control Act

The Toxic Substances Control Act (TSCA), 15 U.S.C. Sections 2601-2692 (Regulations found at 40 CFR part 700-799), originally passed in 1976 and subsequently amended, applies to the manufacturers, importers, processors, distributors, users, and disposers of chemical substances or mixtures. Table 4-56 lists TSCA regulations and testing lists that may be pertinent to surface finishing processes.

Table 4-56. TSCA Regulations and Lists that May Apply to Chemicals Used in Surface Finishing Processes

Chemical [a]	TSCA 8d HSDR	TSCA MTL	TSCA 8a PAIR
Ethylene glycol			
Palladium chloride			

[a] In addition to the chemicals listed, there are 10 CBI chemicals identified as falling under the TSCA regulations discussed.
Abbreviations and Definitions:
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & Safety Data Reporting Rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

Testing Requirements

Section 4 authorizes EPA to require the testing of any chemical substance or mixture for potential adverse health and environmental effects. On finding that such testing is necessary, due to insufficient data from which the chemical's effects can be predicted, and that either: 1) activities involving the chemical may present an unreasonable risk of injury to health or the environment; or 2) the chemical is produced in substantial quantities and enters the environment in substantial quantities, or there is significant or substantial human or environmental exposure to the chemical.

The TSCA Master Testing List (MTL) is a list compiled by the EPA Office of Pollution Prevention and Toxics to set the Agency's testing agenda. The major purposes are to: 1) identify chemical testing needs; 2) focus limited EPA resources on those chemicals with the highest priority testing needs; 3) publicize EPA's testing priorities for industrial chemicals; 4) obtain broad public comments on EPA's testing program and priorities; and 5) encourage initiatives by industry to help EPA meet those priority needs. The 1996 MTL now contains over 500 specific chemicals in 10 categories.

Unpublished Health and Safety Data Reporting Requirements

Under section 8(d) of TSCA, EPA has promulgated regulations that require that any person who manufactures, imports, or, in some cases, processes (or proposes to manufacture, import, or, in some cases, process) a chemical substance or mixture identified under 40 CFR part 716, must submit to EPA copies of unpublished health and safety studies with respect to that substance or mixture.

Preliminary Assessment Information Rule

Under section 8(a) of TSCA, EPA has promulgated regulations at 40 CFR part 712, Subpart B (the Preliminary Assessment Information Rule (PAIR), which establishes procedures for chemical manufacturers and importers to report production, use, and exposure-related information on listed chemical substances. Any person (except a small manufacturer or importer) who imports or manufactures chemicals identified by EPA in this rule, must report information on production volume, environmental releases, and certain other releases. Small manufacturers or importers may be required to report such information on certain chemicals.

4.3.7 Summary of Regulations for Surface Finishing Technologies

Tables 4-57 through 4-62 provide a summary of regulations that may apply to chemicals in each of the surface finishing technology categories.

Table 4-57. Summary of Regulations that May Apply to Chemicals Used in Hot Air Solder Leveling (HASL) Technology

Chemicals Subject to Applicable Regulation															
Process Chemical	**CWA**				**CAA**			**EPCRA**		**SARA**	**TSCA**			**RCRA Waste**	
	304b	**307a**	**311**	**Priority Poll.**	**111**	**112b**	**112r**	**313**	**302a**	**110**	**8d HSDR**	**MTL**	**8a PAIR**	**P**	**U**
Copper sulfate pentahydrate	✓	✓		✓				✓		✓					
Ethylene glycol					✓	✓		✓				✓			
Hydrochloric acid			✓			✓	✓	✓	✓			✓			
Hydrogen peroxide									✓			✓			
Phosphoric acid			✓					✓							
Sodium hydroxide			✓												
Sulfuric acid			✓		✓				✓						
CBI chemicals (13)					1	1		2			3	1	3		

Note: For technologies with more than one process submitted for evaluation (i.e., nickel/gold, OSP, immersion tin), the number of listed chemicals subject to regulation reflects the total number of chemicals for both processed.

Abbreviations and definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory
RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & safety data reporting rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

Table 4-58. Summary of Regulations that May Apply to Chemicals Used in Nickel/Gold Technology

Chemicals Subject to Applicable Regulation															
Process Chemical	**CWA**				**CAA**			**SARA**	**EPCRA**		**TSCA**			**RCRA Waste**	
	304b	**307a**	**311**	**Priority Poll.**	**111**	**112b**	**112r**	**110**	**313**	**302a**	**8d HSDR**	**MTL**	**8a PAIR**	**P**	**U**
Ammonium hydroxide			✓						✓						
Copper sulfate pentahydrate	✓	✓		✓				✓	✓						
Hydrochloric acid			✓			✓	✓		✓	✓		✓			
Hydrogen peroxide										✓		✓			
Malic acid					✓										
Nickel sulfate	✓	✓	✓	✓		✓		✓	✓						
Palladium chloride								✓					✓		
Phosphoric acid			✓						✓						
Sodium hydroxide			✓												
Sulfuric acid			✓		✓					✓					
CBI Chemicals (19)	4	4	10	4	9	4		4	7		1	2	2		

Note: For technologies with more than one process submitted for evaluation (i.e., nickel/gold, OSP, immersion tin), the number of listed chemicals subject to regulation reflects the total number of chemicals for both processed.

Abbreviations and definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory
RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & safety data reporting rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

Table 4-59. Summary of Regulations that May Apply to Chemicals Used in Nickel/Palladium/Gold Technology

Chemicals Subject to Applicable Regulation															
Process Chemical	**CWA**				**CAA**			**SARA**	**EPCRA**		**TSCA**			**RCRA Waste**	
	304b	**307a**	**311**	**Priority Poll.**	**111**	**112b**	**112r**	**110**	**313**	**302a**	**8d HSDR**	**MTL**	**8a PAIR**	**P**	**U**
Ammonium hydroxide			✓						✓						
Copper sulfate pentahydrate	✓	✓		✓				✓	✓						
Ethylenediamine															
Hydrochloric acid			✓			✓	✓		✓	✓		✓			
Hydrogen peroxide										✓		✓			
Nickel sulfate	✓	✓	✓	✓		✓		✓	✓						
Palladium chloride								✓					✓		
Phosphoric acid			✓						✓						
Propionic acid															
Sodium chloride															
Sodium hydroxide			✓												
Sulfuric acid			✓		✓					✓					
CBI Chemicals (20)	3	3	6	3	4	3		3	5		1	2	3		

Note: For technologies with more than one process submitted for evaluation (i.e., nickel/gold, OSP, immersion tin), the number of listed chemicals subject to regulation reflects the total number of chemicals for both processed.

Abbreviations and definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory
RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & safety data reporting rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

Table 4-60. Summary of Regulations that May Apply to Chemicals Used in OSP Technology

Chemicals Subject to Applicable Regulation															
Process Chemical	**CWA**				**CAA**			**SARA**	**EPCRA**		**TSCA**			**RCRA Waste**	
	304b	**307a**	**311**	**Priority Poll.**	**111**	**112b**	**112r**	**110**	**313**	**302a**	**8d HSDR**	**MTL**	**8a PAIR**	**P**	**U**
Acetic acid			✓		✓										
Copper ion	✓	✓		✓				✓	✓						
Copper sulfate pentahydrate	✓	✓		✓				✓	✓						
Ethylene glycol					✓	✓			✓			✓			
Hydrogen peroxide										✓					
Hydrochloric acid			✓			✓	✓		✓	✓		✓			
Phosphoric acid			✓												
Sodium hydroxide			✓												
Sulfuric acid			✓		✓										
CBI Chemicals (9)									1		1		1		

Note: For technologies with more than one process submitted for evaluation (i.e., nickel/gold, OSP, immersion tin), the number of listed chemicals subject to regulation reflects the total number of chemicals for both processed.

Abbreviations and definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory
RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & safety data reporting rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

Table 4-61. Summary of Regulations that May Apply to Chemicals Used in Immersion Silver Technology

Chemicals Subject to Applicable Regulation															
Process Chemical	**CWA**				**CAA**			**SARA**	**EPCRA**		**TSCA**			**RCRA Waste**	
	304b	**307a**	**311**	**Priority Poll.**	**111**	**112b**	**112r**	**110**	**313**	**302a**	**8d HSDR**	**MTL**	**8a PAIR**	**P**	**U**
Hydrogen peroxide										X		X			
Phosphoric acid			X						X						
Silver nitrate	X	X	X	X				X					X		
Sodium hydroxide			X						X						
Sulfuric acid			X		X					X					
CBI chemicals (5)			1			1			1	1					

Note: For technologies with more than one process submitted for evaluation (i.e., nickel/gold, OSP, immersion tin), the number of listed chemicals subject to regulation reflects the total number of chemicals for both processed.

Abbreviations and definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory
RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & safety data reporting rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

Table 4-62. Summary of Regulations that May Apply to Chemicals Used in Immersion Tin Technology

Chemicals Subject to Applicable Regulation															
Process Chemical	**CWA**				**CAA**			**SARA**	**EPCRA**		**TSCA**			**RCRA Waste**	
	304b	**307a**	**311**	**Priority Poll.**	**111**	**112b**	**112r**	**110**	**313**	**302a**	**8d HSDR**	**MTL**	**8a PAIR**	**P**	**U**
Hydrochloric acid			✓			✓	✓		✓	✓		✓			
Phosphoric acid			✓						✓						
Silver nitrate	✓	✓	✓	✓				✓	✓				✓		
Sulfuric acid			✓		✓					✓					
Thiourea									✓						U219
Urea															
CBI Chemicals (16)			2		2	1			3		2	3	2		1

Note: For technologies with more than one process submitted for evaluation (i.e., nickel/gold, OSP, immersion tin), the number of listed chemicals subject to regulation reflects the total number of chemicals for both processed.

Abbreviations and definitions:
CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory
RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & safety data reporting rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

REFERENCES

Badgett, Lona, Beth Hawke and Karen Humphrey. 1995. *Analysis of Pollution Prevention and Waste Minimization Opportunities Using Total Cost Assessment: A Study in the Electronic Industry*. Seattle, WA. Pacific Northwest Pollution Prevention Research Center Publication.

Ferguson, John H. 1996. *Mean Square Foot Costs: Means-Southern Construction Information Network*. Kingston, MA: R.S. Means, Co., Inc. Construction. Publishers and Consultants.

Fisher, Helen S. 1999. *American Wages and Salary Survey*, 3rd Ed. Detroit, MI: Gale Research Inc. (An International Thompson Publishing Co.)

Iman, R.L. et al. 1995. "Evaluation of Low-Residue Soldering for Military and Commercial Applications: A Report from the Low-Residue Soldering Task Force." June.

Iman, R.L., J.F. Koon, et al. 1997. "Screening Test Results for Developing Guidelines for Conformal Coating Usage and for Evaluating Alternative Surface Finishes." CCAMTF Report. June.

Iman, R.L., J. Fry, R. Ragan, J.F. Koon and J. Bradford. 1998. "A Gauge Repeatability and Reproducibility Study for the CCAMTF Automated Test Set." CCAMTF Report. March.

Joint Group on Acquisition Pollution Prevention (JG-APP) Joint Test Protocol CC-P-1-1 for Validation of alternatives to Lead-Containing Surface Finishes, for Development of Guidelines for Conformal Coating Usage, and for Qualification of Low-VOC Conformal Coatings. 1998.

Iman, R.L. 1994. A Data-Based Approach to Statistics. Duxbury Press.

The Institute for Interconnecting and Packaging Electronic Circuits. 1995. "Ionic Analysis of Circuit Boards Ion Chromatography Method." IPC-TM-650 Test Methods Manual. Lincolnwood, IL: IPC.

Vishanoff, Richard. 1995. *Marshall Valuation Service: Marshall and Swift the Building Cost People*. Los Angeles, CA: Marshall and Swift Publications.

White, Allan L., Monica Becker and James Goldstein. 1992. *Total Cost Assessment. Accelerating Industrial Pollution Prevention Through Innovative Project Financial Analysis: With Application to Pulp and Paper Industry*. U.S. EPA's Office of Pollution Prevention and Toxics, Washington, DC.

U.S. EPA (Environmental Protection Agency). 1998. *Pollution Prevention and Control Survey*.

Chapter 5
Conservation

Businesses are finding that by conserving resources, both natural and man-made, and conserving energy, they can cut costs, improve the environment, and improve their competitiveness. Due to the substantial amount of rinse water consumed and wastewater generated by the printed wiring board (PWB) manufacturing process, water conservation is an issue of particular concern to board manufacturers and to the communities in which they are located. This chapter of the Cleaner Technologies Substitutes Assessment (CTSA) evaluates the comparative resource consumption and energy use of the surface finishing technologies. Section 5.1 presents a comparative analysis of the resource consumption rates of the surface finishing technologies, including the relative amounts of rinse water and metals consumed, and a discussion of factors affecting process and wastewater treatment chemicals consumption. Section 5.2 presents a comparative analysis of the energy impacts of the surface finishing technologies, including the relative amount of energy consumed by each process and the environmental impacts of the energy consumption.

5.1 RESOURCE CONSERVATION

Resource conservation is an increasingly important goal for all industry sectors, particularly as global industrialization increases demand for limited resources. A PWB manufacturer can conserve resources through its selection of a surface finishing process and the manner in which it is operated. By reducing the consumption of resources, a manufacturer will not only minimize process costs and increase process efficiency, but also will conserve resources throughout the entire life-cycle chain. Resources typically consumed by the operation of the surface finishing process include water used for rinsing panels, metals that form the basis of many of the surface finishing technologies, process chemicals used on the process line, wastewater treatment chemicals, and energy used to heat process baths and power equipment. A summary of the effects of the surface finishing technology on the consumption of resources is presented in Table 5-1.

To determine the effects that surface finishing technologies have on the rate of resource consumption during the operation of the surface finishing process, specific data were gathered from chemical suppliers of the various technologies, Performance Demonstration participants, and from PWB manufacturers through the Workplace Practices Questionnaire and Observer Data Sheets. Data gathered through these means to determine resource consumption rates include:

- process specifications (e.g., type of process, facility size, process throughput, etc.);
- physical process parameters and equipment description (e.g., automation level, bath size, rinse water system configuration, pollution prevention equipment, etc.);
- operating procedures and employee practices (e.g., process cycle-time, individual bath dwell times, bath maintenance practices, chemical disposal procedures, etc.); and
- resource consumption data (e.g., rinse water flow rates, frequency of bath replacement, criteria for replacement, bath formulations, frequency of chemical addition, etc.).

Table 5-1. Effects of Surface Finishing Technology on Resource Consumption

Resource	Effects of Surface Finishing Technology on Resource Consumption
Water	Water consumption can vary significantly according to the surface finishing process and level of automation. Other factors such as the cost of water, sewage costs, and operating practices also affect water consumption rates.
Metals	Both the type and quantity of metal consumed is dependent on the surface finishing technology used by a facility. Metal plating thicknesses are crucial to surface finishing performance and are set forth in strict guidelines from process suppliers to PWB manufacturers. Facility operating practices can influence metal consumption if baths are not maintained properly causing increased process chemical waste.
Process Chemicals	Reduction in the number of chemical baths comprising the surface finishing process typically leads to reduced chemical consumption. The quantity of process chemicals consumed also is dependent on other factors such as expected bath lives [e.g., the number of surface square feet (ssf) processed before a bath must be replaced or chemicals added], process throughput, and individual facility operating practices.
Treatment Chemicals	Water consumption rates and the associated quantities of wastewater generated, as well as the presence of metal ions and other chemical constituents, can result in differences in the type and quantity of treatment chemicals consumed.
Energy	Energy consumption rates can differ substantially among the baseline and alternative processes. Energy consumption is discussed in Section 5.2.

The focus of this section is to perform a comparative analysis of the resource consumption rates of the baseline [non-conveyorized hot air solder leveling (HASL)] and the alternative surface finishing technologies. Section 5.1.1 discusses the types and quantities of natural resources consumed during a surface finishing process operation, while section 5.1.2 focuses on other resources. Section 5.1.3 presents the conclusions drawn from this analysis.

5.1.1 Consumption of Natural Resources

Process resources that can be found naturally in the environment are considered to be natural resources. Over the last several years there has been a movement towards making society and the world more sustainable. By limiting the consumption of natural resources to a rate at which they can replenished, the availability of these precious resources will be assured for future generations. The concept of sustainability has been adopted by members of the manufacturing community as part of a successful environmental management program, meant to improve environmental performance and, by extension, profitability.

A surface finishing process primarily consumes two natural resources: water and metals. A comparative analysis of the rate of natural resource consumption by each of the surface finishing technologies is presented below.

Water Consumption

The surface finishing process line consists of a series of chemical baths which are typically separated by one or more water rinse steps. These water rinse steps account for virtually all of the water consumed during the operation of the surface finishing process. The water baths dissolve or displace residual chemicals from the panel surface, preventing contamination of subsequent baths, while creating a clean panel surface for future chemical activity. The number of rinse stages recommended by chemical suppliers for their surface finishing processes range from three to nine, but can actually be much higher depending on facility operating practices. The number of separate water rinse stages reported by respondents to the PWB Workplace Practices Questionnaire ranged from three to seventeen.

The flow rate required by each process rinse tank depends on several factors, including the time of panel submersion, the type and amount of chemical residue to be removed, the type of agitation used in the rinse stage, and the purity of rinse water. Because proper water rinsing is critical to the application of the surface finish, manufacturers often use more water than is required to ensure that panels are cleaned sufficiently. Other methods, such as flow control valves and sensors, are available to ensure that sufficient water is available to rinse PWB panels, while minimizing the amount of water consumed by the process.

PWB manufacturers often use multiple rinse water stages between chemical process steps to facilitate better rinsing. The first rinse stage removes the majority of residual chemicals and contaminants, while subsequent rinse stages remove any remaining chemicals. Counter-current or cascade rinse systems minimize water use by feeding the water effluent from the cleanest rinse tank, usually at the end of the cascade, into the next cleanest rinse stage, and so on, until the effluent from the most contaminated, initial rinse stage is sent for treatment or recycle. Other water reuse or recycle techniques include ion exchange, reverse osmosis, as well as reusing rinse water in other plant processes. A detailed description of methods to reduce water consumption, including methods to reuse or recycle contaminated rinse water, is presented in Chapter 6 of this CTSA.

Water consumption rates for each alternative were calculated using data collected from both the PWB Workplace Practices Questionnaire and from the Observer Data Sheets completed during the performance demonstration. Because of the wide variation in the overall, yearly production of the respondents, it was necessary to normalize the water consumption data to account for the variety in the overall throughput of the surface finishing process and the associated water consumption. The daily water consumption for each water rinse reported by a facility was divided by the overall daily production of the facility to develop a water consumption rate in gallons per ssf of PWB produced (gal/ssf) for each rinse. An average water consumption rate was then determined for each automation type and for any specialized rinse conditions (e.g., high pressure rinses). The resulting normalized flow rates for each water rinse type are shown in Table 5-2.

Table 5-2. Normalized Water Flow Rates of Various Water Rinse Types

Rinse Type	Normalized Water Flow Rate [a] (gal/ssf)
Water Rinse, Non-conveyorized	0.258
Water Rinse, Conveyorized	0.176
High Pressure Water Rinse, All automation types	0.465

[a] Data were normalized to account for differences in facility production rates by dividing the yearly water consumption by the total PWB produced for each facility. The individual normalized data points were then averaged.

The normalized flow rates were then combined with the standard configuration for each surface finishing technology (see Section 3.1, Source Release Assessment) to develop an overall water consumption rate for the entire surface finishing process line. The total water consumption rate for each surface finishing process was calculated by multiplying the number of rinse stages (Table 5-3) by the appropriate water flow rate (Table 5-2) for each water rinse category, then summing the results. The calculations are described by the following equation:

$$WCR_{total} = \sum [NRS_i \text{ x } NWCR_i]$$

where,

WCR_{total} = total water consumption rate (gal/ssf)

NRS_i = number of rinse water stages of type I

$NWCR_i$ = normalized water consumption rate for rinse type I (gal/ssf)

The resulting overall rate represents the total water consumption for the entire surface finishing technology in gallons per ssf of PWB produced. Finally, the total volume of water consumed while producing 260,000 ssf was calculated using the total water consumption rate for the process. The number of rinse stages in a standard configuration of each technology, the water consumption rate of the entire surface finishing process, and the total water consumed by the application of the surface finish to 260,000 ssf of PWB for each technology is shown in Table 5-3. The amount of rinse water consumed for each alternative is also displayed graphically in Figure 5-1, from the lowest to the highest total consumption.

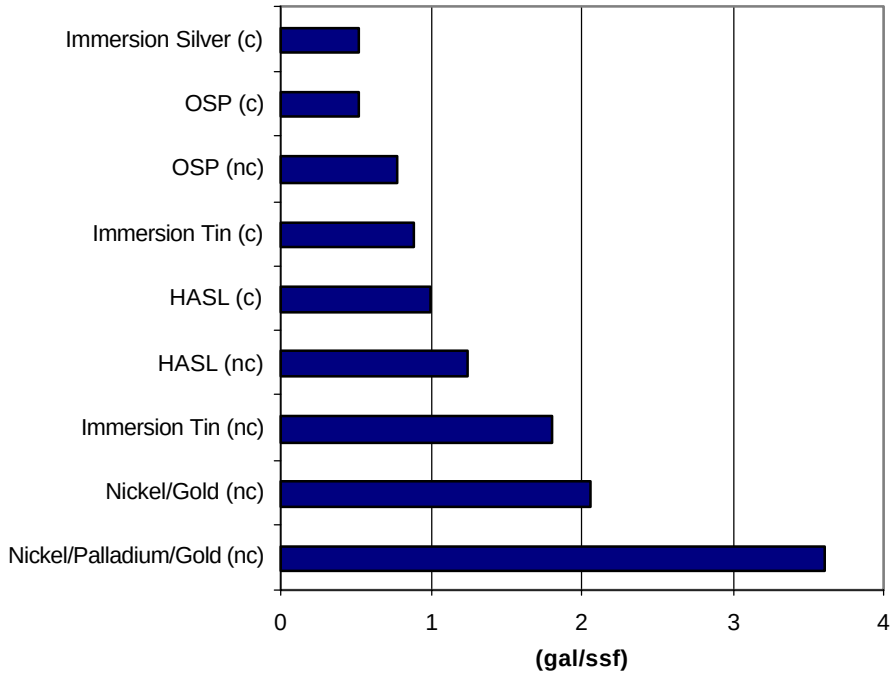
An analysis of the data shows that the type of surface finishing technology, as well as the level of automation, have a profound affect on the amount of water that a facility will consume during normal operation of the surface finishing process line. Five surface finishing processes consume less water than the baseline HASL process, including the conveyorized versions of the HASL, immersion silver, and immersion tin technologies, along with both versions of the organic solderability preservative (OSP) process. Three surface finishing processes consume more water than the baseline HASL process: the non-conveyorized versions of the immersion tin, nickel/gold, and the nickel/palladium/gold technologies.

Table 5-3. Rinse Water Consumption Rates and Total Water Consumed by Surface Finishing Technologies

Surface Finishing Technology	No. of Rinse Stages [a]		Total Water Consumption Rate [b] (gal/ssf)	Rinse Water Consumed (gal/260,000 ssf)
	Normal Flow	High Pressure		
HASL, Non-conveyorized	3	1	1.24	3.22×10^5
HASL, Conveyorized	3	1	0.99	2.58×10^5
Nickel/Gold, Non-conveyorized	8	-	2.06	5.37×10^5
Nickel/Palladium/Gold, Non-conveyorized	14	-	3.61	9.39×10^5
OSP, Non-conveyorized	3	-	0.77	2.01×10^5
OSP, Conveyorized	3	-	0.53	1.37×10^5
Immersion Silver, conveyorized	3	-	0.53	1.37×10^5
Immersion Tin, Non-conveyorized	7	-	1.81	4.69×10^5
Immersion Tin, Conveyorized	5	-	0.88	2.29×10^5

[a] Data reflects the number of rinse stages required for the standard configuration of each surface finishing technology as reported in Section 3.1, Source Release Assessment.

[b] Rinse water consumption rate was calculated by multiplying the number of rinse stages for each rinse type by the corresponding consumption factor listed in Table 5-2. The individual rates were then totaled and divided by 1,000 to determine the overall consumption rate for that technology.



c: conveyorized
nc: non-conveyorized

Figure 5-1. Water Consumption Rates of Surface Finishing Technologies

The rate of water usage is primarily attributable to the number of rinse stages required by the processes. All of the processes with fewer rinse stages than the baseline HASL process show reduced water consumption, while all the processes that consumed more water had significantly more water rinse stages. Only the conveyorized immersion tin process had more water rinse steps than HASL while consuming less water, due primarily to the high pressure rinse tanks used by the HASL process.

The table also demonstrates that the conveyorized version of a process will consume less water during operation than the non-conveyorized version of the same process, a result attributed to the increased efficiency of the conveyorized processes over their non-conveyorized counterparts. The increased efficiency is a result of the higher throughput and shorter cycle time of the conveyorized systems, and is reflected in the normalized water flow rates for rinse stages for each automation type (Table 5-2).

To minimize water usage, some companies have gone a step farther by developing equipment systems that monitor water quality and usage in order to optimize water rinse performance. This pollution prevention technique is recommended to reduce both water consumption and wastewater generation. The actual water usage experienced by manufacturers employing such a system may be less than that calculated in Table 5-3.

Metal Consumption

Many of the surface finishes are formed by the deposition of metal ions onto the surface of the PWB, forming a reliable, solderable finish for further assembly. The metals range from relatively inexpensive, widely available metals such as tin and lead, found in solder, to expensive 'precious' metals such as silver, gold, and palladium. While a portion of the metal consumed can be found in the surface finish of the PWB, metal is also lost through drag-out of the plating bath to subsequent stages, and through the replacement of spent or contaminated plating solutions. In the case of HASL, solder is also lost through the continual removal of dross, a film of contaminated solder.

The amount of metal consumed through the deposition, or plating, of the surface finish is dependent on the thickness of the metal deposit, the amount of PWB surface area that must be plated, and the density of the metal being applied. The recommended plating thickness for a surface finishing technology can be obtained from the appropriate chemical supplier. In addition, plating specifications for surface finishes have been established through testing by both chemical suppliers and by industry. These specifications set forth strict guidelines on minimum plating thicknesses required to insure a reliable, solderable surface finish. The metal deposition rates and the total metal deposited by the surface finishing technologies are presented in Table 5-4.

Table 5-4. Metal Deposition Rates and Total Metal Consumed by Surface Finishing Technologies

Process	Metal	Density [a] (g/cm3)	Thickness [b] (µ in)	Metal Plated [c] (oz. per ssf)	Total Metal Consumed (lb/260K ssf)
HASL	Tin	7.4	126 [d]	0.0194	315
	Lead	11.4	74 [d]	0.0175	285
Nickel/Gold, Nickel/Palladium/Gold	Nickel	8.1	200	0.0337	547
	Palladium	12.0	6	0.0015	24.3
	Gold	19.3	7	0.0028	45.6
Immersion Silver	Silver	10.5	6	0.0013	21.3
Immersion Tin	Tin	7.4	25	0.0038	62.5

[a] Source: *Chemical Engineers' Handbook*, 1994.
[b] Thicknesses of deposits recommended by suppliers of individual product lines unless otherwise noted.
[c] Calculations assume that 25 percent of the PWB surface area requires metal deposition.
[d] Plating thickness calculated using a 200 µ in deposit and 63/37 tin-lead solder.

In addition to the metal consumed by the process through deposition or plating, metal is also lost through drag-out of bath chemicals into subsequent process baths and chemical degradation through contamination. Metal lost through drag-out along with other process chemicals were estimated with the use of a model developed specifically for estimating drag-out in the PWB surface finishing process. A description of the model along with model results are presented in Section 3.2.3 of the Exposure Assessment.

Calculating the metal lost to bath degradation and subsequent bath replacement is problematic due to the variability of metal ion concentrations at the time of replacement. The metal ion concentrations of plating baths are typically replenished regularly rather than replaced to maintain optimal operating conditions and to prevent depletion of the bath. However, because the metal baths are valuable, especially the ones containing precious metals, these baths are typically monitored very closely to prevent a build-up of contaminants and to minimize bath replacement. When replaced, the spent bath solutions are typically sent off for metal reclamation. Section 6.2.1, Recycle and Resource Recovery Opportunities, describes reclamation options and costs for various metals.

A significant amount of solder is also lost through the removal of dross during the operation of the HASL process. Dross is a solid film of contaminated solder that covers the top of the molten solder, requiring constant removal through either manual or mechanical means. Dross is composed of both copper contamination of the solder and the oxidation products of the tin-lead through contact with air. The amount of solder lost through dross removal can be significant, estimated to be as much as 90 percent of the solder consumed (Sharp, 2000), though much can be reclaimed through recycling. If not recycled, dross must be treated as a hazardous waste. A detailed discussion of solder recycling, including methods of recycling and reclamation costs, is presented in Section 6.2.1, Recycle and Resource Recovery Opportunities.

Table 5-4 shows that the use of HASL results in 600 pounds of metal being consumed through deposition onto the PWB, including 285 pounds of lead, a known environmental toxin. Only the nickel/palladium/gold process consumes nearly as much metal. It should be noted also that the values in Table 5-4 only reflect the metal deposited onto the PWBs and do not include any metal consumed or lost through drag-out, bath contamination, or any other losses such as dross removal. These losses can be significant as in the case of HASL, where the amount of lead consumed can be as much as 2,500 pounds if waste solder is not routinely recycled or reclaimed.

Although Table 5-4 shows the relative quantities of metal deposited, any determination of the relative importance of metal savings on the environment also must consider the availability of the metal, the toxicity of the metal at disposal, the price of the metal consumed, and the environmental impacts of mining the metal. While much of this impact analysis is beyond the scope of this project, the risks to human health and the environment are presented and discussed in Chapter 3, Risk Screening and Comparison. The cost of process chemicals containing the metals for each technology are presented in Section 4.2, Cost Analysis.

5.1.2 Consumption of Other Resources

Several resources consumed by the surface finishing processes fall under the category of man-made, rather than natural, resources. These include process chemicals, treatment chemicals, bath filters, board laminate, packaging waste, cleaning materials, and any other consumable materials. Both process chemicals and treatment chemicals are the only resources listed whose consumption rates are expected to vary significantly between the different surface finishing technologies. The remaining resources listed are of little concern to this comparative evaluation because they are either consumed in small quantities, or their consumption rate is not dependent on the type of surface finishing technology, and so will not vary greatly. A comparative analysis of the rate of consumption of man-made resources for each of the surface finishing technologies is presented below.

Process Chemicals Consumption

Bath chemicals that constitute the various chemical baths or process steps are consumed in large quantities during the normal operation of the surface finishing process, either through co-deposition with the metals onto the surface of the PWB or degradation through chemical reaction. Process chemicals are also lost through volatilization, bath depletion, bath drag-out to subsequent process stages, or contamination as PWBs are cycled through the surface finishing process. Lost or consumed process chemicals are replaced through chemical additions, or if the build-up of contaminants is too great, the bath is replaced. Methods for limiting unnecessary chemical loss and thus minimizing the amount of chemicals consumed are presented in Chapter 6 in this CTSA.

Presenting a chemical-by-chemical analysis of process chemical consumption is not possible without disclosing the composition and concentration of the proprietary chemical formulations collected from the chemical suppliers (the actual chemical consumption is a combination of the quantity and concentration of chemicals present, factors which vary greatly,

even with processes within a similar technology category). Legal constraints prevent the disclosure of this information. However, two of the primary conclusions drawn from the analysis are the effects of the chemical consumption on the process cost and on human health. These conclusions are presented in detail in the Risk Characterization (Section 3.4) and in the Cost Analysis (Section 4.2) portions of this document. A qualitative discussion of the factors found to contribute to the consumption of process chemicals is presented below.

Performing a comparative analysis of the process chemical consumption rates is problematic due to both the site-specific nature of many of the factors that contribute to process chemical consumption, and the differences in concentration and chemical composition of the solutions involved (i.e., would the consumption of one pound of hydrochloric acid be equivalent to one pound of ethylene glycol?). Factors affecting the rate at which process chemicals are consumed through the operation of the surface finishing process include:

- characteristics of the process chemicals (i.e., composition, concentration, volatility, etc.);
- process operating parameters (i.e., number of chemical baths, process throughput, automation, etc.); and
- bath maintenance procedures (i.e., frequency of bath replacement, replacement criteria, frequency of chemical additions, etc.).

The chemical characteristics of the process chemicals determine the rate at which chemicals are consumed in the surface finishing process. A chemical bath containing a highly volatile chemical, or mixture of chemicals, can experience significant chemical losses to the air. A more concentrated process bath will lose a greater amount of process chemicals in the same volume of drag-out than a less concentrated bath. These chemical characteristics not only vary among surface finishing alternatives, but can also vary considerably among surface finishing processes offered by different chemical suppliers within the same technology category.

The physical operating parameters of the surface finishing process also have a significant impact on the consumption rate of process chemicals. One such parameter is the number of chemical baths contained within the surface finishing process (the surface finishing process is comprised of several process stages, some of which are chemical process baths). The number of chemical process baths through which a panel must be processed to perform the surface finishing function varies widely among the technologies, with a corresponding affect on chemical consumption. The number of chemical baths (excluding rinse stages) range from three for OSP to eight in the nickel/palladium/gold technology. The process throughput, or quantity of PWBs passed through the surface finishing process, also affects chemical usage since the higher the throughput, the more process chemicals are consumed. However, conveyorized processes tend to consume less chemicals per ssf than non-conveyorized versions of the same process due to the smaller bath sizes and higher efficiencies of the automated processes.

The greatest impact on process chemical consumption can result from the bath maintenance procedures of the facility operating the process. The frequency with which baths are replaced and the bath replacement criteria used are key chemical consumption factors. Chemical suppliers typically recommend that chemical baths be replaced using established

testing criteria, such as concentration thresholds of bath constituents (e.g., 2 g/L of copper). Other bath replacement criteria include ssf of PWB processed and elapsed time since the last bath replacement. The practice of making regular adjustments to the bath chemistry through additions of process chemicals consumes process chemicals, but will extend the operating life of the process baths, reducing chemical use over time. Despite the supplier recommendations, project data showed a wide range of bath replacement practices and criteria for manufacturing facilities operating the same, as well as different, surface finishing technologies.

Wastewater Treatment Chemicals Consumption

The extent to which the consumption of treatment chemicals will be reduced, if any, is dependent on several factors, some of which include the rate at which wastewater is generated (e.g., the amount of rinse water consumed), the type of treatment chemicals used, composition of waste streams from other plant processes, percentage of treatment plant throughput attributable to the surface finishing process, the resulting reduction in surface finishing waste volume realized, and the extent to which the former surface finishing process was optimized for waste reduction. Because many of the above factors are site-specific and not dependent on the type of surface finishing process, a quantitative evaluation would not be meaningful. However, there is a direct correlation between the amount of treatment chemicals required and the amount of process chemicals lost to drag-out that must be treated. A description of a typical wastewater treatment process, along with the types of treatment chemicals used to treat contaminated wastewater, is presented in Section 6.2.2, Control Technologies.

Alternative treatment processes to conventional precipitation treatment may be available to reduce the amount of treatment chemical consumption depending on the type of surface finishing process being operated. A discussion of treatment options for each technology, including a treatment profile for each type of process bath, also is presented in Section 6.2.2, Control Technologies.

5.1.3 Summary and Conclusions

A comparative analysis of the water consumption rates was performed for the surface finishing technologies. A daily water flow rate was developed for each surface finishing technology using survey data provided by industry. Calculated water consumption rates ranged from a low of 0.53 gal/ssf for the immersion silver and OSP conveyorized processes, to a high of 3.6 gal/ssf for the non-conveyorized nickel/palladium/gold process. Several processes were found to consume less water than the HASL baseline including conveyorized versions of the immersion silver and immersion tin technologies, along with both versions of the OSP process. Conveyorized processes were found to consume less water than non-conveyorized versions of the same process. Primary factors influencing the water consumption rate included the number of rinse tanks and the overall efficiency of the conveyorized processes.

Metals are another natural resource consumed by a surface finishing process. The rate of deposition of metal was calculated for each technology along with the total amount of metal consumed for 260,000 ssf of PWB produced. It was shown that the consumption of close to 300

pounds of lead could be eliminated by replacing the baseline HASL process with an alternative technology. In cases where waste solder is not routinely recycled or reclaimed, the consumption of as much as 2,500 pounds of lead could be eliminated by replacement of the HASL process. Although several of the alternative technologies rely on the use of small quantities of other metals, the OSP technology eliminates metal consumption entirely. Other factors influencing metal consumption were identified and discussed.

A quantitative analysis of both process chemicals and treatment chemicals consumption could not be performed due to the variability of factors that affect the consumption of these resources, and for reasons of confidentiality. The role the surface finishing process has in the consumption of these resources was presented and the factors affecting the consumption rates were identified and discussed.

5.2 ENERGY IMPACTS

Energy conservation is an important goal for PWB manufacturers, as companies strive to cut costs and seek to improve environmental performance and global competitiveness. Energy use has become an important consideration in the manufacture of PWBs, as much of the manufacturing process requires potentially energy-intensive operations, such as heating the process baths. This is especially true during the operation of the surface finishing process, where energy is consumed by process equipment such as immersion heaters, fluid and air pumps, agitation devices such as vibrating motors, and by conveyorized transport systems. The focus of this section is to perform a comparative analysis of the relative energy consumption rates of the baseline HASL process and alternative surface finishing technologies.

Data collected for this analysis focus on the energy consumed during the application of the surface finish. Traditional life-cycle analysis indicates that energy consumption during other life-cycle stages also can be significant and should be considered when possible. Although a quantitative life-cycle analysis is beyond the scope and resources of this project, the impacts to the environment from the manufacture of the energy required by the surface finishing process is briefly analyzed and presented at the end of this chapter.

Section 5.2.1 discusses energy consumption during the application of the surface finish, while Section 5.2.2 discusses the environmental impacts of this energy consumption. Section 5.2.3 briefly discusses the energy consumption of other life-cycle stages. Section 5.2.4 presents conclusions of the comparative energy analysis.

5.2.1 Energy Consumption During Surface Finishing Process Operation

To determine the relative rates of energy consumption during the operation of the surface finishing technologies, specific data were collected regarding energy consumption through the Performance Demonstration project and through dissemination of the PWB Workplace Practices Questionnaire to industry members. Energy data collected include the following:

- process specifications (i.e., type of process, facility size, etc.);
- physical process parameters (i.e., number of process baths, bath size, bath conditions such as temperature and mixing, etc.);
- process automation (i.e., conveyorized, computer-controlled hoist, manual, etc.);
- equipment description (i.e., heater, pump, motor, etc.); and
- equipment energy specifications (i.e., electric load, duty, nominal power rating, horsepower, etc.).

Each of the surface finishing technologies contains a series of chemical baths that are typically separated by one or more water rinse steps. In some processes, these chemical stages are supplemented by other stages such as a drying oven or a HASL machine, which applies the solder to the PWB using a mechanical type of process. In order for the process to perform properly, each process stage should be operated within specific supplier recommended parameters, such as parameters for bath temperature and mixing, oven temperatures, or air knife

pressures. Maintaining these process stages within the desired parameters often requires energy-consuming equipment such as immersion heaters, fluid circulation pumps, and air compressors. In addition, the degree of process automation affects the relative rate of energy consumption. Clearly, conveyorized equipment requires energy to operate, but also non-conveyorized systems require additional equipment not found in conveyorized systems, such as panel agitation equipment.

Table 5-5 lists the types of energy-consuming equipment typically used during the operation of a surface finishing process and the function of the equipment. In some cases, one piece of equipment may be used to perform a function for the entire process line. For example, in a non-conveyorized system, panel vibration is typically performed by a single motor used to rock an apparatus that extends over all of the process tanks. The apparatus provides agitation to each individual panel rack that is connected to it, thus requiring only a single motor to provide agitation to every bath on the process line that may require it. Other equipment types such as immersion heaters affect only one process stage, so each process bath or stage may require a separate piece of energy-consuming equipment.

Table 5-5. Energy-Consuming Equipment Used in Surface Finishing Process Lines

Type of Equipment	Function
Conveyor Drive Motor	Powers the conveyor system required to transport PWB panels through the surface finishing process. Not required for non-conveyorized, vertical processes.
Immersion Heater	Raises and maintains temperature of a process bath to the optimal operating temperature.
Fluid Pump	Circulates bath fluid to promote flow of bath chemicals through drilled through holes and to assist filtering of impurities from bath chemistries.
Air Pump	Compresses and blows air into process baths to promote agitation of bath to ensure chemical penetration into drilled through holes. Also provides compressed air to processes using an air knife to remove residual chemicals from PWB panels.
Panel Agitation Motor	Moves the apparatus used to rock panel racks back and forth in process baths. Not required for conveyorized processes.
Gas Heater	Heats PWB panels to promote drying of residual moisture on the panel surface. Can also be used to cure a chemical coating.
Solder Pot	Melts solder and maintains the molten solder at optimal operating temperature, usually between 480 to 550 ^{o}F.
Ventilation Equipment	Provides ventilation required for surface finishing baths and to exhaust chemical fumes.

To assess the energy consumption rate for each surface finishing technology, an energy use profile was developed that identified typical sources of energy consumption during the application of the surface finish. The number of surface finishing process stages that result in the consumption of energy during operation was determined from Performance Demonstration and PWB Workplace Practices Questionnaire data. This information is listed in Table 5-6 according to the function of the energy-consuming equipment. For example, a typical non-conveyorized

OSP process consists of two heated chemical baths, three chemical baths requiring fluid circulation, two process stages requiring compressed air (for air knives in this case), and a single heated drying stage to cure the OSP coating. Panel agitation for the entire process is provided by a single motor used to rock an apparatus that extends over all of the process tanks. Ventilation equipment is not presented in Table 5-6 because the necessary data were not collected during the Performance Demonstration or in the PWB Workplace Practices Questionnaire. However, the amount of ventilation required varies according to the type of chemicals, bath operating conditions, and the configuration of the process line. Because they are enclosed, the ventilation equipment for conveyorized processes are typically more energy efficient than non-conveyorized processes.

Table 5-6. Number of Surface Finishing Process Stages that Consume Energy by Function of Equipment

Process Type	Function of Equipment [a]						
	Conveyor	Panel Agitation [b]	Bath Heat	Air Knife/ Sparging [c]	Fluid Circulation	Panel Drying	Solder Heater
HASL, Non-conveyorized	0	1	1	2	3	1	1
HASL, Conveyorized	1	0	1	2	4	1	1
Nickel/Gold, Non-conveyorized	0	1	4	1	3	0	0
Nickel/Palladium/Gold, Non-conveyorized	0	1	6	1	3	0	0
OSP, Non-conveyorized	0	1	2	2	3	1	0
OSP, Conveyorized	1	0	2	2	3	1	0
Immersion Silver, Conveyorized	1	0	2	0	4	1	0
Immersion Tin, Non-conveyorized	0	1	3	0	4	1	0
Immersion Tin, Conveyorized	1	0	3	0	3	1	0

[a] Table entries for each surface finishing alternative represent the number of process stages requiring each specific function. All functions are supplied by electric equipment, except for drying, which is performed by gas-fired oven.
[b] Processes reporting panel agitation for one or more process stages are entered as one in the summary regardless of the number since a single motor can provide agitation for the entire process line.
[c] Air sparging is used selectively by some manufacturers to enhance bath performance. Sparging may not be required for all product lines or facilities using a surface finishing technology.

The electrical energy consumption of surface finishing line equipment, as well as equipment specifications (power rating, average duty, and operating load), were collected during the Performance Demonstration. In cases where electricity consumption data were not available, the electricity consumption rate was calculated using the following equation:

$$EC = NPR \times OL \times AD \times (1kW/0.746\ HP)$$

where,

EC = electricity consumption rate (kWh/day)
NPR = nominal power rating (HP)
OL = operating load (percent), or the percentage of the maximum load or output of the equipment that is being used
AD = average duty (hr/day), or the amount of time per day that the equipment is being operated at the operating load

Electricity consumption data for each equipment category were averaged to determine the average amount of electricity consumed per hour of operation for each type of equipment per process. The natural gas consumption rate for a drying oven was supplied by an equipment vendor. Electricity and natural gas consumption rates for surface finishing equipment per process stage are presented in Table 5-7.

Table 5-7. Energy Consumption Rates for Surface Finishing Equipment

Function of Equipment	Type of Equipment	Energy Consumption Rates Per Equipment Type	
		Electricity [a] (kW)	Natural Gas [b] (ft^3/hr)
Conveyorized Panel Automation	Conveyor System	14.1	-
Panel Agitation	Panel Agitation Motor	3.1	-
Bath Heater	Immersion Heater	4.1	-
Fluid Circulation	Fluid Pump	0.9	-
Air Knife/Sparging	Air Pump	3.8	-
Panel Drying	Gas Drying Oven	-	90
Solder Heater	Solder Pot	20	

[a] Electricity consumption rates for each type of equipment were calculated by averaging energy consumption data per stage from the performance demonstrations. If required, consumption data were calculated from device specifications and converted to total kW per bath using 1 HP = 0.746 kW.
[b] Natural gas consumption rate for the gas heater was estimated by an equipment vendor (Exair Corp.).

The total electricity consumption rate for each surface finishing alternative was calculated by multiplying the number of process stages that consume electricity (Table 5-6) by the appropriate electricity consumption rate (Table 5-7) for each equipment category, then summing the results. The calculations are described by the following equation:

$$ECR_{total} = \sum [NPS_i \text{ x } ECR_i]$$

where,
ECR_{total} = total electricity consumption rate (kW)
NPS_i = number of process stages requiring equipment i
ECR_i = energy consumption rate for equipment i (kW)

Natural gas consumption rates were calculated using a similar method. The individual energy consumption rates for both natural gas and electricity were then converted to British Thermal Units (Btu) per hour and summed to give the total energy consumption rate for each surface finishing technology. The individual consumption rates for both natural gas and electricity, as well as the hourly energy consumption rate calculated for each of the surface finishing technologies, are listed in Table 5-8.

These energy consumption rates include only the types of equipment listed in Table 5-5, which are commonly recommended by chemical suppliers to successfully operate a surface finishing process. However, equipment such as ultrasonics, automated chemical feed pumps, vibration units, panel feed systems, or other types of electrically powered equipment may be part of the surface process line. The use of this equipment may improve the performance of the surface finishing process, but is not required in a typical process for any of the surface finishing technologies.

Table 5-8. Hourly Energy Consumption Rates for Surface Finishing Technologies

Process Type	Energy Consumption Rates		Hourly Consumption Rate [a] (Btu/hr)
	Electricity (kW)	Natural Gas (ft^3/hr)	
HASL, Non-conveyorized	37.5	90	219,800
HASL, Conveyorized	49.4	90	260,400
Nickel/Gold, Non-conveyorized	26.0	-	88,700
Nickel/Palladium/Gold, Non-conveyorized	34.2	-	116,700
OSP, Non-conveyorized	21.6	90	165,500
OSP, Conveyorized	32.6	90	203,100
Immersion Silver, Conveyorized	25.9	90	180,200
Immersion Tin, Non-conveyorized	19.0	90	156,700
Immersion Tin, Conveyorized	29.1	90	191,100

[a] Electrical energy was converted at the rate of 3,413 Btu per kilowatt hour. Natural gas consumption was converted at the rate of 1,020 Btu per cubic feet of gas consumed.

To determine the overall amount of energy consumed by each technology, the hourly energy consumption rate from Table 5-8 was multiplied by the amount of time needed for each alternative to manufacture 260,000 ssf of PWB (the average HASL throughput of respondents to the PWB Workplace Practices Questionnaire). Because insufficient survey data exist to accurately estimate the amount of time required for each process to produce the 260,000 ssf of board, the operating time was simulated using a computer model developed for each surface finishing technology. The results of the simulation, along with a discussion of the data and parameters used to define each technology, are presented in Section 4.2, Cost Analysis. The hours of surface finishing operation required to produce 260,000 ssf of board from the simulation, the total amount of energy consumed, and the energy consumption rate per ssf of board produced for each technology are presented in Table 5-9.

Table 5-9. Energy Consumption Rate per ssf of PWB Produced for Surface Finishing Technologies

Process Type	Process Operating Time [a] (hours)	Total Energy Consumed (Btu/260,000 ssf)	Energy Consumption Rate (Btu/ssf)
HASL, Non-conveyorized	258	5.67×10^7	218
HASL, Conveyorized	133	3.46×10^7	133
Nickel/Gold, Non-conveyorized	1,310	1.16×10^8	447
Nickel/Palladium/Gold, Non-conveyorized	1,710	2.00×10^8	768
OSP, Non-conveyorized	197	3.26×10^7	125
OSP, Conveyorized	93	1.89×10^7	73
Immersion Silver, Conveyorized	414	7.46×10^7	287
Immersion Tin, Non-conveyorized	480	7.52×10^7	289
Immersion Tin, Conveyorized	710	1.36×10^8	522

[a] Times listed represent the operating time required to manufacture 260,000 ssf of PWB by each process as simulated by computer model. Operating time was considered to be the overall process time minus the downtime of the process.

Table 5-9 shows that three of the process alternatives consumed less energy than the baseline, non-conveyorized, HASL process. Both the non-conveyorized and conveyorized versions of the OSP process, along with the conveyorized HASL process, consumed significantly less energy than the baseline process. The reductions were primarily attributable to the efficiency of the three processes, which resulted in operating times significantly less than that of the traditional non-conveyorized HASL process. Both the immersion silver process and the conveyorized immersion tin processes performed roughly equal to the baseline process, utilizing a lower hourly consumption rate to offset a small disadvantage in operating time.

Three processes consumed significantly more energy than the baseline process. Despite having the lowest hourly consumption rate of all the surface finishing technologies, the nickel/gold process consumed more than twice the energy of the baseline due to its long process operating time. Other processes with high energy consumption rates include nickel/palladium/gold and conveyorized immersion tin.

The performance of specific surface finishing technologies with respect to energy is primarily dependent on the hourly energy consumption rate (Table 5-8) and the overall operating time for the process (Table 5-9). Non-conveyorized processes typically have lower hourly consumption rates than conveyorized processes of the same type because the operation of conveyorized equipment is more energy-intensive. Although conveyorized processes typically have higher hourly consumption rates, these differences are usually more than offset by the shorter operating times that are required to produce an equivalent quantity of PWBs.

When the non-conveyorized and conveyorized versions of a surface finishing technology are compared, the conveyorized versions of the technology seem to be typically more energy efficient. Table 5-10 compares the energy consumption data for those technologies that are

operated in both conveyorized and non-conveyorized modes. This table shows that, although the conveyorized version of all three processes requires more energy *per hour* to operate than the non-conveyorized mode, the added efficiency of the conveyorized system (reflected in the shorter operating time) results in less energy usage per ssf of board produced. The immersion tin processes are the exceptions. The non-conveyorized configuration of this process not only has a better hourly consumption rate than the conveyorized, but also benefits from a faster operating time, a condition due to the long overall cycle-time required for the conveyorized process. These factors combine to give the non-conveyorized immersion tin process a lower energy consumption rate than the conveyorized version. Despite this exception, the overall efficiency of conveyorized systems typically will result in less energy usage per ssf of board produced, as it did for both the HASL and OSP processes.

Table 5-10. Effects of Automation on Energy Consumption for Surface Finishing Technologies

Process Type	Hourly Consumption Rate (1,000 Btu/ssf)	Process Operating Time [a] (hours)	Energy Consumption Rate (Btu/ssf)
HASL, Non-conveyorized	220	258	218
HASL, Conveyorized	260	133	133
OSP, Non-conveyorized	165	197	125
OSP, Conveyorized	203	93	73
Immersion Tin, Non-conveyorized	156	480	289
Immersion Tin, Conveyorized	191	710	522

[a] Times listed represent the operating time required to manufacture 260,000 ssf of PWB by each process as simulated by computer model. Operating time was considered to be the overall process time minus the downtime of the process.

Finally, it should be noted that the overall energy use experienced by a facility will depend greatly upon the operating practices and the energy conservation measures adopted by that facility. To minimize energy use, several simple energy conservation opportunities are available and should be implemented. These include insulating heated process baths, using thermostats on heaters, and turning off equipment when not in use.

5.2.2 Energy Consumption Environmental Impacts

The production of energy results in the release of pollution into the environment, including pollutants such as carbon dioxide (CO_2), sulfur oxides (SO_x), carbon monoxide (CO), sulfuric acid (H_2SO_4), and particulate matter. The type and quantity of pollution depends on the method of energy production. Typical energy production facilities in the U.S. include hydroelectric, nuclear, and coal-fired generating plants.

The environmental impacts attributable to energy production resulting from the differences in energy consumption among surface finishing technologies were evaluated using a computer program developed by the EPA National Risk Management Research Laboratory, *P2P-*

version 1.50214 (U.S. EPA, 1994). This program can, among other things, estimate the type and quantity of pollutant releases resulting from the production of energy as long as the differences in energy consumption and the source of the energy used (e.g., electrical energy from a coal-fired generating plant, thermal energy from a oil-fired boiler, etc.) are known. The program uses data reflecting the "national average" pollution releases per kilowatt-hour derived from particular sources. Electrical power derived from the average national power grid was selected as the source of electrical energy, while natural gas was used as the source of thermal energy for this evaluation. Energy consumption rates from Table 5-8 were multiplied by the operating time required to produce 260,000 ssf of board reported for each technology in Table 5-9. These totals were then divided by 260,000 to get the electrical and thermal energy consumed per ssf of board, which were then used as the basis for the analysis. Results of the environmental impact analysis from energy production are summarized and presented in Table 5-11. Appendix H contains printouts from the P2P program for each alternative.

Although the pollutant releases reported in Table 5-11 are combined for all media (i.e., air, water, and land), they often occur in one or more media, where they may present different hazards to human health or the environment. To allow a comparison of the relative effects of any pollution that may occur, it is necessary to identify the media of releases. Table 5-12 displays the pollutants released during the production of energy, the media into which they are released, and the environmental and human health concerns associated with each pollutant.

The information presented in Tables 5-11 and 5-12 show that the generation of energy is not without environmental consequences. Pollutants released to air, water, and soil resulting from energy generation can pose direct threats to both human health and the environment. As such, the consumption of energy by the surface finishing process contributes directly to the type and magnitude of these pollutant releases. Primary pollutants released from the production of electricity include CO_2, solid wastes, SO_x, and nitrogen oxides. These pollutants contribute to a wide range of environmental and human health concerns. Natural gas consumption results primarily in releases of CO_2 and hydrocarbons, which typically contribute to environmental problems such as global warming and smog. Minimizing the amount of energy usage by the surface finishing process, either by selection of a more energy efficient process or by adopting energy efficient operating practices, will decrease the quantity of pollutants released into the environment resulting from the generation of the energy consumed.

Table 5-11. Pollution Resulting From the Generation of Energy Consumed by Surface Finishing Technologies

Surface Finishing Alternative	Types of Pollutants Released (g/ssf) [a]								
	Carbon Dioxide (CO_2)	Carbon Monoxide (CO)	Dissolved Solids	Hydrocarbons	Nitrogen Oxides (NO_x)	Particulates	Solid Wastes	Sulfur Oxides (SO_x)	Sulfuric Acid (H_2SO_4)
HASL, Non-conveyorized	20	0.026	0.004	0.051	0.079	0.029	2.1	0.16	0.013
HASL, Conveyorized	31	0.039	0.005	0.089	0.124	0.043	3.1	0.23	0.019
Nickel/Gold, Non-conveyorized	92	0.13	0.017	0.11	0.402	0.15	11	0.80	0.067
Nickel/Palladium/Gold, Non-conveyorized	160	0.22	0.030	0.19	0.681	0.26	19	1.4	0.12
OSP, Non-conveyorized	15	0.018	0.003	0.058	0.054	0.019	1.4	0.10	0.008
OSP, Conveyorized	10	0.013	0.002	0.031	0.039	0.014	1.0	0.075	0.006
Immersion Silver, Conveyorized	38	0.044	0.006	0.13	0.134	0.048	3.5	0.26	0.021
Immersion Tin, Non-conveyorized	35	0.039	0.006	0.14	0.124	0.041	3.0	0.22	0.018
Immersion Tin, Conveyorized	70	0.085	0.012	0.23	0.258	0.093	6.7	0.49	0.041

[a] Pollutant totals calculated using the computer program *P2P version 2.70707* developed by EPA's National Risk Management Research Laboratory.

Table 5-12. Pollutant Environmental and Human Health Concerns

Pollutant	Medium of Release	Environmental and Human Health Concerns
Carbon Dioxide (CO_2)	Air	Global warming
Carbon Monoxide (CO)	Air	Toxic organic,[a] smog
Dissolved Solids	Water	Dissolved solids [b]
Hydrocarbons	Air	Odorant, smog
Nitrogen Oxides (NO_x)	Air	Toxic inorganic,[a] acid rain, corrosive, global warming, smog
Particulates	Air	Particulates [c]
Solid Wastes	Soil	Land disposal capacity
Sulfur Oxides (SO_x)	Air	Toxic inorganic,[a] acid rain, corrosive
Sulfuric Acid (H_2SO_4)	Water	Corrosive, dissolved solids [b]

[a] Toxic organic and inorganic pollutants can result in adverse health effects in humans and wildlife.

[b] Dissolved solids are a measure of water purity and can negatively affect aquatic life as well as the future use of the water (e.g., salinity can affect the water's effectiveness at crop irrigation).

[c] Particulate releases can promote respiratory illness in humans.

5.2.3 Energy Consumption in Other Life-Cycle Stages

When performing a comparative evaluation among surface finishing technologies, the energy consumed throughout the entire life cycle of the chemical products in the technology should be considered. The product use phase is only one aspect of the environmental performance of a product. A life-cycle analysis considers all stages of the life of a product, beginning with the extraction of raw materials from the environment, and continuing on through the manufacture, transportation, use, recycle, and ultimate disposal of the product.

Each stage within this life cycle consumes energy. It is possible for a product to be energy efficient during the use phase of the life cycle, yet require large amounts of energy to manufacture or dispose of the product. There are energy consumption differences also in the transportation of wastes generated by a surface finishing process. The transportation of large quantities of sludge resulting from the treatment of processes with chelated waste streams (i.e., nickel/gold) will consume more energy than the transportation of smaller quantities of sludge resulting from processes that do not use chelators. These examples show that energy use from other life-cycle stages can be significant and should be considered when evaluating the energy performance of a product. However, a comprehensive assessment of other life-cycle stages was beyond the scope of this study.

5.2.4 Summary and Conclusions

A comparative analysis of the relative energy consumption rates was performed for the surface finishing technologies. An hourly energy consumption rate was developed for the baseline non-conveyorized HASL process and each alternative using data collected from industry through a survey. A computer simulation was used to determine the operating time required to produce 260,000 ssf of PWB, and an energy consumption rate per ssf of PWB was calculated. The energy consumption rates ranged from 73 Btu/ssf for the conveyorized OSP process to 768 Btu/ssf for the non-conveyorized nickel/palladium/gold process. The results indicate that three surface finishing processes are more energy efficient than the traditional non-conveyorized HASL process, while two others are roughly comparable. It was found also that for alternatives with
both types of automation, the conveyorized version of the process is typically the more energy efficient (HASL and OSP), with the notable exception of the immersion tin process.

An analysis of the impacts directly resulting from the production of energy consumed by the surface finishing process showed that generation of the required energy is not without environmental consequence. Pollutants released to air, water, and soil can result in damage to both human health and the environment. The consumption of natural gas tends to result in releases to the air which contribute to odor, smog and global warming, while the generation of electricity can result in pollutant releases to all media, with a wide range of possible affects. Minimizing the amount of energy usage by the surface finishing process, either by selection of a more energy efficient process or by adopting energy efficient operating practices, will decrease the quantity of pollutants released into the environment resulting from the generation of the energy consumed.

REFERENCES

Chemical Engineers' Handbook. 1994. McGraw-Hill Book Company.

Sharp, John. 2000. Teradyne, Inc. Personal communication to Jack Geibig, UT Center for Clean Products and Clean Technologies.

U.S. EPA (Environmental Protection Agency). 1994. P2P-version 1.50214 computer software program. Office of Research and Development, National Risk Management Lab, Cincinnati, OH.

Chapter 6
Additional Environmental Improvement Opportunities

This chapter of the Cleaner Technologies Substitute Assessment (CTSA) identifies and qualitatively discusses techniques that can be used by printed wiring board (PWB) manufacturing facilities to prevent pollution, minimize waste, recycle and recover valuable resources, and control releases. The Pollution Prevention Act of 1990 set forth the following hierarchy to waste management in order of desirability:

- pollution prevention at the source;
- recycling in an environmentally safe manner;
- treatment in an environmentally safe manner; and
- disposal or other release into the environment only as a last resort and in an environmentally safe manner.

This hierarchy has been adopted by EPA as the preferred method of waste management to reduce or eliminate potential releases by industry. The hierarchy reflects the common sense notion that preventing pollution in an environmentally safe manner is preferable to any subsequent response, be it recycling, treatment, or disposal. Acceptable pollution prevention methods include product and process redesign and the selection of safe substitutes for problem processes/chemicals, along with other traditional pollution prevention techniques that reduce pollution at the source (Kling, 1995).

The hierarchy also recognizes that pollution prevention is not always possible and that other waste management methods are often required. When pollution prevention is not possible, we should turn in order to recycling, treatment, and finally disposal if no other option remains. A manufacturing facility often combines pollution prevention techniques with these other approaches to effectively reduce emissions from a production process. While pollution prevention is generally the most desirable of the above choices, the most important aspect of this hierarchy is to reduce the environmental impacts of the overall process as much as is feasible while maintaining the quality, performance, and safety criteria for the products being manufactured.

This chapter focuses on the application of the waste management hierarchy to waste streams generated by the surface finishing process of the PWB industry. Techniques are identified, organized, and presented in an order corresponding to the hierarchy. Pollution prevention techniques are presented in Section 6.1, while methods for minimizing waste, recycling or recovering resources, and controlling releases are presented in Section 6.2. While the focus of this chapter is on the surface finishing line, many of the techniques described here can be applied to other processes used in PWB manufacturing. A series of pollution prevention case studies developed by the EPA Design for the Environment (DfE) Program for the PWB industry present examples of the successful implementation of techniques available to industry (U.S. EPA, 1995a; U.S. EPA, 1995b; U.S. EPA, 1996a; U.S. EPA, 1996b; U.S. EPA, 1996c; U.S. EPA, 1997a; U.S. EPA, 1997b; U.S. EPA, 1997c; U.S. EPA, 1999).

6.1 POLLUTION PREVENTION

Pollution prevention, defined in the Pollution Prevention Act of 1990, is the reduction in the amounts or hazards of pollution at the source and is often referred to as source reduction. Source reduction, also defined in the Pollution Prevention Act, is any practice which: 1) reduces the amount of any hazardous substance, pollutant, or contaminant entering any waste stream or otherwise released into the environment (including fugitive emissions) prior to recycling, treatment, or disposal; and 2) reduces the hazards to public health and the environment associated with the release of such substances, pollutants, or contaminants. Source reduction/pollution prevention includes equipment or technology modifications, process or procedure modifications, reformulation or redesign of products, substitution of raw materials, and improvements in housekeeping, maintenance, training, or inventory control.

EPA's regulations are moving towards incorporating pollution prevention options. For example, the EPA Office of Water is currently developing a set of proposed effluent guidelines for the metal products and machinery industries, which are expected to be published in October, 2000. The proposed rule will discuss ten options that can be employed to meet effluent guidelines and standards, five of which include specific pollution prevention technologies.

Current pollution prevention practices within the PWB industry were identified and data were collected through contact with industry personnel, extensive review of published accounts, and through the design and dissemination of two information requests to PWB manufacturers. The PWB Workplace Practices Questionnaire, conducted as part of this CTSA, specifically focused on the surface finishing process to identify important process parameters and operating practices for the various surface finishing technologies. For a breakdown of respondents by alternative, refer to Section 1.3 of the Introduction. Facility characteristics of respondents are presented in Section 3.2, Exposure Assessment. The PWB Workplace Practices Questionnaire is presented in Appendix A.

The Pollution Prevention and Control Technology Survey (hereafter referred to as the Pollution Prevention Survey) was an update to a previous survey and was designed to collect information about past and present pollution prevention procedures and control technologies for the entire PWB manufacturing process. This Survey was performed by the DfE PWB Project and is documented in the EPA publication, *Printed Wiring Board Pollution Prevention and Control Technology: Analysis of Updated Survey Results* (U.S. EPA, 1998). The Survey results presented periodically throughout this chapter are compiled from responses to the Pollution Prevention Survey unless otherwise indicated. Results from the Pollution Prevention Survey pertaining to recycle or control technologies are presented in Section 6.2 of this chapter.

Opportunities for pollution prevention in PWB manufacturing were identified in each of the following areas:

- management and personnel practices;
- materials management and inventory control;
- materials selection; and
- process improvements.

The successful implementation of pollution prevention practices can lead to reductions in waste treatment, pollution control, environmental compliance, and liability costs. Cost savings can result directly from pollution prevention techniques that minimize water usage, primary or ancillary material consumption, and process waste generation.

6.1.1 Management and Personnel Practices

Pollution prevention is an ongoing activity that requires the efforts of both management and employees to achieve the best results. While pollution prevention initiatives, such as an ISO 14000-type environmental management system, require a commitment and continued support from management, any pollution prevention measures taken are ultimately implemented by the process employees, making them an integral part of any pollution prevention effort. Management and employees must work together to form an effective pollution prevention program.

Just under two thirds (60.9 percent) of the PWB companies responding to the Pollution Prevention Survey reported having a formal pollution prevention policy statement while just over half (55.1 percent) of the survey respondents reported having a pollution prevention program. Over two thirds (71.2 percent) of PWB companies surveyed reported conducting employee education for pollution prevention. Each of these statistics in the current Pollution Prevention Survey increased between three and eight percent over the same statistics in the prior survey, showing improvement in company perspectives on pollution prevention since the previous survey was conducted.

The scope and depth of pollution prevention planning and the associated activities will vary with the size of the facility. While larger facilities may go through an entire pollution prevention planning exercise (as described below), smaller facilities may require as little as a commitment by the owner to pollution prevention along with cooperation and assistance from employees to meet any stated goals. A list of management and personnel practices that promote pollution prevention, along with the benefits, are listed in Table 6-1.

A company's commitment to pollution prevention begins with a pollution prevention and waste reduction policy statement. This statement, which is the company's public proclamation of its dedication to preventing pollution and reducing waste, should clearly state why a program is being undertaken, include specific pollution prevention and waste reduction goals, and assign responsibility for accomplishing those goals. The statement details to the public and to its employees the depth of the company's commitment to pollution prevention.

Table 6-1. Management and Personnel Practices Promoting Pollution Prevention

Method	Benefits
Create a company pollution prevention and waste reduction policy statement.	Communicates to employees and states publicly the company commitment to achieving pollution prevention and waste reduction goals.
Develop a written pollution prevention and waste reduction plan.	Communicates to employees how to accomplish the goals identified in the company's policy statement. Identifies in writing specific implementation steps for pollution prevention.
Provide periodic employee training on pollution prevention.	Educates employees on pollution prevention practices.
Make employees accountable for their pollution prevention performance and provide feedback on their performance.	Provides incentives to employees to improve pollution prevention performance.
Promote internal communication between management and employees.	Informs employees and facilitates input on pollution prevention from all levels of the company.
Implement total cost accounting or activity-based accounting system.	Identifies true costs of waste generation and the benefits of pollution prevention.

A pollution prevention plan is needed to detail how the pollution prevention and waste reduction goals described in the company's policy statement will be achieved. The pollution prevention plan builds on the company's policy statement by:

- creating a list of waste streams and their point sources;
- identifying opportunities for pollution prevention;
- evaluating and prioritizing waste reduction options;
- developing an implementation strategy for options that are feasible;
- creating a timetable for pollution prevention implementation; and
- detailing a plan for measuring and evaluating pollution prevention and waste reduction progress.

The plan is best developed with input drawn from the experiences of a team of people selected from levels throughout the company. The team approach provides a variety of perspectives to pollution prevention and helps to identify pollution prevention opportunities and methods for implementing them. Team members should include representatives from management, supervisory personnel, and line workers who are familiar with the details of the daily operation of the process. The direct participation of line workers in the development of the pollution prevention plan is important since it is the employees who are responsible for implementing the plan.

Data should be collected by performing an assessment of the process(es) being targeted. It is not possible to develop a pollution prevention plan unless there exists good data on the rate at which primary and ancillary materials are used and wastes are generated. Once the assessment and data collection are complete, pollution prevention options should be evaluated and prioritized based on their cost, feasibility of implementation, and their overall effectiveness of eliminating or

reducing waste. After an implementation strategy and timetable is established, the plan, along with expected benefits, should be presented to the remaining company employees to communicate the company's commitment to pollution prevention.

Once the pollution prevention plan has been finalized and implementation is ready to begin, employees must be given the skills to implement the plan. Training programs play an important role in educating process employees about current pollution prevention practices and opportunities. The goal of the training program is to educate each employee on how waste is generated, its effects on worker safety and the environment, possible methods for waste reduction, and on the overall benefits of pollution prevention.

Employee training should begin at the time of new employee orientation, introducing them to the company's pollution prevention plan, thus highlighting the company's dedication to reducing waste. More advanced training focusing on process operating procedures, potential sources of release, and pollution prevention practices already in place should be provided after a few weeks of work or when an employee starts a new position. Retraining employees periodically will keep them focused on the company's goal of pollution prevention.

Effective communication between management and employees is an important part of a successful pollution prevention program. Reports to employees on the progress of implementing pollution prevention recommendations, as well as the results of actions already taken, reiterate management's commitment to reducing waste, while keeping employees informed and intimately involved in the process. Employee input should also be solicited both during and after the creation of the pollution prevention plan to determine if any changes in the plan are warranted.

Assigning responsibility for each source of waste is an important step in closing the pollution prevention loop. Making individual employees and management accountable for chemical usage and waste generated within their process or department provides incentive for employees to reduce waste. The quantity of waste generated should be tracked and the results reported to employees who are accountable for the process generating the waste. Progress in pollution prevention should be an objective upon which employees will be evaluated during performance reviews, once again emphasizing the company's commitment to waste reduction.

Employee initiative and good performance in pollution prevention areas should be recognized and rewarded. Employee suggestions that prove feasible and cost effective should be implemented and the employee recognized either with a company commendation or with some kind of material award. These actions will ensure continued employee participation in the company's pollution prevention efforts.

Implementing an activity-based or total cost accounting system will identify the costs of waste generation that are typically hidden in overhead costs by standard accounting systems. These cost accounting methods identify cost drivers (activities) within the manufacturing process and assign the costs incurred through the operation of the process to the cost drivers. By identifying the cost drivers, manufacturers can correctly assess the true cost of waste generation and the benefits of any pollution prevention efforts.

The International Standards Organization has developed the ISO 14001 standard which defines specific Environmental Management System (EMS) criteria for certification by the organization. Although the standard has been recently established, many companies are already seeking certification to demonstrate their commitment to environmental performance. More information on the ISO environmental standards can be found at the ISO's website: <http://www.iso.ch/welcome.html>.

An alternative to the ISO 14001 model for EMS is the DfE EMS. It is based on the structure outlined in the ISO 14001 standard and incorporates the five phases of Commitment, Policy, Planning, Implementation, Evaluation and Review. While generally consistent with the ISO 14001 standard, the DfE EMS places less emphasis on management infrastructure and documentation and more emphasis on pollution prevention and risk reduction. The DfE EMS is designed for small- and medium-sized businesses and provides technical guidance and detailed methods for developing an EMS. The DfE EMS allows a company to create a simple yet effective EMS aimed at improving environmental performance by focusing on substitutes assessments, chemical risk reduction, pollution prevention opportunities, and resource and cost savings. DfE has developed an EMS guidance manual and several assessment tools that are available on the DfE EMS website: <http://www.epa.gov/opptintr/dfe/tools/ems/ems.html>.

6.1.2 Materials Management and Inventory Control

Materials management and inventory control focuses on how chemicals and materials flow through a facility in order to identify opportunities for pollution prevention. A proper materials management and inventory control program is a simple, cost effective approach to preventing pollution. Table 6-2 presents materials management and inventory control methods that can be used to prevent pollution.

Table 6-2. Materials Management and Inventory Control Pollution Prevention Practices

Practice	Benefits
Minimize the amount of chemicals kept on the floor at one time.	Provides incentives to employees to use less chemicals.
Manage inventory on a first-in, first-out basis.	Reduces materials and disposal costs of expired chemicals.
Return unused chemicals to inventory.	Reduces chemical and disposal costs.
Centralize responsibility for storing and distributing chemicals.	Provides incentives to employees to use less chemicals.
Store chemical products in closed, clearly marked containers.	Reduces materials loss; increases worker safety by reducing worker exposure.
Use a pump to transfer chemical products from stock to transportation container.	Reduces potential for accidental spills; reduces worker exposure.

Controlling inventory levels and limiting access to inventory are widely used practices in the PWB manufacturing industry (82.7 percent of Pollution Prevention Survey respondents). Keeping track of chemical usage and limiting the amount of chemicals on the process floor provides process operators an incentive to use the minimum quantity of chemical required to do the job. Using chemicals on a first-in/first-out basis reduces the time chemicals spend in storage and the amount of expired chemicals that are disposed. Some companies have contracted with a specific chemical supplier to provide all of their process chemicals and manage their inventory. In exchange for the exclusive contract, the chemical supplier assumes many of the inventory management duties including managing the inventory, material safety data sheets (MSDSs), ordering the chemicals, distributing the chemicals throughout the plant, and disposing of spent chemicals and packaging (Brooman, 1996).

Chemical storage and handling practices also provide pollution prevention opportunities. Ensuring that all chemical containers are kept closed when not in use minimizes the amount of chemical lost through evaporation or volatilization. When transferring chemicals from container to container, utilizing a hand pump can reduce the amount of chemical spillage. These simple techniques not only result in less chemical usage representing a cost savings, but also result in reduced worker exposure and an improved worker environment.

6.1.3 Material Selection

Often times, decreasing the amount of pollution a particular process generates can be as simple as selecting different materials for use in the process. This could include primary materials such as bath chemicals or ancillary materials such as racks or rack coverings, and is dependent upon the availability of alternatives to the currently chosen material.

For example, the selection of the proper flux can greatly reduce the air emissions from the hot air solder leveling (HASL) process. In the HASL process, the boards are immersed in a bath of flux followed by submersion in a bath of solder mixed with oil. A hot air knife is then utilized to remove excess solder and oil from the board. An air emission is created during these steps that is the result of the bath chemicals being heated to fairly high temperatures (e.g., 450°F for the oil and solder mixture) and both the oil and flux having vapor pressures that when heated encourage a portion to evaporate and condense as fine droplets (Lee, 1999).

Most flux manufacturers fabricate multiple types of flux for use in the many different environments that exist in PWB manufacturing, some producing as many as 30 to 40 different fluxes. Each flux is manufactured to work most effectively in a particular environment (e.g., low viscosity, high acidity). Carefully choosing the right flux for a particular PWB application can reduce flux losses, the subsequent emissions generated, and the associated costs.

Another example would include choosing the most appropriate type of racking system surface material. With several different types of racking system materials available (e.g., aluminum, iron, stainless steel, plastic, rubber-coated), the unnecessary build-up of bath chemicals on the racks can be reduced. For instance, the use of plastic racks can prevent the deposition of metal on the racks in plating baths, eliminating the need to strip them, thereby reducing the amount of time, effort, and cost that goes into rack cleaning.

6.1.4 Process Improvements

Improving the efficiency of a production process can significantly reduce waste generation at the source. Process improvements include process or procedural changes in operations carried out by employees, process equipment modification or automation, and redesign of the process altogether. Process improvements that lead to pollution prevention in surface finishing are categorized by the following goals:

- extend chemical bath life;
- reduce air emissions;
- reduce water consumption;
- improve process efficiency through automation; and
- segregate waste streams to reduce sludge generation.

Pollution prevention through process improvement does not always have to be expensive. In fact, some of the most cost effective pollution prevention techniques are simple, inexpensive changes in production procedures. Process improvements that help achieve the goals listed above, along with their benefits, are discussed in detail in the sections below.

Extend Chemical Bath Life

The surface finishing process involves the extensive use of chemicals, many of which are costly and pose a hazard to human health and the environment. Improvements in the efficient usage of these chemicals can occur by accomplishing the following:

- reducing chemical bath contamination;
- reducing chemical bath drag-out; and
- improving bath maintenance.

Inefficiencies in the use of chemicals can result in increased chemical usage, higher operating costs, increased releases to the environment, and increased worker exposure. Techniques to improve the efficient use of chemicals by the surface finishing and other PWB process steps are discussed in detail below.

Reduce Bath Contaminants. The introduction of contaminants to a chemical bath will affect its performance and significantly shorten the life of the chemical bath. Bath contaminants include chemicals dragged in from previous chemical baths, chemical reaction by-products, and particulate matter which may be introduced to the bath from the air. Process baths are replaced when impurities reach a level where they degrade product quality to an unacceptable level. Any measure that prevents the introduction of impurities will not only result in better bath performance, but also will reduce chemical usage and generate less waste. Table 6-3 presents pollution prevention methods for reducing bath contamination.

Table 6-3. Pollution Prevention Practices to Reduce Bath Contaminants

Practices	Benefits
Improve the efficiency of the water rinse system.	Rinses off any residual bath chemistries and dislodges any particulate matter from panels and racks.
Use distilled or deionized water during chemical bath make-up.	Reduces chemical contamination resulting from water impurities.
Maintain and rebuild panel racks.	Prevents the build-up of deposits and corrosion that can dislodge or dissolve into chemical baths.
Clean process tanks efficiently before new bath make-up.	Prevents contamination of the new bath from residual spent bath chemistries.
Utilize chemical bath covers when process baths are not in operation.	Reduces the introduction of unwanted airborne particulate matter; prevents evaporation or volatilization of bath chemistries.
Remove immediately foreign objects that have fallen into chemical tank.	Prevents the contamination and premature degradation of bath chemicals.
Filter contaminants continuously from process baths.	Prevents the build-up of any contaminants.

Thorough and efficient water rinsing of process panels and the racks that carry them is crucial to preventing harmful chemical drag-in and to prolonging the life span of the chemical baths. The results of the PWB Workplace Practices Questionnaire indicate that nearly every chemical bath in the surface finishing process is preceded by at least one water rinse tank. Improved rinsing can be achieved by using spray rinses, panel and/or water agitation, warm water, or by several other methods that do not require the use of a greater volume of water. A more detailed discussion of these methods is presented in the reduced water consumption portion in this section.

A rack maintenance program is also an important part of reducing chemical bath contamination and is practiced by 87 percent of the respondents to the Pollution Prevention Survey. By cleaning panel racks regularly and replacing corroded metal parts, preferably with parts of plastic or stainless steel, chemical deposition and build-up can be minimized. Respondents to the PWB Workplace Practices Questionnaire typically perform rack cleaning using either a chemical process that is either part of the process or a separate acid bath, or a mechanical method. Mechanical methods, such as peeling or filing away the majority of any metal deposits before applying a weak acid solution, can be used to prevent pollution by reducing the quantity of acid required. An added benefit is that the reclaimed metal can be sold or reused in the process.

According to the PWB Workplace Practices Questionnaire, 42 percent of the respondents reported using bath covers on at least some of their baths during periods when the surface finishing process was not operating. Respondents were not specifically questioned about the other methods for reducing bath contamination described above; consequently, no information was collected.

Chemical Bath Drag-Out Reduction. The primary loss of bath chemicals during the operation of the surface finishing process comes from chemical bath drag-out. This loss occurs as the rack full of panels is being removed from the bath, dragging with it a film of chemical solution still coating the panels. The drag-out is then either removed from the panels by a hot air knifing process, which uses air to remove excess chemical solution retained on the boards, or is simply carried into the next bath. In most cases, the panels are deposited directly into the next process bath without first being air knifed.

As an extension of the making holes conductive and surface finishing DfE projects, a mathematical tool was developed to help predict the volume of bath chemistry lost through panel drag-out. The model identifies multiple process parameters (e.g., number of through holes, size of panel, length of drip time, etc.) and bath characteristics (e.g., bath temperature, viscosity, etc.) that directly affect the volume of drag-out. Process data for the model were obtained from the PWB Workplace Practices Questionnaire and from data provided by individual chemical suppliers. Because the primary daily loss of bath chemistry is through drag-out, using the model to minimize drag-out will result in extended bath life, decreases in rinse water and bath chemistry usage, and a reduction in treatment sludge. The drag-out model along with a complete description of the method of development, individual factors in the model, and the model limitations is presented in Appendix E. Drag-out model results for the surface finishing alternatives are presented in Section 3.2, Exposure Assessment.

Techniques that minimize bath drag-out also prevent the premature reduction of bath chemical concentration, extending the useful life of a bath. In addition to extended bath life, minimizing or recovering drag-out losses also has the following effects:

- minimizes bath chemical usage;
- reduces the quantity of rinse water used;
- reduces chemical waste;
- requires less water treatment chemical usage; and
- reduces overall process cost.

Methods for reducing or recovering chemical bath drag-out are presented in Table 6-4 and discussed below.

The two most common methods of drag-out control employed by respondents to the Pollution Prevention Survey that require no capital investment are increased panel drainage time (76.3 percent) and practicing slow rack withdrawal from process tanks (60.5 percent). Increasing the time allowed for the panels to drain over the process bath allows a greater percentage of potentially removable chemicals to remain in the bath. Practicing slow rack withdrawal during rack removal is another step used relatively often to allow more time for the bath chemicals to drip back into the bath. Neither of these techniques requires capital investment and both are effective methods for reducing drag-out.

Another viable option is to use drip shields, which are plastic panels that extend the wall height of the process tank. Drip shields are inexpensive, effective drag-out control options, and require no space between process steps, making them very practical where process space is an issue.

Much of the chemical solution lost to drag-out can be recovered through the use of either static drag-out tanks or drip tanks. A static drag-out tank is a batch water bath that immediately follows the process bath from which the drag-out occurs. The panels are submerged and agitated in the static rinse water, washing the residual chemicals from the panel's surface. When sufficiently concentrated, the rinse water and chemical mixture can be used to replenish the original bath. Drip tanks are similar to static drag-out tanks except that they contain no water. The drip tank collects chemical drag-out which can then be returned to the process bath. Static drag-out tanks are most suitably used in conjunction with heated process baths which lose water by evaporation, requiring frequent replacement.

Table 6-4. Methods for Reducing Chemical Bath Drag-Out

Methods	Benefits
Remove panels slowly from process baths.	Reduces the quantity of residual chemical on panel surfaces.
Increase panel drainage time over process bath.	Allows a greater volume of residual bath chemistries to drip from the panel back into the process bath.
Agitate panels briefly while draining.	Dislodges trapped bath chemistries from drilled through holes.
Install drain boards.	Collects and returns drag-out to process baths.
Install drip shields between process baths.	Prevents bath chemical loss due to splashing.
Add static drag-out tanks/drip tanks to process line where needed.	Recovers chemical drag-out for use in bath replenishment.
Utilize non-ionic wetting agents in the process bath chemistries.	Reduces surface tension of bath solutions, thereby reducing residual chemicals on panel surfaces.
Utilize air knives directly after process bath in conveyorized system. [a]	Blows residual process chemistries from process panels which are recaptured and returned to process bath.
Employ fog rinses/spray rinses over heated baths. [a]	Rinses drag-out from the panels as they are removed from the solution.

[a] May not be a viable pollution prevention technique unless system is fully enclosed to prevent worker exposure to bath chemicals introduced to the air.

Bath Maintenance Improvements. The surface finishing processes and other wet chemistry processes in PWB manufacturing consist of a complex, carefully balanced series of formulated chemical mixtures, each one designed to operate at specific conditions, working together to perform an overall function. A bath testing and control program is essential in preventing the chemical breakdown of process baths, thus extending their useful lives and preventing their premature disposal. The premature disposal of process chemistries results in increased chemical costs for both bath and treatment chemicals, prolonged process down-time, and increased process waste.

Bath maintenance, or control, refers to maintaining a process bath in peak operating condition by identifying and controlling key operating parameters, such as bath temperature, individual chemical concentrations, pH, and the concentration of contaminants. Proper control of bath operating parameters will result in more consistent bath operation, less water usage, and better, more consistent quality of work.

According to Pollution Prevention Survey respondents, the majority of PWB manufacturing facilities (72.4 percent) have a preventative bath maintenance program already in place. Typical bath maintenance methods and their benefits are presented in Table 6-5 below.

Table 6-5. Bath Maintenance Improvement Methods To Extend Bath Life

Methods	Benefits
Monitor bath chemistries by testing frequently.	Determines if process bath is operating within recommended parameters.
Replace process baths according to chemical testing.	Prevents premature chemical bath replacement of good process baths.
Maintain operating chemical balance through chemical additions according to testing.	Maintains recommended chemical concentrations through periodic chemical replenishment as required.
Filter process baths continuously.	Prevents the build-up of harmful impurities that may shorten bath life.
Employ steady state technologies.	Maintains steady state operating conditions by filtering precipitates or regenerating bath solutions continuously.
Install automated/statistical process control system.	Provides detailed analytical data of process operating parameters, facilitating more efficient process operation.
Utilize temperature control devices.	Regulates bath temperatures to maintain optimum operating conditions.
Utilize bath covers.	Reduces process bath losses to evaporation and volatilization.

Frequent monitoring and adjustment of the various chemical concentrations within a process bath are the foundations on which a good bath maintenance program is built. Monitoring is done by regularly testing the bath concentrations of key chemicals to ensure that the bath is chemically balanced. If chemical concentrations are outside of the operating levels recommended by the supplier, a volume of chemical is added to the bath to bring it back into balance. When the concentration of contaminants reaches an established critical level, or some other criterion provided by the supplier, the bath is disposed of and replaced with a new bath.

Bath testing and adjustment can be performed manually or with an automated system that can perform both functions. Either way, controlling the bath through regular testing and bath additions is an inexpensive, effective method for extending bath life and reducing pollution. Nearly all of the PWB facilities surveyed (93.1 percent) reported testing chemical bath concentrations, adding chemicals as necessary and maintaining records of the analysis and additions.

Bath replacement should be based upon chemical testing, instead of some other predetermined criteria. Predetermined criteria, such as times or production volumes, are often given by suppliers as safe guidelines for bath replacement for facilities that do not regularly test their process baths. These criteria are conservative estimates of the effective life of the process bath, but possibly could be exceeded with a proper bath testing and maintenance program. By replacing the process bath only when chemical testing indicates it is required, bath life can be extended while chemical usage and waste are reduced. Most (95.0 percent) of the surveyed PWB facilities reported replacing their process baths only when testing indicated.

The build-up of contaminants in a process bath will eventually require the bath to be replaced. Bath contaminants can be solid matter, such as particulate matter and precipitates, or undesired chemical species in solution, such as reaction by-products or drag-in chemicals. Installing standard cartridge or bag filters to continuously remove solid impurities from the bath is an inexpensive, yet effective method to extend bath life.

Additionally, some baths may be maintained at steady state conditions using readily obtainable systems capable of regenerating or filtering process bath chemistries. Although these systems may require capital investment, maintaining steady state conditions keeps a bath within the optimal operating conditions resulting in extended bath life and increased cost savings (Edwards, 1996).

Statistical process control (SPC) is a method of analyzing the current and past performance of a process bath, using chemical testing results and operating condition records to optimize future bath performance. SPC will lead to more efficient bath operation and extended bath life by indicating when a bath needs maintenance through the tracking and analysis of individual operating parameters and their effect on past performance (Fehrer, 1996).

A method of limiting evaporative losses from process baths is to cover the surface of the solution with floating plastic balls that will not react with the process solution. The plastic balls, similar to ping pong balls which do not interfere with the work pieces being processed, prevent the evaporation of the bath solution by limiting the surface area of solution exposed to the air. Hexagonal shaped balls are now available that leave even less surface area exposed to the air (Brooman, 1996). This method is especially effective for higher temperature process baths where evaporative losses tend to be high. This method is inexpensive, easy to utilize, and will decrease the air emissions from the bath, limiting the amount of operator exposure to the chemicals.

Reduce Air Emissions

During surface finishing, air emissions are generated from some chemical baths. When the chemicals being used pose a hazard to human health, hoods are utilized to collect the emissions and move them away from the workers. These emissions are ducted to air emission control devices as necessary. These emissions increase the costs associated with PWB manufacture, thus efforts that reduce these emissions not only produce cost savings but reduce worker exposure and reduce the environmental impacts of the process.

One particularly troublesome source of air emissions during the HASL process is the application of a flux and a subsequent solder to the PWB, which generates air emissions that can include oil mist, oxides of lead and tin, hydrogen chloride or hydrogen bromide, and copper chloride or copper bromide (chlorine or bromine is typically used as the flux activator). This process typically requires pollution control equipment like a wet scrubber followed by a diffusion-type fiber bed filter, to control not only the pollutants but also the odors created by their release.

The most prominent option available to reduce these HASL process air emissions comes in the form of process redesign, or utilizing an alternative surface finishing (ASF) technology. Although most of the ASF technologies being evaluated in this CTSA also have air emissions of one type or another, it is the current understanding that one or more will offer a reduction in the overall quantity and/or toxicity of the air emissions generated while maintaining product quality and performance criteria. Depending on the characteristics of the particular boards needing surface finishing (e.g., their aspect ratio), an ASF technology might provide performance either similar to or better than the HASL process while reducing the surface finishing process' environmental impacts.

Reduced Water Consumption

Contaminated rinse water is one of the primary sources of heavy metal ions discharged to waste treatment processes from the surface finishing process and other wet chemistry process lines (Bayes, 1996). These contaminants, which are introduced to the rinse water through chemical drag-out, must be treated and removed from the water before it can be reused in the process or discharged to the sewer. Because rinsing is often an uncontrolled portion of the process, large quantities of water are consumed and treated unnecessarily. Reducing the amount of water used by the surface finishing process has the following benefits:

- decreases water and sewage costs;
- reduces wastewater treatment requirements, resulting in less treatment chemical usage and reduced operating costs;
- reduces the volume of sludge generated from wastewater treatment, which results in reduced sludge treatment or disposal costs; and
- improves opportunities to recover process chemicals from more concentrated waste streams.

The surface finishing process line consists of a series of chemical baths, which are typically separated by at least one, and sometimes more, water rinse steps. These water rinse steps account for virtually all of the water used during the operation of the surface finishing line. The water baths act as a buffer, dissolving or displacing any residual drag-in chemicals from the panel surface. The rinse baths prevent contamination of subsequent baths while creating a clean surface for future chemical activity.

Improper rinsing not only leads to shortened bath life through increased drag-in, as discussed previously, but can also lead to a host of problems affecting product quality, such as peeling, blistering, and staining. Insufficient rinsing of panels can lead to increased chemical

drag-in quantities and will fail to provide a clean panel surface for subsequent chemical activity. Excessive water rinsing, done by exposing the panels too long to water rinsing, can lead to oxidation of the copper surface and may result in peeling, blistering, and staining. To avoid insufficient rinsing, manufacturers often use greater water flow rates than are necessary, instead of using more efficient rinsing methods that reduce water consumption but may be more expensive to implement. These practices were found to be true among survey respondents, where facilities with low water and sewage costs typically used much larger amounts of water than comparable facilities with high water and sewer costs.

Many techniques are available that can reduce the amount of water consumed while rinsing. These techniques are categorized by the following:

- methods to control water flow;
- techniques to improve water rinse efficiency; and
- good housekeeping practices.

Flow control methods focus on controlling the flow of water, either by limiting the maximum rate that water is allowed to flow into the rinse system, or by stopping and starting the water flow as it is needed. These methods seek to limit the total water usage while ensuring that sufficient water is made available to cleanse the PWB panels. Examples of these techniques include the use of flow restrictors or smaller diameter piping to limit the maximum flow of water, and control valves that provide water to the rinse baths only when it is needed. Control valves can be either manually operated by an employee, or automated using some kind of sensing device such as conductivity meters, pH meters, or parts sensors. All of the methods are effective water reduction techniques that can be easily installed.

Pollution prevention techniques directed at improving water efficiency in the rinse system seek to control or influence the physical interaction between the water and the panels. This can be done by increasing bath turbulence, improving water quality, or by using a more efficient rinse configuration. All of these methods, discussed below, seek to improve rinsing performance while using less water.

Increasing bath turbulence can be accomplished through the use of ultrasonics, panel agitation, eductors (nozzles below the surface that circulate solution), or air sparging. All of these agitation methods create turbulence in the bath, increasing contact between the water and the part, thereby accelerating the rate that residual chemicals are removed from the surface. Agitating the bath also keeps the water volume well mixed, distributing contaminants throughout the bath and preventing concentrations of contaminants from becoming trapped. However, agitating the bath can also increase air emissions from the bath unless pollution prevention measures are used to reduce air losses.

Water quality can be improved by using distilled or deionized water for rinsing instead of tap water that may include impurities such as carbonate and phosphate precipitates, calcium, fluoride, and iron. Finally, utilizing more efficient rinse configurations such as countercurrent rinse stages, spray rinses, or fog rinses will increase the overall efficiency of the surface finishing rinse system while reducing the volume of wastewater generated. PWB manufacturers often use

multiple rinse water stages between chemical process steps to facilitate better rinsing. The first rinse stage removes the majority of residual chemicals and contaminants, while subsequent rinse stages remove any remaining chemicals. Counter-current or cascade rinse systems minimize water use by feeding the water effluent from the cleanest rinse tank, usually at the end of the cascade, into the next cleanest rinse stage, and so on, until the effluent from the most contaminated, initial rinse stage is sent for treatment or recycle.

Good housekeeping practices focus on keeping the process equipment in good repair and fixing or replacing leaky pipes, pumps, and hoses. These practices can also include installing devices such as spring loaded hose nozzles that shut off when not in use, or water control timers that shut off water flow in case of employee error. These practices often require little investment and are effective in preventing unnecessary water usage. For a more detailed discussion on methods of improving water rinse efficiency and reducing water consumption, refer to Section 5.1, Resource Conservation.

Improve Process Efficiency Through Automation

The operation of the surface finishing process presents several opportunities for important and integral portions of the process to become automated. By automating important functions, operator inconsistencies can be eliminated, allowing the process to be operated more efficiently. Automation can lead to the prevention of pollution by:

- gaining a greater control of process operating parameters;
- performing the automated function more consistently and efficiently;
- eliminating operator errors; and
- making the process compatible with newer and cleaner processes designed to be operated with an automated system.

Automating a part of the surface finishing process can be expensive. The purchase of some automated equipment can require a significant initial investment, which may prevent small companies from automating. Other costs that may be incurred include those associated with installing the equipment, training employees, any lost production due to process down-time, and redesigning other processes to be compatible with the new system. Although it may be expensive, the benefits of automation on productivity and waste reduction will result in a more efficient process that can save money over the long run.

Installation of automated equipment such as a rack or panel transportation system, chemical sampling equipment, or an automated system to make chemical additions can have a major impact on the quantity of pollution generated during the day-to-day operation of the surface finishing process and can also reduce worker exposure. Surface finishing process steps or functions that can be automated effectively include:

- rack transportation;
- bath maintenance; and
- water flow control.

Rack transportation systems present an excellent opportunity for automation, due to the repetitive nature of transporting panel racks. Various levels of automation are available ranging from a manually operated vertical hoist to a computer controlled robotic arm. All of these methods allow for greater process control over panel movement through the surface finishing process line. By building in drag-out reduction methods such as slower panel withdrawl and extended drainage times into the panel movement system, bath chemical loss and water contamination can be greatly reduced.

Automating bath maintenance testing and chemical additions can result in longer bath life and reduced waste. These systems monitor bath solutions by regularly testing bath chemistries for key contaminants and concentrations. The system then adjusts the process bath by making small chemical additions, as needed, to keep contaminant build-up to a minimum and the process bath operating as directed. The resulting process bath operates more efficiently, resulting in prolonged bath life, less chemical waste, reduced chemical cost, and reduced drag-out.

Controlling rinse water flow is an inexpensive process function to automate. Techniques for controlling rinse water flow were discussed previously. The reduction in fresh water usage as a result of automating these techniques will not only reduce water costs, but will also result in reduced treatment chemical usage and less sludge.

A conveyorized system integrates many of the methods described above into a complete automated surface finishing system. The system utilizes a series of process stages connected by a horizontal conveyor to transport the PWB panels through the surface finishing process. Drag-out is greatly reduced due, in part, to the separate process stages, and to the vertical alignment of the drilled holes that trap less chemicals. Since drag-out is reduced, much less rinse water is required to cleanse the panel surfaces, resulting in reduced water and treatment costs. A single water tank is sufficient between process baths, whereas multiple stages may be required in a non-conveyorized process. Thus, automation dramatically reduces the number of process stages required, resulting in a much shorter cycle time and reduced floor space requirements. The enclosed process stages limit evaporative losses, reducing chemical costs, while also reducing the amount of chemical to which an employee is exposed. Several surface finishing alternative chemistry processes have been designed to operate effectively using this type of conveyorized system.

A conveyorized system should also take advantage of other pollution prevention techniques, such as water flow controllers, bath maintenance techniques and other methods discussed throughout this module, to further reduce waste. By integrating all of these methods together into a single surface finishing system, the process operates more efficiently, reducing water and chemical consumption, resulting in less process waste and employee exposure.

Segregate Wastewater Streams to Reduce Sludge Generation

The segregation of wastewater streams is a simple and cost effective pollution prevention technique for the surface finishing process. In a typical PWB facility, wastewater streams from different process steps are often combined and then treated by an on-site wastewater treatment process to comply with local discharge limits.

Some waste streams from the surface finishing process, however, may contain chelating agents. These chelators, which permit metal ions to remain dissolved in solution at high pH levels, must first be broken down chemically before the waste stream can be treated and the heavy metal ions removed. Treatment of waste containing chelators requires extra treatment steps or more active chemicals to break down the chelating agents and precipitate out the heavy metal ions from the remaining water effluent. Because the chelator-bearing streams are combined with other non-chelated streams before being treated, a larger volume of waste must be treated for chelators than is necessary, which also results in a larger volume of sludge.

To minimize the amount of treatment chemical used and sludge produced, the chelated waste streams should be segregated from the other non-chelated wastes and collected in a storage tank. When enough waste has been collected, the chelated wastes should be batch treated to breakdown the chelator and remove the heavy metals. The non-chelated waste streams can then be treated by the on-site wastewater treatment facility without additional consideration. By segregating and batch treating the chelated heavy metal wastes from other non-hazardous waste streams, the volume of waste undergoing additional treatment is minimized and treatment chemical usage and sludge generation reduced.

6.2 RECYCLE, RECOVERY, AND CONTROL TECHNOLOGIES ASSESSMENT

While pollution prevention is the preferred method of waste management, the pollution prevention hierarchy recognizes that pollution prevention is not always practical. Companies often supplement their pollution prevention efforts with additional waste management techniques to further reduce emissions. These techniques, presented in order of preference, include recycling or reclamation, treatment, and disposal. Techniques for pollution prevention are presented in Section 6.1. This section presents waste management techniques typically used by the PWB industry to recycle or recover valuable process resources (Section 6.2.1), and to control emissions to water and air (Section 6.2.2) from the surface finishing process. Typical treatment configurations presented in this section were developed and reviewed by PWB manufacturers participating in this project.

6.2.1 Recycle and Resource Recovery Opportunities

PWB manufacturers have begun to re-emphasize recycle and recovery technologies, due to more stringent pretreatment effluent limits. Recycling or reclamation is the recovery of process material effluent, either on-site or off-site, which would otherwise become a solid waste, air emission, or would be discharged to a wastewater stream. Technologies that recycle water from waste streams concentrate the final effluent, making subsequent treatment more efficient, which reduces the volume of waste generated and lowers overall water and sewer costs. As a result, these technologies are being used more frequently by industry to recycle or recover valuable process resources, while also minimizing the volume of waste that is sent to disposal. This trend was supported by the respondents of the *Printed Wiring Board Pollution Prevention and Control Technology: Analysis of Updated Survey Results* (U.S. EPA, 1998), 81 percent of whom reported using some type of recycle or resource recovery technology.

Recycle and resource recovery technologies include those that recover materials from waste streams before disposal, or recycle waste streams for reuse in another process. Opportunities for both types of technologies exist within a surface finishing process. Rinse water can be recycled and reused in further rinsing operations, while valuable metals such as copper, silver, palladium, and gold can be recovered from waste streams before disposal and sold to a metals reclaimer. These recycle and recovery technologies may be either in-line (dedicated and built into the process flow of a specific process line) or at-line (employed at the line as desired, as well as at other places in the plant), depending on what is required (Brooman, 1996). Each waste stream that cannot be prevented should be evaluated to determine its potential for effective recycle or resource recovery as part of a pollution prevention and waste management plan.

The decision of whether to purchase a recycle or resource recovery process should be based on several factors. Economic factors, such as process operating and effluent disposal costs for the current system, must be compared with those estimated for the new technology. The initial capital investment of the new technology, along with any potential cost savings, and the length of the payback period must also be considered. Other factors such as the characteristics of the waste stream(s) considered for treatment, the ability of the process to accept reused or

recycled materials, and the effects of the recycle or recovery technology on the overall waste treatment process also should be considered.

The entire PWB manufacturing process must be considered when assessing the economic feasibility of a recycle or resource recovery process. An individual recovery process can recover metal from a single stream originating from a surface finishing process, or it may recover the metal from streams that originate from other processes, as well. Only by considering the new technology's impact on the entire PWB manufacturing process can an accurate and informed decision be made. While this section focuses on technologies that may be used to recycle or recover resources from the waste streams that are generated by the surface finishing processes, many of these technologies are also applicable to other PWB process lines. Workplace practices that can lead to the recycle or reuse of resources (e.g., manually recovering copper from panel racks, water recycle using cascade water rinse systems) are discussed in Section 6.1.

Solder Recycling

The application of solder to the surface of PWBs by HASL has been the industry standard finish for many years. The process has long been considered to provide a reliable finish which facilitates assembly and introduces few defects. However, as the concentration of impurities in the solder increases to above 0.3 percent by weight, the quality and appearance of the applied solder finish deteriorates. The solder begins to appear grainy and takes on a dull gray color.

The primary impurity is copper, which is introduced to the molten solder as a by-product of the process reaction. Tin from the molten solder is exchanged with the copper ions on the surface of the exposed copper pads, forming a tin-copper intermetallic layer upon which the solder can adhere. The displaced copper ions remain in the molten solder as a contaminant where they build in concentration until the contamination begins to affect the quality of the solder deposit.

To restore the HASL process to optimum operating conditions, the solder pots typically are refreshed to reduce the contaminant concentration. This maintenance process is performed with the solder in molten form by discarding a substantial quantity of the contaminated solder and replacing it with fresh solder. The contaminated solder (a.k.a. solder dross) can be returned to a recycler to be reclaimed for credit. The effectiveness of the dilution is dependent on the amount of solder replaced, with a 40 percent by weight replacement of solder resulting in roughly a 33 percent decrease in copper contamination, dropping the concentration from 0.3 to 0.2 percent copper. This process is repeated as required to maintain operation of the HASL process (Fellman, 1997).

Solder skimming is another method of purifying the solder. The solder is cooled to a temperature just above the melting point (360 ^{o}F), causing the copper impurities to become insoluble. The copper-tin needles which form are then skimmed from the surface of the solder and handled as waste. Because only the impurities are removed, along with a minimal amount of solder, the skimming process results in much less solder usage over time. However, this method

requires open access to the molten solder pot to perform the skimming, so it is typically only associated with some vertical, non-conveyorized HASL machines.

A solder saver, or solder reclaim system, will purify the solder in HASL machines where access to the solder is restricted by air knives, rollers, pumps, or some other equipment, such as in some vertical HASL machines and nearly all horizontal, conveyorized HASL machines. A solder reclaim system diagram is shown in Figure 6-1. The solder saver continuously siphons a portion of the molten solder from the HASL machine to a separate solder pot, where the temperature is lowered and the impurities are skimmed from the solder.

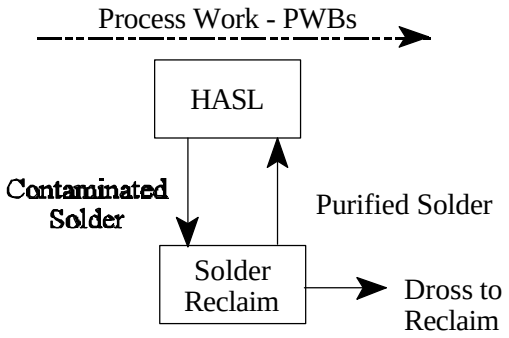


Figure 6-1. Solder Reclaim System Diagram

Impurities that have been skimmed from the solder are collected in a compartment of the machine for removal and disposal, and an equal weight of fresh solder is manually added to maintain operating solder levels. Transfer of the solder from the pot takes place in a heated pipe to prevent the solder from solidifying during the transfer process. The purified portion of the solder is then pumped back through a second heated pipe to the HASL solder pot. The solder reclaim system is an off-line system that operates continuously, without disrupting the operation of the HASL process.

One study found that approximately 96 percent of the solder was retained after skimming with a solder reclaim system, resulting in a remaining copper concentration of 0.16 percent, or a purification efficiency of better than 90 percent (Fellman, 1997). One PWB manufacturer reported a yearly decrease of 86 percent in solder consumption (see inset), decreasing their overall lead usage to below reportable levels (Sharp, 1999).

Solder Recovery Case Study of PWB Manufacturer

Before Solder Reclaim:
- 202,000 lbs solder usage/year
- 75,000 lbs lead usage reported

After Solder Reclaim:
- 27,000 lbs solder usage/year
- Lead usage below reportable level (less than 10,000 lbs)

Cost Comparison:
- Net cost of solder $0.50/lb ($2.10/lb solder - $1.60/lb dross reclaim credit)
- Total solder usage reduction of 175,000 lbs/yr
- Total cost savings of $82,000/yr
- Equipment cost is $70,000
- Payback period is approximately one year

The average capital cost of a solder reclaim unit was reported to be $60,000 to $80,000. A cost analysis performed by one large PWB manufacturer found the expected payback period for this equipment to be one year, based upon an annual solder usage of 200,000 pounds per year, prior to the installation of the equipment.

Electrolytic Recovery

Electrolytic recovery, also known as electrowinning, is a common metal recovery technology employed by the PWB industry. Electrowinning uses an electrolytic cell to recover dissolved metal ions from solution. Operated either in continuous or batch mode, electrowinning can be applied to various process fluids including spent microetch, drag-out rinse water, and ion exchange regenerant. An advantage is its ability to recover only the metal from solution, leaving behind the other impurities that are present. The recovered metal can then be sold as scrap or traded for credit towards future bath chemistry. Electrowinning is typically used by PWB manufacturers to recover copper (effluent limit concerns) and gold (high price) from process baths or rinse tanks. It can also be used to recover other metals such as tin or silver, but this is not usually done because the metal does not exceed effluent treatment limits, or the recovery of the metal is not economically viable. Nickel recovery using electrowinning requires close control of pH; therefore, it is performed less frequently than for other metals, such as copper and gold (U.S. EPA, 1998).

The electrolytic cell is comprised of a set of electrodes (cathodes and anodes) placed in the metal-laden solution. An electric current, or voltage, is applied across the electrodes and through the solution. The positively charged metal ions are drawn to the negatively charged cathode where they deposit onto the surface. The solution is kept thoroughly mixed using air agitation or other proprietary techniques, to permit the use of higher current densities (the amount of current per surface area of cathode). These higher current densities shorten deposition time and improve the recovery efficiency. As the metal recovery continues, the concentration of metal ions in solution becomes depleted, requiring the current density to be reduced to maintain efficiency at an acceptable level. When the concentration of metal becomes too low for its removal to be economically feasible, the process is discontinued and the remaining solution is sent to final treatment.

Electrowinning is most efficient with concentrated solutions. Dilute solutions (less than 100 mg/l of metal) become uneconomical to treat due to the high power consumption relative to the amount of metal recovered (Coombs, 1993). Waste streams that are to be treated by electrowinning should be segregated, only combining streams containing the same metal, to prevent dilution, and to create a pure metal deposit free of other metal impurities. Already diluted solutions can be concentrated first, using ion exchange or evaporation techniques, to improve the efficiency and cost effectiveness of metal recovery.

Process waste solutions containing chlorine ions in any form should not be processed using electrolytic recovery methods, because the electrolysis of these solutions could generate chlorine gas. Solutions containing copper chloride salts should first be converted to non-chloride

copper salt (e.g., copper sulfate) solutions, using ion exchange methods, before undergoing electrowinning to recover the copper content (Coombs, 1993).

The recovered metal(s) can be sold as scrap to a metals reclaimer. Typical metal removal efficiencies of 90 to 95 percent have been achieved using electrolytic methods (U.S. EPA, 1990). The remaining effluent will still contain small amounts of metal and will be acidic in nature (i.e., low pH). Adjusting the pH may not be sufficient for the effluent to meet the standards of some POTW authorities; therefore, further treatment may be required.

Eighteen percent of the Pollution Prevention Survey respondents reported using electrowinning as a resource recovery technology, with 89 percent of those being satisfied with its performance. The median cost of an electrowinning unit reported by the respondents was $15,000; however, electrowinning capital costs are dependent on the capacity of the unit.

Ion Exchange

Ion exchange is a process used by the PWB industry mainly to recover metal ions, such as copper, tin, or palladium, from rinse waters and other solutions. This process uses an exchange resin to remove the metal from solution and concentrate it on the surface of the resin. It is particularly suited to treating dilute solutions, since at lower concentrations the resin can process a greater volume of wastewater before becoming saturated. As a result, the relative economics of the process improve as the concentration of the feed solution decreases. Aside from recovering metals such as copper and silver, ion exchange also can be used for treating wastewater, deionizing feed water, and recovering chemical solutions.

Ion exchange relies on special resins, either cationic or anionic, to remove the desired chemical species from solution. Cation exchange resins are used to remove positively charged ions such as copper, tin, or other metals. When a feed stream containing a metal is passed through a bed of cation exchange resin, the resin removes the metal ions from the stream, replacing them with hydrogen ions from the resin. For example, if a feed stream containing copper sulfate ($CuSO_4$) is passed through the ion exchange resin, the copper ions are removed and replaced by hydrogen ions to form sulfuric acid (H_2SO_4). The remaining water effluent is either further processed using an anion exchange resin and then recirculated into the rinse water system, or pH neutralized and then directly sewered. Ion exchange continues until the exchange resin becomes saturated with metal ions and must be regenerated.

Special chelating resins have been designed to capture specific metal ions that are in the presence of chelating agents, such as metal ions in electroless plating baths. These resins are effective in breaking down the chemical complexes formed by chelators that keep metal ions dissolved in solution, allowing them to be captured by the resin. Hard water ions, such as calcium and magnesium, are not captured, creating a purer concentrate. Chelating resins require that the feed stream be pH-adjusted to reduce acidity, and filtered to remove suspended solids that will foul the exchange bed (Coombs, 1993).

Regeneration of the cation or chelating exchange resin is accomplished using a moderately concentrated (e.g., ten percent) solution of a strong acid, such as sulfuric acid. Regeneration reverses the ion exchange process by stripping the metal ions from the exchange resin and replacing them with hydrogen ions from the acid. The concentration of metal ions in the remaining regenerant depends on the concentration of the acid used, but typically ranges from
10 to 40 g/l or more (Coombs, 1993).

Ion exchange can be combined with electrowinning to recover metal from solutions that would not be cost effective to recover using either technology alone. A typical flow diagram for this type of system is shown in Figure 6-2. It can be used to concentrate a dilute solution of metal ions for electrolytic recovery that would otherwise be uneconomical to recover. For example, a dilute copper chloride solution can be treated by an ion exchange unit that is regenerated using sulfuric acid, producing a concentrated copper sulfate solution. The electrowinning unit can then be used to recover the copper from the solution while regenerating the acid, which could then be used for the next regeneration cycle. The recovery of gold from the drag-out and rinse tanks, following the immersion gold bath, is another example of where this configuration is typically used. The high cost of gold makes this system cost effective over the long term.

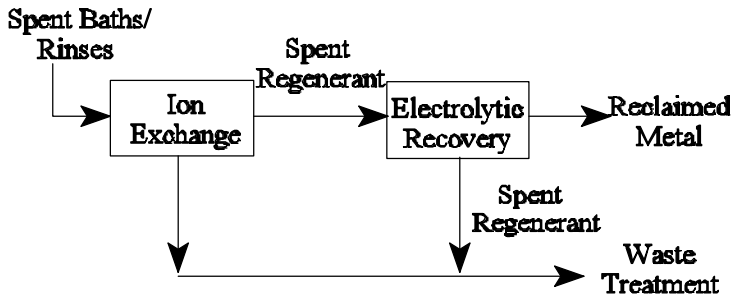


Figure 6-2. Flow Diagram of Combination Ion Exchange and Electrowinning Recovery System for Metal Recovery

A benefit of ion exchange is the ability to control the type of metallic salt that will be formed by selecting the type of acid used to regenerate the resin. In the previous example, the copper chloride was converted to copper sulfate while being concentrated by the ion exchange system. This is particularly useful when electrowinning is used, because it cannot process solutions containing the chlorine ion without usually generating toxic chlorine gas.

Forty-four percent of the respondents to the Pollution Prevention Survey reported using an ion exchange process as a water recycle/chemical recovery technology. Of these facilities, 90 percent indicated that they were satisfied with its overall performance. The average capital cost of a unit, which is related to its capacity, was reported to be $65,000 (with a low of $10,000 and a high of $120,000).

Reverse Osmosis

Reverse osmosis (RO) is a recovery process used by the PWB industry to regenerate rinse waters and to reclaim process bath drag-out for return to the process (U.S. EPA, 1990). It relies on a semi-permeable membrane to separate the water from metal impurities, allowing bath solutions to be reused. It can be used as a recycling or recovery technology to reclaim or regenerate a specific solution, or it can be part of an overall waste treatment process to concentrate metals and impurities before final treatment.

The semi-permeable membrane permits only certain components to pass through, and pressure is used as a driving force to separate the components at a useful rate. The membrane is usually made of a polymer compound (e.g., nylon) with hole sizes ranging from 0.0004 to 0.06 microns in diameter. Pumping of the waste stream, at pressures typically ranging from 300 to 1,500 pounds per square inch (psi) force the solution through the membrane (Capsule Environmental Engineering, Inc., 1993). The membrane allows the water to pass while inhibiting the metal ions, collecting them on the membrane surface. The concentrated metal ions are allowed to flow out of the system, where they are reused as bath make-up solution, or they are sent to treatment. The relatively pure water can be recycled as rinse water or directly sewered (sent to a POTW).

A typical RO system for recycling rinse water is shown in Figure 6-3. The effluent from rinse water tanks throughout the facility is collected in a conditioning tank. Any pretreatment that may be required, such as pH adjustment, takes place in the conditioning tank. The conditioning tank also acts to smooth out any chemical concentration spikes that may occur in the rinse effluent. The water is then passed through the RO membrane, where the metals and other dissolved solids are removed. The purified water is then passed on to a storage tank to be used for further rinsing operations, where required. The removed solids and other materials are sent to the wastewater treatment system to be processed. An RO system of this design will have an efficiency of 70 to 85 percent, with the remainder being sent to waste treatment (Hosea, 1998).

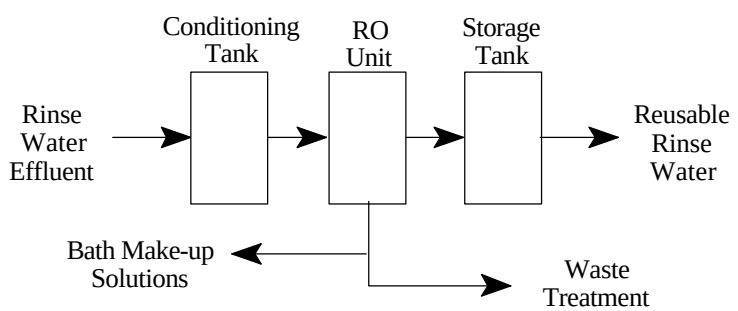


Figure 6-3. Reverse Osmosis Water Reuse System

The RO process has some limitations. The types of waste streams suitable for processing are limited by the ability of the polymeric membranes to withstand the destructive nature of the given waste stream. The membranes are sensitive to solutions with extreme pH values, either low or high, which can degrade them. Pure organic streams likewise are not treatable. Waste streams with suspended solids should be filtered prior to separation to keep the solids from fouling the membrane, to avoid reducing the efficiency of the process. Process membranes also may have a limited life due to the long-term pressure of the solution on the membrane (Coombs, 1993). Data regarding the usage of RO technology by the PWB industry were not collected in the Pollution Prevention Survey.

Off-Site Refining/Reclamation

Many of the surface finishing technologies are based on the deposition of precious metals. Due to the high cost of replacement, these baths are typically recharged rather than discarded, replacing the metal that has been plated to maintain proper operating concentrations. Should the baths become too contaminated to operate properly, the baths are replaced with new chemistry and the spent bath solution is sent to a chemical refinery to reclaim the value of the remaining precious metal content. The most likely solutions to be refined to recover their value are those containing gold and palladium. The value of the recovered metal is based on the current spot market price of the metal. Table 6-6 lists the current value of the metal and the typical methods of recovery.

Table 6-6. Typical Value of Reclaimed Metals (1999) and Recovery Methods

Metal	Price [a,b]	Recovery Method [c]
Gold	$283/oz	Off-site refining or electrolytic
Palladium	$636/oz	Off-site refining
Silver	$4.98/oz	Off-site refining or ion exchange
Copper	$0.80/lb	On-site electrolytic or ion exchange
Solder	$1.60/lb	Manual or solder recovery system

[a] Metal prices received will be current market prices minus a 2 to 5 percent refining fee. Prices listed are spot prices on 7/6/00 obtained from www.kitco.com.

[b] Solder cost obtained from Alpha Metals (03/00). Copper price reflects London metal exchange price on 7/6/00 obtained from www.nickelalloy.com.

[c] Methods of recovery are typical methods and do not represent all recovery options.

Some chemical suppliers provide this service to their customers, accepting spent bath solution in exchange for credit toward future chemical purchases. While the fee charged to recover the metal from the bath is similar to that charged by a refinery service (2 to 5 percent), PWB manufacturers may find it easier to deal with a single company to both supply bath chemicals and to reclaim the spent bath solution, rather than contracting with a separate waste recovery service (Schectman, 1999).

The chemical supplier also benefits from providing this service, because the companies that receive credit are more likely to continue purchasing their chemical products. Chemical suppliers also may be able to reuse the spent solution, regenerating the stock into new bath solution, rather than treating and discarding the remaining solution.

Both gold and palladium plating baths are routinely refined to recover the value of the remaining metal. The value of the metals combined with the high concentration of metal ions remaining, even in a spent bath, makes refining worthwhile. Silver plating baths do not typically have sufficiently high concentrations of silver ions to warrant refining for economic reasons. However, in some instances, silver baths may be combined with other silver-bearing waste streams, such as photo developing solutions, before being refined, making it more cost effective to recover the metal (Sharp, 1999).

Although the low recovery value of copper, tin, and nickel prevent refining from being economically advantageous, these solutions are at times sent off-site to a reclaimer, at a cost to the PWB manufacturer, because the facility lacks the capability to treat the solution or does not want to deal with the extra treatment steps and risks involved. The value of the metal recovered from the solution is credited to the PWB manufacturer, but is usually insufficient to cover the entire expense of the refining and disposal (Schectman, 1999). These metals, particularly copper, also can be recovered on-site using ion exchange or electrowinning, when the recovered metal can be sold to a reclaimer to partially offset the cost of recovery.

Applicability of Recovery Technologies

Recovery and reclamation technologies typically are quite efficient, but are designed for a specific application, which is usually chemical-specific in nature (e.g., electrowinning removes positively charged metal ions), often limiting their applicability. Because surface finishing processes are comprised of a series of chemical baths of different chemical characteristics, it is appropriate to match the recovery technologies with individual chemical baths when identifying opportunities for recycling or reclaiming materials. Table 6-7 displays the applicability of the various recycling and recovery technologies to each of the surface finishing chemical baths. Bath types that do not require additional recycling, are not economically feasible to recycle, or those for which a recycling technology does not exist are not listed in the table. Recovery technologies can sometimes be combined (e.g., ion exchange followed by electrowinning to recover metal) into a more cost effective recovery system that achieves greater removal efficiency.

Table 6-7. Applicability of Recovery/Reclamation Technologies by Bath Type

Bath Type	Process(es)	Solder Recovery	Ion Exchange	Electrolytic Recovery	Reverse Osmosis	Off-Site Refining
Drag-out Rinse (following gold, palladium)	Nickel/Gold and Nickel/Palladium/Gold		X	X		X
Gold	Nickel/Palladium/Gold		X	X		X
Microetch	All		X	X		
Nickel	Nickel/Gold and Nickel/Palladium/Gold		X	X		
Palladium	Nickel/Palladium/Gold					X
Immersion Silver	Immersion Silver		X	X		X
Solder	HASL	X				
Immersion Tin	Immersion Tin		X	X		
Water Rinse	All				X	

6.2.2 Control Technologies

If the release of a hazardous material cannot be prevented or recycled, it may be possible to treat or reduce the impact of the release using a control technology. Control technologies are engineering methods that minimize the toxicity and/or volume of released pollutants. Most of these methods involve altering either the physical or chemical characteristics of a waste stream to isolate, destroy, or alter the concentration of target chemicals. While this section focuses on technologies that are used to control on-site releases from a surface finishing process, many of these technologies are also applicable to other PWB process lines.

Control technologies are typically used to treat on-site releases to both water and air resulting from the application of a surface finish to the PWB. Wastewater containing concentrations of heavy metal ions, along with chelators and complexing agents, are of particular concern. Water effluent standards require the removal of most heavy metals and toxic organics from the plant effluent before it can be disposed to the sewer. On-site releases of concern to air include acid vapors and solvent fumes. This section identifies the control technologies used by PWB manufacturers to treat or control wastewater and air emissions released by the operation of the surface finishing processes.

<u>Wastewater Treatment</u>

The PWB industry typically uses a sophisticated treatment system to pretreat process wastewater and spent bath chemistries prior to discharge. The treatment system is comprised of several parts, including a versatile waste collection system, a flow-through precipitation process, a series of batch treatment tanks, and a sludge thickening process. The treatment also may be supplemented by other treatment technologies, depending on the treatment concerns for the

facility and the effluent permit limits. Together these processes form a complete treatment system capable of treating the waste streams generated by the PWB manufacturing process, including those from the surface finishing line.

A diagram of a typical PWB facility treatment system is presented in Figure 6-4, while the individual treatment processes are discussed below. References to key points of the diagram are included in the descriptions, and are denoted with reference number in brackets.

Waste Collection and Segregation System. Waste streams are collected from processes located throughout the facility by a sophisticated piping and collection system that conducts the individual waste streams to the waste treatment process. The collection system must be versatile, allowing the waste treatment operators complete control over the destination of an incoming wastewater flow. In the case of a chemical spill or harmful accidental discharge, operators must have the ability to divert the wastewater flow into a holding tank to prevent any violations that might be caused by overloading the treatment system.

The treatment process typically has a waste collection tank and one or more holding tanks. The collection system deposits the individual waste streams into one or more collection tanks at the operator's discretion. Waste streams are typically co-mingled in the main collection tank (1) for a period of time prior to entering the waste treatment system, to allow complete mixing and to smooth out any concentration spikes that might occur during normal process operation.

Difficult-to-treat streams, such as those containing chelators or requiring special treatment, are segregated from the others at the source and fed into separate holding tanks. Metal-bearing rinses should be segregated from streams which do not contain metals. Specific segregation of cyanide, solvents, flux, and reflow oils is critically important (Iraclidis, 1998). Waste streams containing oxidizing agents also typically are segregated from others because of the difficulty oxidizing agents present during the flocculation and settling stages (oxidizing agents evolve gas that can hinder floc settling) (Sharp, 1999).

Flow-Through Chemical Precipitation System. In the PWB industry, the majority of facilities surveyed (61 percent) reported using a conventional chemical precipitation system to accomplish the removal of heavy metal ions from wastewater. Chemical precipitation is a process for treating wastewater that depends on the water solubility of the various compounds formed during treatment. Heavy metal cations present in the wastewater are reacted with certain treatment chemicals to form hydroxides, sulfides, or carbonates that have relatively low water solubilities. The resulting heavy metal compounds are precipitated from the solution as an insoluble sludge that is subsequently sent off-site to reclaim the metals content, or sent to disposal. Chemical precipitation can be carried out in a batch process, but is typically operated in a continuous flow-through process to treat wastewater.

In the chemical precipitation treatment of wastewater from PWB manufacturing, the removal of heavy metals may be carried out by a unit sequence of rapid mix precipitation, flocculation, and clarification. The process begins by adjusting the pH of the incoming wastewater (2) to optimum operating conditions (pH 6 to 8). The optimum pH for treatment is

dependant on both the treatment chemistry and the metals being removed from the wastewater. Adjustments are made through the addition of acid or lime/caustic. Treatment chemicals are then dispersed into the wastewater input stream under rapid mixing conditions. The initial mixing unit (3) is designed to create a high intensity of turbulence in the reactor vessel, promoting multiple encounters between the metal ions and the treatment chemical species, which then react to form insoluble metal compounds. The type of chemical compounds formed depends on the treatment chemical employed; this is discussed in detail later in this section. These insoluble compounds form a fine precipitate at low pH levels and remain suspended in the wastewater.

The wastewater then enters the flocculation tank (4). The purpose of the flocculation step is to transform smaller precipitates into large particles that are heavy enough to be removed from the water by gravity settling in the clarification step. The flocculation tank uses slow mixing to promote collisions of precipitate particles suspended in the wastewater. The degree of flocculation is enhanced through the use of flocculating chemicals such as cationic or anionic polymers. These chemicals promote interparticle adhesion by adding charged particles to the wastewater, which attach themselves to the precipitate, thereby increasing the growth rate of the precipitate particles.

Wastewater effluent from the flocculation stage is then fed into a clarification tank (5) where the water is allowed to collect undisturbed. The rather large precipitate particles settle out of the water by gravity, forming a blanket of sludge at the bottom of the clarification tank. A portion of the sludge, typically 10 to 25 percent, is often recirculated to the head of the flocculation step to reduce chemical requirements, as well as to enhance the rate of precipitation (Frailey, 1996). The sludge particles provide additional precipitation nuclei that increase the probability of particle collisions, resulting in a more dense sludge deposit. The remaining 75 to 90 percent of the sludge from the clarifier is fed into the sludge-thickening tank.

The remaining supernatant from the clarifier is decanted through a weir into the bottom of a sand filter (6). As the water flows upward through the sand filter, the sand traps any remaining suspended solids, polishing the treated wastewater stream. When the sand filter becomes saturated with particles, and the effluent quality begins to deteriorate, the filter is taken off-line and back flushed to remove the particulate matter, cleansing the filter for further use. The collected particulate matter is sent to the sludge treatment system.

The treated wastewater then undergoes a final pH adjustment (7) to meet effluent guidelines and is then pumped into a final collection tank prior to being discharged. The collection tank allows for final testing of the water and also can act as a holding tank to capture any water that fails inspection due to a system overload of contaminant or some other treatment system failure. Water from this tank can be returned by the operator to the start of the process if required.

Other process steps are sometimes employed in the case of unusually strict effluent limits. Filtration, reverse osmosis, ion exchange, or additional precipitation steps are sometimes employed to further reduce the concentration of chemical contaminants present in the wastewater effluent.

Batch Treatment of Process Baths. Most spent process baths can be mixed with other wastewater and treated by the on-site wastewater treatment process using chemical precipitation. Chemical suppliers, however, recommend that some process baths be treated separately from the usual waste treatment process. The separate treatment of these baths is usually recommended due to the presence of strong chelating agents, high metal concentrations or other chemicals, such as additives or brighteners, which require additional treatment measures before they can be disposed of properly. Spent bath solution requiring special treatment measures can be processed immediately, but is typically collected and stored until enough has accumulated to warrant treatment. Batch treatment (8) of the accumulated waste is then performed in a single tank or drum, following the specific treatment procedures provided by the chemical supplier for that bath.

Following batch treatment, the remaining solution may be transferred to the flow-through precipitation system for further treatment, drummed for disposal, or discharged directly. Sludge from the process is dewatered by a sludge press and then combined with other treatment sludge to be dried.

Sludge Thickening Process. Sludge formed in the clarifier needs to be thickened and dewatered prior to being shipped off-site. Clarifier sludge is typically light (4 to 5 percent solids) and not very well settled prior to entering the thickening tank (9). Once in the tank, the precipitate is compressed as it moves downward by the weight of the precipitate above and by the constricting funnel at the bottom of the thickening tank. The supernatant separates from the sludge as it thickens. It is pumped from the top of the thickener and returned to the wastewater collection tank to be processed through the treatment system once again. The dense, thickened sludge (8 to 10 percent solids) is then pumped from the bottom of the thickening tank to a sludge press.

The sludge press (10) and sludge dryer (11) minimize the volume of sludge by increasing the solids content through dewatering, thus reducing the cost of disposal. The sludge press is usually a plate filter press, but belt filter presses also may be used. Dewatering occurs when the sludge is passed under high pressure through a series of cloth covered plates. The cloth quickly becomes coated with sludge, forming a layer that retains the solids, while the water is forced through the cloth. The sludge cake (30 to 35 percent solids) is sufficiently dry for direct disposal or recovery (Pontius, 1990). A sludge dryer (up to 70 percent solids) may be utilized to further dewater the sludge, if desired.

Treatment of Non-Chelated Wastewater. The absence of complexing chemicals (e.g., ammonia) or chelating agents (e.g., EDTA) in the wastewater stream simplifies the removal of metal ions by precipitation. Metal removal from such waste streams is accomplished through simple pH adjustment using hydroxide precipitation. Caustic soda is typically used while other treatment chemicals include calcium hydroxide and magnesium hydroxide. The heavy metal ions react with the caustic soda to form insoluble metal hydroxide compounds that precipitate out of solution at a high pH level. After the precipitate is removed by gravity settling, the effluent is pH adjusted to a pH of seven to nine and then sewered. The treatment can be performed in a chemical precipitation process similar to the one shown in Figure 6-4, resulting in a sludge contaminated with metals that is then sent to recycling or disposal.

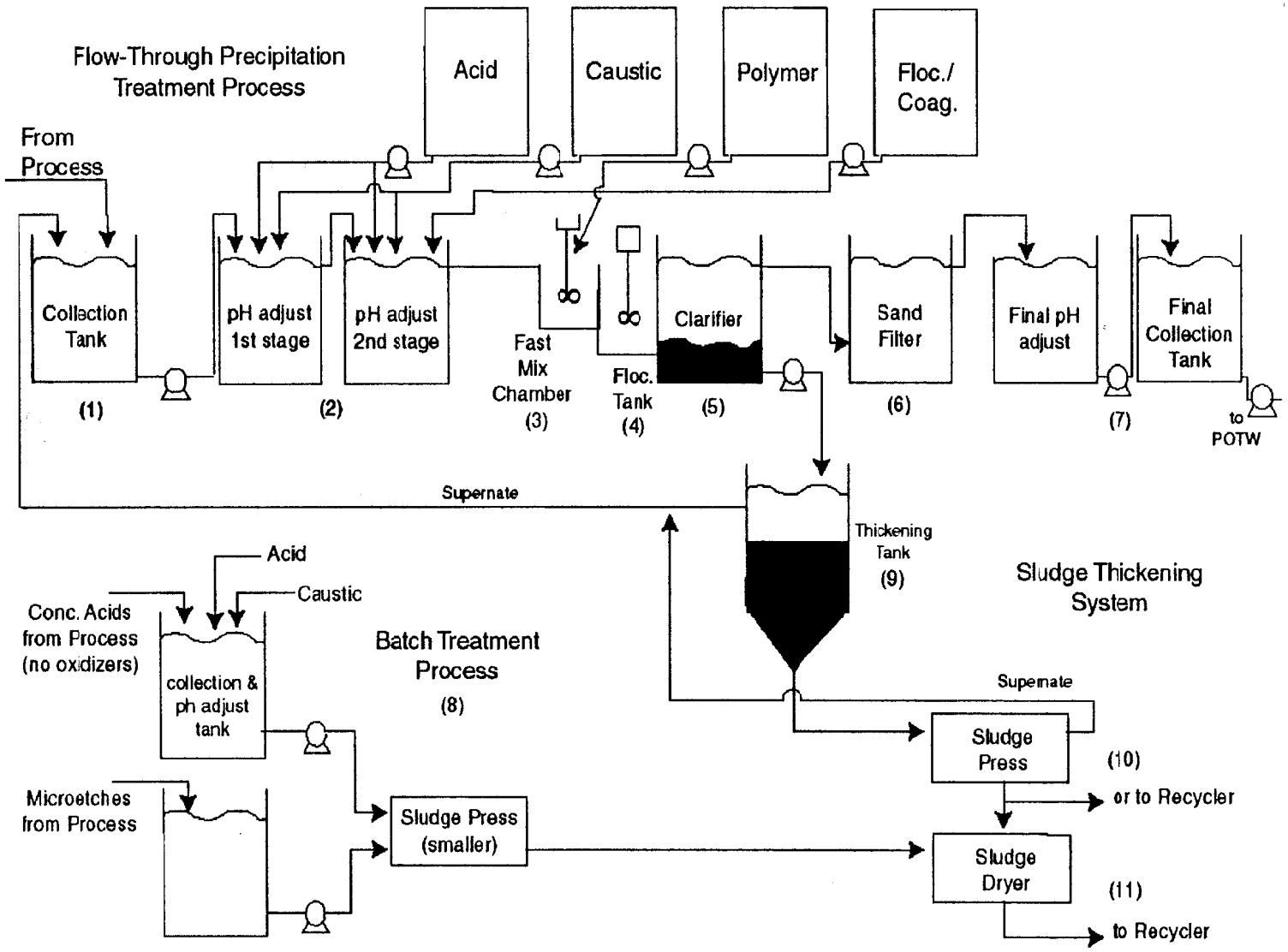


Figure 6-4. Typical PWB Waste Treatment System

Treatment of Wastewater Containing Chelated Metals. The presence of complexing chemicals or chelators, such as EDTA, formaldehyde, thiourea, and quadrol require a more vigorous effort to achieve a sufficient level of metal removal. Chelators are chemical compounds that inhibit precipitation by forming chemical complexes with the metals, allowing them to remain in solution beyond their normal solubility limits. These chemicals are found in spent surface finishing plating baths, in cleaners, and in the water effluent from the rinse tanks following these baths. Treatment chemicals enhance the removal of chelated metals from water by breaking the chelate-to-metal bond, destroying the soluble complex. The freed metal ions then react to form insoluble metal compounds, such as metal hydroxides, that precipitate out of solution.

Several different chemicals are currently being used to effectively treat chelator contaminated wastewater resulting from the manufacture of PWBs. Some common chemicals used in the treatment of wastewater produced by the surface finishing process are briefly described in Table 6-8. For more information regarding individual treatment chemicals and their applicability to treating specific wastes, consult a supplier of waste treatment chemicals.

Chelated waste streams are typically segregated from non-chelated streams to minimize the consumption of expensive treatment chemicals. Treatment of small volumes of these waste streams is typically done in a batch treatment tank. A facility with large volumes of chelated waste often will have a separate, dedicated flow-through chelated precipitation system to remove the chelated metals from the wastewater.

Alternative Treatment Processes. Although chemical precipitation (61 percent of those surveyed) is the most common process for treating wastewater used by PWB manufacturers, other treatment processes exist. Survey respondents reported the use of ion exchange (30 percent) to successfully treat wastewater generated from the manufacture of PWBs. Thirty-six percent of the ion exchange systems also combined with electrowinning to enhance treatment. These processes operate separately or in combination to efficiently remove metal ions from chelated or non-chelated waste streams, typically yielding a highly concentrated sludge for disposal. These processes were discussed in Section 6.2.1.

Despite the supplier's recommendations, PWB facilities sometimes treat individual process baths using their typical wastewater treatment process. Spent bath solutions can be mixed slowly, in small quantities, with other wastewater before being treated, thus diluting the concentration of the chemical species requiring treatment. However, the introduction of concentrated wastes to the wastewater could result in increased treatment chemical consumption and more sludge produced than if batch treated separately. Also, the introduction of a chemical species not typically found in the wastewater may adversely affect the treatment process or require more vigorous treatment chemicals or processes. Factors affecting the success of this approach include the type of treatment chemicals used, the contaminant concentrations in the wastewater, and the overall robustness of the existing, in-house treatment process.

Table 6-8. Treatment Chemicals Used to Remove Metals From Chelated Wastewater

Chemical	Description
Ferrous Sulfate	Inexpensive treatment that requires iron concentrations in excess of 8:1 of copper and other metals to form an insoluble metal hydroxide precipitate (Coombs, 1993). Ferrous sulfate is first used as a reducing agent to break down the complexed copper structures under acidic conditions before forming the metal hydroxide during subsequent pH neutralization. Drawbacks include the large volumes of sludge generated and the presence of iron which reduces the value of sludge to a reclaimer.
DTC (Dimethyl-dithiocarbamate)	Moderately expensive chemical that acts as a complexing agent, exerting a stronger reaction to the metal ion than the chelating agent, effectively forming an insoluble heavy metal complex. The sludge produced is light in density and difficult to separate by gravity (Guess, 1992; Frailey, 1996).
Sodium Sulfide	Forms metal sulfides with extremely low solubilities that precipitate even in the presence of chelators. Produces large volume of sludge that is slimy and difficult to dewater (Guess, 1992).
Polyelectrolyte	Polymers that remove metals effectively without contributing to the volume of sludge. Primary drawback is the high chemical cost (Frailey, 1996).
Sodium Borohydride	Strong reducing agent reduces metal ions, then precipitate out of solution forming a dense, low volume sludge. Drawbacks include its high chemical cost and the evolution of potentially explosive hydrogen gas (Guess, 1992; Frailey, 1996).
Ferrous Dithionite	Reduces metal ions under acidic conditions to form metallic particles that are recovered by gravity separation. Excess iron is regenerated instead of being precipitated, producing a low volume sludge (Guess, 1992).
TMT 15 (Tri-mercaptotriazine)	Designed specifically to precipitate silver ions, which are unaffected by other treatment chemicals, from wastewater. Primary drawbacks are the high chemical to silver removed weight ratio and the high chemical cost (Sharp, 1999).

Individual Alternative Treatment Profiles

There are often many approaches from which a facility can choose to properly treat and dispose of a process waste stream. Several of the approaches, which have been discussed in this CTSA chapter, include reclamation, recycling, treatment, disposal, or a combination of these. The treatment or recycling method used by a facility for each waste stream is dependent on a number of factors including discharge permit effluent limits (is more vigorous treatment required to meet effluent limits?), economics (is the treatment cost effective?), the capability of on-site treatment system (e.g., the presence of reclamation technologies), the treatment requirements of processes other than the surface finishing line (e.g., can the waste stream be combined with other waste streams to make other treatment options more applicable), and a facility's preference, based on experience. One, or a combination of several of these factors, will dictate the treatment options available to a particular facility.

Chemical suppliers offer guidance on the proper treatment and disposal of their process chemicals and are available to consult with facilities investigating treatment options. Process baths often contain proprietary ingredients that are known only to the chemical manufacturer. These may impact the manner in which the bath can be successfully treated. Prior to deciding on a treatment method for a particular bath, a PWB manufacturer should consult with the chemical supplier to confirm the applicability of the method and to identify any problems or concerns that may arise.

A profile for treating PWB surface finishing chemical baths is given in Table 6-9. The profile was developed and reviewed by PWB manufacturers participating in this project as an example of the treatment requirements of the individual chemical baths. Treatment of similar baths by individual facilities may differ from that presented in Table 6-9, according to the requirements/preferences of each facility.

Batch treatment is indicated for bath types containing chemicals or metals that require special treatment considerations beyond that provided by the precipitation system. Batch treatment could be required due to the presence of chelating agents, oxidizers, pH concerns, chemical constituents not affected by precipitation (e.g., organic compounds, silver which is unaffected by typical treatment chemicals, etc.), or to minimize the use of expensive treatment chemicals. After batch treatment, the remaining supernatant may be fed through the precipitation system for additional treatment, if required, drummed and sent out, or disposed directly to the POTW, if it meets the effluent limits of the facility.

The batch treatment of microetches is typically done separately from other process wastes due to the presence of chemical oxidizers in the microetch baths. Oxidizers commonly found in PWB waste streams include nitric acid, peroxides, persulfates, and permanganates. These compounds evolve gas during the treatment process, which hinders floc settling and, thereby, reduces the overall efficiency of the treatment process. Waste streams containing oxidizers can often be combined during treatment.

Metal reclamation is indicated for baths with metal concentrations that might typically exceed effluent limits, or that are too valuable to simply discard. Metals reclamation can be performed on-site using one, or a combination of metal recovery technologies, or can be sent off-site to a metal refiner.

Table 6-9. Treatment Profile of PWB Surface Finishing Process Baths

Bath Type	Process(es)	Chelated	Typical Treatment Method [a]
Acid Dip	Nickel/Gold and Nickel /Palladium/Gold	N	Batch treatment - no oxidizers.
Catalyst	Nickel/Gold and Nickel /Palladium/Gold	N	Metals reclamation on-site or off-site.
Cleaner	All	Y	Batch treatment - no oxidizers.
Drag-out Rinse (following gold, palladium)	Nickel/Gold and Nickel /Palladium/Gold	Y	Metals reclamation on-site or off-site.
Electroless Gold	Nickel/Gold and Nickel /Palladium/Gold	Y	Metals reclamation on-site or off-site.
Electroless Nickel	Nickel/Gold and Nickel /Palladium/Gold	Y	Batch treatment - no oxidizers for chelated waste streams.
Electroless Palladium	Nickel/Gold and Nickel /Palladium/Gold	Y	Metals reclamation on-site or off-site.
Flux	HASL	N	Hazardous waste disposal.
Immersion Silver	Immersion Silver	Y	Point of generation treatment equipment (e.g., ion exchange, iron exchange, etc.) to remove silver, then to batch treatment - no oxidizers for chelated streams.
Immersion Tin	Immersion Tin	Y	Batch treatment for the destruction of thiourea followed by precipitation treatment to remove the remaining tin.
Microetch	All	N	Batch treatment - oxidizers only.
OSP	OSP	N	Batch treatment - no oxidizers.
Predip	Immersion Tin and Immersion Silver	N	Batch treatment - no oxidizers.
Solder/Dross	HASL	N	Metals reclamation off-site.
Water Rinse	All	N	Flow-through precipitation system.

Source: Sharp, 1999.

[a] Treatment methods represent the typical method by which the bath is treated. Indicated method is not the only way a bath may be treated by an individual facility. Typical methods were developed and reviewed by PWB manufacturer project participants.

Air Pollution Control Technologies

Air pollution control technologies are often used by the PWB industry to cleanse air exhaust streams of harmful fumes and vapors. Exactly half (50 percent) of the PWB facilities surveyed have installed air scrubbers to control air emissions from various manufacturing processes, and almost a quarter of the facilities (23 percent) scrub air releases from surface finishing processes. The first step of any air control process is the effective containment of fugitive air emissions at their source of release. This is accomplished using fume hoods over the

process areas from which the air release of concern occurs. These hoods may be designed to continuously collect air emissions for treatment by one of the methods described below.

Gas Absorption. One method for removing pollutants from an exhaust stream is by gas absorption in a technique sometimes referred to as air scrubbing. Gas absorption is defined as the transfer of material from a gas to a contacting liquid or solvent. The pollutant is chemically absorbed and dispersed into the solvent, leaving the air free of the pollutant. The selection of an appropriate solvent should be based on the liquid's solubility for the solute, and the cost of the liquid. Water is used for the absorption of water-soluble gases, while alkaline solutions are typically used for the absorption of acid gases. Air scrubbers are used by the PWB industry to treat wet process air emissions, such as formaldehyde and acid fumes, and emissions from other processes other than the surface finishing process.

Gas absorption is typically carried out in a packed gas absorption tower, or scrubber. The gas stream enters the bottom of the tower and passes upward through a wetted bed of packing material before exiting the top. The absorbing liquid enters the top of the tower and flows downward through the packing before exiting at the bottom. Absorption of the air pollutants occurs during the period of contact between the gas and liquid. The gas is either physically or chemically absorbed and dispersed into the liquid. The liquid waste stream then is sent to water treatment before being discharged to the sewer. Although the most common method for gas absorption is the packed tower, other methods exist such as plate towers, sparged towers, spray chambers, or venturi scrubbers (Cooper and Alley, 1990).

Gas Adsorption. The removal of low concentration organic gases and vapors from an exhaust stream can be achieved by the process of gas adsorption. Adsorption is the process in which gas molecules are retained on the interface surfaces of a solid adsorbent by either physical or chemical forces. Activated carbon is the most common adsorbent, but zeolites, such as alumina and silica, are also used. Adsorption is used primarily to remove volatile, organic compounds from air, but is also used in other applications such as odor control and drying process gas streams (Cooper and Alley, 1990). In a surface finishing process, gas adsorption can be used to recover volatile organic compounds, such as formaldehyde.

Gas adsorption occurs when the vapor-laden air is collected and then passed through a bed of activated carbon or another adsorbent material. The gas molecules are adsorbed onto the surface of the material, while the clean, vapor-free air is exhausted from the system. The adsorbent material eventually becomes saturated with organic material and must be replaced or regenerated. Adsorbent canisters, which are replaced on a regular basis, are typically used to treat small gas flow streams. Larger flows of organic pollutants require packed beds of adsorbent material, which must be regenerated when the adsorbent becomes saturated (Cooper and Alley, 1990).

Regeneration of the adsorbent is typically accomplished by a steam-stripping process. The adsorbent is contacted with low-pressure steam which desorbs the adsorbed gas molecules from the surface of the packed bed. Following condensation of the steam, the organic material is recovered from the water by either decanting or distillation (Campbell and Glenn, 1990).

REFERENCES

Bayes, Martin. 1996. Shipley Company. Personal communication to Jack Geibig, UT Center for Clean Products and Clean Technologies. January.

Brooman, Eric. 1996. Concurrent Technologies Corporation. Personal communication to Lori Kincaid, UT Center for Clean Products and Clean Technologies. August 5.

Campbell, M. and W. Glenn. 1990. "Profit from Pollution Prevention." Pollution Probe Foundation.

Capsule Environmental Engineering, Inc. 1993. "Metal Finishing Pollution Prevention Guide." Prepared for Minnesota Association of Metal Finishers in conjunction with The Minnesota Technical Assistance Program. Prepared by Capsule Environmental Engineering, Inc., 1970 Oakcrest Avenue, St. Paul, MN 55113. July.

Coombs, Jr., Clyde. 1993. *Printed Circuits Handbook*. 4th ed. McGraw-Hill.

Cooper, David C. and F.C. Alley. 1990. *Air Pollution Control: A Design Approach*. Waveland Press, Prospect Heights, IL.

Edwards, Ted. 1996. Honeywell. Personal communication to Lori Kincaid, UT Center for Clean Products and Clean Technologies. July 10.

Fehrer, Fritz. 1996. Silicon Valley Toxics Coalition. Personal communication to Lori Kincaid, UT Center for Clean Products and Clean Technologies. July 22.

Fellman, Jack D. 1997. "On-Site Solder Purification for HASL." In: Proceedings of the IPC Printed Circuits Expo 97, San Jose, CA, March 9-13.

Frailey, Dean. 1996. Morton International. Personal communication to Jack Geibig, UT Center for Clean Products and Clean Technologies. May 7.

Guess, Robert. 1992. Romar Technologies. United States Patent # 5,122,279. July 16.

Hosea, J. Michael. 1998. "Water Reuse for Printed Circuit Boards - When Does It Make Sense?" In: Proceedings of the IPC Printed Circuits Expo 98, Long Beach, CA. April 26-30.

Iraclidis, Taso. 1998. "Wastewater Treatment Technologies of Choice for the Printed Circuit Board Industry." In: Proceedings of the IPC Printed Circuits Expo 98, Long Beach, CA. April 26-30.

Kling, David J. 1995. Director, Pollution Prevention Division, Office of Pollution Prevention and Toxics. Memo to Regional OPPT, Toxics Branch Chiefs. February 17.

Lee, Matthew A. 1999. "*Controlling Emissions Stemming From The Hot Air Solder Leveling*

Process." From the Proceedings of the Technical Conference, IPC Printed Circuits Exposition 1999, March 14-18, Long Beach, CA. Prepared by Ceco Filters, Conshohocken, PA.

Pontius, Frederick W. (ed). 1990. *Water Quality and Treatment: A Handbook of Community Water Supplies*. 4th ed. American Water Works Association, McGraw-Hill, Inc.

Schectman, Michael. 2000. Technic. Personal communication to Jack Geibig, UT Center for Clean Products and Clean Technologies. (Series of personal communications.)

Sharp, John. 1999. Teradyne. Personal communication to Jack Geibig, UT Center for Clean Products and Clean Technologies. (Series of personal communications.)

U.S. EPA (Environmental Protection Agency). 1990. *Guides to Pollution Prevention: The Printed Circuit Board Manufacturing Industry*. EPA Office of Resource and Development, Cincinnati, OH. EPA/625/7-90/007. June.

U.S. EPA (Environmental Protection Agency). 1995a. "Printed Wiring Board Case Study 1: Pollution Prevention Work Practices." Pollution Prevention Information Clearinghouse (PPIC). Washington, D.C. EPA 744-F-95-004. July.

U.S. EPA (Environmental Protection Agency). 1995b. "Printed Wiring Board Case Study 2: On-Site Etchant Regeneration." Pollution Prevention Information Clearinghouse (PPIC). Washington, D.C. EPA 744-F-95-005. July.

U.S. EPA (Environmental Protection Agency). 1996a. "Printed Wiring Board Project: Opportunities for Acid Recovery and Management." Pollution Prevention Information Clearinghouse (PPIC). Washington, D.C. EPA 744-F-95-009. September.

U.S. EPA (Environmental Protection Agency). 1996b. "Printed Wiring Board Project: Plasma Desmear: A Case Study." Pollution Prevention Information Clearinghouse (PPIC). Washington, D.C. EPA 744-F-96-003. September.

U.S. EPA (Environmental Protection Agency). 1996c. "Printed Wiring Board Project: A Continuous-Flow System for Reusing Microetchant." Pollution Prevention Information Clearinghouse (PPIC). Washington, D.C. EPA 744-F-96-024. December.

U.S. EPA (Environmental Protection Agency). 1997a. "Pollution Prevention beyond Regulated Materials." Pollution Prevention Information Clearinghouse (PPIC). Washington, D.C. EPA744-F-97-006. May.

U.S. EPA (Environmental Protection Agency). 1997b. "Identifying Objectives for Your Environmental Management System." Pollution Prevention Information Clearinghouse (PPIC). Washington, D.C. EPA744-F-97-009. December.

U.S. EPA (Environmental Protection Agency). 1997c. "Building an Environmental Management System - HR Industry Experience." Pollution Prevention Information Clearinghouse (PPIC).

Washington, D.C. EPA744-F-97-010. December.

U.S. EPA (Environmental Protection Agency). 1998. *Printed Wiring Board Pollution Prevention and Control Technology: Analysis of Updated Survey Results.* Design for the Environment Printed Wiring Board Project. EPA Office of Pollution Prevention and Toxics. Washington, D.C. EPA 744-R-98-003. August.

U.S. EPA (Environmental Protection Agency). 1999. "Pollution Prevention beyond Regulated Materials." Pollution Prevention Information Clearinghouse (PPIC). Washington, D.C. EPA744-F-97-004. May.

Chapter 7
Choosing Among Surface Finishing Technologies

This chapter of the Cleaner Technologies Substitutes Assessment (CTSA) organizes data collected or developed throughout the assessment of the baseline non-conveyorized hot air soldering level (HASL) process and alternatives, in a manner that facilitates decision-making. First, risk, competitiveness, and conservation data are summarized in Section 7.1. This information is used in Section 7.2 to assess the private and external benefits and costs (which constitute the societal benefits and costs) of implementing an alternative as compared to the baseline. Section 7.3 provides summary profiles for the baseline and alternatives.

Information is presented for six technologies for performing the surface finishing function. These technologies are HASL, nickel/gold, nickel/palladium/gold, organic solderability preservative (OSP), immersion silver, and immersion tin. All of these technologies are wet chemistry processes, except the HASL technology, which combines a wet chemistry pre-cleaning process with the mechanical process of applying the solder. The wet chemistry processes can be operated using vertical, immersion-type, non-conveyorized equipment or horizontal, conveyorized equipment. The HASL process can be applied in either equipment mode. Table 7-1 presents the processes (alternatives and equipment configurations) evaluated in the CTSA.

Table 7-1. Surface Finishing Processes Evaluated in the CTSA

Surface Finishing Technology	Equipment Configuration	
	Non-Conveyorized	Conveyorized
HASL (Baseline)	X	X
Nickel/Gold	X	
Nickel/Palladium/Gold	X	
OSP	X	X
Immersion Silver		X
Immersion Tin	X	X

The results of the CTSA comparing alternative surface finishes are mixed, with some of the alternatives offering environmental and/or economic benefits, or both, when compared to the baseline non-conveyorized HASL process. The results of the risk screening and comparison of the alternatives were also mixed, while results of the performance demonstration indicate that all of the alternative finishes perform as well as the baseline. In addition, it is important to note that there are additional factors beyond those assessed in this CTSA that individual businesses may consider when choosing among alternatives. None of these sections make value judgements or recommend specific alternatives. The intent of this document is to provide information for decision-makers to consider, although the actual decision of whether or not to implement an alternative is made outside of the CTSA process.

7.1 RISK, COMPETITIVENESS, AND CONSERVATION DATA SUMMARY

Earlier sections of the CTSA evaluated the risk, performance, cost, and resource requirements of the baseline surface finishing technology as well as the alternatives. This section summarizes the findings associated with the analysis of surface finishing technologies. Relevant data include the following:

- Risk information: occupational health risks, public health risks, ecological hazards, and process safety concerns.
- Competitiveness information: technology performance, cost and regulatory status, and international information.
- Conservation information: energy and natural resource use.

Sections 7.1.1 through 7.1.3 present risk, competitiveness, and conservation summaries, respectively.

7.1.1 Risk Summary

The risk screening and comparison uses a health-hazard based framework and a model facility approach to compare the potential health risks of one surface finishing process technology to the potential risks associated with switching to an alternative technology. As much as possible, reasonable and consistent assumptions are used across alternatives. Data to characterize the model facility and exposure patterns for each process alternative were aggregated from a number of sources, including printed wiring board (PWB) shops in the United States, supplier data, and input from PWB manufacturers at project meetings. Thus, the model facility is not entirely representative of any one facility, and actual risk could vary substantially, depending on site-specific operating conditions and other factors.

When using the risk results to compare potential health effects among alternatives, it is important to remember that this is a screening level rather than a comprehensive risk characterization, both because of the predefined scope of the assessment and because of exposure and hazard data limitations. It should also be noted that this approach does not result in any absolute estimates or measurements of risk, and even for comparative purposes, there are several important uncertainties associated with this assessment (see Section 3.4).

The Exposure Assessment, whenever possible, used a combination of central tendency and high-end assumptions, as would be used for an overall high-end exposure estimate. Some values used in the exposure calculations, however, are better characterized as “what-if,” especially pertaining to exposure frequency, bath concentrations, use of gloves, and process area ventilation rates for a model facility. Because some part of the exposure assessment for both inhalation and dermal exposures qualifies as a “what-if” descriptor, the entire assessment should be considered “what-if.”

As with any evaluation of risk, there are a number of uncertainties involved in the measurement and selection of hazard data, and in the data, models, and scenarios used in the exposure assessment. Uncertainties arise both from factors common to all risk characterizations (e.g., extrapolation of hazard data from animals to humans, extrapolation from the high doses used in animal studies to lower doses to which humans may be exposed, and missing toxicity data, including data on the cumulative or synergistic effects of chemical exposure), and other factors that relate to the scope of the risk characterization (e.g., the surface finishing characterization is a screening level characterization rather than a comprehensive risk assessment). Key uncertainties in the risk characterization include the following:

- The risk estimates for occupational dermal exposure are based on limited dermal toxicity data, using oral toxicity data with oral to dermal extrapolation when dermal toxicity data were unavailable. Coupled with the high uncertainty in estimating dermal absorption rates, this could result in either over- or under-estimates of exposure and risk.
- The exposure assessment is based on modeled estimates of average, steady-state chemical concentrations in air, rather than actual monitoring data of average and peak air concentrations.
- The exposure assessment does not account for any side reactions occurring in the baths, which could either underestimate exposures to toxic reaction products or overestimate exposures to toxic chemicals that react in the bath to form more benign chemicals.
- Due to resource constraints, the risk screening and comparison does not address all types of exposures that could occur from surface finishing processes or the PWB industry, including short-term or long-term exposures from sudden releases due to fires, spills, or periodic releases.
- For aquatic risk, surface water concentrations are based on estimated releases to a modeled, representative stream flow for the electronics industrial sector.

The Risk Characterization section of the CTSA (Section 3.4) discusses the uncertainties in this characterization in more detail.

Occupational Health Risks

Health risks to workers are estimated for inhalation exposure to vapors and aerosols from surface finishing baths and for dermal exposure to surface finishing bath chemicals. Inhalation exposure estimates are based on the assumptions that emissions to indoor air from conveyorized lines are negligible, that the air in the process room is completely mixed and chemical concentrations are constant over time, and that no vapor control devices (e.g., bath covers) are used in non-conveyorized lines. Dermal exposure estimates are based on the conservative assumptions that workers do not wear gloves and that all non-conveyorized lines are operated by manual hoist. Dermal exposure to line operators on non-conveyorized lines is estimated for routine line operation and maintenance (e.g., bath replacement, filter replacement), and on conveyorized lines for bath maintenance activities alone.

Based on the number of chemicals with risk results above concern levels, some alternatives to the non-conveyorized HASL process appear to pose lower occupational risks (i.e., immersion silver, conveyorized and non-conveyorized immersion tin, and conveyorized HASL),

some may pose similar levels of risk (i.e., conveyorized and non-conveyorized OSP), and some may pose higher risk (i.e., nickel/gold and nickel/palladium/gold). There are occupational inhalation risk concerns for chemicals in the non-conveyorized HASL, nickel/gold, nickel/palladium/gold, and OSP processes. There are also occupational risk concerns for dermal contact with chemicals in the non-conveyorized HASL, nickel/gold, nickel/palladium/gold, OSP, and immersion tin processes, and the conveyorized HASL and OSP processes.

Table 7-2 presents chemicals of concern for potential occupational risk from inhalation. Table 7-3 presents chemicals of concern for potential occupational risk from dermal contact.

Table 7-2. Surface Finishing Chemicals of Concern for Potential Occupational Inhalation Risk

Chemical	Process [a] (Non-Conveyorized, 260,000 ssf)			
	HASL	Nickel/Gold	Nickel/Palladium/Gold	OSP
Alkyldiol		X	X	
Ethylene glycol	X			X
Hydrochloric acid		X	X	
Hydrogen peroxide		X	X	
Nickel sulfate		X	X	
Phosphoric acid		X	X	
Propionic acid			X	

[a] Non-conveyorized immersion silver process not evaluated. Occupational exposure and risk from all conveyorized process configurations are below concern levels.
X Line operator risk results above concern levels (non-cancer health effects).

The non-conveyorized nickel/gold process contains the only chemical for which an occupational cancer risk has been estimated (inorganic metallic salt A). The line operator inhalation exposure estimate for inorganic metallic salt A results in an estimated upper bound excess individual life time cancer risk of 2×10^{-7} (one in five million) based on high end exposure. Cancer risks less than 1×10^{-6} (one in one million) are generally considered to be of low concern. Risks to other types of workers[1] were assumed to be proportional to the average amount of time spent in the process area, which ranged from 12 to 69 percent of the risk for a line operator.

[1] These include laboratory technicians, maintenance workers, and wastewater treatment operators. Other types of workers may be present for shorter or longer times.

Table 7-3. Chemicals of Concern for Potential Dermal Risks

Chemical	Process Configuration [a]						
	HASL (NC)	HASL (C)	Nickel/Gold (NC)	Nickel/ Palladium/Gold (NC)	OSP (NC)	OSP (C)	Immersion Tin (NC)
Ammonia compound A				X			
Ammonium chloride			X				
Ammonium hydroxide			X	X			
Copper ion					XX	XX	
Copper salt C					XX	X	
Copper sulfate pentahydrate	XX	XX	XX	XX	XX	XX	
Ethylene glycol monobutyl ether							X
Hydrogen peroxide			X	X			
Inorganic metallic salt B			XX	XX			
Lead	†	†					
Nickel sulfate			XX	XX			
Urea compound C							X

[a] No risk results were above concern levels for the conveyorized immersion silver or conveyorized immersion tin processes.
X Line operator risk results above concern levels (non-cancer health effects).
XX Line operator and laboratory technician risk results above concern levels (non-cancer health effects).
†: Risk indicators were not calculated for lead as with the other chemicals (see Section 3.4.6). Other information, however, indicates that incidental ingestion of lead from contact with hands could result in lead exposure at levels of concern.
C: Conveyorized (horizontal) process configuration
NC: Non-conveyorized (vertical) process configuration.

Other identified chemicals in the surface finishing processes are suspected or known carcinogens. Lead and thiourea have been determined by IARC to be possible human carcinogens (IARC Group 2B); lead has also been classified by EPA as a probable human carcinogen (EPA Class B2). Lead is used in tin-lead solder in the HASL process. Thiourea is used in the immersion tin process. Urea compound B, a confidential ingredient in the nickel/gold and nickel/palladium/gold processes, is possibly carcinogenic to humans. Exposure for workers from these chemicals has been estimated, but cancer potency and cancer risks are unknown. Additionally, strong inorganic and acid mists of sulfuric acid have been determined by IARC to be a human carcinogen (IARC Group 1). Sulfuric acid is used in diluted form in every surface finishing process in this evaluation. It is not expected, however, to be released to the air as a strong acid mist. There are potential cancer risks to workers from these chemicals, but because there are no slope factors, the risks cannot be quantified.

For non-cancer risk, risk indicators exceeding concern levels – a hazard quotient (HQ) greater than one, a margin of exposure (MOE) based on no-observed adverse effect level (NOAEL) lower than 100, or MOE based on a lowest-observed adverse effect level (LOAEL) lower than 1,000 – were estimated for occupational exposures to chemicals in the non-conveyorized and conveyorized HASL processes, non-conveyorized nickel/gold process, non-

conveyorized nickel/palladium/gold process, non-conveyorized and conveyorized OSP processes, and the non-conveyorized immersion tin process.

Based on calculated occupational exposure levels, there may be adverse health effects to workers exposed to chemicals with a HQ exceeding 1.0 or an MOE less than 100 or 1,000. However, it should be emphasized that these conclusions are based on screening level estimates. These numbers are used here for relative risk comparisons between processes, and should not be used as absolute indicators for actual health risks to surface finishing line workers.

Worker blood-lead levels measured at one PWB manufacturing facility were below any federal regulation or guideline for workplace exposure. Modeling data, however, show that it may be possible for blood-lead levels to exceed recommended levels for an adult and fetus, given high incidental ingestion rates of lead from handling solder. These results are highly uncertain; ingestion rates are based on incidental soil ingestion rates for adults in contact with soil. However, this indicates the need for good personal hygiene for HASL line operators, especially wearing gloves and hand washing to prevent accidental hand-to-mouth ingestion of lead.

Public Health Risks

Potential public health risk was estimated for inhalation exposure for the general public living near a PWB facility. Public exposure estimates are based on the assumption that emissions from both conveyorized and non-conveyorized process configurations are vented to the outside. The risk indicators for ambient exposures to humans, although limited to airborne releases, indicate low concern for nearby residents. The upper bound excess individual cancer risk for nearby residents from inorganic metallic salt A in the non-conveyorized nickel/gold process was estimated to be from approaching zero to 2×10^{-11} (one in 50 billion). This chemical has been classified as a human carcinogen.[2] All hazard quotients are less than one for ambient exposure to the general population, and all MOEs for ambient exposure are greater than 1,000 for all processes, indicating low concern from the estimated air concentrations for chronic non-cancer effects.

Estimated ambient air concentrations of lead from a HASL process are well below EPA air regulatory limits for lead, and risks to the nearby population from airborne lead are expected to be below concern levels.

Ecological Risks

We calculated ecological risk indicators (RI_{ECO}) for non-metal surface finishing chemicals that may be released to surface water. Risk indicators for metals are not used for comparing alternatives because it is assumed that on-site treatment is targeted to remove metal so that permitted concentrations are not exceeded. Estimated surface water concentrations for non-metals exceeded the concern concentration (CC) in the following processes: four in the non-

[2] A cancer classification of known human carcinogen has been assigned by either the EPA, IARC, and/or NTP. Further details about the carcinogen classification are not provided in order to protect the confidential chemical identity.

conveyorized HASL process, three in the conveyorized HASL process, one in the non-conveyorized OSP process, one in the conveyorized OSP process, one in the conveyorized immersion silver process, and one in the non-conveyorized immersion tin process. Table 7-4 presents chemicals of concern based on ecological risk indicator results.

Table 7-4. Aquatic Risk of Non-Metal Chemicals of Concern

Chemical	HASL (NC)	HASL (C)	OSP (NC)	OSP (C)	Immersion Silver (C)	Immersion Tin (NC)
Alkylaryl imidazole			X	X		
Alkylaryl sulfonate	X	X				
1,4-Butenediol	X					
Hydrogen peroxide	X	X			X	
Potassium peroxymonosulfate	X	X				X

Estimated surface water concentration > concern concentration (CC) after POTW treatment.

A CC is the concentration of a chemical in the aquatic environment which, if exceeded, may result in significant risk to aquatic organisms. CCs were determined by dividing acute or chronic toxicity values by an assessment factor (ranging from one to 1,000) that incorporates the uncertainty associated with toxicity data. CCs are discussed in more detail in Section 3.3.3.

Process Safety

Workers can be exposed to two types of hazards affecting occupational safety and health: chemical hazards and process hazards. Workers can be at risk through exposure to chemicals and because of close proximity to automated equipment. In order to evaluate the chemical safety hazards of the various surface finishing technologies, material safety data sheets (MSDSs) for chemical products used with each of the surface finishing technologies were reviewed. Table 7-5 summarizes the hazardous properties of surface finishing chemical products.

Other potential chemical hazards can occur because of hazardous decomposition of chemical products, or chemical product incompatibilities with other chemicals or materials. With few exceptions, most chemical products used in surface finishing technologies can decompose under specific conditions to form potentially hazardous chemicals. In addition, all of the surface finishing processes have chemical products with incompatibilities that can pose a threat to worker safety if the proper care is not taken to prevent such occurrences.

Table 7-5. Chemical Hazards

Process	No. of MSDS [a]	Hazardous Property [b]							
		F	C	E	FH	CO	O	SRP	U
HASL	33	1		1	3	4	1	1	1
Nickel/Gold	19					8	1	1	
Nickel/Palladium/Gold	18					12	1	1	
OSP	9	1			2	4	1	1	
Immersion Silver	4			1	1	2	1		1
Immersion Tin	14			1		7			

[a] For alternative processes with more than one product line, the hazard data reported represent the most hazardous bath of each type for the two product lines (e.g., of the microetch baths from the two product lines, the one with the most hazardous chemicals is reported).
[b] Formulations for HASL process baths were unavailable because cleaner and microetch bath chemistries are not made specifically for the HASL process. Hazards reported for HASL bath types were reported as the worst case of the results of similar baths from other processes.
F = Flammable; C = Combustible; E = Explosive; FH = Fire Hazard; CO = Corrosive; O = Oxidizer; SRP = Sudden Release of Pressure; U = Unstable

Work-related injuries from equipment, improper use of equipment, bypassing equipment safety features, failure to use personal protective equipment, and physical stresses that may appear gradually as a result of repetitive motion are all potential process safety hazards to workers. Regardless of the technology used, of critical importance is an effective and ongoing safety training program. Characteristics of an effective worker health and safety program include:

- an employee training program;
- employee use of personal protective equipment;
- proper chemical storage and handling; and
- safe equipment operating procedures.

Without appropriate training, the number of worker accidents and injuries is likely to increase, regardless of the technology used. A key management responsibility is to ensure that training is not compromised by pressure to meet production demands or by cost-cutting efforts.

7.1.2 Competitiveness Summary

The competitiveness summary provides information on basic issues traditionally important to the competitiveness of a business: the performance characteristics of its products relative to industry standards; the direct and indirect costs of manufacturing its products; and its need or ability to comply with environmental regulations. The final evaluation of a technology involves considering these traditional competitiveness issues along with issues that business leaders now know are equally important issues: the health and environmental impacts of alternative products, processes, and technologies.

Performance

The performance of the surface finishing technologies was tested using production run tests following a strict testing protocol. Functional test boards were fabricated using a complex test board design (a modified version of the IPC-B-24 board) developed by the Circuit Card Assembly and Materials Task Force (CCAMTF). A surface finish was then applied to test boards at each of thirteen volunteer PWB manufacturing facilities. Test boards were then collected together and assembled at an assembly facility, using either a halide-free low-residue flux or a halide-containing water-soluble flux, before being tested under thermal and mechanical stress, and accelerated aging conditions. Additional residue testing was conducted to determine the mechanism of failure. The test methods used to evaluate performance were intended to indicate characteristics of a technology's performance, not to define parameters of performance or to substitute for thorough on-site testing; the study was intended to be a "snapshot" of the technologies. The Performance Demonstration was conducted with extensive input and participation from PWB manufacturers, their suppliers, and PWB testing laboratories. The testing protocol was designed to be consistent with the industry-led CCAMTF testing of surface finishes.

The technologies tested included HASL (baseline), nickel/gold, nickel/palladium/gold, OSP, immersion silver, and immersion tin. The test vehicle measured roughly 6" x 5.8" x 0.062" and was designed to contain at least 80 percent of the circuitry used in military and commercial electronics. The test vehicle was also designed to be representative of a variety of circuits, including high current low voltage (HCLV), high voltage low current (HVLC), high speed digital (HSD), high frequency (HF), stranded wire (SW) and other networks, which were used to measure current leakage. Overall, the vehicle provided 23 separate electrical responses for testing the performance of the surface finish. Types of electrical components in the HCLV, HVLC, HSD, and HF circuits included both plated through hole (PTH) and surface mounted components.

Test sites were submitted by suppliers of the technologies, and included production facilities and supplier testing facilities. Because the test sites were not chosen randomly, the sample may not be representative of all PWB manufacturing facilities (although there is no specific reason to believe that they are not representative). In addition, the number of test sites for each technology ranged from one to four. Due to the smaller number of test sites for some technologies, statistical relevance could not be determined.

The results of the performance testing showed that all of the surface finishes under study were very robust to the environmental exposures, with two exceptions. Failures during the mechanical shock testing, resulting in the separation of the surface mount components, were attributable to the severity of the testing, and spread evenly across all finishing technologies, including the baseline HASL process. Failures in the high frequency, low pass filter circuits, resulting from open PTH, were found to be attributable to a combination of board fabrication materials and board design. From an overall contamination standpoint, the five non-HASL surface finishes performed as well, if not better than the HASL finish. The few solder joint cracking failures were greater with the HASL finish, than with the alternative finishes.

Cost

Comparative costs were estimated using a hybrid cost model that combined traditional costs with simulation modeling and activity-based costs. The cost model was designed to determine the total cost of processing a specific amount of PWB through a fully operational surface finishing line, in this case, 260,000 surface square feet (ssf). Total costs were divided by the throughput to determine a unit cost in $/ssf. Costs not related to the steady-state operation of the surface finishing line, such as start-up costs or the costs of process changes required to other process to implement a change in surface finishing technology, can vary widely by facility and were not estimated by the model.

The cost components considered include capital costs (primary equipment & installation costs, and facility costs), materials costs (limited to chemical costs), utility costs (water, electricity, and natural gas costs), wastewater cost (limited to wastewater discharge cost), production costs (production labor and chemical transport costs), and maintenance costs (tank cleanup, bath setup, sampling and analysis, and filter replacement costs). Other cost components may contribute significantly to overall costs, but were not quantified because they could not be reliably estimated. These include wastewater treatment cost, sludge recycling and disposal cost, other solid waste disposal costs, and quality costs (i.e., costs from decreased production efficiency due to boards that do not meet quality specifications). However, Performance Demonstration results indicate that each surface finishing technology has the capability to achieve comparable levels of performance to HASL. Thus, quality costs are not expected to differ among the alternatives.

Table 7-6 presents results of the cost analysis. The results indicate that all of the surface finishing alternatives were more economical than the baseline non-conveyorized HASL process, with the exception of the two technologies containing gold, an expensive precious metal. Unit costs ranged from $0.10/ssf for the conveyorized OSP process to $1.54/ssf for the non-conveyorized nickel/palladium/gold process. Three processes had a substantial cost savings of at least 50 percent of the cost per ssf over that of the baseline HASL process (conveyorized OSP at 72 percent, non-conveyorized OSP at 69 percent, and non-conveyorized immersion tin at 50 percent). Three other process alternatives realized a somewhat smaller cost savings over the baseline HASL process (conveyorized immersion tin at 31 percent, conveyorized immersion silver at 22 percent, and the conveyorized HASL process at 3 percent).

In general, conveyorized processes cost less than non-conveyorized processes of the same technology due to the cost savings associated with their higher throughput rates. The lone exception, immersion tin, was more costly because the combination of process cycle time and conveyor length resulted in a lower throughput rate than its non-conveyorized version.

Chemical cost was the single largest component cost for all of the nine processes. Labor costs were the second largest cost component, though far less than the cost of process chemicals.

Table 7-6. Cost of Surface Finishing Technologies

Cost Category	Cost Components	HASL (NC)	HASL (C)	Nickel/Gold (NC)
Capital Cost	Primary Equipment & Installation	$9,360	$11,100	$7,260
	Facility	$432	$398	$2,930
Material Cost	Chemicals	$74,800	$75,200	$109,000
Utility Cost	Water	$706	$565	$1,180
	Electricity	$669	$452	$2,360
	Natural Gas	$88	$45	$0
Wastewater Cost	Wastewater Discharge	$1,100	$851	$2,050
Production Cost	Transportation of Material	$167	$130	$668
	Labor for Line Operation	$3,940	$1,790	$19,100
Maintenance Cost	Tank Cleanup	$1,210	$938	$4,820
	Bath Setup	$272	$211	$1,090
	Sampling and Testing	$499	$249	$3,530
	Filter Replacement	$967	$482	$1,580
Total Cost		**$94,200**	**$92,400**	**$156,000**
Unit Cost ($/ssf)		**$0.36**	**$0.35**	**$0.60**

Cost Category	Cost Components	Nickel/Palladium/Gold (NC)	OSP (NC)	OSP (C)
Capital Cost	Primary Equipment & Installation	$15,400	$1,640	$2,880
	Facility	$6,090	$313	$264
Material Cost	Chemicals	$321,000	$18,500	$18,800
Utility Cost	Water	$2,060	$441	$301
	Electricity	$4,050	$313	$208
	Natural Gas	$0	$67	$32
Wastewater Cost	Wastewater Discharge	$3,530	$704	$462
Production Cost	Transportation of Material	$1,030	$158	$121
	Labor for Line Operation	$25,200	$3,170	$1,320
Maintenance Cost	Tank Cleanup	$7,440	$1,140	$871
	Bath Setup	$1,680	$257	$196
	Sampling and Testing	$8,900	$1,610	$738
	Filter Replacement	$2,830	$330	$151
Total Cost		**$399,000**	**$28,700**	**$26,300**
Unit Cost ($/ssf)		**$1.54**	**$0.11**	**$0.10**

Table 7-6. Cost of Surface Finishing Technologies (cont.)

Cost Category	Cost Components	Immersion Silver (C)	Immersion Tin (NC)	Immersion Tin (C)
Capital Cost	Primary Equipment & Installation	$10,500	$2,950	$16,800
	Facility	$937	$892	$2,340
Material Cost	Chemicals	$52,700	$29,000	$28,900
Utility Cost	Water	$301	$1,030	$702
	Electricity	$739	$494	$1,230
	Natural Gas	$140	$162	$240
Wastewater Cost	Wastewater Discharge	$529	$1,620	$1,215
Production Cost	Transportation of Material	$167	$204	$167
	Labor for Line Operation	$5,260	$6,780	$8,770
Maintenance Cost	Tank Cleanup	$1,210	$1,470	$1,210
	Bath Setup	$272	$332	$272
	Sampling and Testing	$937	$1,260	$1,800
	Filter Replacement	$80	$705	$1,000
Total Cost		**$73,800**	**$46,900**	**$64,700**
Unit Cost ($/ssf)		**$0.28**	**$0.18**	**$0.25**

Regulatory Status

Discharges of surface finishing chemicals may be restricted by federal, state, or local air, water, or solid waste regulations, and releases may be reportable under the federal Toxics Release Inventory program. Federal environmental regulations were reviewed to determine the federal regulatory status of surface finishing chemicals.[3] Table 7-7 lists the number of chemicals used in a surface finishing technology with federal environmental regulations restricting or requiring reporting of their discharges. Different chemical suppliers of a technology do not always use the same chemicals in their particular product lines. Thus, all of these chemicals may not be present in any one product line.

[3] In some cases, state or local requirements may be more restrictive than federal requirements. However, due to resource limitations, only federal regulations were reviewed.

Table 7-7. Regulatory Status of Surface Finishing Technologies

Process Chemical	Number of Chemicals Subject to Applicable Regulation														
	CWA				CAA			EPCRA			TSCA			RCRA Waste	
	304b	307a	311	Priority Pollutant	111	112b	112r	313	110	302a	8d HSDR	MTL	8a PAIR	P	U
HASL	1	1	4	1	3	3	1	6	1	3	3	4	3	-	-
Nickel/Gold	6	6	16	6	11	6	1	12	7	3	1	4	3	-	-
Nickel/Palladium/Gold	5	5	12	5	5	5	1	10	6	3	1	4	4	-	-
OSP	2	2	5	2	3	2	1	5	2	2	1	2	1	-	-
Immersion Silver	1	1	5	1	1	1	-	313			-	1	1	-	-
Immersion Tin	1	1	6	1	3	2	1	7	1	2	2	4	3	-	2

Abbreviations and definitions:

CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants -Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA - Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory
RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
SDWA - Safe Drinking Water Act
SDWA NPDWR - National Primary Drinking Water Rules
SDWA NSDWR - National Secondary Drinking Water Rules
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & Safety Data Reporting Rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

7.1.3 Resource Conservation Summary

Resources typically consumed by the operation of the surface finishing process include water used for rinsing panels, process chemicals used in the process line, energy used to heat process baths and power equipment, and wastewater treatment chemicals. A quantitative analysis of the energy and water consumption rates of the surface finishing process alternatives was performed to determine if implementing an alternative to the baseline process would reduce consumption of these resources during the manufacturing process. A quantitative analysis of both process chemical and treatment chemical consumption could not be performed due to the variability of factors that affect the consumption of these resources. Section 5.1 discusses the role that the surface finishing process has in the consumption of these resources and the factors affecting the consumption rates.

The relative water and energy consumption rates of the surface finishing process alternatives were determined as follows:

- the daily water consumption rate and hourly energy consumption rate of each alternative were determined based on data collected from the PWB Workplace Practices Questionnaire;
- the operating time required to produce 260,000 ssf of PWB was determined using computer simulations models of each of the alternatives; and
- the water and energy consumption rates per ssf of PWB were calculated based on the consumption rates and operating times.

Table 7-8 presents the results of these analyses.

Table 7-8. Energy and Water Consumption Rates of Surface Finishing Alternatives

Process Type	Water Consumption (gal/ssf)	Energy Consumption (Btu/ssf)
HASL, Non-conveyorized (BASELINE)	1.24	218
HASL, Conveyorized	0.99	133
Nickel/Gold, Non-conveyorized	2.06	447
Nickel/Palladium/Gold, Non-conveyorized	3.61	768
OSP, Non-conveyorized	0.77	125
OSP, Conveyorized	0.53	73
Immersion Silver, Conveyorized	0.53	287
Immersion Tin, Non-conveyorized	1.81	289
Immersion Tin, Conveyorized	0.88	522

The water consumption rates for the surface finishing alternatives ranged from a low of 0.53 gal/ssf for the immersion silver and OSP conveyorized processes to a high of 3.6 gal/ssf for the non-conveyorized nickel/palladium/gold process. Several processes were found to consume less water then the HASL baseline, including conveyorized versions of the immersion silver and immersion tin technologies, along with both versions of the OSP process. Conveyorized processes were found to consume less water than non-conveyorized versions of the same process. Primary factors influencing the water consumption rate included the number of rinse tanks and the overall efficiency of the conveyorized processes.

The energy consumption rates for the surface finishing alternatives ranged from 73 Btu/ssf for the conveyorized OSP process to 768 Btu/ssf for the non-conveyorized nickel/palladium/gold process. The results indicate that three surface finishing processes are more energy efficient than the traditional non-conveyorized HASL process (conveyorized HASL, non-conveyorized OSP, and conveyorized OSP), while two others are roughly comparable (conveyorized immersion silver and non-conveyorized immersion tin). It was also found that for alternatives with both types of automation, the conveyorized version of the process is typically the more energy efficient (HASL and OSP), with the notable exception of the immersion tin process.

An analysis of the impacts directly resulting from the consumption of energy by the surface finishing process showed that the generation of the required energy has environmental impacts. Pollutants released to air, water, and soil can result in damage to both human health and the environment. The consumption of natural gas tends to result in releases to the air which contribute to odor, smog, and global warming, while the generation of electricity can result in pollutant releases to all media with a wide range of possible effects. Minimizing the amount of energy usage by the surface finishing process, either by selection of a more energy efficient process or by adopting energy efficient operating practices, will decrease the quantity of pollutants released into the environment resulting from the generation of the energy consumed.

Metals are another natural resource consumed by the surface finishing process. The rate of deposition of metal was calculated for each technology along with the total amount of metal consumed for 260,000 ssf of PWB produced, the average annual PWB production rate reported by facilities using HASL. It was shown that the consumption of close to 300 pounds of lead could be eliminated by replacing the baseline HASL process with an alternative technology (see Section 5.1, Resource Conservation). In cases where waste solder is not routinely recycled or reclaimed, the consumption of as much as 2,500 pounds of lead could be eliminated by replacement of the HASL process. Although several of the alternative technologies rely on the use of small quantities of other metals (especially nickel, palladium, gold, silver, and tin) the OSP technology eliminates metal consumption entirely.

7.2 SOCIAL BENEFITS/COSTS ASSESSMENT

7.2.1 Introduction to Social Benefits/Costs Assessment

Social benefits/costs analysis[4] is a tool used by policy makers to systematically evaluate the impacts to all of society resulting from individual decisions. The decision evaluated in this analysis is the choice of a surface finishing technology. PWB manufacturers have a number of criteria they may use to assess which surface finishing technology they will use. For example, a PWB manufacturer might ask what impact their choice of a surface finishing alternative might have on operating costs, compliance costs, liability costs, and insurance premiums. This business planning process is unlike social benefit/cost analysis, however, because it approaches the comparison from the standpoint of the individual manufacturer and not from the standpoint of society as a whole.

A social benefits/costs analysis seeks to compare the benefits and costs of a given action, while considering both the private and external costs and benefits.[5] Therefore, the analysis will consider both the impact of the alternative surface finishing processes on the manufacturer itself (private costs and benefits) and the impact the choice of an alternative has on external costs and benefits, such as environmental damage and the risk of illness for the general public. External costs are not borne by the manufacturer, but by society. Table 7-9 defines a number of terms used in benefit/cost analysis, including external costs and external benefits.

---

[4] The term "analysis" is used here to refer to a more quantitative analysis of social benefits and costs, where a monetary value is placed on the benefits and costs to society of individual decisions. Examples of quantitative benefits/costs analyses are the regulatory impact analyses done by EPA when developing federal environmental regulations. The term "assessment" is used here to refer to a more qualitative examination of social benefits and costs. The evaluation performed in the CTSA process is more correctly termed an assessment because many of the social benefits and costs of the surface finishing technologies are identified, but not monetized.

[5] Private costs typically include any direct costs incurred by the decision-maker and are generally reflected in the manufacturer's balance sheet. In contrast, external costs are incurred by parties other than the primary participants to the transaction. Economists distinguish between private and external costs because each will affect the decision-maker differently. Although external costs are real costs to some members of society, they are not incurred by the decision-maker and firms do not normally take them into account when making decisions. A common example of these "externalities" is the electric utility whose emissions are reducing crop yields for the farmer operating downwind. The external costs experienced by the farmer in the form of reduced crop yields are not considered by the utility when making decisions regarding electricity production. The farmer's losses do not appear on the utility's balance sheet.

Table 7-9. Glossary of Benefits/Costs Analysis Terms

Term	Definition
Exposed Population	The estimated number of people from the general public or a specific population group who are exposed to a chemical through wide dispersion of the chemical in the environment (e.g., DDT). A specific population group could be exposed to a chemical due to its physical proximity to a manufacturing facility (e.g., residents who live near a facility using a chemical), use of the chemical or a product containing a chemical, or through other means.
Exposed Worker Population	The estimated number of employees in an industry exposed to the chemical, process, and/or technology under consideration. This number may be based on market share data as well as estimations of the number of facilities and the number of employees in each facility associated with the chemical, process, and/or technology under consideration.
Externality	A cost or benefit that involves a third party who is not a part of a market transaction; "a direct effect on another's profit or welfare arising as an incidental by-product of some other person's or firm's legitimate activity" (Mishan, 1976). The term "externality" is a general term which can refer to either external benefits or external costs.
External Benefits	A positive effect on a third party who is not a part of a market transaction. For example, if an educational program results in behavioral changes which reduce the exposure of a population group to a disease, then an external benefit is experienced by those members of the group who did not participate in the educational program. For the example of non-smokers exposed to second-hand smoke, an external benefit can be said to result when smokers are removed from situations in which they expose non-smokers to tobacco smoke.
External Costs	A negative effect on a third party who is not part of a market transaction. For example, if a steel mill emits waste into a river which poisons the fish in a nearby fishery, the fishery experiences an external cost as a consequence of the steel production. Another example of an external cost is the effect of second-hand smoke on non-smokers.
Human Health Benefits	Economic benefit from reduced health risks to workers in an industry or business as well as to the general public as a result of switching to less toxic or less hazardous chemicals, processes, and/or technologies. An example would be switching to a less volatile organic compound, lessening worker inhalation exposures as well as decreasing the formation of photochemical smog in the ambient air.
Human Health Costs	The cost of adverse human health effects associated with production, consumption, and disposal of a firm's product. An example is respiratory effects from stack emissions, which can be quantified by analyzing the resulting costs of health care and the reduction in life expectancy, as well as the lost wages as a result of being unable to work.
Illness Costs	A financial term referring to the liability and health care insurance costs a company must pay to protect itself against injury or disability to its workers or other affected individuals. These costs are known as illness benefits to the affected individual.
Indirect Medical Costs	Indirect medical costs associated with a disease or medical condition resulting from exposure to a chemical or product. Examples would be the decreased productivity of patients suffering a disability or death and the value of pain and suffering borne by the afflicted individual and/or family and friends.

Term	Definition
Private (Internalized) Costs	The direct costs incurred by industry or consumers in the marketplace. Examples include a firm's cost of raw materials and labor, a firm's costs of complying with environmental regulations, or the cost to a consumer of purchasing a product.
Social Costs	The total cost of an activity that is imposed on society. Social costs are the sum of the private costs and the external costs. Therefore, in the example of the steel mill, social costs of steel production are the sum of all private costs (e.g., raw material and labor costs) and the sum of all external costs (e.g., the costs associated with the poisoned fish).
Social Benefits	The total benefit of an activity that society receives (i.e., the sum of the private benefits and the external benefits). For example, if a new product yields pollution prevention opportunities (e.g., reduced waste in production or consumption of the product), then the total benefit to society of the new product is the sum of the private benefit (value of the product that is reflected in the marketplace) and the external benefit (benefit society receives from reduced waste).
Willingness-to-Pay	Estimates used in benefits valuation are intended to encompass the full value of avoiding a health or environmental effect. For human health effects, the components of willingness-to-pay include the value of avoiding pain and suffering, impacts on the quality of life, costs of medical treatment, loss of income, and, in the case of mortality, the value of life.

7.2.2 Benefits/Costs Methodology and Data Availability

The methodology for conducting a social benefits/costs assessment can be broken down into four general steps: 1) obtain information on the relative human and environmental risk, performance, cost, process safety hazards, and energy and natural resource requirements of the baseline and the alternatives; 2) construct matrices of the data collected; 3) when possible, monetize the values presented within the matrices; and 4) compare the data generated for the alternative and the baseline in order to produce an estimate of net social benefits. Section 7.1 presented the results of the first task by summarizing risk, competitiveness, and conservation information for the baseline and alternative surface finishing technologies. Section 7.2.3 presents information relevant to private and external benefits and costs, in matrix form and in monetary terms where possible. Section 7.2.4 presents the private and external benefits and costs together to produce an estimate of net social benefits.

Ideally, the analysis would quantify the social benefits and costs of using the alternative and baseline surface finishing technologies, allowing identification of the technology whose use results in the largest net social benefit. However, because of resource and data limitations and because individual users of this CTSA will need to apply results to their own particular situations, the assessment presents a qualitative description of the risks and other external effects associated with each substitute technology compared to the baseline. Benefits derived from a reduction in risk are described and discussed, but not quantified. Nonetheless, the information presented can be very useful in the decision-making process. A few examples are provided to qualitatively illustrate some of the benefit considerations. Personnel in each individual facility will need to examine the information presented, weight each piece according to facility and community characteristics, and develop an independent choice.

7.2.3 Social Benefits/Costs Associated with Choice of Surface Finishing Alternative

The selection of a surface finish results in costs and benefits to society, in the form of both private and external costs and benefits. For example, an alternative that releases less toxic chemicals into the workplace air results in both private and external benefits. The manufacturer pays less for health care costs and worker sick time, while workers benefit from working in a healthier environment. Society as a whole benefits from a more competitive company in the marketplace and from reduced long-term health care costs; in other words, from the cumulative affect of the benefits or costs, both the private and external. This type of example is why particular aspects of the surface finishing process are discussed in terms of both private benefits and costs and external benefits and costs.

Private and/or external costs and benefits may occur in a number of areas, including:

- manufacturing
- occupational health/worker risk;
- public health/population risk;
- wastewater contaminants and ecological risk; and
- energy and natural resource consumption.

Table 7-10 presents an overview of potential private benefits or costs and external benefits or costs associated with the evaluated areas. Each of these is discussed in turn below. While it is difficult to obtain an overall number to express the private benefits and costs of alternative surface finishing processes, some data were quantifiable, such as manufacturing costs. However, in order to determine the overall private benefit/cost comparison, a qualitative discussion of the data is also necessary. Following the discussion of manufacturing costs are discussions of costs associated with occupational and population health risks and other costs or benefits that could not be put in terms of monetary equivalents, but are important to the decision-making process.

Manufacturing

The cost of manufacturing is considered strictly a private cost, with little or no bearing on social costs and benefits. The cost analysis estimated the average manufacturing costs of the surface finishing technologies for several categories of costs. Results of the cost analysis are shown in Table 7-11. Results show that implementation of several of the alternative processes are likely to result in reduced private costs to the manufacturing facility, and that reductions were primarily due to the lower cost of process chemicals between surface finish processes. Other cost components may contribute significantly to overall private costs for a surface finish, but were not quantified because they could not be reliably estimated. These include wastewater treatment cost, sludge recycling and disposal cost, other solid waste disposal costs, and quality costs. Refer to Chapter 4.2, Cost Assessment, for a more detailed discussion of the methodology and results of the cost assessment for surface finish alternatives.

Table 7-10. Potential Private Benefits or Costs Associated with the Selection of a Surface Finish Technology

Evaluation Category	Private Benefit or Cost [a]	External Benefit or Cost [a]
Manufacturing Costs	Capital costs. Materials (chemical) costs. Utility costs. Wastewater discharge costs. Production cost. Maintenance costs.	Not Applicable
Occupational Health/ Worker Risk	Worker sick days. Worker efficiency. Health insurance costs to the PWB manufacturer.	Long-term medical costs to workers. Pain and suffering associated with work-related illness.
Public Health/ Population Risk	Potential liability costs.	Long-term medical costs. Pain and suffering associated with illness.
Wastewater and Ecological Risk	Treatment costs to meet wastewater permit requirements. Possible fines if permits are violated. Increased liability costs.	Loss of ecosystem diversity. Reduction in the recreational value of streams and rivers.
Energy Use	Direct costs from the use of energy in the manufacturing process.	Increased air emissions. Depletion of natural resources.
Water Use	Direct costs from the use of water in the manufacturing process.	Water costs for the surrounding area. Costs paid to treatment facilities to clean the water. Changes to water quality available to society.

[a] A benefit would be a change in a beneficial direction (e.g., ⊂⊃∪⊕⊃↖⊖capitol costs), while a cost would be a detrimental change (e.g., ∅≪∪⊕⊃↖⊖worker sick days).

Table 7-11. Overall Manufacturing Cost Comparison

Process	Estimated Cost to Manufacture 260,000 ssf ($/ssf)
HASL, Non-conveyorized	$0.36
HASL, Conveyorized	$0.35
Nickel/Gold, Non-conveyorized	$0.60
Nickel/Palladium/Gold, Non-conveyorized	$1.54
OSP, Non-Conveyorized	$0.11
OSP, Conveyorized	$0.10
Immersion Silver, Conveyorized	$0.28
Immersion Tin, Non-conveyorized	$0.18
Immersion Tin, Conveyorized	$0.25

Private Benefits/Costs. Reductions in the cost of manufacturing are reflected primarily in reduced private costs for the PWB manufacturer. Implementation of an alternative surface finish can potentially result in significant operating cost savings for a manufacturing facility, as shown above. Decreased manufacturing costs allow companies more operating flexibility and are critical to the long-term ability of the manufacturer to remain competitive in the global marketplace.

External Benefits/Costs. There are no significant external benefits derived directly from the cost of manufacturing. However, several aspects that affect the manufacturing cost of the process result in external benefits. For instance, the conservation of water or material results in a more sustainable operating process with reduced environmental burdens that must be borne by society. See the discussion of cost and benefits based on energy and natural resource consumption presented later in this section for a more complete discussion of the external benefits

Costs and Benefits Based on Occupational Health

Operation of the surface finish process requires workers to work in close contact with chemicals, some of which may pose a threat to occupational health. Unacceptably high risks to workers from chemicals in the workplace may hurt company and worker alike. The reduction of risks to workers through the implementation of an alternative surface finish can result in tangible benefits, both private and external.

Health risks to workers were estimated for inhalation exposure to vapors and aerosols from surface finishing baths, and for dermal exposure to surface finishing bath chemicals. Worker risk to chemicals were compared to EPA guidelines for acceptable risk to identify chemicals of concern within the workplace. Occupational cancer risks were estimated for inhalation exposure to inorganic metallic salt A, a suspected or probable human carcinogen in the non-conveyorized nickel/gold process. The cancer risks to worker health from inorganic metallic salt A are below the EPA concern level of one in one million for inhalation exposure. Occupational cancer risks associated with other suspected carcinogens could not be quantified because cancer slope factors have not yet been established for these chemicals.

Table 7-12 summarizes the number of chemicals of concern for the exposure pathways evaluated and lists the number of suspected carcinogens in each technology. Table 7-13 lists potential health effects associated with surface finishing chemicals of concern. Detailed descriptions of the risk assessment methodology and results are presented in Chapter 3, while the risk results are also summarized in Chapter 7.1.

Table 7-12. Summary of Occupational Hazards, Exposures, and Risks of Potential Concern

Surface Finishing Technology	No. of Chemicals of Concern by Pathway [a]		No. of Suspected Carcinogens [d]
	Inhalation [b]	Dermal [c]	
HASL, Non-conveyorized (BASELINE)	1	1	2
HASL, Conveyorized	0	1	2
Nickel/Gold, Non-conveyorized	5	6	3
Nickel/Palladium/Gold, Non-conveyorized	6	6	1
OSP, Non-conveyorized	1	3	1
OSP, Conveyorized	0	3	1
Immersion Silver, Conveyorized	0	0	1
Immersion Tin, Non-conveyorized	0	1	1
Immersion Tin, Conveyorized	0	0	1

[a] Number of chemicals of concern for a surface finishing line operator (the most exposed individual). Occupational health risks could not be quantified for one or more chemicals in each surface finish due to lack of toxicity or chemical property data. See Chapter 3.3 for a more detailed explanation.
[b] See Table 3-30 for further information on inhalation risks.
[c] See Table 3-31 for further information dermal risks.
[d] See Table 3-21 for further information on cancer classifications.

Health endpoints potentially associated with surface finishing chemicals of concern include:

- skin, eye, nose, throat, and respiratory irritation or damage;
- allergic contact dermatitis;
- gastrointestinal/digestive pain or damage;
- kidney damage;
- liver damage; and
- damage to the nervous system and immune system.

Based on the number of chemicals with risk results above concern levels (Table 7-12), some alternatives to the non-conveyorized HASL process may have private and external benefits resulting from reduced occupational risks. These alternatives include the conveyorized HASL, conveyorized immersion silver, and conveyorized and non-conveyorized immersion tin processes. Some alternatives, however, may have increased costs due to higher risks; these include the non-conveyorized nickel/gold and nickel/palladium/gold processes. Potential risks from conveyorized and non-conveyorized OSP are similar to those of non-conveyorized HASL.

It is important to note that surface finishing chemicals are not the only factor contributing toward the illnesses described in Table 7-13; other PWB manufacturing process steps may also contribute toward adverse worker health effects. With the exception of determining the cancer risk from inorganic metallic salt A, the risk characterization did not link exposures of concern with particular adverse health outcomes or with the number of incidences of adverse health outcomes.[6] Thus, the benefits or costs of illnesses avoided by switching to a surface finishing alternative could not be quantified

Private Costs/Benefits. There are potential economic benefits associated with reduced exposure to surface finishing chemicals. Private benefits for PWB manufacturers may include increased worker productivity, increased worker morale, reduced worker absenteeism due to illness, and a reduction in liability and health care insurance costs. While reductions in insurance premiums as a result of pollution prevention are not currently widespread, the opportunity exists for changes in the future.

External Costs/Benefits. External benefits are not as easily quantifiable, but no less important than the private benefits listed above. Many of the health endpoints described in Table 7-13 lead to long-term illnesses in workers that result in hardship for the entire family. Many states are struggling under the economic burden of providing adequate health care to an aging population using an overburdened health care system experiencing rapidly increasing health care costs. External benefits of a switch to an alternative surface finish system may include reductions in illness to workers along with the associated decreases in both short-term and long-term medical costs and insurance premiums. Other benefits include a higher quality of life for workers and their families.

Table 7-13. Potential Health Effects Associated with Surface Finishing Chemicals of Concern

Chemical of Concern	Alternatives with Exposure Levels of Concern	Pathway of Concern [a]	Potential Health Effects
Ammonium chloride	Nickel/Gold	Dermal	Contact with ammonium chloride solution or fumes irritate the eyes. Large doses of ammonium chloride may cause nausea, vomiting, thirst, headache, hyperventilation, drowsiness, and altered blood chemistry. Ammonia fumes are extremely irritating to skin, eyes, and respiratory passages. The severity of effects depends on the amount of dose and duration of exposure.
Ammonia compound A	Nickel/Palladium/Gold	Dermal	
Ammonium hydroxide	Nickel/Gold, Nickel/Palladium/Gold	Dermal	
Alkyldiol	Nickel/Gold, Nickel/Palladium/Gold	Inhalation	Can affect the respiratory system if inhaled, and kidneys if absorbed into the body.

[6] Cancer risk from inorganic metallic salt A exposure was expressed as a probability, but the exposure assessment did not determine the size of the potentially exposed population (e.g., number of surface finishing line operators and others working in the process area). This information would be necessary to estimate the number of illnesses avoided by switching to an alternative from the baseline.

Chemical of Concern	Alternatives with Exposure Levels of Concern	Pathway of Concern [a]	Potential Health Effects
Copper ion and copper salt C	OSP	Dermal	Long-term exposure to high levels of copper may cause liver damage. Copper is not known to cause cancer. The seriousness of the effects of copper can be expected to increase with both level and length of exposure.
Copper sulfate pentahydrate	HASL, Nickel/Gold, Nickel/Palladium/Gold, OSP	Dermal	
Ethylene glycol	HASL, OSP	Inhalation	In humans, low levels of vapors produce throat and upper respiratory irritation. When ethylene glycol breaks down in the body, it forms chemicals that crystallize and can collect in the body, which prevent kidneys from working. The seriousness of the effects can be expected to increase with both level and length of exposure.
Hydrochloric acid	Nickel/Gold, Nickel/Palladium/Gold	Inhalation	Hydrochloric acid in air can be corrosive to the skin, eyes, nose, mucous membranes, respiratory tract, and gastrointestinal tract.
Hydrogen peroxide	Nickel/Gold, Nickel/Palladium/Gold	Inhalation	Hydrogen peroxide in air can irritate the skin, nose, and eyes. Ingestion can damage the liver, kidneys, and gastrointestinal tract.
	Nickel/Gold, Nickel/Palladium/Gold	Dermal	
Inorganic metallic salt B	Nickel/Gold, Nickel/Palladium/Gold	Dermal	Exposure to this material can damage the nervous system, kidneys, and immune system.
Nickel sulfate	Nickel/Gold, Nickel/Palladium/Gold	Inhalation	Skin effects are the most common effects in people who are sensitive to nickel. Workers who breathed very large amounts of nickel compounds have developed lung and nasal sinus cancers.
	Nickel/Gold, Nickel/Palladium/gold	Dermal	
Phosphoric acid	Nickel/Gold, Nickel/Palladium/Gold	Inhalation	Inhaling phosphoric acid can damage the respiratory tract.
Propionic acid	Nickel/Palladium/Gold	Inhalation	No data were located for health effects of propionic acid exposure in humans, although some respiratory effects were seen in laboratory mice.
Urea compound C	Immersion Tin	Dermal	Dermal exposure to urea compound C has resulted in allergic contact dermatitis in workers, and exposure has caused weight loss in mice.

[a] Inhalation concerns only apply to non-conveyorized processes. Dermal concerns may apply to non-conveyorized and/or conveyorized processes (see Table 7-3).

Costs and Benefits Based on Public Health

In addition to worker exposure, members of the general public in close physical proximity to a PWB plant may be exposed to surface finishing chemicals dispersed into the air. Both private and external cost savings could be realized if an alternative surface finish reduced public health risks.

Public health risk was estimated for inhalation exposure for the general populace living near a facility. Risk was characterized for long-term ambient exposures to the population, rather than short-term exposures to high levels of hazardous materials (e.g., fire, spill). The risk indicators for ambient exposures to humans, although limited to airborne releases, indicated low concern from the estimated air concentrations for chronic non-cancer effects. The excess cancer risks were also found to be well below EPA concern levels (one in 50 billion). Refer to Chapter 3 for a description of the risk assessment methodology and results.

These results suggest little change in public health risks would result from a switch to an alternative surface finish technology. While the study found little difference among the alternatives for those public health risks that were assessed, it was not within the scope of this comparison to assess all community health risks. Risk was not characterized for exposure via other pathways (e.g., drinking water, fish ingestion) or short-term or long-term exposures to high levels of hazardous chemicals when there is a spill, fire, or other periodic release.

Private Costs/Benefits. Private benefits could result from reductions in potential liability costs resulting from adverse effects of emissions released from the facility into the environment. Risk results for the nearby public from inhalation of air emissions from a PWB facility indicate that no substantive difference in risk, and thus, liability cost would be realized. However, private cost savings could result from reduced liability for other types of emissions (e.g. releases to surface water) should they pose a threat to human health.

External Costs/Benefits. External benefits could result from reduced medical costs for members of the public who become ill as a result of exposure to emissions from a nearby PWB manufacturing facility. However, because the health risks from air emissions are all of low concern, a change in alternatives would not be expected to result in significant changes to public health. The effects of other emissions on the public, and the resulting differences in external costs/benefits are unknown.

Costs and Benefits Based on Wastewater and Ecological Risks

Surface finishing chemicals in wastewater are potentially damaging to terrestrial and aquatic ecosystems, resulting in private costs borne by manufacturers as well as external costs borne by society. The CTSA evaluated the ecological risks of the baseline and alternatives for aquatic life by calculating ecological risk indicators for non-metal surface finishing chemicals (metals were assumed to be removed by treatment) that may be released to surface water.

Table 7-14 presents the number of chemicals in each technology with an estimated surface water concentration above their CC. CCs are discussed in more detail in Section 3.3.3. These

results suggest that all of the alternatives may pose lower private and external costs based on wastewater contaminants and ecological risks than the baseline process.

Table 7-14. Number of Chemicals with Estimated Surface Water Concentration Above Concern Concentration

Surface Finishing Technology	No. of Chemicals
HASL, Non-conveyorized (BASELINE)	4
HASL, Conveyorized	3
Nickel/Gold, Non-conveyorized	0
Nickel/Palladium/Gold, Non-conveyorized	0
OSP, Non-conveyorized	1
OSP, Conveyorized	1
Immersion Silver, Conveyorized	1
Immersion Tin, Non-conveyorized	1
Immersion Tin, Conveyorized	0

Private Costs/Benefits. The primary cost borne by the manufacturer is the cost of pretreating the wastewater to meet wastewater permit requirements. Pretreatment could include both in-line (e.g. electrowinning) or end-of-pipe treatment techniques (see Chapter 6.2). Other potential private costs include possible fines if permits are violated and increased liability costs.

External Costs/Benefits. Pollution of streams and rivers can damage the aquatic ecosystems, endangering species and reducing ecosystem diversity. Wastewater discharged to streams and other surface waters, even if within permit levels, can have effects on the complex ecosystems in ways that are difficult to predict. Reductions in chemicals of concern through the adoption of alternative surface finish technologies preserves ecosystem diversity, while maintaining the recreational value of surface waters for society.

Costs and Benefits Based on Energy and Natural Resources

Conservation of energy and natural resources has become a national priority with effects on both society and the private sector. Energy shortages in western states have caused periodic rolling blackouts responsible for large economic losses to companies, while at the same time driving up energy costs for citizens and companies alike.

The natural resource and energy consumption of the surface finish technologies was assessed in this CTSA. A detailed discussion of the methods used in evaluating individual consumption rates is presented in Chapter 5, Conservation. Table 7-15 summarizes the water and energy consumption rates and percent changes in consumption from the baseline to the surface finishing alternatives. The results suggest that several of the alternatives use less water per ssf, less energy per ssf, or both, than the baseline non-conveyorized HASL process. The consumption rates of other natural resources, such as precious metals, were also evaluated in Chapter 5.

Table 7-15. Energy and Water Consumption of Surface Finishing Technologies

Surface Finishing Technology	Water Consumption		Energy Consumption	
	gal/ssf	% change	Btu/ssf	% change
HASL, Non-conveyorized (BASELINE)	1.24		218	
HASL, Conveyorized	0.99	-20	133	-39
Nickel/Gold, Non-conveyorized	2.06	+66	447	+105
Nickel/Palladium/Gold, Non-conveyorized	3.61	+191	768	+252
OSP, Non-conveyorized	0.77	-38	125	-43
OSP, Conveyorized	0.53	-57	73	-66
Immersion Silver, Non-conveyorized	0.53	-57	287	+32
Immersion Tin, Non-conveyorized	1.81	+46	263	+21
Immersion Tin, Conveyorized	0.88	-29	522	+239

Private Costs/Benefits. Private benefits associated with the conservation of energy and natural resources are reflected in reduced manufacturing costs for the process (see the discussion of costs and benefits associated with manufacturing presented previously in this section).

Indirect private costs may occur in situations of extreme energy or water shortages, affecting the availability and the cost of the resource required. Energy shortages in some western states resulted in energy price increases and rolling blackouts that at times caused the complete shut down of manufacturing facilities, and the loss of income associated with that shut down. Conservation of energy protects the company and society from the affects of an energy crisis, and acts to prevent another crisis from occurring.

External Costs/Benefits. While the private costs of natural resource and energy consumption are reflected directly in the PWB manufacturers bottom line, the external costs and benefits of conservation are no less tangible, becoming a key issue in the national and local debate of public policy. Companies and governments worldwide are moving towards sustainable production goals that will insure the continued availability of our natural resources, while protecting the business and environmental climates.

Energy shortages have placed energy conservation on the front page of public discussion. Reduced energy consumption through conservation results in the preservation of non-renewable supplies of energy-producing raw materials such as coal, natural gas, or oil. Conservation also acts to reduce air emissions resulting from the generation of energy, including compounds such as carbon dioxide, nitrogen dioxide, carbon monoxide, sulfur oxide compounds (SO_x), and particulate matter. Pollution resulting from the generation of energy consumed by surface finish technologies was summarized in Table 5-11 in Section 5.2, Energy Impacts. Environmental and human health concerns associated with these pollutants include global warming, smog, acid rain, and health effects from toxic chemical exposure.

The use of water and consequent generation of wastewater also results in external costs to society. While the private costs of this water usage are included in the cost estimates in Table 7-

15, the external costs are not. Clean water is quickly becoming a scarce resource, and activities that utilize water therefore impose external costs on society. Higher water costs, inadequate water supplies, decreased water supply quality, and higher costs for public treatment facilities due to increased sewage volumes are all potential external costs bourne by society as a result of increased industrial water consumption.

Other Private Benefits and Costs

Table 7-16 gives additional examples of private costs and benefits that could not be quantified in this CTSA. These include wastewater treatment, solid waste disposal, compliance, and improvements in company image that accrue from implementing a substitute. Some of these were mentioned above, but are included in the table due to their importance to overall benefits and costs.

7.2.4 Summary of Benefits and Costs

The objective of a social benefits/costs assessment is to identify those technologies or decisions that maximize net benefits. Ideally, the analysis would quantify the social benefits and costs of using the alternative and baseline surface finishing technologies in terms of a single unit (e.g., dollars) and calculate the net benefits of using an alternative instead of the baseline technology. Due to data limitations, however, this assessment presents a qualitative description of the benefits and costs associated with each technology compared to the baseline.

Each alternative presents a mixture of private and external benefits and costs. In terms of worker health risks, conveyorized processes have the greatest benefits for reduced worker inhalation exposure to bath chemicals; they are enclosed and vented to the atmosphere. However, dermal contact from bath maintenance activities can be of concern regardless of the equipment configuration for HASL and OSP processes, as well as non-conveyorized nickel/gold, nickel/palladium/gold, and immersion tin processes. Little or no improvement is seen in public health risks because concern levels were very low for all technologies. Differences in estimated wastewater contaminant levels and aquatic risk concerns suggest that alternatives to non-conveyorized HASL post lower potential private and external costs (or higher benefits). Conveyorized processes consumed less water than that consumed by non-conveyorized processes, resulting in net private and external benefits. Only the OSP technology, along with the conveyorized HASL technology, are expected to reduce potential private and external costs of energy consumption, resulting in increased social benefits.

Other benefits and costs discussed qualitatively include wastewater treatment, solid waste disposal, compliance costs, and effects on the company image. The effects on jobs of wide-scale adoption of an alternative was not evaluated in the CTSA.

Table 7-16. Examples of Private Costs and Benefits Not Quantified

Category	Description of Potential Costs or Benefits
Wastewater Treatment	Alternatives to the baseline HASL technology may provide cost savings by reducing the quantity and improving the treatability of process wastewaters. In turn, these cost savings can enable the implementation of other pollution prevention measures. Several alternatives to the baseline process use less rinse water and, consequently, produce less wastewater. However, some alternatives may also introduce additional metals, such as silver or nickel, whicht are toxic to aquatic organisms. These metals, which might not otherwise be present in the plant wastewater, may require additional treatment steps. All of these factors contribute to both the private benefits and costs of implementing a surface finishing alternative.
Solid Waste Disposal	All of the alternatives result in the generation of sludge, off-specification PWBs, and other solid wastes, such as spent bath filters or solder dross. These waste streams must be recycled or disposed of, some of them as hazardous waste. For example, many PWB manufacturers send the contaminated copper waste generated by the HASL process to a recycler to reclaim the metal content. Solder wastes that cannot be effectively reclaimed will likely be landfilled. It is likely that the manufacturer will incur costs in order to recycle or landfill these solid wastes; however, these costs were not quantified (reducing the volume and toxicity of solid waste also provides social benefits to the community).
Compliance Costs	The cost of complying with all environmental and safety regulations affecting the surface finish process line was not quantified. However, chemicals and wastes from several of the surface finish alternatives posed similar environmental compliance problems as the HASL baseline. Two alternatives were subject to greater overall federal environmental regulations than the baseline, suggesting that implementing those alternatives could potentially increase compliance costs. It is easier to assess the relative cost of complying with OSHA requirements, because several of the alternatives pose reduced occupational safety hazards (non-automated, non-conveyorized equipment may also pose less overall process hazards than working with mechanized equipment).
Company Image	Many businesses are finding that using cleaner technologies results in less tangible benefits, such as an improved company image and improved community relations. The elimination of lead from consumer products has been a key feature in many company marketing plans. While it is difficult to put a monetary value on these benefits, they should be considered in the decision-making process.

7.3 TECHNOLOGY SUMMARY PROFILES

This section of the CTSA presents summary profiles of each of the surface finishing technologies. The profiles summarize key information from various sections of the CTSA, including the following:

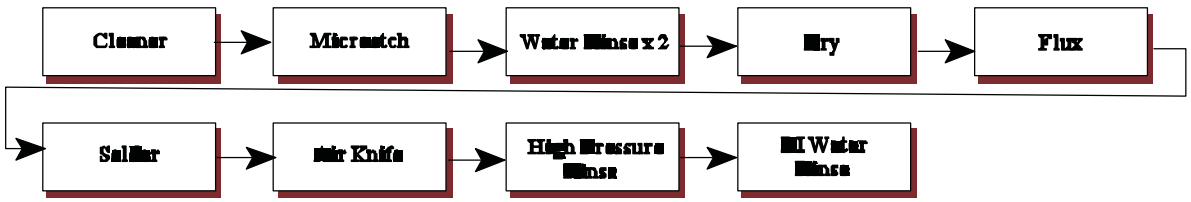
- generic process steps, typical bath sequences, and equipment configurations evaluated in the CTSA;
- human health and environmental hazards data and risk concerns for non-proprietary chemicals;
- production costs and resource (water and energy) consumption data;
- Federal environmental regulations affecting chemicals in each of the technologies; and
- conclusions of the social benefits/costs assessment.

The summary profiles in this section present data for the HASL, nickel/gold, nickel/palladium/gold, OSP, immersion silver, and the immersion tin technologies, respectively. Data are presented for both the non-conveyorized and the conveyorized equipment configurations, when applicable.

As discussed in Section 7.2, each of the alternatives appear to provide benefits in at least one or more areas over the non-conveyorized HASL (the baseline process). However, the overall benefits or costs associated with the alternatives could not be quantified without a more thorough assessment of the factors involved. The actual decision of whether or not to implement an alternative occurs outside of the CTSA process. Individual decision-makers may consider a number of additional factors, such as their individual business circumstances and community characteristics, together with the information presented in this CTSA.

7.3.1 HASL Technology

<u>Generic Process Steps and Typical Bath Sequence</u>



<u>Equipment Configurations Evaluated</u>: Non-conveyorized (the baseline process) and conveyorized.

Risk Screening and Comparison

Table 7-17 summarizes human and environmental hazards and risk concerns for chemicals in the HASL technology. The risk characterization identified occupational inhalation risk concerns for one chemical in the non-conveyorized HASL process and dermal risk concerns for two chemicals for either equipment configuration. No public health risk concerns were identified for the pathways evaluated.

Table 7-17. Summary of Human Health and Environmental Risk Concerns for the HASL Technology

Chemical	Human Health Hazard and Occupational Risk [a]			Carcinogenicity Weight-of-Evidence Classification	Aquatic Risk Concerns
	Inhalation Risk Concerns [b]	Dermal Risk Concerns [c]	SAT Rank [d]		
1,4-Butenediol	NE	NE	LM	None	NC: Yes C: No
Alkylalkyne diol	NA	No [e]	L	None	No
Alkylaryl sulfonate	NE	No [e]	L	None	Yes
Alkylphenol ethoxylate	NA	No [e]	LM	None	No
Alkylphenol polyethoxyethanol	NA	No [e]	LM	None	No
Arylphenol	NE	No	M	None	No
Citric acid	NA	No [e]	L	None	No
Copper sulfate pentahydrate	NA	Yes		Not classifiable (EPA Class D)	Not considered
Ethoxylated alkylphenol	NA	No [e]	LM	None	No
Ethylene glycol	Yes	No		None	No
Ethyleneglycol monobutyl ether	No	No		None	No
Fluoboric acid	NA	NE		None	No
Gum	NA	No [e]		None	No
Hydrochloric acid	No	NE		Not classifiable (IARC Group 3)	No
Hydrogen peroxide	No	No		Not classifiable (IARC Group 3)	Yes
Hydroxyaryl acid	NA	No [e]	M	None	No
Hydroxyaryl sulfonate	NA	No [e]	LM	None	No
Lead	No	Yes [f]		Probable or possible human carcinogen (EPA Class B2; IARC Group 2 B)	No water releases expected
Phosphoric acid	No	No		None	No

Chemical	Human Health Hazard and Occupational Risk [a]			Carcinogenicity Weight-of-Evidence Classification	Aquatic Risk Concerns
	Inhalation Risk Concerns [b]	Dermal Risk Concerns [c]	SAT Rank [d]		
Potassium peroxymonosulfate	NA	No [e]	M	None	Yes
Sodium benzene sulfonate	NA	No [e]	M	None	No
Sodium hydroxide	NA	NE		None	No
Sulfuric acid	NA	NE [g]		Human carcinogen (IARC Group 1)	No
Tin	NA	NE		None	No water releases expected
Summary	No or NA: 20 NE: 3 Yes: 1	No: 16 NE: 6 YES: 2		2 suspected or known	No: 19 Yes: 4 Not considered: 1

[a] Risk concerns are for surface finishing line operators (the most exposed individual).
[b] Inhalation risk concerns for non-conveyorized process only. Inhalation risk from fully enclosed, conveyorized process is assumed to be negligible.
[c] Dermal risk concerns apply to both conveyorized and non-conveyorized equipment.
[d] Structure-Activity Team rank for human health concerns:
L: Low concern; LM: Low-Moderate concern; M: Moderate concern.
[e] Chemical has very low skin absorption (based on EPA's Structure-Activity Team evaluation); risk from dermal exposure not expected to be of concern.
[f] Lead evaluated by modeling potential blood-lead levels from incidental ingestion.
[g] Although chronic toxicity values have not been established, repeated skin contact with low concentrations of sulfuric acid causes skin desiccation, ulceration of the hands, and chronic inflammation around the nails.
NE: Not Evaluated; due to lack of toxicity measure.
NA: Not Applicable. Inhalation exposure was not calculated because the chemical is not volatile (vapor pressure below 1×10^{-3} torr) and is not used in any air-sparged bath.

Performance

The performance of the HASL technology was demonstrated at four test facilities, one of which operated conveyorized HASL equipment. Performance test results were not differentiated by the type of equipment configuration used. The Performance Demonstration determined that each of the alternative technologies has the capability of achieving comparable levels of performance to the HASL finish.

Production Costs and Resource Consumption

Computer simulation was used to model key operating parameters, including the time required to process a job consisting of 260,000 ssf and the amount of resources (water and energy) consumed. This information was analyzed with a hybrid cost model of traditional cost (i.e., capital costs, etc.) and activity-based costs to determine average manufacturing costs per ssf and water and energy consumption per ssf.

Average manufacturing costs for the baseline process (the non-conveyorized HASL process) were $0.36/ssf, while water and energy consumption were 1.24 gal/ssf and 218 Btu/ssf, respectively. However, the conveyorized HASL process consumed less water and energy and was more cost-effective than the baseline process (non-conveyorized HASL). Figure 7-1 lists the results of the production cost and resource consumption analyses for the conveyorized HASL process and illustrates the percent changes in costs and resource consumption from the baseline. Manufacturing costs, water consumption, and energy consumption are less than the baseline by three percent, 20 percent, and 39 percent, respectively.

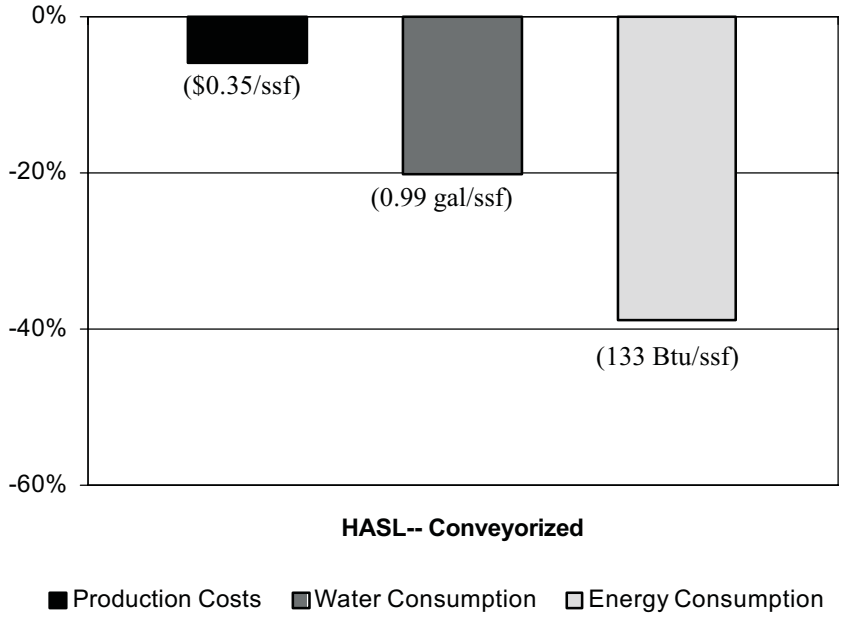


Figure 7-1. Production Costs and Resource Consumption of Conveyorized HASL Technology
(Percent Change from Baseline with Actual Values in Parentheses)

Regulatory Concerns

Chemicals contained in the HASL technology are regulated by the Clean Water Act (CWA), the Clean Air Act (CAA), the Emergency Planning and Community Right-to-Know Act (EPCRA), the Superfund Amendments and Reauthorization Act (SARA), and the Toxic Substances Control Act (TSCA). A summary of the number of HASL chemicals subject to applicable federal regulations is presented in Table 7-18.

Table 7-18. Number of HASL Chemicals Subject to Applicable Federal Regulations

Regulation		No. of Chemicals	Regulation		No. of Chemicals
CWA	304b	1	EPCRA	313	6
	307a	1		302a	3
	311	4	SARA	110	1
	Priority Pollutant	1	TSCA	8d HSDR	3
CAA	111	3		MTL	4
	112b	3		8a PAIR	3
	112r	1	RCRA	U	--

Abbreviations and Definitions:
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
EPCRA 313 - Toxic Chemical Release Inventory
EPCRA 302a - Extremely Hazardous Substances
SARA 110 - Superfund Site Priority Contaminant
TSCA 8d HSDR - Health & Safety Data Reporting Rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule
RCRA U Waste - Characteristic hazardous waste

Social Benefits and Costs

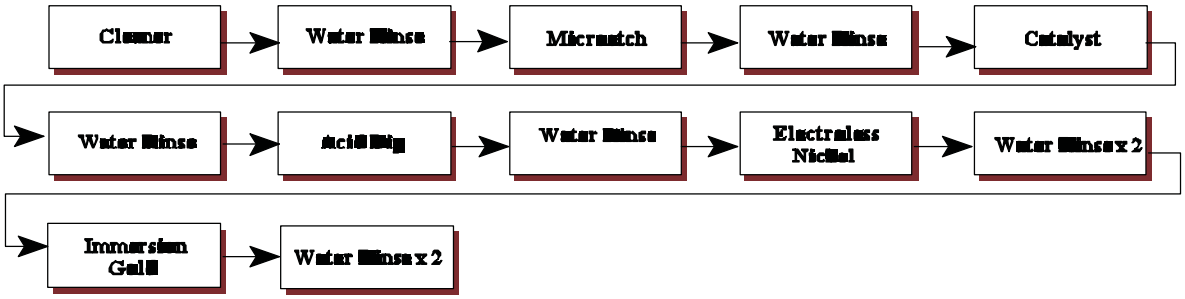
Social cost is the total cost that an activity imposes on society (i.e., the sum of private and external costs) while social benefit is the total benefit of an activity that society receives (i.e., the sum of the private benefits and the external benefits). A qualitative assessment of the social benefits and costs of the baseline and alternative technologies was performed to determine if there would be net benefits or costs to society if PWB manufacturers switched to alternative technologies from the baseline. (Net cost or benefit could not be completely assessed without a more thorough assessment of effects on jobs and wages.)

In comparing the baseline (non-conveyorized HASL) to conveyorized HASL, there appears to be a net benefit for switching to conveyorized HASL because — for the aspects included in the evaluation — results are similar to or better than the baseline. Specifically, changing from baseline to conveyorized HASL may result in:

- benefits from decreased worker and ecological risk (based on fewer chemicals of concern), decreased water use, and decreased energy use; and
- no discernible cost or benefit for manufacturing cost and risk to the public.

7.3.2 Nickel/Gold Technology

Generic Process Steps and Typical Bath Sequence



Equipment Configurations Evaluated: Conveyorized.

Risk Screening and Comparison

Table 7-19 summarizes human and environmental hazards and risk concerns for chemicals in the nickel/gold technology. The risk characterization identified occupational inhalation risk concerns for five chemicals and dermal risk concerns for six chemicals in the non-conveyorized nickel/gold process. No public health risk concerns were identified for the pathways evaluated, although cancer risks as high as one in 50 billion were estimated for the non-conveyorized nickel/gold process.

Table 7-19. Summary of Human Health and Environmental Risk Concerns for the Nickel/Gold Technology

Chemical	Human Health Hazard and Occupational Risks [a]			Carcinogenicity Weight-of-Evidence Classification	Aquatic Risk Concerns
	Inhalation Risk Concerns [b]	Dermal Risk Concerns [c]	SAT Rank [d]		
Aliphatic acid A	NE	No		None	No
Aliphatic acid B	NE	No [e]	M	None	No
Aliphatic acid E	NE	NE		None	No
Aliphatic dicarboxylic acid A	NE	No [e]	LM	None	No
Aliphatic dicarboxylic acid C	NE	No		None	No
Alkylamino acid B	NA	NE		None	No
Alkyldiol	Yes	No		None	No
Alkylphenol polyethoxyethanol	NA	No [e]	LM	None	No
Ammonia compound B	NE	No [e]	MH	None	No
Ammonium chloride	NA	Yes		None	No

Chemical	Human Health Hazard and Occupational Risks [a]			Carcinogenicity Weight-of-Evidence Classification	Aquatic Risk Concerns
	Inhalation Risk Concerns [b]	Dermal Risk Concerns [c]	SAT Rank [d]		
Ammonium hydroxide	No	Yes		None	No
Citric acid	NA	No [e]	L	None	No
Copper sulfate pentahydrate	NA	Yes		Not classifiable (EPA Class D)	Not considered
Ethoxylated alkylphenol	NA	No [e]	LM	None	No
Hydrochloric acid	Yes	NE		Not classifiable (IARC Group 3)	No
Hydrogen peroxide	Yes	Yes		Not classifiable (IARC Group 3)	No
Hydroxyaryl acid	NA	No [e]	M	None	No
Inorganic metallic salt A	No	No		Human carcinogen or probable human carcinogen [f]	Not considered
Inorganic metallic salt B	No	Yes		Probable or possible human carcinogen [f]	Not considered
Inorganic metallic salt C	No	No		Probable or possible human carcinogen [f]	Not considered
Malic acid	NE	No [e]	M	None	No
Nickel sulfate	Yes	Yes		None	Not considered
Palladium chloride	NA	NE		None	Not considered
Phosphoric acid	Yes	No		None	No
Potassium compound	NE	NE	L	None	No
Potassium gold cyanide	NA	No		None	Not considered
Potassium peroxymonosulfate	NA	No [e]	M	None	No
Sodium hydroxide	NA	NE		None	No
Sodium hypophosphite	NE	No [e]	LM	None	No
Sodium salt	NA	No		None	No
Substituted amine hydrochloride	NA	No [e]	M	None	No
Sulfuric acid	NA	NE [g]		Human carcinogen (IARC Group 1)	No
Transition metal salt	NA	No [e]	M	None	Not considered
Urea compound B	NE	NE		Possible human carcinogen [f]	No

Chemical	Human Health Hazard and Occupational Risks [a]			Carcinogenicity Weight-of-Evidence Classification	Aquatic Risk Concerns
	Inhalation Risk Concerns [b]	Dermal Risk Concerns [c]	SAT Rank [d]		
Summary	No or NA: 19 NE: 10 Yes: 5	No: 20 NE: 8 Yes: 6		5 suspected or known	No: 26 Yes: 0 Not considered: 8

[a] Risk concerns are for surface finishing line operators (the most exposed individual).
[b] Inhalation risk concerns for non-conveyorized process only. Inhalation risk from fully enclosed, conveyorized process is assumed to be negligible.
[c] Dermal risk concerns apply to both conveyorized and non-conveyorized equipment.
[d] Structure-Activity Team rank for human health concerns:
L: Low concern; LM: Low-Moderate concern; M: Moderate concern; MH: Moderate-High concern.
[e] Chemical has very low skin absorption (based on EPA's Structure-Activity Team evaluation); risk from dermal exposure is not expected to be of concern.
[f] Specific EPA and/or IARC groups not reported in order to protect proprietary chemical identities.
[g] Although chronic toxicity values have not been established, repeated skin contact with low concentrations of sulfuric acid causes skin desiccation, ulceration of the hands, and chronic inflammation around the nails.
NE: Not Evaluated; due to lack of toxicity measure.

Performance

The performance of the nickel/gold technology was demonstrated at three test facilities. The Performance Demonstration determined that this technology has the capability of achieving comparable levels of performance to the HASL finish. In addition, the nickel/gold process is both gold and aluminum wire-bondable, though testing of wire-bondability was not included in the performance testing protocol.

Production Costs and Resource Consumption

Computer simulation was used to model key operating parameters, including the time required to process a job consisting of 260,000 ssf and the amount of resources (water and energy) consumed. This information was analyzed with a hybrid cost model of traditional cost (i.e., capital costs, etc.) and activity-based costs to determine average manufacturing costs per ssf and water and energy consumption per ssf.

Analyses results determined that the non-conveyorized nickel/gold technology consumed more water and energy and was less cost-effective than the baseline non-conveyorized HASL. Average production costs for nickel/gold were $0.60/ssf, while water and energy consumption rates were determined to be 2.06 gal/ssf and 447 Btu/ssf, respectively. Figure 7-2 lists the results of these analyses and illustrates the percent changes in costs and resources consumption from the baseline. Manufacturing costs, water consumption, and energy consumption are more than the baseline by 67 percent, 66 percent, and 105 percent, respectively.

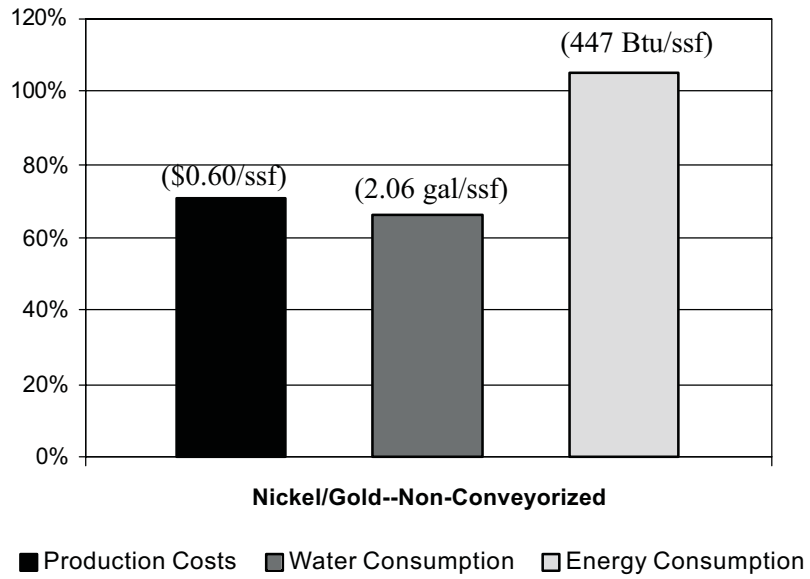


Figure 7-2. Production Costs and Resource Consumption of the Nickel/Gold Technology (Percent Change from Baseline with Actual Values in Parentheses)

Regulatory Concerns

Chemicals contained in the nickel/gold technology are regulated by the CWA, CAA, EPCRA, SARA, and TSCA. None of the nickel/gold process chemicals were regulated under RCRA. A summary of the number of nickel/gold chemicals subject to applicable federal regulations is presented in Table 7-20.

Social Benefits and Costs

A qualitative assessment of the private and external benefits and costs of the this technology suggests a mixture of benefits and costs to society if PWB manufacturers switched to the nickel/gold technology from the baseline. (Net social cost or benefit could not be determined.) For the aspects included in the evaluation, changing from baseline to nickel/gold may result in:

- costs from increased manufacturing cost, increased worker risk (based on fewer chemicals of concern), increased water and energy use;
- benefits from decreased ecological risk (based on fewer chemicals of concern); and
- no discernible cost or benefit for risk to the public.

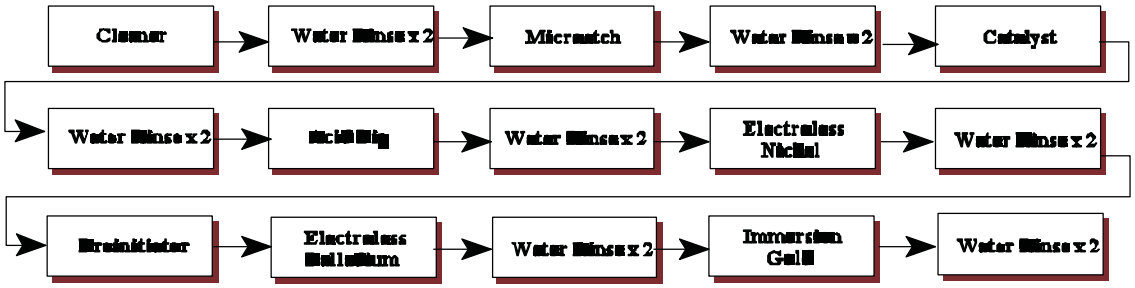
Table 7-20. Number of Nickel/Gold Chemicals Subject to Applicable Federal Regulations

Regulation		No. of Chemicals	Regulation		No. of Chemicals
CWA	304b	6	EPCRA	313	12
	307a	6		302a	3
	311	16	SARA	110	7
	Priority Pollutant	6	TSCA	8d HSDR	1
CAA	111	11		MTL	4
	112b	6		8a PAIR	3
	112r	1	RCRA	U	--

Abbreviations and Definitions:
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
EPCRA 313 - Toxic Chemical Release Inventory
EPCRA 302a - Extremely Hazardous Substances
SARA 110 - Superfund Site Priority Contaminant
TSCA 8d HSDR - Health & Safety Data Reporting Rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule
RCRA U Waste - Characteristic hazardous waste

7.3.3 Nickel/Palladium/Gold Technology

Generic Process Steps and Typical Bath Sequence



Equipment Configurations Evaluated: Non-conveyorized.

Risk Screening and Comparison

Table 7-21 summarizes human and environmental hazards and risk concerns for chemicals in the nickel/palladium/gold technology. The risk characterization identified occupational inhalation risk concerns for six chemicals and dermal risk concerns for six chemicals in the non-conveyorized nickel/palladium/gold process. No public health risk concerns were identified for the pathways evaluated.

Table 7-21. Summary of Human Health and Environmental Risk Concerns for the Nickel/Palladium/Gold Technology

Chemical	Human Health Hazard and Occupational Risks [a]			Carcinogenicity Weight-of-Evidence Classification	Aquatic Risk Concerns
	Inhalation Risk Concerns [b]	Dermal Risk Concerns [c]	SAT Rank [d]		
Aliphatic acid B	NE	NE	M	None	No
Aliphatic acid E	NE	No		None	No
Aliphatic dicarboxylic acid A	NE	NE	LM	None	No
Aliphatic dicarboxylic acid C	NE	No		None	No
Alkylamino acid B	NA	No		None	No
Alkyldiol	Yes	No		None	No
Alkyl polyol	NA	No		None	No
Amino acid salt	NA	NE	LM	None	No
Amino carboxylic acid	NA	No		None	No
Ammonia compound A	NA	Yes		None	No
Ammonia compound B	NE	NE	MH	None	No
Ammonium hydroxide	No	Yes		None	No
Citric acid	NA	No [e]	L	None	No
Copper sulfate pentahydrate	NA	Yes		Not classifiable (EPA Class D)	Not considered
Ethoxylated alkylphenol	NA	No [e]	LM	None	No
Ethylenediamine	No	No		None	No
Hydrochloric acid	Yes	NE		Not classifiable (IARC Group 3)	No
Hydrogen peroxide	Yes	Yes		Not classifiable (IARC Group 3)	No
Hydroxyaryl acid	NA	No [e]	M	None	No
Inorganic metallic salt B	No	Yes		Probable or possible human carcinogen [f]	Not considered
Maleic acid	NA	No [e]	M	None	No
Malic acid	NE	No [e]	LM	None	No
Nickel sulfate	Yes	Yes		None	Not considered

Chemical	Human Health Hazard and Occupational Risks [a]			Carcinogenicity Weight-of-Evidence Classification	Aquatic Risk Concerns
	Inhalation Risk Concerns [b]	Dermal Risk Concerns [c]	SAT Rank [d]		
Palladium salt	NA	NE		None	Not considered
Phosphoric acid	Yes	No		None	No
Potassium compound	NE	NE	L	None	No
Potassium gold cyanide	NA	No		None	Not considered
Propionic acid	Yes	No		None	No
Sodium hydroxide	NA	NE		None	No
Sodium hypophosphite monohydrate	NE	No [e]	LM	None	No
Sodium salt	NA	No		None	No
Substituted amine hydrochloride	NA	No [e]	M	None	No
Sulfuric acid	NA	NE [g]		Human carcinogen (IARC Group 1)	No
Surfactant	NA	NE		None	NE
Transition metal salt	NA	No [e]	M	None	Not considered
Urea compound B	NE	NE		Possible human carcinogen [f]	No
Summary	No or NA: 21 NE: 9 Yes: 6	No: 19 NE: 11 Yes: 6		2 suspected or known	No: 29 Yes: 0 Not considered: 6

[a] Risk concerns are for surface finishing line operators (the most exposed individual).
[b] Inhalation risk concerns for non-conveyorized process only. Inhalation risk from fully enclosed, conveyorized process is assumed to be negligible.
[c] Dermal risk concerns apply to both conveyorized and non-conveyorized equipment.
[d] Structure-Activity Team rank for human health concerns:
L: Low concern; LM: Low-Moderate concern; M: Moderate concern; MH: Moderate-High concern.
[e] Chemical has very low skin absorption (based on EPA's Structure-Activity Team evaluation); risk from dermal exposure not expected to be of concern.
[f] Specific EPA and/or IARC groups not reported in order to protect proprietary chemical identities.
[g] Although chronic toxicity values have not been established, repeated skin contact with low concentrations of sulfuric acid causes skin desiccation, ulceration of the hands, and chronic inflammation around the nails.
NE: Not Evaluated; due to lack of toxicity measure.
NA: Not Applicable. Inhalation exposure level was not calculated because the chemical is not volatile (vapor pressure below 1×10^{-3} torr) and is not used in any air-sparged bath.

Performance

The performance of the nickel/palladium/gold technology was demonstrated at one test facility. The Performance Demonstration determined that this technology has the capability of achieving comparable levels of performance to the HASL finish. In addition, the nickel/palladium/gold process is both gold and aluminum wire-bondable, though testing of wire-bondability was not included in the performance testing protocol.

Production Costs and Resource Consumption

Computer simulation was used to model key operating parameters, including the time required to process a job consisting of 260,000 ssf and the amount of resources (water and energy) consumed. This information was analyzed with a hybrid cost model of traditional cost (i.e., capital costs, etc.) and activity-based costs to determine average manufacturing costs per ssf and water and energy consumption per ssf.

The non-conveyorized nickel/palladium/gold technology consumed more water and energy than the baseline process (non-conveyorized HASL). Average production costs for nickel/palladium/gold were $1.54/ssf, while water and energy consumption rates were 3.61 gal/ssf and 768 Btu/ssf, respectively. Figure 7-3 lists the results of these analyses and illustrates the percent changes in resources consumption from the baseline. Manufacturing costs, water consumption, and energy consumption are greater than the baseline by 327 percent, 191 percent, and 252 percent, respectively.

Regulatory Concerns

Chemicals contained in the nickel/palladium/gold technology are regulated by the CWA, CAA, EPCRA, SARA, and TSCA. None of the nickel/palladium/gold process chemicals were regulated under RCRA. A summary of the number of nickel/palladium/gold chemicals subject to applicable federal regulations is presented in Table 7-22.

Social Benefits and Costs

A qualitative assessment of the private and external benefits and costs of the this technology suggests a mixture of benefits and costs to society if PWB manufacturers switched to the nickel/palladium/gold technology from the baseline. (Net social cost or benefit could not be determined.) For the aspects included in the evaluation, changing from baseline to nickel/palladium/gold may result in:

- costs from increased manufacturing cost, increased worker risk (based on fewer chemicals of concern), increased water and energy use;
- benefits from decreased ecological risk (based on fewer chemicals of concern); and
- no discernible cost or benefit for risk to the public.

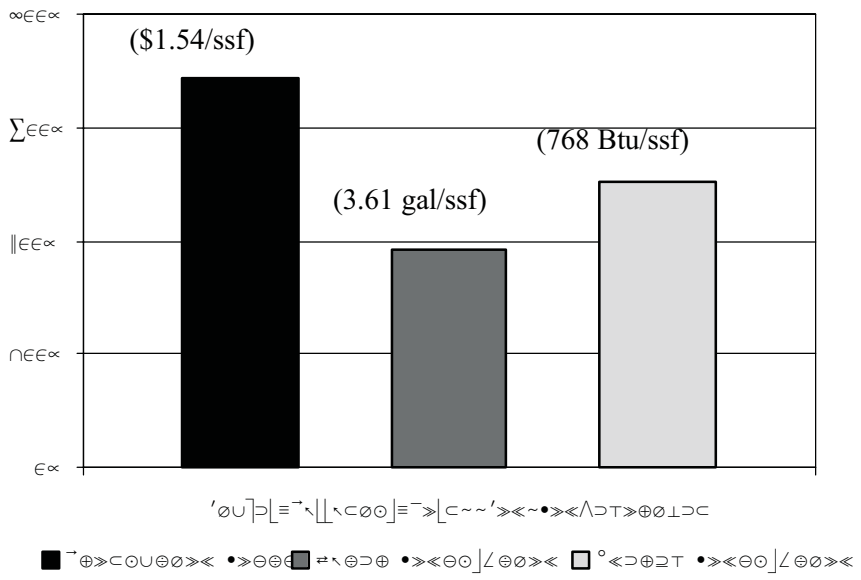


Figure 7-3. Production Costs and Resource Consumption of Nickel/Palladium/Gold Technology
(Percent Change from Baseline with Actual Values in Parentheses)

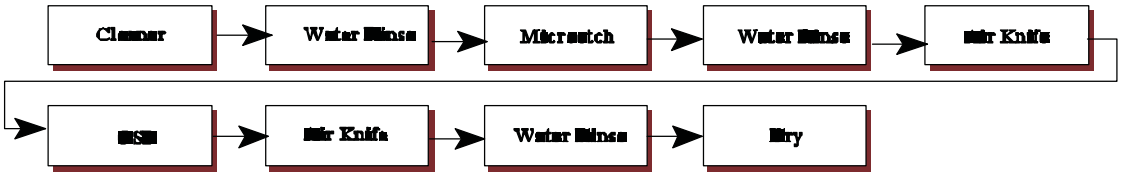
Table 7-22. Number of Nickel/Palladium/Gold Chemicals Subject to Applicable Federal Regulations

Regulation		No. of Chemicals	Regulation		No. of Chemicals
CWA	304b	5	EPCRA	313	10
	307a	5		302a	3
	311	12	SARA	110	6
	Priority Pollutant	5	TSCA	8d HSDR	1
CAA	111	5		MTL	4
	112b	5		8a PAIR	4
	112r	1	RCRA	U	--

Abbreviations and Definitions:
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
EPCRA 313 - Toxic Chemical Release Inventory
EPCRA 302a - Extremely Hazardous Substances
SARA 110 - Superfund Site Priority Contaminant
TSCA 8d HSDR - Health & Safety Data Reporting Rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule
RCRA U Waste - Characteristic hazardous waste

7.3.4 OSP Technology

Generic Process Steps and Typical Bath Sequence



Equipment Configurations Evaluated: Non-conveyorized and conveyorized.

Risk Screening and Comparison

Table 7-23 summarizes human and environmental hazards and risk concerns for chemicals in the OSP technology. The risk characterization identified occupational inhalation risk concerns for one chemical in the non-conveyorized OSP process and dermal risk concerns for three chemicals in the non-conveyorized OSP process and two chemicals in the conveyorized OSP process. No public health risk concerns were identified for the pathways evaluated.

Performance

The performance of the OSP technology was demonstrated at three test facilities, one of which operated conveyorized OSP equipment. Performance test results were not differentiated by the type of equipment configuration used. The Performance Demonstration determined that this technology has the capability of achieving comparable levels of performance to the HASL finish.

Production Costs and Resource Consumption

Computer simulation was used to model key operating parameters, including the time required to process a job consisting of 260,000 ssf and the amount of resources (water and energy) consumed. This information was analyzed with a hybrid cost model of traditional cost (i.e., capital costs, etc.) and activity-based costs to determine average manufacturing costs per ssf and water and energy consumption per ssf.

Both the non-conveyorized and conveyorized OSP technologies consume less water and energy and are more cost-effective than the baseline (non-conveyorized HASL process). Figure 7-4 lists the results of these analyses and illustrates the percent changes in costs and resource consumption from the baseline. Manufacturing costs, water consumption, and energy consumption for the non-conveyorized OSP process are less than the baseline by 69 percent, 38 percent, and 43 percent, respectively. The conveyorized OSP process is even more efficient than its non-conveyorized counterpart, reducing manufacturing costs from that of the baseline by 72 percent, and reducing water and energy consumption by 57 percent and 67 percent, respectively.

Table 7-23. Summary of Human Health and Environmental Risk Concerns for the OSP Technology

Chemical	Human Health Hazard and Occupational Risks [a]			Carcinogenicity Weight-of-Evidence Classification	Aquatic Risk Concerns
	Inhalation Risk Concerns [b]	Dermal Risk Concerns [c]	SAT Rank [d]		
Acetic acid	NE	No		None	No
Alkylaryl imidazole	NA	NE	LM	None	Yes
Aromatic imidizole product	NA	NE		None	NE
Arylphenol	NE	No	M	None	No
Copper ion	NA	Yes		Not classifiable (EPA Class D)	Not considered
Copper salt C	NA	Yes [e]		Not classifiable (EPA Class D)	Not considered
Copper sulfate pentahydrate	NA	Yes		Not classifiable (EPA Class D)	Not considered
Ethoxylated alkylphenol	NA	No [f]	LM	None	No
Ethylene glycol	Yes	No		None	No
Gum	NA	No [f]		None	No
Hydrochloric acid	No	NE		Not classifiable (IARC Group 3)	No
Hydrogen peroxide	No	No		Not classifiable (IARC Group 3)	No
Hydroxyaryl acid	NA	NE		None	No
Hydroxy aryl sulfonate	NA	No [f]	LM	None	No
Phosphoric acid	No	No		None	No
Sodium hydroxide	NA	NE		None	No
Sulfuric acid	NA	NE [g]		Human carcinogen (IARC Group 1)	No
Summary	No or NA: 14 NE: 2 Yes: 1	No: 8 NE: 6 Yes: 3		1 suspected or known	No: 12 Yes: 1 Not considered: 3

[a] Risk concerns are for surface finishing line operators (the most exposed individual).
[b] Inhalation risk concerns for non-conveyorized process only. Inhalation risk from fully enclosed, conveyorized process is assumed to be negligible.
[c] Dermal risk concerns apply to both conveyorized and non-conveyorized equipment unless otherwise noted.
[d] Structure-Activity Team rank for human health concerns:
LM: Low-Moderate concern; M: Moderate concern.
[e] Applied to non-conveyorized configuration only.
[f] Chemical has very low skin absorption (based on EPA's Structure-Activity Team evaluation); risk from dermal exposure not expected to be of concern.
[g] Although chronic toxicity values have not been established, repeated skin contact with low concentrations of sulfuric acid causes skin desiccation, ulceration of the hands, and chronic inflammation around the nails.
NA: Not Applicable. Inhalation exposure level was not calculated because the chemical is not volatile (vapor pressure below 1×10^{-3} torr) and is not used in any air-sparged bath.
NE: Not Evaluated; due to lack of toxicity measure.

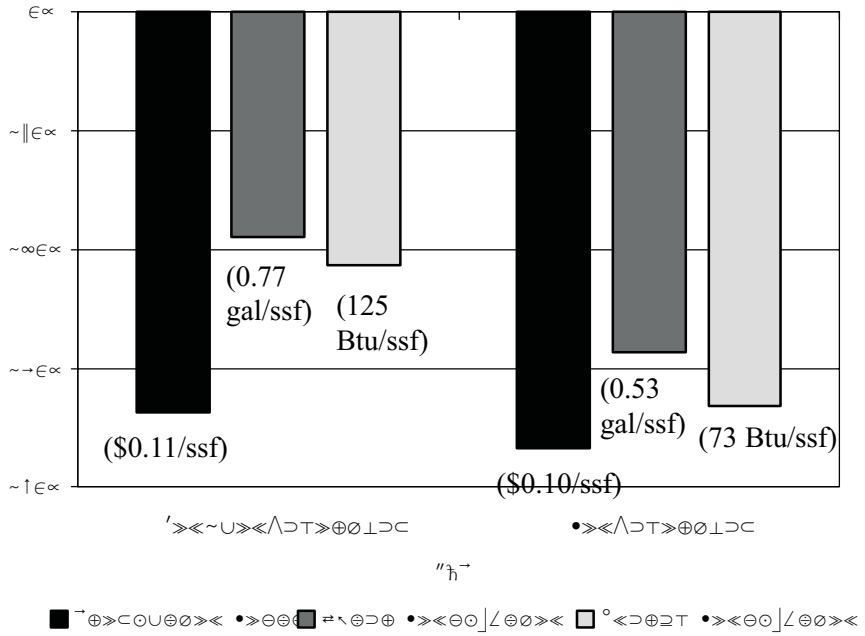


Figure 7-4. Production Costs and Resource Consumption of OSP Technology
(Percent Change from Baseline with Actual Values in Parentheses)

Regulatory Concerns

Chemicals contained in the OSP technology are regulated by the CWA, CAA, EPCRA, SARA, and TSCA. None of the OSP process chemicals were regulated under RCRA. A summary of the number of OSP chemicals subject to applicable federal regulations is presented in Table 7-24.

Social Benefits and Costs

A qualitative assessment of the private and external benefits and costs of the this technology suggests a mixture of benefits and costs to society if PWB manufacturers switched to the OSP technology from the baseline. For the aspects included in the evaluation, changing from baseline to OSP may result in:

- benefits from decreased manufacturing cost and ecological risk (based on fewer chemicals of concern), decreased water and energy use;
- mixed results for worker risk (based on fewer carcinogens or suspected carcinogens used in the process, but more chemicals of concern for non-cancer worker risk); and
- no discernible cost or benefit for risk to the public.

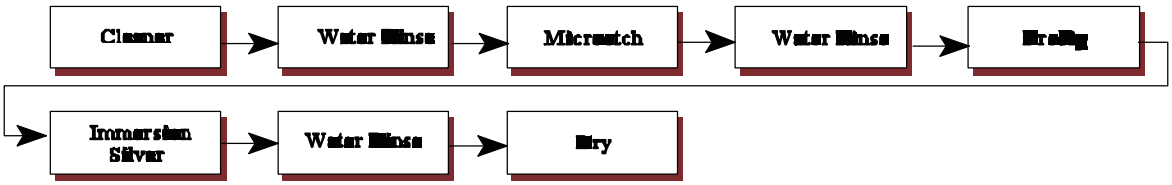
Table 7-24. Number of OSP Chemicals Subject to Applicable Federal Regulations

Regulation		No. of Chemicals	Regulation		No. of Chemicals
CWA	304b	2	EPCRA	313	5
	307a	2		302a	2
	311	5	SARA	110	2
	Priority Pollutant	2	TSCA	8d HSDR	1
CAA	111	3		MTL	2
	112b	2		8a PAIR	1
	112r	1	RCRA	U	--

Abbreviations and Definitions:
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
EPCRA 313 - Toxic Chemical Release Inventory
EPCRA 302a - Extremely Hazardous Substances
SARA 110 - Superfund Site Priority Contaminant
TSCA 8d HSDR - Health & Safety Data Reporting Rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule
RCRA U Waste - Characteristic hazardous waste

7.3.5 Immersion Silver Technology

Generic Process Steps and Typical Bath Sequence



Equipment Configurations Evaluated: Conveyorized.

Risk Screening and Comparison

Table 7-25 summarizes human and environmental hazards and risk concerns for chemicals in the immersion silver technology. The risk characterization did not identify any occupational or dermal risk concerns for chemicals in the conveyorized immersion silver process. No public health risk concerns were identified for the pathways evaluated.

Table 7-25. Summary of Human Health and Environmental Risk Concerns for the Immersion Silver Technology

Chemical	Human Health Hazard and Occupational Risks [a]			Carcinogenicity Weight-of-Evidence Classification	Aquatic Risk Concerns
	Inhalation Risk Concerns [b]	Dermal Risk Concerns [c]	SAT Rank [d]		
1,4-Butenediol	NA	NE	LM	None	No
Alkylamino acid A	NA	No [e]	LM	None	No
Fatty amine	NA	No [e]	M	None	No
Hydrogen peroxide	NA	No		Not classifiable (IARC Group 3)	Yes
Nitrogen acid	NA	NE		None	No
Phosphoric acid	NA	No		None	No
Silver nitrate	NA	No		Not classifiable (EPA Class D)	Not considered
Sodium hydroxide	NA	NE		None	No
Sulfuric acid	NA	NE [f]		Human carcinogen (IARC Group 1)	No
Summary	NA: 9	No: 5 NE: 4		1 suspected or known	No: 7 Yes: 1 Not considered: 1

[a] Risk evaluated for conveyorized process only. Inhalation risk from fully enclosed, conveyorized process is assumed to be low. Risk concerns are for line operator (the most exposed individual).
[b] Inhalation risk concerns for non-conveyorized process only. Inhalation risk from fully enclosed, conveyorized process is assumed to be negligible.
[c] Dermal risk concerns apply to both conveyorized and non-conveyorized equipment.
[d] Structure-Activity Team rank for human health concerns:
LM: Low-Moderate concern; M: Moderate concern.
[e] Chemical has very low skin absorption (based on EPA's Structure-Activity Team evaluation); risk from dermal exposure is not expected to be of concern.
[f] Although chronic toxicity values have not been established, repeated skin contact with low concentrations of sulfuric acid causes skin desiccation, ulceration of the hands, and chronic inflammation around the nails.
NE: Not Evaluated; due to lack of toxicity measure.
NA: Not Applicable. Inhalation exposure level was assumed to be negligible for conveyorized lines.

Performance

The performance of the immersion silver technology was demonstrated at two test facilities. The Performance Demonstration determined that this technology has the capability of achieving comparable levels of performance to the HASL finish. In addition, the immersion silver process is both gold and aluminum wire-bondable, though testing of wire-bondability was not included in the performance testing protocol.

Production Costs and Resource Consumption

Computer simulation was used to model key operating parameters, including the time required to process a job consisting of 260,000 ssf and the amount of resources (water and energy) consumed. This information was analyzed with a hybrid cost model of traditional cost (i.e., capital costs, etc.) and activity-based costs to determine average manufacturing costs per ssf and water and energy consumption per ssf.

Analysis results showed that the conveyorized immersion silver process consumed less water and was more cost-effective than the baseline non-conveyorized HASL process, while consuming more energy. Average production costs for immersion silver were $0.28/ssf, while water and energy consumption rates were determined to be 0.53 gal/ssf and 287 Btu/ssf, respectively. Figure 7-5 lists the results of these analyses and illustrates the percent changes in costs and resource consumption from the baseline. Manufacturing costs and water consumption are less than the baseline by 22 percent and 57 percent, respectively, while energy consumption increased by 32 percent.

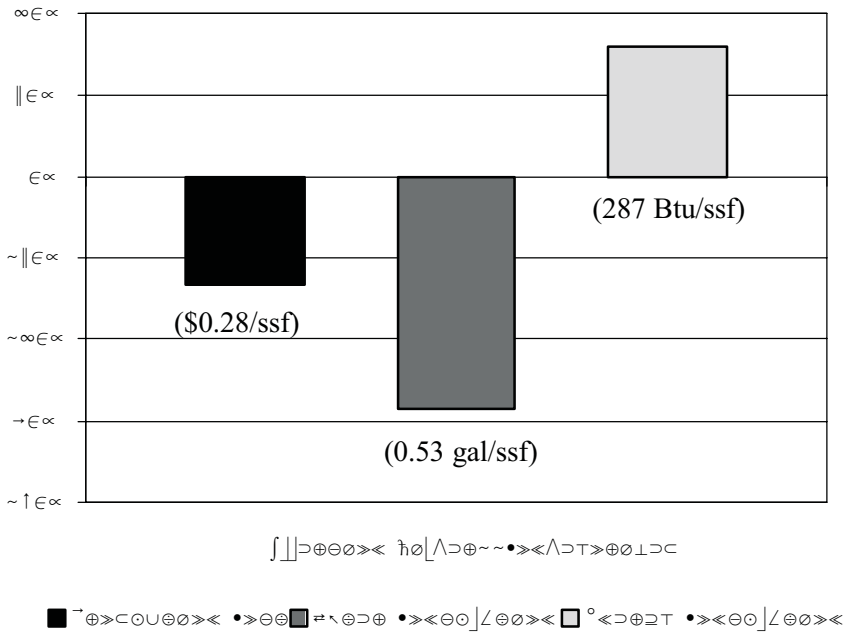


Figure 7-5. Production Costs and Resource Consumption of Immersion Silver Technology
(Percent Change from Baseline with Actual Values in Parentheses)

Regulatory Concerns

Chemicals contained in the immersion silver technology are regulated by the CWA, CAA, EPCRA, SARA, and TSCA. None of the immersion silver process chemicals were regulated under RCRA. A summary of the number of immersion silver chemicals subject to applicable federal regulations is presented in Table 7-26.

Table 7-26. Number of Immersion Silver Chemicals Subject to Applicable Federal Regulations

Regulation		No. of Chemicals	Regulation		No. of Chemicals
CWA	304b	1	EPCRA	313	3
	307a	1		302a	3
	311	5	SARA	110	1
	Priority Pollutant	1	TSCA	8d HSDR	--
CAA	111	1		MTL	1
	112b	1		8a PAIR	1
	112r	--	RCRA	U	--

Abbreviations and Definitions:
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
EPCRA 313 - Toxic Chemical Release Inventory
EPCRA 302a - Extremely Hazardous Substances
SARA 110 - Superfund Site Priority Contaminant
TSCA 8d HSDR - Health & Safety Data Reporting Rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule
RCRA U Waste - Characteristic hazardous waste

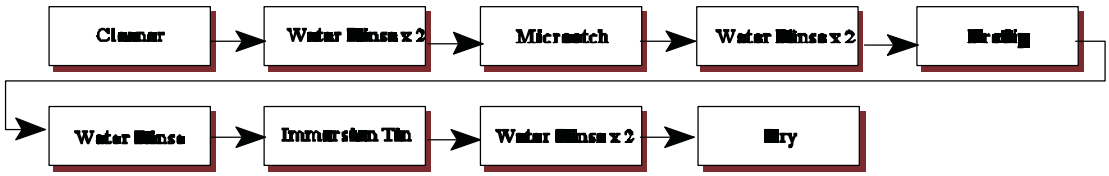
Social Benefits and Costs

A qualitative assessment of the private and external benefits and costs of the this technology suggests a mixture of benefits and costs to society if PWB manufacturers switched to the immersion silver technology from the baseline. For the aspects included in the evaluation, changing from baseline to immersion silver may result in:

- benefits from decreased manufacturing cost, worker and ecological risk (based on fewer chemicals of concern), and decreased water use;
- costs from increased energy use; and
- no discernible cost or benefit for risk to the public.

7.3.6 Immersion Tin Technology

Generic Process Steps and Typical Bath Sequence



Equipment Configurations Evaluated: Non-conveyorized and conveyorized.

Risk Screening and Comparison

Table 7-27 summarizes human and environmental hazards and risk concerns for chemicals in the immersion tin technology. The risk characterization identified occupational dermal risk concerns for one chemical for either equipment configuration. No occupational inhalation concerns or public health risk concerns were identified for the pathways evaluated.

Table 7-27. Summary of Human Health and Environmental Risk Concerns for the Immersion Tin Technology

Chemical	Human Health Hazard and Occupational Risks [a]			Carcinogenicity Weight-of-Evidence Classification	Aquatic Risk Concerns
	Inhalation Risk Concerns [b]	Dermal Risk Concerns [c]	SAT Rank [d]		
Aliphatic acid D	No	No		None	No
Alkylalkyne diol	NA	No [e]	L	None	No
Alkylimine dialkanol	NA	No [e]	M	None	No
Alkylamino acid B	NA	No		None	No
Alkylaryl sulfonate	NE	No [e]	L	None	No
Alkylphenol ethoxylate	NA	No [e]	LM	None	No
Bismuth compound	NA	No [f]	M	None	No
Citric acid	NA	No [e]	L	None	No
Cyclic amide	No	No		None	No
Ethoxylated alkylphenol	NA	No [e]	LM	None	No
Ethylene glycol monobutyl ether	No	No		None	No
Fluoboric acid	NA	NE		None	No
Hydrochloric acid	No	NE		Not classifiable (IARC Group 3)	No
Hydroxy carboxylic acid	No	No		None	No
Methane sulfonic acid	NA	NE		None	No
Phosphoric acid	No	No		None	No
Potassium peroxymonosulfate	NA	No [e]	M	None	NC: Yes C: No

Chemical	Human Health Hazard and Occupational Risks [a]			Carcinogenicity Weight-of-Evidence Classification	Aquatic Risk Concerns
	Inhalation Risk Concerns [b]	Dermal Risk Concerns [c]	SAT Rank [d]		
Quantenary alkyl ammonium chlorides	NA	No [e]	M	None	No
Silver salt	NA	No		Not classifiable [g]	Not considered
Sodium benzene sulfonate	NA	No [e]	M	None	No
Sodium phosphorus salt	NA	NE		None	No
Stannous methane sulfonic acid	NA	No		Not classifiable (EPA Class D)	Not considered
Sulfuric acid	NA	No		Human carcinogen (IARC Group 1)	No
Thiourea	NA	NE		Possibly carcinogenic (IARC Group 2B)	No
Tin chloride	NA	No		Not classifiable (EPA Class D; IARC Group 3)	Not considered
Unspecified tartrate	NA	No		None	No
Urea	NA	No		None	No
Vinyl polymer	NA	No		Not classifiable [g]	No
Urea compound C	NE	Yes		None	No
Summary	No or NA: 27 NE: 2 Yes: 0	No: 23 NE: 5 Yes: 1		2 suspected or known	No: 25 Yes: 1 Not considered: 3

[a] Risk concerns are for surface finishing line operators (the most exposed individual).
[b] Inhalation risk concerns for non-conveyorized process only. Inhalation risk from a fully enclosed, conveyorized process is assumed to be negligible.
[c] Dermal risk concerns apply to both conveyorized and non-conveyorized equipment.
[d] Structure-Activity Team rank for human health concerns:
L: Low concern; LM: Low-Moderate concern; M: Moderate concern.
[e] Chemical has very low skin absorption (based on EPA's Structure-Activity Team evaluation); risk from dermal exposure is not expected to be of concern.
[f] No absorption expected through skin, however, in water this compound will cause irritation of all moist tissues (SAT report).
[g] Specific EPA and/or IARC groups not reported in order to protect proprietary chemical identities.
NE: Not Evaluated; due to lack of toxicity measure.
NA: Not Applicable. Inhalation exposure level was not calculated because the chemical is not volatile (vapor pressure below 1×10^{-3} torr) and is not used in any air-sparged bath.

Performance

The performance of the immersion tin technology was demonstrated at four test facilities, two of which operated conveyorized immersion tin equipment. Performance test results were not differentiated by the type of equipment configuration used. The Performance Demonstration determined that this technology has the capability of achieving comparable levels of performance to the HASL finish.

Production Costs and Resource Consumption

Computer simulation was used to model key operating parameters, including the time required to process a job consisting of 260,000 ssf and the amount of resources (water and energy) consumed. This information was analyzed with a hybrid cost model of traditional cost (i.e., capital costs, etc.) and activity-based costs to determine average manufacturing costs per ssf and water and energy consumption per ssf.

Both the non-conveyorized and conveyorized methods of immersion tin were more economical than the baseline process, with the non-conveyorized process proving less expensive ($0.18/ssf vs. $0.25/ssf) overall. Only the conveyorized immersion tin process showed a reduction in water consumption, while both equipment configurations consumed more energy than the baseline. Figure 7-6 lists the results of these analyses and illustrates the percent changes in costs and resource consumption for either equipment configuration from the baseline. Non-conveyorized immersion tin manufacturing costs are less than the baseline by 50 percent, while the water and energy consumption rates increased by 46 percent and 33 percent, respectively. Manufacturing costs and the water consumption for the conveyorized immersion tin process are less than the baseline by 31 percent and 29 percent respectively, while energy consumption increased 139 percent.

Regulatory Concerns

Chemicals contained in the immersion tin technology are regulated by the CWA, CAA, EPCRA, SARA, and TSCA. In addition, two of the chemicals in the immersion tin process chemicals is regulated under RCRA. A summary of the number of immersion tin chemicals subject to applicable federal regulations is presented in Table 7-28.

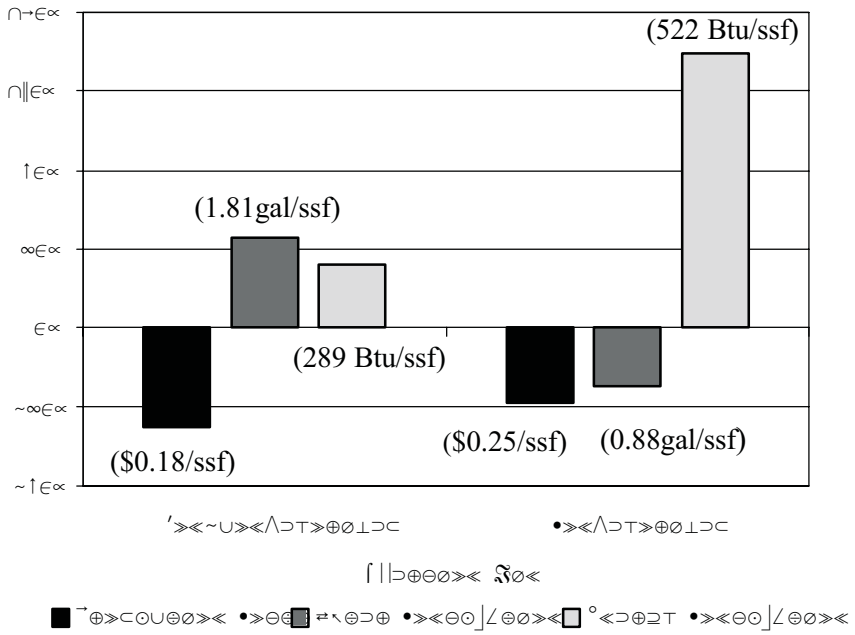


Figure 7-6. Production Costs and Resource Consumption of Immersion Tin Technology
(Percent Change from Baseline with Actual Values in Parentheses)

Table 7-28. Number of Immersion Tin Chemicals Subject to Applicable Federal Regulations

Regulation		No. of Chemicals	Regulation		No. of Chemicals
CWA	304b	1	EPCRA	313	7
	307a	1		302a	2
	311	6	SARA	110	1
	Priority Pollutant	1	TSCA	8d HSDR	2
CAA	111	3		MTL	4
	112b	2		8a PAIR	3
	112r	1	RCRA	U	2

Abbreviations and Definitions:
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants-Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
EPCRA 313 - Toxic Chemical Release Inventory
EPCRA 302a - Extremely Hazardous Substances
SARA 110 - Superfund Site Priority Contaminant
TSCA 8d HSDR - Health & Safety Data Reporting Rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule
RCRA U Waste - Characteristic hazardous waste

Social Benefits and Costs

A qualitative assessment of the private and external benefits and costs of the this technology suggests a mixture of benefits and costs to society if PWB manufacturers switched to the immersion tin technology from the baseline. For the aspects included in the evaluation, changing from baseline to non-conveyorized immersion tin may result in:

- benefits from decreased manufacturing cost, worker and ecological risk (based on fewer chemicals of concern);
- costs from increased water and energy use; and
- no discernible cost or benefit for risk to the public.

Changing from baseline to conveyorized immersion tin may result in:

- benefits from decreased manufacturing cost, worker and ecological risk (based on fewer chemicals of concern) and decreased water use;
- costs from increased energy use; and
- no discernible cost or benefit for risk to the public.

REFERENCES

Mishan, E.J. 1976. Cost-Benefit Analysis. Praeger Publishers: New York.