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Draft IV
June 2000

IPC Roadmap:

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2215 Sanders Road, Northbrook, IL 60062-6135
Tel. 847.509.9700 Fax 847.509.9798
www.ipc.org

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INTRODUCTION

Leaded solders have been used in electronics applications for more than 50 years. Leaded solders (usually 60/40 tin-lead) have predominated because they are inexpensive relative to other alloys and perform reliably under a variety of operating conditions. They also possess unique characteristics (e.g., low melting point, high strength ductility and fatigue resistance, and high thermal cycling, electrical conductivity and joint integrity) that are well suited for electronics applications. Finally, leaded solders predominate in the electronics industry because of the large installed manufacturing base that supports their use.

Leaded solders perform three basic functions in electronics interconnection: (1) they provide the final surface finish for printed circuit boards, (2) they are applied to component leads to achieve a compatible solderable surface, and (3) they are used to attach electronic components to printed circuit boards. Although many PCB manufacturers have succeeded in eliminating lead from the surface finish step of PWB manufacturing by switching to new alternatives, such as organic solder protectorates (OSPs), leaded solder continues to be the predominant component lead finish and choice for assembly soldering.

The U.S. electronics interconnection industry uses less than two percent of the world's annual lead consumption. Although electronics manufacturing accounts for only 0.6% of the annual lead consumption, legislation and competitive pressures from around the world to eliminate the use of this element are increasing, and showing no signs of subsiding. This roadmap capsulizes the steps already taken, and sets a timetable for implementation and integration of lead-free processes and materials throughout the electronics industry.

1 SCOPE

This roadmap is a compilation of information gathered by IPC and approved for inclusion by industry. This document does not intend to set timelines for the U.S. industry to remove lead from electronics. Its sole purpose is to keep the industry abreast of this situation so companies can prepare themselves for any action they see fit.

The lead elimination dates in this document are not an indication of what IPC proposes as timelines. These dates, which mostly come from Japanese companies and legislation in Europe, are included so companies will have an idea of what their competitors and customers are doing. The IPC Board of Directors (BoD) drafted a position statement on this issue (see 3.1.1) which supports the voluntary removal of lead from electronics.

Because this is a roadmap, this document will constantly evolve to keep current with the status of this subject. IPC and industry will make a determination as to how often the document needs to be revised (i.e., every quarter, biannually, etc.) and whether or not meetings will be required.

2 DRIVERS

2.1 Environmental Although the European Union (EU) has proposed banning lead from electronics by the year 2008, there have been no calls for a domestic ban on lead use in the U.S. since the early 1990s. Collaborative industry action to convince legislators that lead use in the U.S. no longer posed environmental or health risks helped defeat such legislation.

Currently, lead use in the U.S. is controlled through environmental and safety statutes that minimize the amount of lead that enters the environment through management controls.

Other metals that may be used in lead-free solders are heavily regulated at the state and federal level. Although silver is not regulated as heavily as lead, there are environmental restrictions imposed on silver users. Its regulation may increase in the future, although it is unlikely that a ban would ever be proposed.

2.2 Legislation Several pieces of legislation in effect or under review heavily impact the move to lead-free electronics. With this these legislation and their requirements come the need to understand exactly what is meant by lead-free electronics. In the US, 0.2% alloy contamination of virgin is considered lead free for plumbing solders and fluxes[1]. Europe's level is 0.1%, which is the position being considered by ISO, but there is still no definition of a lead-free electronic assembly.

Setting the alloy contamination level for the PWB industry needs to consider all three components (solder, PWB finish, and component finish).

2.2.1 U.S.

2.2.1.1 Environmental Protection Agency (EPA) The U.S. EPA has taken regulatory action to remove lead from common consumer products such as gasoline, plumbing and paint products, and to impose strict management requirements on lead-acid batteries to prevent disposal in the solid waste stream. These actions have successfully resulted in the average blood lead levels of persons in the U.S. dropping 78% from 12.8 to 2.8 micrograms per deciliter during the last decade (Trumble).

The EPA has also proposed reducing the Toxic Release Inventory (TRI) reporting threshold for lead and lead compounds from 25,000 pounds to 10 pounds, which, if enacted, would increase reporting burdens for facilities that use lead. IPC opposes this initiative and will continue to monitor its status. As of time of publication of this document the TRI is still a proposal.

The EPA held public meetings in Chicago and Los Angeles in late 1999 to discuss this issue and have posted reports on their Web site (www.epa.gov/opptintr/tri/pb_rule.htm).

No federal lead legislation is pending in the U.S. Congress. Some states (e.g., New Jersey), however, are exploring legislation or programs that would require the recycling of consumer electronic products to reduce lead-content in landfill leachate. Consumer electronics have been targeted because they represent a large portion of the municipal solid waste stream. For example, more than 12 million computers are discarded each year, resulting in as much as 600 million pounds of waste (Trumble).

Although IPC will continue to track Federal legislation, companies are encouraged to contact their state and local government to track any activities with lead bans that may affect them.

2.2.1.2 State Activities Although there are no known legislation requiring the elimination of lead from electronics on a state level, several states are initiating stepped-up recycling for electronics, recognizing the long-term effects their materials could have on the environment.

The Electronics Recycling Initiative (ERI) offers continuing updates on activities at both the state and county levels (http://www.nrc-recycle.org/Programs/electronics/policy.htm). The following are some state activities as of publication of this draft.

2.2.1.2.1 California In November 1986, California voters approved an initiative to address growing concerns about exposures to toxic chemicals. That initiative became The Safe Drinking Water and Toxic Enforcement Act of 1986, better known by its original name: Proposition 65. Proposition 65 requires the Governor to publish a list of chemicals that are known to the State of California to cause cancer, birth defects or other reproductive harm. This list must be updated at least once a year.

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[1] EPA Code of Federal Regulations (CFR) Title 40, *Protection of the Environment*, Chapter 1, Subsection D, *Water Programs*, Section 141, *National Primary Drinking Water Regulations*, 1999.

In June 2000, the Santa Clara County Pollution Prevention Council (PPC) held a meeting to discuss policies and programs to reduce the discharge of persistent, bioaccumulative and toxic (PBT) pollutants. In an early statement the PPC indicated it is seeking regulatory reduction/elimination of lead solders. PPC staff indicated this encompasses solders used in electronics assemblies.

2.2.1.2.2 Connecticut The Connecticut Department of Environmental Protection (DEP) anticipates issuing a general permit for collecting certain recyclables, including consumer electronics in early 2000.

2.2.1.2.3 Florida The Florida Department for Environmental Protection (DEP) is moving forward with a pilot program for end-of-life electronics management for cathode ray tubes (CRTs), computers, and other electronic equipment.

2.2.1.2.4 New Jersey The U.S. EPA has funded a greant for a pilot educational outreach project coordinated by the New jersey Solid Waste Policy Group at Rutgers Univ. In this program, students will produce a video geared at children grades 3 through 6 on electronics recycling.

2.2.1.2.5 South Carolina South Carolina's legislature evaluated a bill that would establish a statewide electronic equipment recycling program.

2.2.1.2.6 Wisconsin The Department of Natural Resources (DNR) has instituted a program on computer collection that meets on a monthly basis. Since its inception three cities in Wisconsin have held computer collection efforts.

2.2.2 Japan No federal legislation specifically banning lead use in electronics is pending. However, the Japanese Ministry of Trade proposed in May 1998 take-back (recycling) legislation. The Japanese EPA and government “suggest” reduced use of lead as part of increased recycling (DTI).

The Japanese Home Electronics Recycling Law, which was revised in 1998, calls for OEMs to be prepared to collect and recycle four major products by April 1, 2001. Although this law doesn't mention the use of leaded products, there is another law forbidding these companies from putting any kind of waste leaching toxic elements into the environment. The combination of these two laws is one of the driving forces behind lead elimination in electronics.

2.2.3 Europe The EC has proposed banning the use of lead in automotive vehicles unless those uses can be easily separated from the vehicle prior to shredding at the end of the vehicle’s useful life (printed wiring boards are specifically excluded from the ban).

Some European countries and the European Commission (EC) have proposed regulations on the use of lead (see 2.2.3.1 through 2.2.3.4).

2.2.3.1 Austria There are restrictions on the lead content of fertilizers, as well as on the use of sewage sludge if the heavy metal content in either the soil or the sludge exceeds certain limits. A similar ordinance has been adopted by Finland and drafted by the German government.

2.2.3.2 Denmark A regulation on lead-containing products is under way. The draft regulation contains a general prohibition (with exemptions) on the sale of products containing lead substances. The sale of a range of specified products containing lead is also prohibited.

2.2.3.4 Sweden There are initiatives to phase out lead use in many products including cables, solder, light bulbs, cathode rays and keels.

2.2.3.5 European Council (EC) Due to mounting pressures by countries in the European Union, the European Council (EC) felt the need to draft legislation on the regulation of toxic element usage in electronics. The first document developed, the Waste Electrical and Electronic

Equipment (WEEE) Directive (see 2.2.3.5.1), found much popularity in the electronics industry, but will its sister document, Environment of Electrical and Electronic Equipment (EEE) Directive (see 2.2.3.5.2) get the same amount of attention?

2.2.3.5.1 Waste Electrical and Electronic Equipment (WEEE) The draft legislation, known as the Waste Electrical and Electronic Equipment (WEEE) Directive, has caught the attention of the industry worldwide, as it is the only known legislation on the dockets that would call for the reduction/elimination of lead in PWBs.

The WEEE Directive, in and of itself, has since become a riddle. The EC went through a shake down and restructuring of sorts in late 1999, causing the delay of the much-anticipated 4th draft of WEEE. While awaiting the 4th draft, the industry was presented with a sister Environment of Electrical and Electronic Equipment (EEE) Directive (see 2.2.3.5.2).

Still a 4th draft of the directive made its way out of EC's Environment-Directorate General (DG), the group responsible for the WEEE Directive. In this latest draft, which IPC has posted for free download (www.leadfree.org), it appears as though the DG has moved more toward recycling issues and has expanded the elimination date for listed materials, including lead, from 2004 to January 2008.

2.2.3.5.2 Environment of Electrical and Electronic Equipment (EEE) Although some in the industry forecasted this move in early 1999, the release of a sister Directive to WEEE still caught some by surprise. The Environment of Electrical and Electronic Equipment (EEE) Directive's primary focus is on the design and manufacture of electronics to reduce the impact the electronics may have on the environment.

Although it does call for manufacturers to avoid the undue use of materials or substances presenting a threat to the environment, the main focus of this document is on how the product's production and life cycle affect the environment. This includes pollution during production and reclamation of parts at the end of its life.

IPC has made a copy of the draft EEE Directive for download (www.leadfree.org).

2.3 Marketing Strategies Further to legislative pressures, Japanese OEMs have found it prudent to take a very proactive stance on this issue and have shown some signs of success in doing so. Several Japanese companies have set very tight deadlines and advanced steps to reducing or completely eliminating lead from some or all of their products.

Because most of these products are consumer electronics, they have also found a way of using lead elimination to increase market share. One OEM has even gone so far as to place a sticker on their products indicating that it was manufactured with lead-free solder. If first signs say anything, the fact that the first product they did this with, a minidisk player, enjoyed a 11 percent jump in its market, and without any further accessories than other manufacturer's comparable products. Since that margin increase, there have been no further reports of such successes from that or any other company.

The Japanese companies have also been very open to sharing with industry their status and objectives. These can be seen in several press releases from the past year and by visiting their Web sites.

All of these activities have resulted in U.S. companies seeing the need to prepare for lead-free product to reach the U.S. Although there are no data known that would indicate whether or not the U.S. consumer would feel the need to purchase a lead-free product, these companies still want to be prepared.

The greatest concern of these companies is that marketing drivers, stepped up activities by Japanese companies and U.S. companies trying to keep up with them will drive legislation. Most manufacturers would agree that doing a per product lead elimination would be much easier than a requirement to remove lead from all of their products by a given date.

3 ACTIVITIES OF TRADE AND RESEARCH ORGANIZATIONS

3.1 U.S.

3.1.1 IPC- Association Connecting Electronics Industries

Position on Lead-Free Electronics, adopted by the IPC board of directors, April 1999
The US electronics interconnection industry, represented by the IPC, uses less than 2% of the world's annual lead consumption. Furthermore, all available scientific evidence and US government reports indicate that the lead used in US printed wiring board (PWB) manufacturing and electronic assembly produces no significant environmental or health hazards.

Nonetheless, in the opinion of IPC, the pressure to eliminate lead in electronic interconnections will continue in the future from both the legislative and competitive sides. IPC encourages and supports research and development of lead-free materials and technologies. These new technologies should provide product integrity, performance and reliability equivalent to lead-containing products without introducing new environmental risks or health hazards. IPC prefers global rather than regional solutions to this issue, and is encouraging a coordinated approach to the voluntary reduction or elimination of lead by the electronics interconnection industry.

Based on this statement and worldwide activities, IPC has established the following levels of lead-free product and their requirement(s). These levels were developed to establish an industry recognbized system of understanding the amount of lead in a certain product.

Lead Free 1 -- Wave solder and solder paste used to manufacture the product are lead free.
Lead Free 2 -- Lead Free 1 is in place, and the PWB finishes contain no lead.
Lead Free 3 -- Lead Free 1 and Lead Free 2 are in place, and lead-free component finishes are in place.

3.1.2 Electronics Industries Alliance (EIA) The Electronics Industries Alliance (EIA) (www.eia.org) is a trade organization representing the U.S. high technology community. EIA develops technical standards, market analysis, government relations, trade shows and seminar programs.

EIA believes the goal of protecting all citizens, especially children, from lead exposure is consistent with the safe use of lead in electronics. The electronics industry uses lead in strict accordance with applicable state, local, and federal laws including, but not limited to those administered by the EPA, DOT, and OSHA. Through compliance with these requirements the industry strives to assure the protection of workers, consumers, and the environment. Indeed, some manufacturing specifications require lead to protect against other serious health effects, such as x-ray shielding. As many of the applications are vital to the industry and have no viable alternatives, it is premature at best to restrict lead use in the industry.

As an alternative, EIA would support further research that could lead to minimizing lead use in the electronics industry, including the funding of a university-affiliated research program. Such research should be conducted along with consumer education campaigns on proper use and disposal of lead-containing products. Disposal of sealed lead-acid batteries and other products containing lead should be minimized and their recycling encouraged when sufficient technologies exist.

3.1.3 National Center for Manufacturing Sciences (NCMS) The National Center for Manufacturing Sciences (NCMS) (www.ncms.org) is a not-for-profit collaborative research consortium of North American corporations. The largest cross-industry consortium in the United States, NCMS is backed by some 175 member companies, an annual R&D project portfolio exceeding $80 million, and a ten-year track record in the successful performance of complex, multi-partner manufacturing technology programs

NCMS published a study conducted with several major OEMs of nearly 80 solder alloys in 1997. The study chose three alloys as potential replacements but none were considered drop-in replacements. No industry implementation date recommended.

3.1.4 National Electronics Manufacturing Initiative (NEMI) The National Electronics Manufacturing Initiative (NEMI) (www.nemi.org) is a partnership of the North American electronics manufacturing industry, including commercial and consumer electronics manufacturers, semiconductor manufacturers, substrate suppliers, materials suppliers, equipment manufacturers, and electronics service providers.

NEMI has been actively involved in providing the industry with recommended alternative alloys through the NEMI Lead-Free Assembly Project: The following are the objectives of this project:

- To have the capability for North American companies to produce lead-free products by 2001, with an eye toward total lead elimination by 2004 (timing of actual deployment is, of course, left to the participating companies to determine).
- To demonstrate production-ready parts, materials and processes for lead-free assemblies.
- To cooperate with component, PWB, and equipment manufacturers to allow for the smooth transition to manufacturing processes that may require temperatures up to 260°C.
- To develop criteria for the industry to evaluate lead-free processes.
- To modify or develop appropriate JEDEC, IPC, or other related standards for lead-free electronics manufacturing.

This team has recommended Sn-3.9Ag-0.6Cu (+/- 0.2%) as the recommended alloy for surface mount assembly.

3.2 Japan

3.2.1 Japanese Ministry of Industry and Trade Institute (MITI) The Japanese Ministry of International Trade and Industry (MITI) (www.miti.go.jp) formed in 1949 from a reorganization of the former Ministry of Commerce and Industry. MITI has since played a central role in the development of policies on industry and international trade through the implementation of many measures under its jurisdiction. Responding to changes in social and business requirements, MITI has made efforts to attain a more affluent society and improve the quality of life in Japan.

MITI calls for the use of lead to be reduced to half by 2000 and two-thirds by 2005.

3.2.2 Japan Institute for Electronic Packaging (JIEP) The Japan Institute for Electronic Packaging (JIEP) conducts research, investigation, technology information exchange and distribution, and international activities in the area of electronic packaging technology. This is done to support Japanese electronics industry and universities, and eventually to contribute to the nation's economic growth, and to improve social life for the people.

Mass production using Pb-free solder	1999-2000
Adoption of Pb-free components	1999
Increased adoption of Pb-free components	2000-2001
Full scale recycling of assembly board	2001-2002
Adoption of Pb-free solders in reflow soldering process	2001
Pb-free solder used for new products preferentially	2003
Pb-containing solder used only exceptionally	2005-2010
Elimination of Pb solders	2010-2015

3.3 Europe

3.3.1 Printed Circuits Interconnection Federation (PCIF)/International Tin Research Institute (ITRI) The Printed Circuits Interconnection Federation (PCIF) (www.pcif.org.uk) and the International Tin Research Institute (ITRI) - SOLDERTEC (www.lead-free.org) conducted a study to determine a drop-in replacement for SnPb. Although no drop-in replacement was found, the study concluded the SnAgCu family to be a workable alternative.

4 ROADMAPS AND ACTIVITIES

4.1. U.S. The following statements are those provided to IPC by companies while preparing the 1st draft of the roadmap. To guarantee accuracy it is important for representatives of the companies listed in the following to review their statement and determine its accuracy. Please be sure to indicate if the statement applies to a specific division of the company or if your company would like to have their statement removed for the next draft of the roadmap.

The following are some areas of consideration when preparing your statement.

Manufacturing for electronics interconnection (i.e., components, alloys, PWBs)?
Market served (i.e., military, consumer electronics)?
Gathering information?
Evaluating (i.e., processes, alloys, packages, etc.)?
Impact studies (i.e., technical, financial)?
Qualifying?
Manufacturing consumables (i.e., consumer electronics)?
Dates for implementation?

Delphi/Delco
Seriously pursuing lead-free products in anticipation of customer pull.

Hadco
Investigating processes to replace Sn-Pb board finishes.

Honeywell
Has formed a team to formulate activities on lead-free.

IBM
Currently formulating a plan to have an interim strategy by end of 1999. Plans to be on par with, if not ahead of, the industry in general.

Lockheed Martin
Is investigating the issue, but will not make a decision on whether or not to move to lead free until they see a real need or requirement to do so.

Lucent Technologies
Aligning with industry through consortia activities.

Northrop Grumman

Waiting to see what steps industry takes.

Raytheon
Approach for military business is:

- Leverage existing industry work.
- Develop a test protocol in conjunction with our military customers.
- Execute the test protocol.
- Implement proven alternatives through the Single Process Initiative process.

According to Raytheon, this is a two- to three-year effort.

Texas Instruments
Has a Ni-PD component finish.

Viasystems
Has a patent on an OSP.

Boeing
Qualifying a non-lead finish (immersion Ag) for PWBs in 1999 and some designs that use Ni-Au. Will likely accept lead-free finishes on PWBs in 2000. Will probably implement initially on new PWB drawings. Decisions to transition older PWB drawings to allow or require a lead free finish will be done on a case by case basis based on cost & customer preferences.

Did some work on no-lead alloys and conductive adhesives about three years ago, but is not looking to develop a new alloy. Planning a more accelerated look for data and reliability testing on alloys for FY2000. Will probably be 2001 or later before acceptance of no-lead solders will commence, depending on availability of data applicable to Boeing's specific products.

Siemens
Recognize the need to switch but do not yet have a global policy.

Sun Microsystems
Participating in industry consortia and watching closely the political, technical, and customer drivers.

4.2 Japan Although there is no legislation, pending or otherwise, in Japan calling for the reduction or elimination of lead in electronics, several Japanese OEMs have taken upon themselves to be as proactive in this market as possible. These companies have been more than open regarding their environmental policies and planned release of products.

These companies have also used the reduction of lead in their consumer products to their advantage by marketing the electronics as such (see 2.3). By noticing the "green leaf" sticker or other marking, the consumer is made aware that the product is low or no lead.

By using consumer electronics, which have a typical three-year life span, these companies are also able to gather reliability data as they go along, thus preparing them for any regulations calling for a complete elimination of lead.

4.2.1 Hitachi Hitachi reduced their lead usage in 1999 will by half of that used in 1997, and all products will be lead free by 2001. They are currently investing 1.2 billion Yen ($11.2 million) to expand production of lead-free solder

4.2.2 Matsushita (Panasonic) Matsushita announced lead solder will be totally removed in the fiscal year 2000, and all consumer electronics to be lead free by 2001. They have also indicated they will begin marketing lead-free products in the US in 2000.

4.2.3 Sony Sony reduce their lead usage in 1999 by half of that used in 1996, and they plan to completely eliminate lead from all products except high-density packaging by 2001. Their suppliers have been instructed to provide only lead-free materials and parts.

4.2.4 Toshiba Toshiba plans to remove lead from all cell phones by 2002.

4.2.5 NEC NEC Launched the world's first three notebook computers with lead-free motherboards, manufactured with SnZn. They plan to install lead-free motherboards in desktops PCs next.

They have announced that their lead usage by 2002 will be 50% of that used in 1997. They are currently using lead-free semiconductors and began shipping lead-free product in January.

Like most of their counterparts, they are labeling lead-free from lead bearing products

4.2.6 Fujitsu Fujitsu announced plans for a staged reduction in the use of lead in its products, with the goal of making all products lead free by December 2002. This initiative includes not only components internally produced at Fujitsu but also parts supplied by outside vendors. Based on this, Fujitsu has announced the following goals:

Complete lineup of lead-free LSI products to be available by October 2000.
Half of all printed circuit boards used in Fujitsu products to be lead-free by December 2001.
Total elimination of lead from all Fujitsu products by December 2002.

4.3 Military Applications One area of industry served that may be "held hostage" by the industry making the transition to lead-free electronics would be those companies that serve the military sector. One of the major concerns addressed has been the possibility that the demand for leaded materials may decrease so much that the cost of those materials may increase.

Because the military is required to build product that will maintain reliability for at least 20 years, this area of the industry will most likely lag instead of lead. These companies will most likely not make a move towards lead-free product until required to do so by some sort of legislation. Right now the only existing pending legislation (WEEE Directive) doesn't include military applications.

The greatest concern of the elimination of lead from military applications is the fact that there is no real long-term reliability data available for the alternatives. A best case scenario to the military, should it be required to eliminate or reduce lead, would be to use the data gathered by the commercial industry.

Should those data be unavailable or not worthwhile, the following is a possible scenario as to how the military may approach this issue:

- Leverage off existing industry work.
- Develop a test protocol in conjunction with our military customers.
- Execute the test protocol.
- Implement proven alternatives.

This is a two to three year journey full of pitfalls.

4.4 NASA With each mission NASA runs, there are requirements for unique, possibly one-time only, products that require extensive qualification and acceptance testing, which would make a transition to lead reduction or elimination no moonwalk.

Impact on reliability and build schedules, as well as cost implications, due to the required analyses of the alloy choices and reengineering of manufacturing processes, would be of tremendous concern. With no similar products to track and literally hundreds of suppliers around the country building hardware for NASA, the risk to space flight hardware manufactured using alloys and processes that have not been carefully evaluated for each application is a great concern.

5 ON-LINE RESOURCES

5.1 IPC

5.1.1 Leadfree E-mail Forum IPC established was the leadfree@ipc.org listserv for the industry to interact with their peers regarding this issue. At the time IPC started the forum, there were 23 subscribers, and within a week that number jumped to 189 and continued to grow to the 460+ people on the forum today.

Although the conversations on the forum primarily consist of technical issues around lead elimination, other areas such as marketing of products and impending legislation are discussed regularly. Through this forum the industry is able to stay current on the issues and get an understanding for the history of what is going on and how the developments in Japan and Europe may affect their companies.

To subscribe to the forum, send an e-mail:

TO: listserv@ipc.org
SUBJECT: (leave blank)
MESSAGE: Subscribe LeadFree Your Name

5.1.2 Lead Free Web Site IPC developed a Web site exclusive to lead-free electronics (www.leadfree.org). This Web site hosts technical papers and articles, information on IPCWorks '99 and the Lead-Free Grapevine. The Grapevine is a constantly growing page full of up to date news and information on legislation, technology, marketing, etc., regarding lead elimination.

Since its inception in August 1999, the site has had nearly 6400 unique visitors, and total hits for the site were an all-time high of greater than 28,000. The highest amount of traffic seems to occur following postings of the roadmap drafts. The second and third drafts of the roadmap have been downloaded more than 2000 times.

6 MATERIALS

6.1 Solders There are numerous lead-free solders available today, some of which have been used regularly. High-temperature solders have been used successfully in underhood applications, and some companies blended these materials into their processes for consumer and military/aerospace applications. It should also be noted that once a lead-free solder has been chosen, the qualification of the process could take as long as two years.

The user needs to be aware of the sensitivity the solders have for their elemental make up. Variations in the intended solder, due to manufacturing tolerances, need to be characterized by the user. The use of binary, ternary, or quaternary alloys complicates matters of elemental make up because of the permutations possible.

Testing should be done with the main constituents at either concentration extremes of their allowed tolerance, as supplied by the solder manufacturer. Variations in the percentage of the alloy constituents will impact the alloy's physical properties and the actual price of the manufactured alloy. Since some of the no-lead alloys will contain more expensive metals, it would be prudent to have an assay conducted periodically to certify actual elemental make up.

Table 6-1 lists some known solders and their area of industry served, and Table 6-2 lists solders studied by organizations. The table will be modified as information presents itself.

To eliminate ambiguities this report will also detail whether or not the lead-free solders were sold for high temperature (i.e., underhood) applications. The report will also break the alloys down by composition (i.e., SnAgCu, SnCu, etc.) so the industry can see which alloys are in use.

Table 6-1 Solders Used by Area of Industry Served

SOLDER	MELTING RANGE (°C)	INDUSTRY SERVED	COMPANY
SnAg	221 - 226	Automotive	Visteon (Ford)
SnAgBi	206 - 213	Military/Aerospace	Panasonic
		Consumer	Hitachi
SnAgBiCu		Military/Aerospace	Panasonic (FA Controller?)
SnAgBiCuGe		Consumer	Sony
SnAgBiX	206 - 213	Consumer	Panasonic
SnAgCu	217	Automotive	Panasonic
		Telecommunications	Nokia
			Nortel
			Panasonic
			Toshiba
SnBi	138	Consumer	Panasonic
SnCu	227	Consumer	Panasonic
		Telecommunications	Nortel
SnZn	198.5	Consumer	NEC
			Panasonic
			Toshiba

Table 6-2 Specific Alloy Compositions Reviewed and/or Recommended by Other Organizations

Organization	Solder
NEMI	Sn0.7Cu
	Sn3.5Ag
	SnAgCu
NCMS	Sn3.5Ag
	Sn58Bi
	Sn3.0Ag2.0Bi
	CASTIN
	Sn3.4Ag4.8Bi
	Sn20In2.8Ag (Indalloy)
	Sn3.5Ag0.5Cu1.0Zn
ITRI	SnAgCu Sn2.5Ag0.8Cu0.5Sb Sn0.7Cu Sn3.5Ag SnBiAg SnBiZn

6.1.1.1 SnAgCu This alloy composition (with or without the addition of a fourth element) appears to be the most popular replacement. This alloy has also been chosen to be the benchmark, with SnPb being the baseline, for testing any other alloys to be included in the listing to be provided to the industry.

Concerns with this alloy family include higher processing temperatures, their compatibility with lead bearing finishes and the leaching of Ag. It should also be noted that metals cost for this alloy are about 2.2 to 2.7 times that of SnPb eutectic at current market values.

6.1.1.2 SnCu This alloy composition is a low cost alternative for wave soldering, its main area of use and is compatible with most lead bearing finishes. Process considerations must be addressed with this alloy, which has a higher melting temperature than most SnAgCu alloys. This alloys is also 1.5 times more expensive than SnPb eutectic at current market values.

6.1.1.3 SnAgBi This alloy has been chosen as a candidate alloy, especially for use in SMT applications. The major concerns of Bi are fillet lifting that occurs in SnPb through hole applications, embrittlement, its toxicity, and low melting phase. There are also concerns with the leaching of Ag and difficulties with reclaiming other metals during recycling due to Bi.

According to NCMS study, SnAgBi has better thermal cycle reliability for certain surface mount components than SnAgCu using 1206 resistors and capacitors with lead-free finishes and PWBs with lead-free finishes. The study also showed this alloy having better wetting characteristics than SnAg and SnAgCu.

Metals cost for this alloy are 2.2 to 2.7 times more that of SnPb eutectic at current market values.

6.1.1.4 SnZn Although this alloy has lower melting temperatures (<200°C), there are concerns with the oxidation of Zn and the long term corrosion of the finishes solder joint. This alloy also requires special fluxes, and its wetting characteristics aren't as good as SnAgCu.

Industry needs more long-term data for this alloy to determine if it is a strong candidate alternative.

6.1.1.5 SnAg This alloy has a slightly higher melting point (221°C) than SnAgCu, and is comparably priced to this alloy as well. Because it has been used for years in step soldering and special applications (i.e., die attach), there is an extensive database, which is attractive to companies looking for backup data, but there are concerns with leaching of Ag.

6.2 Fluxes Selection of a new alloy will require deviations in flux chemistries used; don't plan on plugging a currently used flux into the new process. Expect to tweak current chemistries for high-temperature alloys and possibly use entirely different chemistries for Zn-based alloys.

Variations in flux chemistries will also affect the cleaning process, solder mask, coating, materials, etc. If voiding occurs after making the transition, the user may need to work with solvent or resin systems to alleviate the problem.

6.2.3 Soldering Atmospheres

6.2.3.1 Nitrogen Inerting Atmosphere Soldering Most lead-free solders have higher melting temperatures than that of the eutectic tin-lead solder (e.g. 260°C vs. 220°C) and thus the oxidation of the solders becomes more of an issue[2]. Conventional no-clean fluxes may dissipate or become inactive before reaching the peak solder temperature.

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[2] C. Christine Dong, John C. Ivankovits, and Alexander Schwarz, *Oxygen Concentration in the Soldering Atmosphere----How Low Must We Go?*, Nepcon West Proceedings 1996, page 1498-1512.

Solderability studies[2] of lead-free alloys and component finishes in both air and nitrogen (i.e., NPL) have concluded that lead-free solderability is reduced, especially when using weaker no-clean and pure rosin fluxes versus that of SnPb. Studies have further shown that these solderabilities are improved considerably with the use of nitrogen processing atmospheres.

In addition, the required process temperatures for good wetting has shown to be reduced (up to 30°C) with the use of nitrogen, thereby reducing the potential damage to temperature-sensitive components. Therefore nitrogen atmospheres may be necessary, especially with complex boards with varying finishes and thermal requirements.

Based on published reports, oxygen levels in nitrogen atmospheres should generally be kept <1000 ppm O_2 to minimize soldering defects and to maximize wetting. The oxygen level may need to be even lower for certain lead-free alloys currently under consideration.

6.3 Components Several types of lead-free component finishes are available to the industry and have been successfully used in assembly operations. There are concerns over cost, reliability, and workability with lead-free alloys due to factors such as higher melting temperatures.

For those companies who choose to use components with lead bearing finishes, there is also the concern with fillet lifting resulting from the use of some lead-free alloys. Although the fillet lifting does not occur in all circumstances of through hole or surface mounting applications, it is an important consideration for companies in deciding whether to use alternative component finishes.

The industry is also seeking information on the dissolution of various lead finishes in new solder alloys and the damage inflicted by test probes on new alloys. The most common alloy used in component finishes is palladium, which is usually used with nickel, silver or as a stand-alone finish.

Some other concerns expressed by industry include requalification that may be needed for temperature-sensitive components

6.3.1 Molded Components With molded components come concerns with "popcorning" and delamination and the time needed to define new materials and that temperature-sensitive components may need time for requalification and redesign (see J-STD-028). The industry has also noted the concern for the time needed to develop new molding compounds. The compounds developed to meet the higher temperature lead-free requirements should also meet the requirements of halogen-free materials in the WEEE Directive.

Table 6-3 lists some molded component surface finishes (some without manufacturing experience) and their concerns.

Table 6-3 Surface Finishes for Molded Components

Finish	Manufacturing Experience	Concerns
NiPd	Yes	Material cost
NiPdAu	Yes	Material cost
SnBi	No	The assembly must be totally Pb free.
Sn	Yes	Tin whiskers
SnCu	Yes	Tin whiskers (needs evaluation)

6.3.2 Ball Grid Array (BGA) Chip Scale Packaging (CSP) TBGA, and Flip Chip One resolution for die applications seems to be the use of balls formed with solder from the SnAgCu

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[2] National Physical Laboratory (NPL) Report, "Solderability of Lead-Free Alloys," Dr. Christopher Hunt, Deborah Lea.

family. If this path is chosen concerns need to be addressed regarding the affects of high-temperature solders on the substrate and warpage of BGAs. One must also have an understanding of the intermetallics and shear strength of balls made with new materials.

There is very limited reliability data available for these applications, but work is being done to gather data.

6.3.3 Connectors/Through Hole Materials for connectors and through hole components will be the same as those for molded components. The one concern for these components is warpage under higher melting temperatures, but more data is necessary before making specific determinations on these applications.

6.3.4 Tin Whiskers A large area of concern with the use of tin-plated or pure tine component finishes is the occurrence of tin whiskers. This condition, also known as tin pest and tin disease, arises when tin reaches a certain temperature (usually below 10°C) and begins to grow tiny dendrites known as whiskers. These whiskers tend to flake off, leading to concerns with reliability of the solder joint.

The critical precursors that increase the propensity towards whiskering include:

Stress in the coating.
Purity.
Thickness range.
To a degree, the crystal structure.

Highly stressed deposits of 2 - 10 microns of pure tin are probably the most susceptible and, hence electrolytically plated deposits can be a particular problem. This stress effect can also be demonstrated by scratching tin deposits and watching these areas preferentially whisker. Immersion deposits, which are thinner (say 0.5 - 1.5 microns), and which have a more polygonized structure are much less prone.

Ways of avoiding whiskers include the addition of another element to the plating bath, such as bismuth. Adding bismuth brings concerns with its sometimes poor workability with lead bearing alloys and the difficulty in controlling the solder bath.

Several tests have been conducted to stimulate tin whisker growth to determine whether whiskers pose a reliability problem or not. One such test currently underway through the auspices of the EIA Soldering Technology Committee and the IPC Alternate Finishes Task Group subjects samples to a 51°C ambient air bake. The groups are testing a variety of plated samples including flat strips, 180° bend coupons and actual gull wing formed leaded surface mount components.

6.4 PWBs

6.4.1 Roadblocks for Implementation The following issues have been addressed as roadblocks for PWBs when implementing lead-free electronics:

- Need to know the process requirements.
- There may be no single finish, but industry should select a set of candidates (i.e., lead-free HASL, and reflowable finish).
- Implementation issues – performance & reliability with alternatives.
- Toxicity/environmental impact of alternatives aren't clear – need data from EPA's DfE Alternate Surface Finishes (ASF) project.
- Environmental requirements not uniform or stable – need to monitor activity.
- Fire safety issues in HASL with higher-temperature solders.
- Worker safety/exposure issues – need data from EPA's DfE ASF project.
- Equipment limitations (HASL) – must be cost comparable.
- Cost of additional lead free lines during transition.

- Lack of industry partnerships.
- Higher reflow temperature increases warpage and causes stress on PTHs.
- Higher temperature affects inks, adhesives, and markings.
- New flux chemistries will be required for fusing fluid and cleanliness impacts.

The following are some issues being addressed by the EPA's Dfe ASF Project:

- Higher temperature stability.
- Solder processes.
- Long term reliability.
- What is lead free (need more definition – possible <0.2%)?
- Recycling requirements.
- Finishes must be SnPb compatible.
- Rework and repair impact.
- Inspection and quality criteria.
- Impact on standards and specifications.
- Good global source of supply.
- Marking for lead-free PWBs .
- Impact on solder mask.

6.4.2 Resolutions The following are resolutions to some of the roadblocks and issues noted in 6.4.1:

- Need coordination of industry activities to gather test data (up to 260°C).
- OEMs and EMSs need to make their alloy selection(s).
- IPC consensus standard and guideline/revisions to existing specifications.
- Alternatives must be recyclable.
- Fabricator/customer agreement.
- Input from metallurgical societies.
- Material choice that will not drive price increase.

6.4.3 Available Finishes Because it is important to protect the copper conductors on PWBs from degradation, PWBs are applied with finishes via hot air solder leveling (HASL), electroless metals, and organic solderability protectants (OSPs). Because a fully lead-free electronic assembly will call for there to be no lead in the finish, board fabricators must select an alternative rated on cost, reliability, and shelf life.

6.4.3.1 Organic Solderability Proctectants (OSPs) OSPs are a viable candidate because they are almost in the same price range as SnPb (about 25 cents/sq. ft. in the current market) and contain no lead. These finishes are also easily processable, relatively free of ionic contaminants, and are smoother than HASL. They also have good solderability (based on flux/solder atmosphere selection) and are reworkable.

These finishes are known for their short storage life, which can be up to 12 months if stored properly (i.e., dry nitrogen, desiccants), but manufacturers with quick turnover of PWBs may not see this as an issue. There are also concerns with handling of these finishes, durability with higher soldering temperatures, and flux chemistries used.

6.4.3.2 Lead-Free Hot Air Solder Level (HASL) Even though lead-free HASL is available for PWBs, some manufacturers may choose to move away from this process if required to produce lead-free product.

If chosen, alternative HASL finishes will most likely work well with most alternative alloys and will wet faster than plated finishes or coatings. Concerns with this finish include warpage due to higher processing temperatures and PWB absorbed process chemistries, although they can sometimes be removed with cleaning.

6.4.3.3 Immersion Finishes Immersion finishes have been considered as one replacement for HASL because of its surface flatness and ease of process.

Concerns must be addressed regarding the thinness of the coating, because higher soldering temperatures could result in out-diffusion of base metals and oxidation, leading to reduced solderability.

6.4.3.4 Electroless NiAu These finishes are attractive because of their resistance to damage during handling/processing and improved shelf life over other finishes. These finishes are also free of ionic contaminants, compatible with most flux chemistries, and smoother than HASL.

7 PROCESSING EQUIPMENT SOLDERING REQUIREMENTS

7.1 Lead Free Reflow Solders Industry is moving towards formulations like SnAgCu no-clean heavy flux paste, with SnAgCuBi compositions being used in Japan because of their room temperature strength and relatively low liquidus (see 6.1).

7.2 Lead Free Solder Profiles Devices shall be exposed to a reflow process such that component temperature loaded on PWB satisfies the conditions in 7.2.1 through 7.2.6.

7.2.1 The ramp rate for solder paste is 1°C to 2°C/sec maximum up to soak temperatures, and may be up to 3.5°C/sec from 215°C peak temperature.

7.2.2 Linear profiles are preferred over the conventional preheat – soak – spike profile for SnAgCu solders. If a soak is required, soak times are typically between zero and 60 seconds. Soak temperatures will be dependent upon the solder paste formulation, laminate temperature stability, component temperature resistance (popcorning or thermal shock), and thermal equilibrium characteristics.

7.2.3 Time above solder liquidus temperature (217°C) will typically range between 30 and 90 seconds. An extended period may be required to ensure proper wetting.

7.2.4 Peak temperature will typically be between 235°C and 250°C. A lower peak temperature (closer to 235°C) is preferred to minimize component damage, but 260°C may be necessary with some designs to maximize wetting.

7.2.5 Cool-down rates will typically be between 2°C and 4°C/sec.

7.2.6 Atmosphere requirements for SnAgCu depend on the components and flux, therefore, should be evaluated to determine if enhanced wetting performance and reduced oxidation will be obtained.

7.3 Convection Dominant Reflow Systems

7.3.1 Higher temperatures will be required due an approximate 34°C increase in liquidus temperature over eutectic SnPb. Peak temperature set points are likely to range between 280°C and 325°C. Peak temperature set points as high as 350°C may be required for larger boards and heavy mass components at lower convection levels.

7.3.2 Forced convection heat transfer will be required to minimize peak temperature set points and prevent overheating light components. This will be very critical for heating large boards and heavy components.

7.3.3 Forced cooling capability will be required to meet exit temperatures of 50°C ±5°C. Products will be coming from higher peak temperatures, therefore requiring stronger cooling capabilities and longer cooling time.

7.3.4 The difference between solder liquidus temperature and component damage temperature will be smaller, thus the process window will tighten. As a result, the furnace will require closed loop control and monitoring of the system to ensure tight process control.

7.3.5 FR-4 and other PWB materials will be softer at the higher processing temperatures, and the reflow systems will require conveyor systems capable of supporting the products in the center to prevent warping and damage, and capable of running reliably and smoothly at the higher temperatures.

7.3.6 Flux management systems will be required to operate with higher temperatures and new fluxes to prevent contamination of the products and the environment.

8 STANDARDS AND SPECIFICATIONS

Several standards and specifications (both industry consensus and internal) will be affected by lead-free electronics. Because of the number of industry-approved standards and specifications available today, it would be best not to make lead free-specific standards and specifications but incorporate their requirements into the available standards and specifications.

8.1 Standards and Specifications Affected

8.1.1 Assembly Standards The following are some industry standards could be affected by lead-free electronics. Some of these standards already cover this technology, and others are being discussed in committee on how/if to make the adjustment.

Proposed changes to these standards should be directed to Jack Crawford, IPC Director of Assembly Standards and Technology, staff liaison to the IPC Assembly and Joining Committee and IPC Cleaning and Coating Committee.

J-STD-001 Requirements for Soldered Electrical and Electronic Assemblies - Although it is too late for any requirements specific to lead-free electronics to make it into the C revision of this document, this task group has already announced that they will address this technology in the next revision. Development of this revision should begin following publication of J-STD-001C.

J-STD-005 Requirements for Soldering Pastes - This specification will be adjusted the same way as J-STD-006 to make lead-free alloy selection easier.

J-STD-006 Requirements for Electronic Grade Solder Alloys & Fluxed & Non-Fluxed Solid Solders for Electronic Soldering Applications - Although this specification already covers several lead-free alloys, the chairman of this group has asked for the alloy listing table to be split into three tables. The three tables will divide the alloys into traditional (i.e., SnPb) and lead-free alloys.

J-STD-020 Moisture/Reflow Sensitivity Classification for Non-Hermetic Solid State Surface Mount Devices - This document, which deals with moisture and reflow sensitivity of plastic integrated surface mount components, is currently open for comment.

J-STD-028 Performance Standard for Flip Chip/Chip Scale Bumps- Some lead-free mounting surface substrate finishes are covered in this document. The flip chip bumps covered in the standard are comprised of SnPb or high-Pb solder compositions. Lead-free alternatives are not addressed.

J-STD-033 Standard for Handling, Packing, Shipping and Use of Moisture/Reflow Sensitive Surface Mount Devices - This document, which deals with packaging and handling of moisture sensitive, non-hermetic, solid state surface mount devices, is currently open for comment.

IPC-A-610 Acceptability of Electronic Assemblies - Although one of the primary issues with lead-free alloys is its lack of a shiny finish, this topic is already covered in IPC-A-610. This issue is noted by stating that high temperature solders may have a dull appearance.

8.1.2 PWB Standards The primary concern regarding PWB standards is the use of lead-free PWB finishes and platings. Because lead-free platings and coatings have been used for some time, they are already addressed in:

IPC-6012 Qualification and Performance Specification for Rigid Printed Boards

IPC-6013 Qualification & Performance Specification for Flexible Printed Boards

IPC-6015 Qualification & Performance Specification for Organic Multichip Module (MCM-L) Mounting & Interconnecting Structures

IPC-6016 Qualification & Performance Specification for High Density Interconnect (HDI) Layers or Boards

8.1.3 Design Standards Common lead-free platings and coatings are also covered in:

IPC-2221 Generic Standard on Printed Board Design

IPC-2222 Sectional Standard on Rigid PWB Design

IPC-2223 Sectional Design Standard for Flexible Printed Boards

IPC-2224 Sectional Standard of Design of PWB for PC Cards

IPC-2225 Sectional Design Standard for Organic Multichip Modules (MCM-L) and MCM-L Assemblies

9 ROADBLOCKS AND RESOLUTIONS

9.1 Lack of Singularity of Alloy In order to resolve this issue, industry needs to continue consortia efforts in down-selection of alloys. The continued efforts of IPC working with other organizations, such as ITRI (UK) and NEMI will enable companies to have the best information possible when selecting an alloy or alloys that meet their product(s) requirements. These efforts will achieve IPC's goals of making the transition as cost effective as possible, all the while maintaining quality and reliability in end product as well as avoiding delays in time to market.

9.2 Rework and Repair Impact In cases where companies would be required legislatively to work with non-lead-bearing alloys, it's essential for the operator to have an understanding of existing materials on any PWBs they may need to rework or repair. Although there may not be a conclusive workable alloy, it is essential for the PWBs to have a marking indicating the materials used on the PWBs.

9.3 Recycling Requirements IPC will continue to monitor state-level activities, such as those already in place in Massachusetts. In order to maintain workability of these activities, it may be necessary for industry consortia to take the first step in developing recycling requirements.

9.4 Worker Safety/Exposure Issues For companies to properly prepare themselves for worker safety/exposure issues, it will need data from EPA's Design for Environment (DfE) efforts.

9.5 No Definition for Lead Free Because there is no industry recognized definition for lead-free electronics, IPC may be called upon to take the initiative to make this recommendation. Based on current practices, OEM requirements and environmental restrictions, the proposed definition is <0.1%. More studies and work with other consortia activities is necessary before making such a statement.

9.6 Lack of Industry Partnership Although many US companies are reluctant to share or communicate their lead elimination/reduction efforts, it is essential for them to work together in this effort, because it is one that affects them, one and all. This partnership is already seen and continually growing through efforts by IPC, NEMI, ITRI, etc., as well as through regular conversations taking place on the IPC lead free e-mail forum.

9.7 Need to Know Process Requirements It is essential for companies to share their process experiences. This is being seen already through the suppliers and PWB manufacturers, who are discussing results of using alternative alloy systems and other experiences.

IPC has been called upon to deliver training and informative programs on the issue. As a result it co-sponsored a lead-free assembly training seminar, and IPC staff has given several presentations in the US and Japan on the issue.

9.8 Lack of Reliability and Long-Term Data Again, it is essential for industry to share their data and experiences using alternative alloy systems. Because most of the alternatives don't have a long history of use (if any at all), this will most likely be seen through commercial/consumer electronics. Because these products usually carry a life of three years, they will be the best host for this information.

As this information is gathered and shared over the next two to three years, it will be easier for companies with products with long-term reliability requirements to make their selections. In the meantime it is important to focus on what data are needed and to scope the dissemination and acceptance of those data.

9.9 Toxicity/Environmental Impact of Alternatives Not Clear There is tremendous concern in selecting an alloy that could contain a material that could be considered for an eventual ban. A frustrating issue for many in the industry is that some of the alternatives being used are just as harmful to the environment as lead.

Working closely with the EPA and other environmental testing laboratories will enable the industry to make sound decisions in their selection of alternative solutions.

9.10 No Government Pressure in US to Switch to Lead Free To preclude any possible legislative activities, the US electronics industry should take the initiative to research alternatives in anticipation of US legislation. In doing so, they can be prepared for any future legislation calling for the reduction or removal of lead from PWBs.

9.11 Slow Pace of Standards Development A rigorous streamlining of standards revision process is necessary, and standards under revision must focus on lead-free as a priority.

To ensure the US electronics industry is on par with requirements in Asia and Europe, IPC staff must intensify liaison work with international associations. As requirements for lead elimination/reduction change to affect certain areas of industry, there may be a need for sectorization of standards and specifications (i.e., telecommunications, consumer, automotive).

10 REFERENCES/RELATED LITERATURE

The information included in this roadmap came from issues addressed by industry during the breakout sessions for the development of the IPC Roadmap for Lead-Free Electronics

Assemblies, which took place during IPCWorks '99. Further to these discussions, all other data provided came from the following list of resources:

IPCWorks '99, An International Summit on Lead-Free Electronics Assemblies Conference Proceedings, IPC, October 1999.

The IPC National Technology Roadmap for Electronic Interconnections, IPC, 1997.

A Benchmark Process for the Lead-Free Assembly of Mixed Technology PCBs, Chris Bastecki.

Lead-Free Solder Project Final Report, National Center for Manufacturing Sciences, August 1997.

Get the Lead Out: Lead-Free Electronics Come of Age, William Trumble, *IEEE Spectrum,* January 1998.

Electroplating of Lead-Free Solder Alloys Composed of Sn-Bi and Sn-Ag, Isuma Yanada, C. Uyemura & Co., Osaka, Japan, IPC Printed Circuits Expo Proceedings, April 1998.

A Summit of PWB Surface Finishes and Solderability Proceedings, IPC, September 1998.

Lead Free Solders – A Push in the Wrong Direction? Edwin B. Smith III, and L. Kristine Swanger, April 1999.

Lead-Free Soldering: An Analysis of the Current Status of Lead-Free Soldering, Department of Trade and Industry, April 1999.

The Continued Use of Leaded Solders in Electronic Applications and Possible Replacement Technologies, IPC White Paper, April 1999.

Connecting to Lead-Free Solders, Angela Grusd, *Circuits Assembly,* August 1999.