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LEAD-FREE ELECTRONIC SOLDER

WHY?

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TABLE OF CONTENTS

Note: Two lead-using applications are not considered in this report: (A) Surface finishes and (B) Bare printed circuit fabrication.
Their contribution to electronic solder, already under 0.6% of all lead usage, is a miniscule percent of that 0.6%. Use of lead-free solder does not raise major reliability or economic issues in either application.

FOREWORD

HISTORY OF THE RELATIONSHIP BETWEEN BUSINESS AND THE ENVIRONMENT

There are understandable reasons for corporate support or silence re lead-free solder in electronic assembly, based on history. Opportunism is the motive for support in some cases, an attempt to show "environmental correctitude" to the nth degree. (Unfortunately, this scramble to comply will be viewed by some anti-corporate idealogues only as protective coloration). Most electronic manufacturers are silent, fearful of appearing to be anti-environment. The companies that support lead-free electronic solder may not fully understand the enormous cost and environmental detriment of lead-free solder.

Today almost all businesses in the developed world are good citizens with active environmental programs. But in the years before the 1960s, public and business consciousness of environmental toxins was low. The result was pervasive use of harmful substances that had very great industrial utility. When the damage to human and other life became clear to all, the initial company reaction was often Denial. Three examples are representative:

In 1962 Rachel Carson's "Silent Spring" was published. It spotlighted the toxicity of DDT, a very effective (by hormone mimicry) insecticide that moved up the food chain to humans.

Asbestos litigation began in the late '60s. That "very effective" and very lethal insulation material was subsequently banned in new applications.

In 1968, rice-containing PCBs poisoned a village in Japan. By the 1970's, this "very useful" insulating liquid was banned from power capacitors, transformers, and lighting ballasts.

Corporate denial was based on lack of immediate replacements and on fear of litigation. The result was a public perception that corporations are uncaring about environmental toxins. The reaction sparked rise of world environmental organizations that often assumed that Business was always guilty of the crime of pollution.

Politicians were quick to take advantage. So were some companies, motivated by market opportunism.

LEAD ACETATE IN PAINT; TETRA-ETHYL LEAD IN GASOLINE

Lead has been noted as a poison for centuries. In modern times two examples stand out:

Lead in the form of two compounds had great utility for smoother application of paint and for smoother burning gasoline in internal combustion engines. Almost everyone knows about the incidence of infant and child poisoning from eating flakes of peeled paint. Breathing exhaust fumes from vehicles elevated lead blood and tissue concentrations of entire populations. The Nation, March 20, 2001, tells the story of lead anti-knock, the corporate decisions and denial from 1923 to 1976 (The Secret History of Lead).

Following are key dates from the Tetraethyl Lead Timeline.

TETRAETHYL LEAD TIMELINE
(from NATION, March 20,2001)

1923… Tetraethyl lead added to fuel for anti-knock
1976… Tetraethyl lead phased ban in U.S. passenger automobiles
1983… Lead in gasoline down 50%, U.S. blood levels down 37% (EPA)
1994… U.S. blood levels down 78%%, 1978 TO 1991 (EPA)

50 years of tetraethyl lead have given us a legacy, soil everywhere is contaminated. It is fortunate that lead sulphate and oxide are so insoluble, so un-bioavailible. It passes right through living creatures. That's why the infants of Aspen CO were not poisoned by soil consumed (discussed below). The story was quite different with the infants who have eaten paint chips. They have consumed soluble lead acetate.

Lead toxicity is central to the perception that lead in electronic solder is a danger to life. But toxicity is only one dimension; bioavailability is equally important. Because of the history of the "bad" applications, there is a movement to ban lead in all applications. It is not chemically or physically possible to replace lead in lead-acid batteries or x-ray shielding. These applications account for 90% of all lead usage.

If all E-waste were dumped in landfills, *lead from solder* would constitute about 0.45% of that e-waste (documented in following pages). If E-waste were 5% (very high estimate) of all waste, lead from solder would constitute 0.023% of total waste. That level is far less than the 500 parts per million that the EPA considers natural background!

It is proposed to ban lead in solder, which accounts for under 0.6% of all usage. Recycling all lead in closed systems that would keep most out of the environment is a better alternative.

Those who recite the "inevitability" argument because of "legislative mandates" or company declarations might consider the mutability of human decisions, particularly those that are not only irrational but also very, very expensive. With regard to legislation from the European Union, there is a history of showcase legislation[1], passed with no intention to enforce. The practical politicians at the European nation level will not consider lead-free solder worth the cost, industrial disruption, competitive disadvantage, nor a major trade war.

If principle guides our actions and our positions, not apparent expediency, the signal will shine bright and clear, through all the obfuscation, to those final decision makers. Our moral courage will provide an example for others.

Harvey Miller
Fabfile Online

[1] Jonas Tallberg, Lund University, Paths to Compliance: Enforcement, Management, and the European Union, *International Organization 2000*

INTRODUCTION

Considering the very high economic and reliability stakes, it is surprising that, generally, the people ultimately most concerned, consumers of electronic equipment, know almost nothing of the lead-free solder issue. Within the world electronics industry, our extensive interviews indicate that there are three camps: (a) some, usually outside of the Electronics industry, really believe that advocating lead-free solder, either the image or reality, constitutes environmental purity. (b) Many think that facts indicate that replacing tin-lead with lead-free solder will actually be deleterious, on balance, to the environment, the economy, and the electronics industry. (In a 1997 report, the National Center for Manufacturing Sciences estimated the cost of no-lead solder to the U.S. alone in the tens of billions of dollars.) (c) Then there is a very large middle group that rather cynically serves demand for lead-free solder for opportunistic reasons related to sales of equipment, materials, or services; or simply, job assignments. Most members of this third group freely admit that expediency, not principle, drives their lead-free solder activities.

The differences among the groups have particular relevance for evaluating conflicting test results comparing tin-lead and lead-free solders. We would not impugn the objectivity or competence of investigators on all sides of the lead-free issues. But differences in bias as well as methodology stem from differences in how the parties would be affected. The OEM and Electronic Manufacturing Service companies will bear the costs of implementation and product failures. They have much more at stake than either academics (including research organizations and consortia) or vendors who are seeking a source of new business.

TWO RECENT DEVELOPMENTS (FROM EUROPE AND THE U.S.) DEFINE "WORST" AND "BEST" OUTCOMES

The <u>worst</u> real life resolution of the lead-free solder issue is the direction in which we are now headed— multi-track, multi-solder alloy electronics manufacturing leading to a logistic/ supply chain/ manufacturing nightmare. Some assemblies will use traditional (63% tin- 37% lead) solder; others will use various lead-free alloys.

For standardization, it would be preferable to go 100% lead-free, but that is not a possible alternative. Several assembly categories will not tolerate 260°C temperatures needed for most lead-free reflow (such as fiber optics, MEMS, microwave); some entire, very important equipment categories (Medical, Aerospace, Telecom, Networking) are being exempted from any ban on lead, de facto or by regulation, because of questionable reliability (ref. EU legislation cited in next paragraph).

The best resolution would be a general understanding that the lead-free solder movement is based on erroneous premises. This outcome is quite possible still. Hopefully that will happen soon enough to redirect the industry's money and energy to more constructive efforts: recycling lead and electronic solder in a closed system; E-waste handling automation.

Two new developments that may influence the outcome:

1. On May 15, 2001, the European Parliament accepted and passed on to the Council of Nations a "Proposal for a. …Directive on the restriction of the use of certain hazardous substance in electrical and electronic equipment". It bans use of lead after January 1, 2006. (Article 4 (1)) The statement immediately following recognizes "exceptions" to be specified in an Annex. It proceeds in another statement to exempt material and components if substitution is "impossible".

   Then in the before- mentioned Annex, there is a final blow to across-the–board totally lead-free manufacturing: "lead in servers, storage, and voice and data transmission and networking equipment" are exempted from the ban. (The overwhelming preponderance of lead usage for x-ray shielding, storage batteries, tire weights, bullets—aren't even mentioned in the document, exempt by default)

Altogether RoHS is a convoluted document whose lead-free provisions would be very difficult to enforce There is potential for a trade war

2. April 10, 2001-- IPC and 35 other trade associations initiated a **successful** suit against the EPA. This action **may be a precedent in amending the lead-free solder provisions of RoHS** even though it was not specifically aimed at that objective. It was directed against the EPA ruling that reduces reporting thresholds of lead used from 10,000 pounds to 100 pounds per year.

Both the lead-free solder movement and the EPA reporting reduction are politically motivated, crowd-pleasing products of pressure from so-called environmental interest groups. Both the movement and the regulation share a flawed premise that lead, among other metals, is a PBT chemical. PBT stands for persistent, bioaccumulative, and toxic; that is the combination that characterizes another class of toxins, often confused with metals—Persistent Organic Pollutants (POPs), such as PCB, DDT, and other synthetic creations of the last 50 years that are truly dangerous to life. These chemicals cause cancer, disrupt metabolism, and hormonal signals. It is very difficult to eliminate them or reverse their damage. Metals, even essential ones, can present toxic effects when excessive amounts are present, but on every other score, they are relatively benign.

The suit against the EPA challenged application of the PBT label to metals. "In January 2000, EPA co-sponsored an 'Experts Workshop' during which numerous scientific experts explained why application of PBT methodology to metals is not consistent with sound science." EPA called experts, toxicologists, and environmental scientists who testified that lead and other metals do not accumulate in the food chain, that organisms control and excrete metals, that even in cases of poisoning, reversal and elimination generally mitigate problems. (Children are an exception because of effects on early development, but toxicity can be reversed if apprehended early.)

In spite of all the contrary evidence, the EPA **had** invoked the new reporting thresholds. Like the lead-free solder issue, politics **had** overcome science and common sense. The difference **was** that the IPC (et al) suit marks the first time that the issues **were** being taken out of the political arena into one where science and common sense may prevail. **It was a precedent that may portend the end of the irrational hysteria ultimately behind lead-free solder. The successful IPC suit showed the way.**

LEAD-FREE SOLDER DECLARATIONS FROM JAPAN

U. K.'s SMART Group recently sponsored a "Mission to Japan"[2].

They interviewed major Japanese electronics companies that have posted roadmaps for accomplishment of "lead-free" manufacturing, in many cases by 2002. But in mid-2001, according to Senju Metals, Japan's leading lead-free solder paste producer, penetration is only about 10%. (Senju owns the patent on the Sn-3.5% Ag-0.7% Cu. Dennis Bernier, Chief Technologist at Kester Solder, pointed out to me that deviation of the Ag % from that optimum leads to granularity and reliability problems. Percentage deviation may occur simply from use of a different alloy composition in the process. Jasbir Bath of Solectron in a recent paper[3] compared the reliability of most lead-free alloys for hole-fill, visual and x-ray defects, wetting ability, pull strength, and solder ball formation to Sn-Pb solder. Figures 3, 4, 5, and 7 demonstrate the general superiority of Sn-Pb solder in wave soldering. (Note that this my interpretation, not explicitly stated by the author.) Sammy Yi of Flextronics International conducted a similar comparison experiment[4]. In this case, three lead-free solder pastes in the Sn-Ag-Cu family were compared to Sn Pb for printability, pot life, wettability, reflow process window, inspection criteria. Sn Pb was superior in wetting angle and wetting on components, in absence of solder voids, and process window. Perhaps these reliability considerations explain the low lead-free penetration compared to that claimed, in Japanese electronics. Part I of this report will detail many other Reliability Issues. By **September 2004, lead free solder penetration increased to only 17%, as reported by Anthony Hilvers of the IPC.**

Another finding by the SMART Group was that, contrary to many preconceptions; market forces were not a factor in "pushing along the move to lead-free". The initiative came from the manufacturers that wish to appear environmentally friendly (and ultimately from MITI, the Japanese government body that seems to be orchestrating it all—our comment).

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[2] Electronics Manufacture & Test (UK), pg 25, April 2001

[3] J. Bath and G Hueste, LEAD-FREE SN3.5AG AND SN0.7 WAVE SOLDER EVALUATION WITH VOC-FREE NO-CLEAN AND WATER SOLUBLE FLUXES, SMTA Conference, Boston MA, June 13, 2001

[4] S. Yi et al, Flextronics, A CASE STUDY OF LEAD-FREE ASSEMBLY IMPLEMENTATION IN EMS ENVIRONMENT, SMTA Lead Free Symposium, June 12, 2000

The group refers to the contradictory approaches by different Japanese companies and jurisdictions re the issue of landfill vs. recycling. Other confirmations of this contradiction are reported on in Part III of this report. As recycling gains more support, in Japan as elsewhere, the advantages of continuing to use Sn Pb solder will become evident to all. Lead battery recycling provides a successful model that can be emulated for lead in electronic solder[5]. That is the subject of chapter IV of this report.

[5] Conversation with Jim Taggart, ECS Refining Co.

I. TOXICITY AND BIOAVAILABILITY ISSUES

Underlying the moves to lead-free solder in electronics is the claim that “lead is bad”, wherever it is used. Solder is a metallic alloy used to join electronic components electrically and mechanically. Every metal used may be shown to be potentially toxic. The most reasonable answer to threats from environmental release is to create closed systems by recycling.

Some environmental groups to justify banning lead in solder have invoked the Precautionary Principle, described below.

Does the “Precautionary Principle” apply to Tin- Lead solder??

The precautionary principle states that, "When an activity raises threats to the environment or human health, precautionary measures should be taken, even if some cause-and-effect relationships are not fully established scientifically. In this context, the proponent of an activity, rather than the public, should bear the burden of proof”.' (From the Wingspread Conference Statement, Jan 23, 1998.) Expressed in greater detail (my italics):

1. People have a duty to take anticipatory action to prevent harm.
2. The burden of proof of harmlessness of a new technology, process, activity, or chemical lies with the proponents, not with the general public. Before using a new technology, process, or chemical, or starting a new activity, people have an obligation to examine "a full range of alternatives" including the alternative of doing nothing. *(Their text, my underlines)*
3. Decisions applying the precautionary principle must be "open, informed, and democratic" and "must include affected parties."

In the 1992 Ospar meeting (concerned with marine environments), the Precautionary Principle was enunciated along with a list of "hazardous substances" included silver, copper, zinc, as well as lead. They might have included nickel and oxygen.

In Europe, lead-free roots go back to the oil spill of the Torrey Canyon (1967) and the Stella Maris aborted attempt to dump chlorinated solvents in the North Sea (1971). The heightened environmental consciousness unleashed then has come very, very far.

The 1992 Ospar proceedings document seemed very reasonable in its sensitivity to scientific evidence and economic impacts. Even the 1998 document aimed at 2020 for elimination of hazardous substance releases. But in May 2001, the EU Parliament voted to ban lead in solder by 2006, with a host of equipment exemptions—servers, storage equipment, telecom, datacom, medical. So far, the lead ban deadline dates emanating from this body have shifted, in pronouncements from 1999 to 2001, from 2004 to 2008 to 2006 to 2007 and currently back to 2008. None of the dates are realistic as we discuss in our Reliability chapter. If toxicity is the concern, the ban singling out lead in solder has a very weak basis

There is scientific "evidence" for environmental toxic impacts of all the metals mentioned and tin, as well. A case might be made for persistence and bioaccumulation for silver, copper, and zinc. Ban them all? Or simply recycle lead in a closed system?

Following is a discussion of metals used in lead free solder.

TIN TOXICITY

Tin is generally regarded as benign and in cans, as tin plate, contacts food. Nevertheless some studies identify problems. A Japanese study called attention to tin compound negative effects on immunity suppression[6].

OTHER LEAD-FREE METALS

A meta-survey by the National Center for Manufacturing Sciences[7] rates copper, silver, and antimony high in toxicity. Minimum lethal dose for humans (mg/kg) are respectively 0.12, 1, and 15, compared to lead, also rated toxic, at 450! But toxicity to microorganisms affects the entire food chain—"Silver is probably the most toxic element to microorganisms".[8]

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[6] Y. Arakawa, University of Shizuoka,*Sangyo Eiseigaku Zasshi,* Jan 1997
[7] Duane Napp, LEAD-FREE SOLDER AS A REPLACEMENT…., NCMS, Feb 28, 2001
[8] Sasha Shafikhani, Toxic Metals, UC Berkeley Dept of Molecular Cell Biology, 2000

Indium and Bismuth are often suggested for lower lead-free alloy eutectic temperatures. Indium's problem is not toxicity but economics and supply. Its usefulness for semiconductor and LCD display applications and future photovoltaic applications will drive price beyond recent $140/pound (compare to $0.45 for lead and about $4 for tin). Extensive use of Indium solder would also strain supply besides penalizing other applications. Bismuth toxicity was investigated by Japanese researchers[9] who found significant mammalian chromosomal aberration. This was surprising in view of common medicinal applications.

MIS-APPLICATION OF THE PRECAUTIONARY PRINCIPLE TO TIN-LEAD SOLDER

The Precautionary Principle allows for proof that a substance is not hazardous. There is an abundance of proof that lead in electronic solder has no measurable negative impact at any stage of its life cycle.

The Precautionary Principle is certainly justified in its application to potential organic hormone disrupters. That was the context in which the principle has been advanced. It has been misapplied to tin-lead solder; there is no evidence that lead in solder is a hazard to life or the environment or is a hormone disrupter.

<u>The record shows almost no toxic impact from lead in electronic solder or from lead in soil:</u>

1. OSHA compiled a listing of industries and occupations where exposure to lead (mostly by inhalation) on the job leads to high blood levels[10], May 2000. 82 case studies were described for affected workers in industries ranging from printing to paint to plumbing. There were no cases from the electronics industry. (NOTE: In most of these industries, lead has been eliminated. In others, OSHA regulations mandate safe practices.)
2. The EPA declared Aspen Colorado a Superfund site in 1986[11]. At some locations, lead concentrations were over 20,000 parts per million, 40 times acceptable. The people potentially affected asked for tests to measure impacts of the high lead soil concentration.

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[9] H. Satoh et al, Tohoku University, Evaluation of Biological Impact of Pb-Free Solder, Ecodesign 2000, Tokyo

[10] www.haz-map.com/reports.htm, May 12, 2000

[11] Jeremy Bernstein, *REPORT FROM ASPEN*, New Yorker, Nov 25, 1991

"The results …showed insignificant levels in air, and no levels in water.[12]"

> **Re people: Lead level averages in the lead-contaminated Aspen area were 2.8 micrograms per deciliter for children and 3.4 for adults, compared to U.S. average ranging from 4 to 6 uG/dL[13].**

3. "Lead soldering usually does not represent an inhalation risk since controlling temperatures of lead below 900˚F is effective in controlling lead fuming."[14]
4. "Drinking water is one of several sources of lead exposure. Its relative contribution to total lead exposure is usually low. Lead in rivers, streams, and aquifers usually is found at low levels or occurs at levels below detection." [15]
5. "Forty long-term hand solderers were found to have blood lead indices comparable to a control group of office workers with no exposure to lead."[16] Western Electric (predecessor to Lucent) submitted the study to OSHA.
6. The EPA has set limits and test methods for leaching levels (Toxicity Characteristic Leaching Procedure). These leaching levels have been tested for lead and lead free solder alloys with the following comparative results:

    - All lead free alloys containing silver and antimony leached above regulatory limits… When groundwater was used in this test for silver, the silver levels went above the regulatory limit[17]".
    - By comparison, per an EPA document re lead:" Leaching is not important under normal circumstances..."[18]

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[12] Hazardous Waste Conference, 1983, T.C. Dunlop
[13] *REPORT FROM ASPEN op cit*
[14] OSHA (HTTP://WWW.OSHA-SIC.GOV/sltc/lead/index.html)
[15] American Water Works Association 1995 (http://www.awwa.org)
[16] C.D Barrett et al, Blood Lead Study, JOM. 19:791-794 (1977)
[17] E. Smith, K. Swanger, Lead Free Solders—A Push in the Wrong Direction? IPC Printed Circuits Expo, March1999
[18] USEPA, Health Effect Assessment for Lead",540/1-86-055 (1984)

- Other studies have made it clear that lead is virtually immobile in soil. McCulley, Frick, and Gilman studied the geochemical fate and transport of lead in soil in 1991 and found that "…except in rare conditions, lead that infiltrates into the sub-surface is immobilized…"

Toxicity issues are further considered in Life Cycle Analysis, covered along with Recycling, in chapter IV.

THE BENEFITS AND PROBLEMS OF IMPLEMENTING LEAD-FREE IN PLUMBING AND VEHICLE RADIATORS DO NOT TRANSLATE TO ELECTRONIC SOLDER

In 1986, lead was banned in U.S. plumbing solder. The previous joining alloy had been 50% lead, 50% tin. Replacement metals include antimony and silver; benefit from reduced toxicity to water consumers is highly questionable[19]. Perhaps the very small reduction of toxic exposure to plumbers is a benefit. The same benefit applies to automotive aftermarket radiators in much greater degree. There are actually documented case histories of elevated lead in blood of radiator workers, probably due to larger quantity of solder used. We have pointed out above that there are no hazards to workers or to users from lead in electronic solder. That applies both to workplaces; with over 50 years of experience, now controlled for safety as never before, and to aftermarket repair.

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[19] Fry Technology, Products and Marketing, 1999

II. LEAD-FREE SOLDER RELIABILITY IMPACTS ON ELECTRONIC EQUIPMENT

G.E. Medical White Paper, August 20, 2004, is included in its entirety as Supplement I to this report, *"Fragility of Pb-Free Solder Joints"*

Many of the lead-free reliability deficits, discussed in this section, may be addressed by **enough** application of money and time. The NCMS (National Center for Manufacturing Sciences) estimated lead-free implementation costs in "tens of billions of dollars" (1998 report)). Time required to achieve **"reliable"** lead-free solder is even more incalculable.

There are special reliability issues with lead-free wave soldering beside the very high cost. The response of some is to try to overcome the reliability obstacles, whatever the cost. *All statements below should be tempered by the realization that almost any reliability problem is solvable, with application of enough money. The question is "Whose money?" Thus Reliability and Economic issues cannot be separated.*

All levels of electronic products are impacted by the choice of solder alloy and its higher melting temperature: A) Component-substrate joint; B) component, whether Integrated Circuit, discrete, or passive; C) substrates, inside the IC package and the printed circuit interconnect; D) the entire printed circuit assembly (covered in discussions of A), B) and C). *Flip-chip solder balls interconnects are a special component-substrate joint in a high growth application that will be discussed in the context of IC reliability. Buildup substrate reliability is also impacted.*

Every choice of an alternative alloy involves changes in interconnect systems, processes, and capital equipment. Moving from tin-lead solder, well-characterized through 50 years, to relatively unknown lead-free alloys, raises reliability issues that cannot be resolved in a **two**-year time frame. (the EU is mandating lead-free solder by 2006.) Too many materials and process interactions are involved. The new material set and longer reflow time ramp called for by the moisture sensitivity degradation findings of the NEMI report of January 17 2001 (see footnote 16 and discussion at this section's end) raise the time and money ante for implementing lead-free solder, to new levels.

A) The joint, comparing alloys for reliability (fatigue life due to temperature cycling)

63% tin-37% lead alloy is eutectic solder because when temperature is raised to 183˚C, state changes from solid to liquid for the entire volume. On cooling back down to 183˚C, a solid alloy joint is formed. "The eutectic behaves exactly like a pure metal having a definite solidification temperature and a specific heat of fusion."[20] Eutectic tin-lead solder exhibits small symmetric pasty (mix of liquid and solid) regions even at 5% composition variations.

Tin- silver, tin-copper, and tin-silver-copper alloys, the major replacement candidates, have eutectics above 217˚C and form very large, asymmetric pasty zones for very small deviations from precise percentage composition, making them "more susceptible to "disturbed solder and other reflow process-related defects".[21] This translates into open and high-resistance joints[22].

The very small silver (3.5%) and/or copper (0.7%) percentages required for eutectic alloys are difficult to establish and maintain in production environments.

Carefully controlled laboratory experiments with the above lead-free eutectic alloys have indicated that lead-free alloys can provide joints as strong or stronger than eutectic tin-lead, particularly on PCB electroless nickel, immersion gold (a finish that has exhibited problems of its own). [23] Pull strength was significantly higher after thermal cycling, for the Tin-Silver-Copper (SAC) alloy. But there is evidence that points to lead-free failures, from Lynn Norman of Daimler Chrysler, in leadfree@ipc.org, August 1, 2001, next page.

Production case studies by Flextronics and Solectron[24], for both surface- mount and through-hole, found

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[20] H.H. Manko. Solders and Soldering, McGRAW-HILL, 2001, pg 66
[21] R. Robertson and J. Smetana, Alcatel, USA, SOME FUNDAMENTAL CONCERNS IN LEAD-FREE IMPLEMENTATION, SMTA Lead-Free Symposium, June 12, 2000
[22] Manko, pp78-80
[23] S. Shina, Lead Free Conversion Project for PWB's, Etronix NEPCON 2001
[24] See footnotes 2 and 3 above

deficiencies for lead-free alloys in defect counts, solder ball formation, and wetting, compared to tin-lead. They also disagreed with the Shina study, referenced above, on pull strength superiority of lead-free joints.

Certainly, there are cases of lead-free success. At Philips Lighting Electronics Oss in the Netherlands, three years of full flow lead-free mass production on one wave soldering line (mixed hole-mounting and SMD at soldering side) provided a consistent very high first-pass-yield. The fall-off rate is less than 25 ppm.

The OEM and Electronic Manufacturing Service companies will bear the costs of implementation and product failures. They have much more at stake than either academics who go from project to project for hire or vendors who are seeking a source of new business.

An exchange on the IPC (printed circuit fabrication and assembly trade association) e-mail forum[25] is illustrative. Tetsuro Nishimura is Executive Director of a solder company. Werner Engelmaier is a scientist, formerly with Bell Labs, who is expert in solder joint reliability. Below is a quotation from the statement of the latter in the exchange, summarizing the positions:

Hi Tetsuo,
I have no arguments with most of what you wrote, but I need to set the record straight on 2 of your points, so people do not draw the wrong conclusions.
[1] You write "the Sn-Ag-Cu system (and the Sn-Cu) system is stronger than the Sn-Pb alloys."
That maybe, and is likely, the case--however strength is not a good indicator of fatigue resistance.
[2] You state "the experience with commercial products that have been in the field for nearly two years seems to confirm that. This is particularly the case in regard to thermal fatigue, possibly the main cause of failure in electronic circuitry, where the lead-free alloys have a much longer life."
There have not been good data, following IPC-SM-785 testing guidelines, published, that really characterize the creep-fatigue life of lead-free solders; without such data nobody can make any statements as to the inferiority, equality, or superiority of any of these alloys. To anecdotally refer to '2 years of commercial

[25] T. Nishimura vs. W. Engelmaier, Re: Eutectic alloys?????, Leadfree@IPC.ORG, 8/1 and 2/01

products in the field' is totally meaningless; 2 years of cheap [read throw-away] consumer products not prove anything, one way or the other. It may be more impressive under the hood of an automobile, but even that is meaningless because of a total lack of definition of the actual loading conditions on the solder joints.

So as far as I am concerned, the jury is still out as to the reliability of lead-free solders.

Werner Engelmaier
Engelmaier Associates, L.C.

Of course, the reliability of lead-free solder joints may be established, but at what cost? And is the effort truly justified for very dubious (or negative) environmental improvement?
These are among the many tradeoffs that must be addressed. Two other citations from the IPC lead-free forum are illustrative:

Subj: **Re: [LF] Eutectic alloys?????**
Date: 8/1/01 10:03:20 AM Pacific Daylight Time
From: LN25@DAIMLERCHRYSLER.COM (Lynn Norman)

Working in the automotive electronic industry, I can tell you that we AREN'T "running to embrace lead-free". On the contrary we are against it. The main reason we're evaluating lead-free is purely market driven. We have test data that shows the SAC alloy is much less reliable at high (underhood)
temperatures and with longer dwell times. We won't start manufacturing modules for underhood applications with lead-free until we are forced to.

From Andrew Hoggan of BBA Associates, "*What really worries me is the research... that indicates the so-called improvement in strength by using lead-free alloys… is conditional, not absolute.*
In other words, the initial testing. was limited. It indicated (specific) lead-free alloys gave improvements in physical performance over tin lead alloy.
Unfortunately if you were to take the same alloys and run the testing past the 1000 hours or change the cycle rate

or stress and/or frequency applied, the results don't indicate performance improvement. (IPC lead-free forum, August 1, 2001)
Andrew Hoggan has consulted for a Japanese OEM on lead-free alloy choice, making his comments especially important.

Re joint temperature cycling reliability, tin-silver-copper lead- free and tin-lead may turn out to be about the same in most low temperature (under 100° C) surface mount applications. But for wave soldering through-hole joints using tin-copper alloy, there are special problems, discussed below.

It should be mentioned again that concentrated effort can lead to reliable application of lead-free soldering. For example, wave-soldering experiments led to the following results[26].

Ratio of fatigue lives between different alloys:

- ***SnPb40 = 1 (reference)***
- ***SnCu0.7 = 0.6***
- ***SnAg3.8Cu0.7 = 1 (at moderate temperature cycling; to +100 deg.C)***
- ***SnAg3.8Cu0.7 = 0.8 (at severe temperature cycling; to +125 deg.C)***

THE SPECIAL IMPORTANCE OF WAVE SOLDERING RELIABILITY

Three ways to quantify wave soldering's economic importance in an assembly world dominated by surface mount reflow.

1. Comparing the ratio of wave solder machines to reflow ovens
   a. I to 5, according to Kim Hyland of Solectron California
   b. (The total economic impact will be discussed in a following chapter)

[26] E. de Kluizenaar, IPCWorks 2000

2. "Approximately 4,000 metric tons of solder paste and 35,000 metric tons of solder bars are consumed annually by the electronics industry."[27]
3. Wave soldering accounts for 30% of electronic assembly according to Richard Parker of Delphi Delco Electronics (CircuiTree, August 2000)

These data do not represent points on a declining trajectory for wave soldering. There are large classes of equipment that use through hole mounting for connectors, axial and radial passive components. "The market share for such components is still over 40% in the passive area, the main segments being power supplies, lighting, monitors, and so on."[28] Analog systems, in general, use many passive components.

"The market for axial and radial (insertion) machines has remained relatively stable since 1995."[29] The relative simplicity of Through Hole Technology makes it appropriate for TV, VCR, radios, and appliance electronics production in developing countries.

THE PROBLEMATIC IMPACT OF LEAD-FREE SOLDER ON WAVE SOLDERING AND HOT AIR SOLDER LEVELLING

The following quotation (abridged) expresses possible production scenarios using lead-free solders such as Sn 0.7Cu. It should be balanced against a controlled experiment that will be discussed below.

The issue of a pasty (or "plastic") range relates entirely to wave soldering. Specifically, it concerns what happens as the circuitry leaves the solder pot. If the pasty range falls within temperatures that the solder may reach during the assembly's exit from the solder wave, the probability of bridging and other forms of excess solder increases.

After decades of use, we know that tin/lead alloys near the 63/37 eutectic, even for the common 60/40 alloy, produce very narrow pasty temperature ranges. Probably more significant, most companies run their wave solder pots at

[27] Alan Rae, Cookson Electronics, Lead-free- After the Shouting is Over, APEX, March 16, 2000
[28] Uwe Leers, Marketing Manager for Panasonic Factory Automation Europe, quoted in Hyperelectronics, July 2001
[29] Same article, same publication as above

excessively high temperatures, which help explain why deviations in purity of the tin/lead alloy generally do not cause havoc. On the other hand, there are limits to how much deviation is acceptable. There is a reason why 60/40 solder was employed for wire solder but not in solder pots. And the reason is bridging. The problem becomes more serious as leads are placed closer together.

Unlike tin/lead alloys, there is little experience with the behavior of lead-free alloys. With sufficiently high process temperatures, the pasty range can be avoided. The question is: how much extra heat above the eutectic point is needed to avoid bridging and other forms of excess solder? After all, we're already talking about melting temperatures 34 degrees C higher than for the old standby. (217 instead of 183)

Those who have referenced existing products assembled with high-temperature solder are missing the point. Those products are assembled in manners other than wave soldering and, therefore, do not run into the pasty range issue. There's nothing mysterious about those lead-free products; the industry has been turning out products with high-temperature solders for decades.

To sum up:

1. Pasty range is a concern almost exclusively limited to wave soldering
2. We have vast experience using tin/lead alloys in wave soldering
3. Our experience shows that excess solder problems (most notably bridging) increase as the deviations from eutectic tin/lead increase
4. There's little information (that I, at least, have seen) about the forgiveness of lead-free alloys in wave solder uses
5. Until more work is done with lead-free solders in wave soldering, there's cause for concern.[30]

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[30] IPC LeadFree@IPC.ORG, Aug 1, 2001

A much more positive result for the lead-free alloy in wave soldering was reported in a previously cited experiment by Jasbir Bath of Solectron and Gregory Hueste of Electrovert.

"The current equipment and solder fluxes available can be used for lead-free wave soldering. … The process window is narrowed but… successful lead-free soldering can be achieved." Interpretation: It can be done, at a cost. The cost is dealt with in Chapter 3, Economics.

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The experiment used eutectic Sn 0.7Cu solder. But the tin-copper alloy copper content increases, dissolved from the boards that pass through. The changed composition moves the alloy into the pasty range cited in the reference by Jim Smith cited above, along with the potential bridging potential.

Finally, correspondence August 8, 2001, to the leadfree@ipc.org forum by Keith Sweatman of Nihon Superior, a solder/solder paste company based in Japan, is very instructive with respect to reliability issues using Sn0.7Cu in wave soldering. Extracting:

……the problem with straight Sn0.7Cu in wave soldering is the high incidence of bridges (shorts) and sometimes rough and cracked joints.

Note that Nihon Superior has proprietary way of dealing with this problem. Sn0.7Cu is already twice as costly as 63Sn37Pb, a very considerable economic penalty because of the volumes used in wave soldering. (This impact is analyzed in the Economics chapter.)

"SnCu eutectic melts at 227 deg.C. This obliges one to solder at minimum 275 deg.C. That appears to be possible for low-end electronics. However, I would not dare to solder professional equipment with this alloy, because of thermal damage to components and boards and the shorter fatigue life (0.6 x SnPb) of the joints."[31]

PHILIPS Oss lead-free experience is an interesting special case, not representative of mainstream electronic assembly. They use quaternary SnBi5Ag1Sb2 solder, melting range 180-220 deg.C. They solder single-sided boards only (*because of the solder lifting effect in plated holes)* with this alloy having an extremely large melting range.

[31] note from Erik de Kluizenaar, Philips

Nevertheless, they have a high process yield. The secret behind this: process optimization and control combined with the absence of any mechanical loading to the soldered board until one is absolutely sure that the solder has completely solidified.
The PHILIPS experience shows that reliability risk of lead-free can be neutralized adequately by enough effort.

B) Component reliability concerns with lead-free solder: Integrated Circuits, discrete, passive components, printed circuit board substrates, optical components/ fiber

Four quoted sources below describe the many concerns regarding reliability of component when subjected to high lead-free solder reflow temperatures.

1) "The higher processing temperatures are expected to cause internal cracks and delamination in components"[32]

2) "…whether or not the components or substrates used can sustain the process becomes a big question mark. For instance, electrolytic capacitors are highly susceptible to high temperature damage. Wound components such as relays are also susceptible to high temperature damage.
In addition, the higher processing temperatures are likely to increase the tendency to cause the "popcorn" effect for encapsulated ICs near their expiration date. Parametric damage to memory ICs processed around 250° is possible, PC board, BGA polymeric substances and solder masks may also suffer from higher processing temperatures. This is particularly true for flexible circuitry. The plastic insulation of connectors may also distort.[33]"

3) NEMI, January 17, 2001[34] reported definitively on the degradation of the Moisture Sensitivity Level of IC's in a wide range of packages due to lead-free assembly reflow requirements. The paper raised many grave reliability issues about the effects of ramping to temperature 260°C. We quote and summarize extensively below from this seminal

[32] from Sonoscan, Inc sales bulletin promoting their acoustic imaging test, 2000
[33] Dr. Ning-Cheng Lee, VP Technology, Indium Corporation, *ChipScale Review,* March/April 2000
[34] Lead Free Component Team Status Richard Parker, Delphi Delco Electronics

report, sponsored by leading world electronics companies, including Sony.

Explaining why 260° was chosen as the Peak Reflow Temperature (PRT):
" .. to accommodate the spectrum of small boards to large backplane boards" and "Solder joint wetting performance is a function of temperature. Hotter is better, so users tend to prefer hotter (to achieve a) larger process window."

A low delta T across the board is desired so "managing thermal mass of circuit board and components is a processing issue."

Among those issues is measurement location for Peak Reflow Temperature, driven by different interests of Assembler (at solder joint) and IC Company (at top center of package surface). The Assembler desires to balance the joint reflow window with maximum production output, i.e. conveyor speed. Also small components will be hotter, another incentive for speed, except that large components must be heated enough to melt solder. There can be a 14°C delta between hottest and coldest assembly points at peak. **That's what makes reduction of Peak Reflow Temperature (PRT), based on alloy melting temperature, so difficult. It's a tradeoff with time. Slowing the production line introduces another cost element to the many lead-free solder debits. And not only cost, but more energy consumption, typically one third more than with SnPb.**

All the above is prelude to explain why 260°C reflow, 40°s above liquidus for the NEMI-preferred SAC (Sn3.9Ag0.6Cu), was chosen.

<u>The NEMI Report: Moisture Sensitivity Levels (MSLs) increase with PRT</u>. Moisture sensitivities are defined by level from 1-best to 6-worst. MSL "is a primary concern for IC manufacturers and IC users alike. this rating determines humidity exposure limitations prior to using in a reflow soldering process". Level 1 signifies that the device has unlimited floor life and no dry bake is required; Level 6 devices require dry bake before use. But even more significant, you wouldn't want to use equipment with Level 6 devices on a humid day. Failure is almost guaranteed.

MSL was measured before and after reflow to 260°C PRT. Summarizing tests:

- 12 package types were tested
- 52 lead count combinations

Summarizing results:

- "There is no generic solution for maintaining an IC's MSL with a higher reflow profile"
- …." Construction and materials employed have major impact. Material & process interactions are not completely understood yet"
- **"MSL typically degrades by one level for every 5 to 10°C increase of PRT. Degradation of MSL may increase with increasing profile dwell above 200°C.**

There are two bottom lines to all this: more money, more time, more energy consumption and CO_2/SO_2 emission (global warming, acidification). That is the price of pursuing lead-free solder. Some of the items that would have to be addressed include:

- lower PRT (but 260°C PRT is really required by some, the report states)

With a melting point of 217 deg.C, the minimum reflow peak temperature for a proper soldered joint is 235 deg.C. If the biggest component has to reach that temperature, the small ones and the bare board areas will reach 250-260 deg.C. So, 260C is not required, but it will be difficult to avoid this on the small components. All technological tricks will be needed to keep boards temperatures within an acceptable temperature range in the reflow peak zone.[35]

- new convection ovens
- new die attach materials
- new mold compounds

4) <u>Printed circuit reliability is threatened by Conductive Anodic Filament (CAF) formation.</u> "Conductive Anodic Filaments are copper corrosion byproducts that emanate from the anode of a circuit and 'grow' subsurface toward the

[35] note from Erik de Kluizenaar, Philips

cathode, frequently along separated fiber-epoxy interfaces."[36]

The main factors are moisture and voltage; higher temperatures accelerate the failure mechanism. Comparing "the number of CAF formed on boards reflowed at 201°C vs. 241°C after aging under 100V bias at 85°C/85% RH for 28 days…CAF under the higher (temperature) reflow conditions was typically 1-2 orders of magnitude greater than at the lower reflow conditions. The data provide additional reliability concerns for lead-free soldering."[37]

The CAF problem is addressable[38] for FR-4, by

- Modifying the glass cloth finish and its application
- Ultra purification of the resin
- Vaporization of volatiles
- Low profile copper

Much development will be required to actually implement these measures. The cost will exact a penalty from all using electronic equipment.

More direct, more easily measured costs are discussed and quantified in the next chapter.

FIBER OPTIC (PHOTONIC) COMPONENTS AND FIBER CAN'T STAND LEAD-FREE SOLDER TEMPERATURES[39]

Agilent Technologies and Celestica have initiated a controlled experiment to judge the effect of lead-free production line reflow on board mounted photonic components and materials. At 240 degrees C, the lowest melting temperature for SAC (Tin-Silver-Copper) alloys, the LED's melt and plastics discolor.

The study is ongoing, February 2002. At present, it looks as though yet another exemption to a lead-free ban will be needed.

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[36] Dr. Laura Turbini et al, Conductive Anodic Filament Formation: A Potential Reliability Problem for Fine-Line Circuits, The Reliability Lab. Georgia Institute of Technology

[37] Dr. Laura Turbini et al, IMPACT OF HIGHER MELTING LEAD-FREE SOLDERS ON THE RELIABILITY OF PRINTED WIRING ASSEMBLIES, SMTA Conference, September 24, 2000

[38] Terence Smith, Matsushita Electronic Materials, Reducing Conductive Anodic Filament in High Density Printed Wiring Boards, IPC PRINTED CIRCUITS EXPO, 1999

[39] discussions with Karl Tiefert, Product Steward, AGILENT TECHNOLOGIES, 2001, 2002

III. ECONOMIC IMPACT OF LEAD-FREE SOLDER ON THE ELECTRONICS INDUSTRY

There is a prospect that lead- free and Sn-Pb solders will co-exist for a long time, creating an expensive nightmare for manufacturing logistics.

Lead-free solder will have to share the stage with Sn-Pb solder while it is being phased–in. No amount of preliminary testing can readily equal 50 years of Sn-Pb experience. There are exceptional materials that are simply not compatible with lead-free processing temperatures, such as fiber optics, microwave circuits on PTFE, and delicate MEMS. The EU Commission has "exempted" several important equipment categories: Servers, Storage, Network and Telecom equipment. Medical, Aerospace, and Automotive are also beyond the scope of the "ban".

Duplicate production lines, par numbers, and materials will be very costly and disruptive.

SUMMING UP THE COSTS TO THE WORLD ELECTRONICS INDUSTRY	
COST ELEMENT	$B
Component cost increase	3
Labor Experience Curve	32
Machine Replacement	1
Yield Loss	20
Increased Production Cycle Time	3
Supply Chain Cost	13
SUMMARY	**$72 B**

It is possible to address most, but not all, of the reliability problems due to implementation of lead-free solder, discussed in Chapter II, with application of enough capital.

The questions are, “How much money?” and “Whose?” With application of enough money and time, most of the lead-free solder problems can be solved. The materials and process changes needed to withstand higher lead-free solder reflow temperatures can be developed, tested, and qualified, both singly and together. These development costs are very difficult to measure. They would be reflected in higher materials, component, and manufacturing costs. Our analysis below is based on a one-time hypothetical transition cost spread over 5 years, but most of its elements would continue to burden electronic assembly indefinitely.

Beyond the direct costs, there are many indirect and transition costs— supply chain disruptions and inventory investments. These costs of multiple stocking, productivity loss, new learning curves, are extremely complex and difficult to measure.

To estimate lead-free solder cost impacts on the World Electronics industry at the manufacturing level, a first task is to analyze electronic manufacturing materials and process impacts of alternatives compared to lead. Major cost burdens due to lead-free solder include materials cost increases, process capital equipment replacement, higher energy cost, slower assembly line cycle time, increased yield loss. The largest and most difficult to evaluate impacts are the supply chain disruptions, including logistics, part number duplication and stocking, and training.

The Many Dimensions of Lead-free Cost: Life Cycle (Societal) Costs vs. Electronic Manufacturing; Electronic Manufacturing vs. Supply Chain and Associated Costs.

There are three levels of lead-free solder implementation cost—1) to the “Firm”, 2) to the Electronics Industry (and the consuming public), 3) to all of Society (Industrial Ecology).

Societal impacts need to be considered in the context of product life cycle analysis from production to wear-out. One of society’s most important goals is a sustainable economy that includes optimizing end-of-life paths for electronic equipment. For example, recycling tin lead solder would contain lead in a closed system, minimizing environmental impact. This is the model already provided by lead-acid storage batteries. The complications in recovery of low concentration tin-lead from shredded printed circuits will be discussed in the next chapter.

The costs of lead-free solder to society will be evaluated in another chapter. "Modern insights in ECO-impact studies show that the depletion of natural resources (relatively rare Sn and Ag versus abundant Pb) is a major factor."[40]

Discussion of the first 2 cost levels follows.

A MODEL FOR EVALUATING MANUFACTURING COST IMPACTS—at the assembly level

A useful reference[41] measures the elements of cost for a sample assembly and derives the percentage of each in the mix. It is valuable for the perspective since it demonstrates for each element its sensitivity in impacting the total assembly cost. The methodology also illustrates the major importance of cycle time, that is, throughput, in maximizing profit. Increase in cycle time by use of lead free solder is its greatest contribution to higher pro-rated manufacturing cost per unit assembly produced. This is due to reduced line speed and to increased need for baking printed circuit boards and assemblies. We shall use the referenced model in our substitutional cost analysis of lead-free solder impacts.

Below are tabulated the cost element percentages for sample assembly, a modem card, in decreasing order.

Components: 72.2%
PCB: 14.4%
Labor: 11.8%
Machine costs (amortized over 5 years): 0.8%
Consumables: 0.5%
Rework: 0.3%
Floor space, utilities: 0.1%

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[40] correspondence from Erik de Kluizenaar, Philips, December 2001
[41] Daniel Baldwin, Joe Belmonte, Ronald Lasky, and Kathleen Murray "Real-time Cost Estimates Measure ROI" SMT Magazine, September 1999, pg 46

The production factors are analyzed in following paragraphs.

1) Components: 72.2% of initial assembly cost

The same percentage increase in Components cost will have 70 times the impact of capital equipment. ICs are the largest component cost contributor, about 55% of manufacturing cost. Components in general, IC's in particular, rank first in potential lead free solder cost impact.

In the Reliability chapter, the NEMI assembly tests were described and the resulting moisture sensitivity degradation after 260°C reflow ramp. That degradation is potentially addressable by development of new material sets along with process, profile and capital equipment changes.

Improved material sets include higher temperature die attach, molding powders, and underfill, depending on package type. It has been estimated[42] that the current resulting component cost increment will be "5% to 10%". The increased cost differential would go down with volume. But in the near term, using a conservative 5% increase at the assembly level, assembly cost would raise $2.50. This is based on the modem model used in the reference model[43] in which components originally cost $75 and ICs (our estimate), $57. Although the premium would hypothetically go down with volume, *getting from here to there, in a competitive environment, is very problematic.* We have neglected passive components and connectors although their costs for lead-free temperature materials will also rise. Their cost base is lower and they aren't nearly so sensitive to moisture sensitivity degradation.

In the referenced model, manufacturing profit was assumed to be $6.10, about 6%, typical for Electronic Manufacturing Service Providers. The assembly-level profit is reduced 40% by lead free components, unless costs can be passed on.

We do not question the potential for lead-free-ready component price differentials' decline with volume, but for already low margin EMS companies the initial cost

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[42] Conversation with Swaminath Prasad, ChipPac, Oct 1, 2001
Also Skip Fehr, OSE
Note that the higher temperature polymers initially cost 30% to 50% more than current, representing from 10% to 15% of finished package cost.

[43] Baldwin, et al, op cit

burden in this era's competitive environment, will be a very strong disincentive to comply with lead free solder. The same is true, by extension, to the OEMs. Both are very reluctant to order large quantities of components after their very expensive experience with excess inventories in 2001.

While production decisions are made at the firm level, economic impacts at national and world economy levels ultimately have political repercussions.

LEAD-FREE CAPABLE COMPONENT COST CONTRIBUTION AT THE WORLD ECONOMY LEVEL

In 2000, World IC production was over $200B, using our conservative 3% initial cost increment, the result is a potential over- $6B cost increase to the world's consumers, just from component price increases, for lead-free solder.

<u>2) PCB: 14.4% of initial assembly cost</u>
<u>PRINTED CIRCUIT BOARD SUBSTRATE</u>

The PCB in the modem model selected to measure cost impact of lead-free solder represents 14.4% of total assembly cost. Laminate contribution to the PCB cost is typically 15%, resulting in a laminate contribution about 2% of total cost. Thus a 50% increase in laminate cost would increase total cost 1%, still large in absolute terms. Firm profit in our model would decline by 15% in circuit applications requiring high reliability.

Actually, laminates such as GETEK and N4000-13 with high thermal stability measured by low x, y, and z expansion up to 180° - 200° Tg (softening temperature) do cost approximately 50% more than 170° Tg FR4.

<u>3) LABOR: 11.8% of initial assembly cost</u>
<u>LEAD-FREE SOLDER'S NEW EXPERIENCE CURVE</u>

Impact of lead-free solder on labor cost is comprised by three factors:
Productivity loss with introduction of new processes
Slower production line.
Transitional reduction of yield—discussed further under REWORK.

The Experience Curve principle provides a way to estimate direct cost of factor 1). The Experience Curve states the common aphorism, “Practice makes perfect” in more quantitative terms. For example, it has been empirically demonstrated that semiconductor prices fall 25% with every doubling of production volume[44].

Surface mount production using SnPb solder paste emerged in the early 1980s and came to dominate printed circuit assembly during the 1990’s. SMT using SnPb solder is now mature. Replacing it with the NEMI- favored SnAgCu paste would change many production parameters such as oven profile and length, add additional pre-heat and bake processing. The ultimate result would be to superimpose a new experience curve, effectively reversing the existing mature curve with no compensating increase in productivity.

World electronics equipment manufacturing value grew from $350B in 1991 to $710B in 2001 (InfraFOCUS estimate) at a rate of 13%/year. (Choice of a recessionary year as end-point makes for a more conservative analysis.) Approximate doubling of output was accompanied by 15% cost decline, due to lower labor cost per production unit. (Again these are conservative estimates for the electronics industry productivity increase and price declines.) If lead-free solder set the clock back only 3 of those 10 years for adjustment to the new production parameters, the increased labor cost would be 4.5%. Applying this to the 11.8% for labor in our model assembly, lead-free solder would add 0.6% to assembly cost. That’s another 60 cents deduction from the $6.10 profit, before labor cost changes due to slowing the line and to yield reduction.

Extended to the entire $710 billion World Electronics Industry, increased labor cost due to the new experience curve factor: $32 billion.

Two other labor cost factors, slower production line cycle time for lead-free solder and reduced yield, exact direct labor cost penalties for additional time and rework. These indirect cost impacts due to increased cycle time result in lower throughput, analyzed below.

4) MACHINE COSTS: 0.8% OF ASSEMBLY VALUE

New reflow ovens may be required to meet the narrow process windows and higher temperatures needed for lead-free solder. Ovens represent only 6% of total equipment

[44] Bruce Henderson, Boston Consulting Group, numerous citations

cost, translating at board assembly level to less than 0.05%/year over 5 years. Acquisition would be a burden to larger companies and a real hardship to smaller ones. But other factors dwarf its direct cost contribution at the firm level, assuming production levels at capacity. (Pro-rated costs would go up as production levels decrease.)

Capital equipment cost to implement lead-free solder at the world industry level would be over $1B. This is based on a conservative estimate of 20,000 lines and a conservative estimate of $50K replacement cost per line. This figure covers both reflow and wave soldering machines, which generally cost more than twice our estimate.

Higher temperatures will take a toll on equipment lifetimes, raise maintenance and operating costs. Wave soldering temperatures are even higher than reflow (260°C for SnAgCu) because the heat transfer medium is the solder itself. "NEMI is recommending a wave soldering temperature of 275°C" [45] One problem is that no one knows how much equipment reliability will be impaired because there is no real production experience.

5) <u>CONSUMABLES: 0.5% of initial assembly cost</u>

Solder costs dominate this category and for simplicity will be used as surrogate. Two applications use solders with very divergent cost impacts – reflow solder paste for surface- mount and wave solder for through- hole assembly.

In the former case, formulated paste, materials cost increases of lead-free are out-balanced by its lower density. Since it "goes further", there is actually a very small decrease in net cost[46] of solder paste.

In wave soldering the cost differential for the preferred lead-free solder bar alternative, Sn0.7Cu, is $5.66 (1999) compared to $3.80 for Sn-Pb[47], difference $1.86. For a typical 1800-pound production pot, this increased cost is $3,340. Corrected by relative density (7.3/8.4 g/cc) for the lower density lead-free alloy[48], the solder cost differential for lead-free is about $2,900. That is a 48% increase in solder cost for wave soldering. Relative to cost of our model board, it's small, but in an absolute sense, a shock.

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[45] R. Parker, Delphi, The Next no-lead Hurdle: The Components Supply Chain, EP&P, August 2000

[46] A. Rae, R Lasky, Cookson Electronics, Economics and Implications of Moving to Lead-Free Assembly, NEPCON 2000

[47] Op. cit.

[48] Op/ cit.

Wave soldering solder markets are mature and stable, not declining.

The solder prices cited above are based on higher constituent metal costs in 1999. But those are long-term; more immediate costs will go up more than material cost, because of "tremendous costs of researching and proving out new alloys."[49] It is impossible to estimate what final pricing decisions might be forthcoming for solder paste. Which flux choice and inter-vendor product compatibility issues further complicate this question and add to cost.

6) REWORK: 0.3% of initial assembly cost

The cumulative impact of new solders, new profiles, new equipment on yield will be significant, another imponderable. But a reference point may be gained by going back to the 1980's, when Surface Mount Technology was still new. Then yields were in the high 80%s[50]. We'll use the model of Rae and Lasky[51] to quantify potential costs.

> To demonstrate the effect of yield loss on cost, we will use SPACE™ to perform a cost analysis on the assembly of a modem over one year of production. We assume the modem will sell for $110 and will have an assembled cost in the $104 range. This 6% gross margin is typical in the industry, if not slightly high. Assembly parameters were chosen from metrics NEMI designated as "typical". Yield loss is a legitimate concern in lead-free processes because the lead-free alloys do not wet copper pads as well as the SnPb37 solder and poor wetting is known to increase voiding.
>
> Let us assume that the no-lead process results in lower first-pass yields, 92% versus the standard baseline case's 97%. The lost yield is completely reworkable in both cases. As another example, let us assume that the first-pass yield is 92%, but only 80% of the yield fall out is reworkable. What are the transitional cost implications of both of these yield reduction scenarios?

Long-term (based on the experience of Philips Lighting[52] after over 2 years of development- first pass yield can be

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[49] D. Suraski, AIM, leadfree@ipc.org 11/15/1999

[50] discussion with Phil Marcoux, founder of AWI, now SCI, Oct 16,2001

[51] Rae and Lasky, op. cit.

[52] correspondence with Erik de Kluizenaar, Philips, January 2002

equal to that of SnPb soldering and reworkability of lead-free circuits equaled that of SnPb-soldered circuits.

The general experience is lower assembly yields due to 1) poorer wetting by lead-free alloys and 2) loss of device self- centering that is one of the benefits of the more plastic tin-lead alloy[53]

Assuming a year's worth of production, the unit cost increases $0.52 in the 92% all-reworkable yield case, compared to the baseline case. This scenario results in a decrease in profit of almost $350K. However, the worse case turns out to be the one in which only 80% of the yield loss is reworkable. In this example, the unit cost skyrockets more than $2 and profits plummet by almost $1.4 million…. If the results of our final case were inflicted on the entire $1000 million electronics industry, it would result in $20 billion of lost profit!

Cost Impact of Increased Cycle Time

Lead-free solder assembly cycle time is inherently longer than present assembly with Sn-Pb solder because of need for pre-baking, slower ramp, and longer cool cycles. Concerns about 260°C peak temperature degradation effects on components and substrates have led to efforts to reduce that temperature. The inevitable tradeoff would be to slow the production line even further in order to assure thorough heating of assemblies for reflow.

The modem assembly model, in another exemplification[54], illustrates the dramatic cost impact of slowing the production cycle. In the model cited, 200K units per year are produced and sold at $100 each for a gross profit at $5, total profit: $1 million per year on $20 million sales. Slowing the cycle time 15% from the nominal 25 second will lead to output reduction to 173,900 units. "The effect on gross profits is disastrous...reduced from $1 million to $895,600." At the net profit level, this $104,400 impact is twice as severe, since net is typically half of gross. That's the potential impact at the firm operational level.

At the Electronic Industry level, we will use our estimate of $710 Billion for the world total value of manufactures. Extended to the World Electronics Industry,

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53 J. Smetana, Alcatel, *op. cit.*

54 R. Lasky, D. Baldwin, B. Lewis, METRICS: THE KEY TO PRODUCTIVITY, IPC/SMTA Electronics Assembly Expo, October 1998

slowing the production line to accommodate lead-free solder will cost over $3 billion.

Inventories, Part Number Creation, and other Supply Chain Costs— These Account for the Largest Cost Impacts of Lead-Free Solder, at Many Levels

A "table cloth" estimate from a friend at Intel suggests that lead-free part numbers might double the total from 40,000 to 80,000 at paperwork and minimal stocking cost of $100,000(Intel's unofficial figure) each.

In the real world, a transition to lead-free solder would be gradual. The lead-free supply chain infrastructure is far from established. The reliability and manufacturing economic issues are far from resolution. That means duplication of production and supply.

Furthermore, lead-free alloys cannot be contaminated by the presence of lead[55]. Formation of lower temperature eutectic would result. That also requires part number duplication.

The Intel model requires downward modifications that arise from two sources: 1) Devices with lead-free surface finishes based on tin are mutually compatible with tin-lead solder paste, thus may not require duplicate P/Ns. They will probably continue to account for over 80% of units. But the high growth BGA and flip chip devices for both in-package and on-board markets are a different story. Their tin-lead bumps are not compatible with on-board lead-free solder. "…lead-free alloys can suffer decreased reliability when contaminated with lead"[56] Flip chip in package and on board will require duplicate part numbers for tin lead and lead-free environments because of the effects of higher lead-free reflow temperatures[57]. 2) Integrated companies such as Philips and Sony that control the entire supply chain for specialized products that use captive ICs will not need duplicate P/Ns. But this equipment category is comparatively insignificant.

For the U.S Integrated Device Manufacturers alone, the figures are estimated to be 200,000 doubling to 400,000 P/Ns. If we assume that the part number impact at North American industry level be only 10%, 40,000 to be duplicated, the resulting cost would be $4 billion. At the

[55] FRY TECHNOLOGY, Products & Marketing, 1999
[56] K. Seelig and D. Suraski, Lead-Free Electronics Assembly for the Real World, *APEX 2002*
[57] B. Bivins, R. Mao, et al, Latest Developments in Post-Solder Cleaning of Lead-Free Solder Residues, *APEX 2002*

World semiconductor package level, $8 billion is a conservative estimate.

This duplication impact would ripple up and down the supply chain. Over 20% of ICs move through distribution (such as Avnet and Arrow), that part of the chain would be similarly impacted. In the case of some device categories, e.g. programmable, it's even worse. Xilinx moves 95% of devices through distribution[58]. $1 billion is a minimal cost impact estimate for Distribution (North America).

The impact on Electronic Manufacturing Service providers (such as Flextronics and Solectron) would be similar to that felt by the Distribution group. They fill the same supply chain inventory buffer role. EMS companies' share of device markets approaches 20% (Year 2000). $1 billion is a minimal cost impact estimate for the EMS group due to lead-free solder.

Original Equipment Manufacturers (such as Nokia and NEC) and Embedded Subsystem/Private Label Manufacturers (such as Intel Hillsboro and Motorola Computer Systems) together accounted for over 80% of electronic equipment assembly. Scaling from the IDM cost impact figure above, $3 billion is a conservative estimate for supply chain cost increment due to lead-free solder.

These figures will be further magnified by need to stock significant quantities of duplicate parts inventories—ICs, discrete semiconductors, and passive components, lead-free and conventional tin-lead.

Our modest total for supply chain cost impacts of lead-free solder is $13 billion. The NCMS report of 1998 suggested that these costs might actually amount to "tens of billions of dollars".

Total cost of implementing lead-free solder just to the electronics industry and consumers of its products is $72 billion.

That doesn't count the costs to society and the environment of increased CO_2 and SO_2 emissions or despoiling due to mining alternative metals and **unnecessary** depletion of natural resources.

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[58] discussion with Terry Trumbull, former head of Distribution Sales at Cypress Semiconductor

IV. END-OF-LIFE ELECTRONIC EQUIPMENT— MODELS FOR MINIMIZING LEAD IMPACT ON ENVIRONMENT

Recycling for all waste and end-of-life products is an attractive proposition. It's called "Sustainable Environmentalism", alternative to landfill or incinerator disposal. Recycling replaces primary extraction and processing. It theoretically uses less energy, assuming optimization of recycling technologies. It would end the common practice of dumping the Developed World's wastes in the Developing World.

The economics for each commodity requires individual study. Two critically important disciplines apply to all materials, including lead in electronic solder: 1) Design for the Environment, to choose and assemble materials with end-of-life recycling in mind (beyond the scope of this report) and 2) Industrial Ecology. It may provide the final epitaph for lead-free electronic solder in the mainstream.

The list of recyclables includes plastics, paper, metals—that includes electronic lead. Recycling technology development is a different challenge for each material. Initially, recycling creates cost, not profit centers. But the growing magnitude of electronic end-equipment makes it a prime candidate for recycling, lead content included. Recycling is certainly preferable to dumping waste in developing countries.

The popular perception is that lead in the environment, however chemically inert, is hazardous to human and other life forms. Regulations reflect this unproven perception. We will accept the lead toxicity assumption only in the belief that recycling of electronic waste, lead included, offers net benefits to society. In electronic waste, unlike bullets, tire balance weights, plumbing, radiator lead and leaded solder, the lead is recyclable.

MAGNITUDE OF ELECTRONIC WASTE, CRTs, AND LEAD CONTENT

Compared to all waste in the Municipal Solid Waste stream, end-of-life electronic equipment has been minor. The North Carolina environmental agency[59] found in 1997 that

[59] N.C. Division of Pollution Prevention

electronics accounted for less than 3% of generated MSW, compared to paper at 40%.

Furthermore, CRTs account for over 96% of electronic equipment lead[60].

The low 3% figure masks the future impact of electronic equipment. Stockpiled personal computers and TVs in California were estimated to number 6.1 million, 121,400 tons in 2001[61]. Extrapolating to the U.S., an estimated 61 million units are

potentially waiting to be recycled or sent to landfills, just from stockpiles. With regard to continuing equipment flows, the National Safety Council found that 89% of U.S. 20 million annual obsolete computers are not recycled in the U.S[62]. They are either dumped or stockpiled. The 20 million shipped to the rest of the world annually may be assumed to have a longer useful life, say twice as long. Our world estimate for dumped or stockpiled computers is 27 million annually. Generally each includes a CRT monitor

Color TVs are a much larger source of CRT and other electronic waste. "Unit shipments will increase from 154 million in 2001 to nearly 200 million in 2007 (World)."[63] Cathode ray tubes are expected to dominate displays, with well over 90%.

North American CRT population in 1996 was 300 million[64]. Extrapolating to the world*, the figure exceeds1 billion CRT population* (Note that U.S. current TV shipments are only about 24 million[65] annually compared to 154 million World. For Personal Computers, the U.S. rate is about 40 million, about 1/3d of World shipments, about 120 million[66].)

CRTs from computer monitors and TV sets were tested for comparison to leachability regulatory limits. 21 of 36 exceeded them[67].

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[60] University of Florida CRT disposal study, 1998
[61] MGT of America report for CA/EPA, Dec 12,2001
[62] Calvert Group, Dec 20, 2001
[63] Stanford Resources 'Television Systems 2002', January 2002
[64] J.D. Porter, "Computers and electronics recycling: challenges and opportunities", **Resource Recycling**, April 1998
[65] EIA
[66] Dataquest release, April 24, 2000
[67] "Characterization of Lead Leachability from CRTs Using the TCLP"--Dept of Environmental Engineering Sciences, University of Florida, 12/1999

CRT RECYCLING IN MASSACHUSETTS—POTENTIALLY AN ECONOMICALLY VIABLE REALITY[68] (MODEL FOR ALL ELECTRONICS RECYCLING?)

"I was contacted by Robin Ingenthron,..VP of the state's CRT collection and recycling company, Electronicycle. He points out that the cost of CRT recycling is coming down, and that his company charges about half of what other states charge to recycle, because of high volume. He predicted a time when the cost of recycling was at a parity with properly calculated cost of disposal… He also said that there is a significant need for enabling technology: a better way to separate the CRT face plate which contains barium and is worth about $800 per ton.." (edited for brevity)

THE COMPOSITION OF ELECTRONIC WASTE MAKES IT A PRIME CANDIDATE FOR RECYCLING

"In 1998, over 112 million pounds of materials were recovered from electronics, including steel, glass, and plastics..."[69] "… a PC today is typically 40 percent steel, 30 to 40 percent plastic, 10 percent aluminum..[70]

A comprehensive study by the University of Massachusetts Office of Waste Management[71] broke down all collected E-waste (electronic waste--CPUs, monitors, and printers) outgoing composition, by weight, as follows after "de-manufacturing":

Scrap metal 26%, CRTs 19%, Circuit Boards 15%, Plastic/Trash 14%, iron/aluminum 8%, power supplies 5%, wire 4%.

Recycling infrastructure is already in place to recycle most of
Components and materials. We are at an early life cycle stage on the path to make it profitable.

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[68] Gordon Davey, Northrop-Grumman, leadfree@ipc.org, **8/24/01**

[69] "Electronics: A New Opportunity for Waste Prevention, Reuse, and Recycling", EPA 530-F-01-006, June 2001

[70] H. Scheussler,"Breaking Down All Those Computers: Glass Over Here, Plastics There" **New York Times**, Nov 23, 2000

[71] Research project by Office of Waste Management, U of Massachusetts (1998), to collect and process data for the University's electronics de-manufacturing and recycling program. Revenue equaled expense, even after negative entry for CRTs. Hauling/disposal costs and toxic pollution liability were avoided; wages were generated. Electronic waste stream categories including boards were quantified, making it an interesting model. 1st part of larger project reported.

One major cost element is disassembly. A case history from the automotive scrap business shows the possibilities of automation[72]. "…William Hyman can strip a car in as little as 45 minutes..(he) runs the only semi automated "disassembly" line in the U.S… can dismantle up to 30,000 vehicles a year, compared with about 600 at an average junkyard, reclaiming 99% of the carcass (versus the typical 75%)." Money spent on lead-free solder might pay for e-waste handling automation, hastening the day of self-sufficient payback.

RECYCLING LEAD IN ELECTRONIC EQUIPMENT

Five approaches to recycling lead in electronic solder serve as a sample of what might be done. Populated PCBs are the feedstock, in the form of shredded populated boards that are about 3% Pb by weight, (using Dr. Alan Rae's 7% figure for average solder percentage of populated board):

1. Cu smelter-- most lead ends up in slag as oxide, used in roadbeds-- lead much less than 10% of volume *before* cement is added, final composite meets leaching standards (Noranda Micro Metallics and Hewlett-Packard are exemplars, using the copper smelter at Horne Quebec).

2. Primary Pb smelter-- Dr. Queneau of Colorado School of Mines states that some lead ores have similar Pb concentrations as shredded PCBs. Umicore's lead smelter, Hoboken Belgium, is a leader[73] in processing printed circuit board lead. (Umicore is former Union Miniere.)

The following approaches might eliminate the need to deal with lead at the smelter level. These would support complete closed loop recycling and potentially reduce printed circuit recycling costs.

3. Electrolytic removal of solder from shredded boards (Cookson, Cambridge University et al) -- before smelting for Cu, etc.

4. Solvent removal of lead (Carl Nesbitt, Michigan Technological University) -- before smelting. The success of Michigan Technological University in separating lead (as

[72] C. Ghosh, "JUNKYARD DOG", **Forbes**, April 16, 2001, pg 314
[73] discussion with Ara Aposhin, FRY TECHNOLOGY (COOKSON), Feb 25, 2002

low as 1% concentration) from brass waste is based on lead compound low solubility[74].

5. Hot oil air knives, electronics recycling: Challenges and Opportunities reversing solder application of Hot Air Solder Leveling[75].

In summary many technologies for cost-effectively recycling lead are possible, using its unique physical properties. These include:

Low lead solubility
High density
Electrowinning

The cost of Pb substance ban in electronic solder (approaching $100B to the electronics industry alone) might pay many times over to launch any of the recycling technologies.

AN EPITAPH FOR MAINSTREAM USE OF LEAD-FREE ELECTRONIC SOLDER?—FROM "INDUSTRIAL ECOLOGY"[76]

Industrial Ecology is a new discipline that addresses total impact of human activities on the environment. Two examples of its application to lead in electronic solder follow.

1. ANNUAL ELECTRONIC SOLDER ENERGY CONSUMPTION[77]

Assembly Oven Power Consumption… 21kW - SnPb solder; 26kW – Pb-free Oven Power Consumption (World)… 5.1B kWh-SnPb; 6.3B KWh—Pb-free

> The increased power, **over 1.2B kWh**, for lead-free reflow ovens would require the output from about 60

[74] "**Recycling Lead from Metal Wastes of Brass Foundries**", Michigan Technological University, 2001 (?): "The hydrometallurgy of copper and zinc suggests them to be easily recovered in pure form by dissolving in acid or ammoniacal solutions. Lead, on the other hand, is only soluble in nitric and acetic acid or strongly basic solutions. Lead sulfate has a low solubility that may be exploited as a means of separating Cu and Zn from lead."

[75] Discussion with Brian Ellis, Leadfree@IPC.org, 2/2002
[76] B. Allenby and T. Graedel, Industrial Ecology, Prentice Hall, 1995
Dr. Allenby is Vice President, Environment, Health, and Safety, AT&T
Dr. Graedel is a professor of Industrial Ecology at Yale
[77] K. Tiefert, Agilent Technologies, February 2001

power plants the size of the Diablo Nuclear Plant. Assumptions: operation 24 hours, 365 days, 27,500 reflow ovens.

Note: Additional CO_2 emissions not included. Also lead-free usage would require pre-baking ovens and higher energy use for solder leveling PCBs. These are not included.

2. The Materials and Process Audit for Electronic Solders and Alternatives: A Detailed Case Study[78]
3. Design for the Environment analysis application to lead in electronic solder resulted in the following conclusion, **the position of a prominent industrial ecologist.**

   "The results of the impact assessment can be stated simply: the status quo, lead solder, is preferable to substantial substitution of alloys containing significant amounts of bismuth or tin or by epoxies containing significant amounts of silver. When the relatively minor component of overall lead demand attributable to printed wiring board assembly applications is contrasted with the significantly expanded mining and processing the other options would entail, lead-based solders are the least environmentally harmful choice. Thus a systematic analysis has led to what, for many people, is a counterintuitive result."

Allenby, op cit.

SUPPLEMENT I
FRAGILITY OF Pb-FREE SOLDER JOINTS

White Paper
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ABSTRACT
Recent investigations have revealed that Pb-free solder joints may be fragile, prone to premature interfacial failure particularly under shock loading, as initially formed or tend to become so under moderate thermal aging. Depending on the solder pad surface finish, different mechanisms are clearly involved, but none of the commonly used surface finishes appear to be consistently immune to embrittlement processes. This is of obvious concern for products facing relatively high operating temperatures for protracted times and/or mechanical shock or strong vibrations in service.

While fragility problems and the associated embrittlement mechanisms have long been known for both electroless and electrolytically deposited Ni/Au coatings, soldering to copper has been viewed as 'safer' as far as robustness is concerned. However, recent observations suggest the existence of two or more embrittlement mechanisms in Pb-free solder joints on Cu pad structures, each leading to brittle interfacial fracture at the pad surfaces. With risks of embrittlement associated with all the commonly used solderable surface finishes, the electronics industry is currently confronting very difficult problems. The variability in their manifestation does, however, lend hope that some of these problems may be avoidable or controllable.

INTRODUCTION
The microelectronics packaging industry relies on solder joints for the robust mechanical attachment and electrical interconnection of a wide variety of components. Thermal excursions and mechanical shock or vibration often lead to substantial loads on these joints. Notwithstanding, we have a detailed technical understanding, based on decades of experience, by which to assess and predict the consequences for Sn-Pb soldering technology. Over the last few years a significant amount of work has also been done in developing Pb-free soldering technology. Although we are still far from the level of experience and understanding reached for the Sn-Pb system, the commonly preferred Pb-free (Sn-Ag-Cu) alloy system is usually claimed to offer superior or comparable thermomechanical fatigue resistance and, at worst, a minimal reduction in mechanical shock resistance. These claims are still the subjects of intensive research, notably in terms of the effects of the evolution of the solder joint microstructure in thermal cycling and with time at elevated temperatures. Recent reports do, however, suggest some unexpected embrittlement problems associated with both Cu and electrolytic Ni/Au-coated solder pad surfaces. In fact, apparently no commonly used solderable surface coating is consistently immune to embrittlement problems. This circumstance may pose a serious reliability concern and infrastructure problem for the microelectronics industry, as it moves towards the implementation of Pb-free soldering technology. However the variability in the manifestation of embrittlement mechanisms, at least in the Cu pad system, lends some insight and hope to the prospect that some of the embrittlement mechanisms can be controlled.

In simple terms, the mechanical forces on a solder joint originate from externally imposed forces on its card assembly or from mismatched thermal expansions within the structures to which the solder joint is attached. The plastic deformation properties of the solder serve to limit the imposed stresses in the solder joint at sufficiently high stress values. Even moderate thermal cycling usually requires some joints to survive loads which induce significant plastic deformation in each cycle, making it paramount for the interfacial intermetallic compound structures in the solder pads to survive such loads. In contrast, in handling and service, externally imposed mechanical loading, such as that associated with system mechanical shock, may often be limited to a level that does not involve as much plastic flow of the solder. In addition, the solder flow stress is invariably higher under high frequency mechanically imposed shock loads, due to the elevated strain rate levels. It is therefore not necessarily immediately critical if one of the intermetallic structures becomes the ultimate weakest link in a shear or pull test. However, a switch from failure through the solder to failure at a pad surface or within the intermetallics in such a test is invariably an indication of an ongoing weakening. In general, solder joints which demonstrate brittle interfacial fracture without significant plastic deformation of the solder joints, represent an inherent problem in applications, where shock loading of the solder joints can be anticipated. In such instances very little energy is dissipated in the solder joint in the fracture process and the solder joint structures are inherently prone to shock reliability problems. Some of the embrittlement mechanisms may also cause sufficient weakening to allow for premature solder joint failure even under a CTE mismatch stress in some applications. In fact, continued void growth in the intermetallics may even cause failure at very low load values.

EMBRITTLEMENT PHENOMENA AND RECENT FINDINGS

While issues with soldering to Ni/Au coated pads have long been recognized recent observations appear to involve new phenomena, as outlined below. In contrast, until now Cu pads coated with OSP, immersion Ag, immersion Sn, or solder have been viewed as 'safer' in this respect. This does not mean that degradation mechanisms are completely absent, even for Sn-Pb soldering. In fact, rapid diffusion of Cu through both the Cu_3Sn and the Cu_6Sn_5 intermetallic layers commonly leads to the growth of Kirkendall voids at the Cu/Cu_3Sn interface [1, 2] and/or the Cu_3Sn/Cu_6Sn_5 interface [3]. However, these voids often remain very low in density and too small to be visible by optical microscopy [1, 2], and they are not considered to be of practical concern.

Recent reports of rapid mechanical weakening of Sn-Ag-Cu solder joints on Cu pads in thermal aging have caused considerable stir in the microelectronics packaging community [4, 5]. The effect appeared to be caused by the growth of Kirkendall voids along the Cu_3Sn/Cu interface (Figure 1). Extensive voiding was observed after only moderate aging (20-40 days at 100°C) making it an obvious practical concern, at least for products facing elevated operating temperatures and mechanical shock or vibrations in service. In fact, the apparent temperature dependence might suggest a risk of failure within a few years under even quite mild conditions. The behavior was confirmed independently by others [5, 6], but fortunately this embrittlement problem may be avoidable. Initial experiments by UIC did not reproduce the voiding [7], and work by IBM suggests a dependence on plating lot (Figure 2). These findings may suggest an effect of impurities. In some instances contamination has been shown to strongly enhance Kirkendall voiding, as impurities are less soluble in the intermetallic phases and thus may be 'swept' ahead of the transformation front and precipitate to act as heterogenous nucleation sites for voids [8]. It can, however, also not be excluded that sub-microscopic voids or bubbles were somehow incorporated at the Cu-surface during reflow and subsequently serve as sinks for vacancies.

IBM also reports another brittle interfacial intermetallic compound failure phenomenon which does not appear to be associated with Kirkendall voiding [6]. Ball pull testing demonstrated interfacial failure within the intermetallics on Cu pads immediately after assembly, and this phenomenon was invariably enhanced by thermal aging. It remains to be ascertained whether this is a practical concern as continued aging did not necessarily, unlike in the case of voiding, lead to a further reduction in pull strength.

The only mature alternative to soldering to copper would be nickel, usually coated with a layer of Au to protect it from oxidation. There have been reports [9] that prolonged reaction between electroless Ni(P) and Sn-Pb may also lead to the formation of Kirkendall voids near the Ni surface, but this appears to be a less likely problem than for copper. A more complex mechanism is observed when the package includes a Cu-pad on the opposite side of the Sn-Pb joint, and thus a ready supply of Cu to the solder. In this case, a build-up of a ternary $(Cu,Ni)_6Sn_5$ layer is observed on top of the Ni_3Sn_4 (which was formed on a nickel surface). Aging has here been seen to lead to void growth at the $Ni_3Sn_4/(Cu,Ni)_6Sn_5$ interface [10]. A similar problem might be expected with Sn-Ag-Cu solder on nickel.

A unique and widely recognized concern, specifically associated with electroless nickel immersion gold (ENIG), is the so-called 'black pad' phenomenon. This is, in fact, a somewhat ubiquitous term which encompasses a number of phenomena related to failure at or near the $Ni(P)/Ni_3Sn_4$ interface. Most generally it refers to a lack of solderability of the Ni(P) surface due to a high amount of corrosion during the immersion Au process, but often the effects of various alloys or combinations of alloys near the interface are included as well. 'Black pad' usually refers to a 'time zero' phenomenon, whether reflected in obvious fragility or just reduced mechanical fatigue resistance at/within the contact pad. However an alternative mechanism by which a seemingly perfect intermetallic structure may degrade over time may also be related to the corrosive 'black pad' effect. The mechanism appears to involve the growth of Ni_3Sn_4, a resulting enrichment in P and formation of Ni_3P underneath and the growth of a ternary phase in between. In either case the problem seems exacerbated by a transition from Sn-Pb to Sn-Ag-Cu solder [11, 12].

Electrolytic nickel is usually coated with an electrolytically deposited layer of Au. The problem with this approach is that realistic manufacturing tolerances do not allow for the control of electroplated Au thicknesses to much less than 25-50 micro-inches (0.63-1.3μm). Depending on, among other things, the maximum load in service this may present a concern. Extensive research [13-19] has shown the Au to dissolve into Sn-Pb solder during reflow only to gradually return to the nickel surface during subsequent aging and contribute to the build-up of a $(Ni, Au)Sn_4$ layer on top of the Ni_3Sn_4 intermetallic there. The resulting interface is mechanically unstable with a strength that continues to decrease with increasing $(Ni, Au)Sn_4$ thickness. Indications are that the increased dissolution of Ni at the higher reflow temperatures associated with Sn-Ag-Cu soldering may tend to stabilize the Au within ternary precipitates in the bulk of the solder, but further studies may be required to quantify effects of various parameters. Qualcomm recently reported observations of 'time zero' failures of Sn-Ag-Cu CSP joints on electrolytic Ni/Au in drop testing, a problem that was reduced or eliminated by reductions in reflow temperature and time. The authors ascribed the brittle failures to a mismatch between the Ni_3Sn_4 and an overlying $(Cu, Ni)_6Sn_5$ layer [20], but similar thicknesses of $(Cu, Ni)_6Sn_5$ usually appear to be stable on top of $(Ni, Cu)_3Sn_4$. Still, the phenomenon appears to be different from the well established Au-related problem.

SUMMARY

Transitioning to Pb-free soldering the industry seems to be facing significant risks of solder joint fragility associated with all the commonly used solder pad surface finishes.

Well established 'black pad' effects and an alternative aging induced embrittlement of the intermetallic structure on ENIG pads appear even more critical for Sn-Ag-Cu than for Sn-Pb joints. Yet another mechanism associated with the larger Au-thicknesses in electrolytically deposited Ni/Au coatings may be eliminated or reduced in Pb-free soldering. However, usually soldering of Sn-Ag-Cu to Ni pads leads to the build-up of a $(Cu, Ni)_6Sn_5$ layer on top of the Ni_3Sn_4. Some such structures have been found to be brittle immediately after assembly, and aging of a $Ni_3Sn_4/(Cu, Ni)_6Sn_5$ structure, albeit in a Sn-Pb joint, has been seen to lead to strong voiding and porosity.

Too often extensive Kirkendall voiding may weaken Sn-Ag-Cu solder joints on Cu pads after only moderate aging, and a seemingly independent embrittlement mechanism was found to occur even without aging. Initial results may suggest a dependence on plating lot, but other factors such as materials (solder, flux, solder paste, pad finish, plating parameters, …) and process parameters (reflow profiles and ambient, oxidation and contamination of solder and pads, pad configuration, paste volumes, …) are expected to be important as well.

In general, the variability of most of these embrittlement mechanisms does lend hope that at least some of them may be avoidable or controllable.

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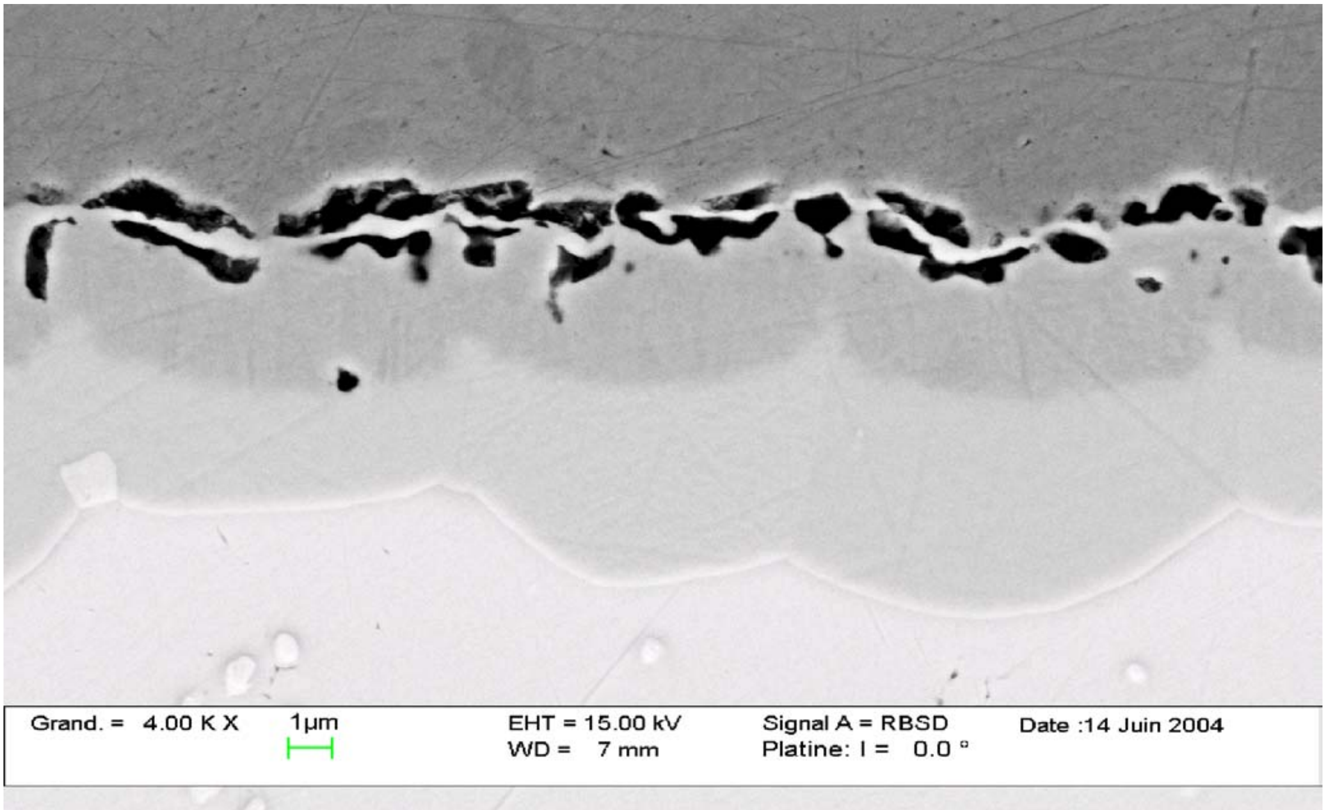

Figure 1: Interface between Sn-Ag-Cu solder ball and Cu pad after 1000 hours at 150°C.

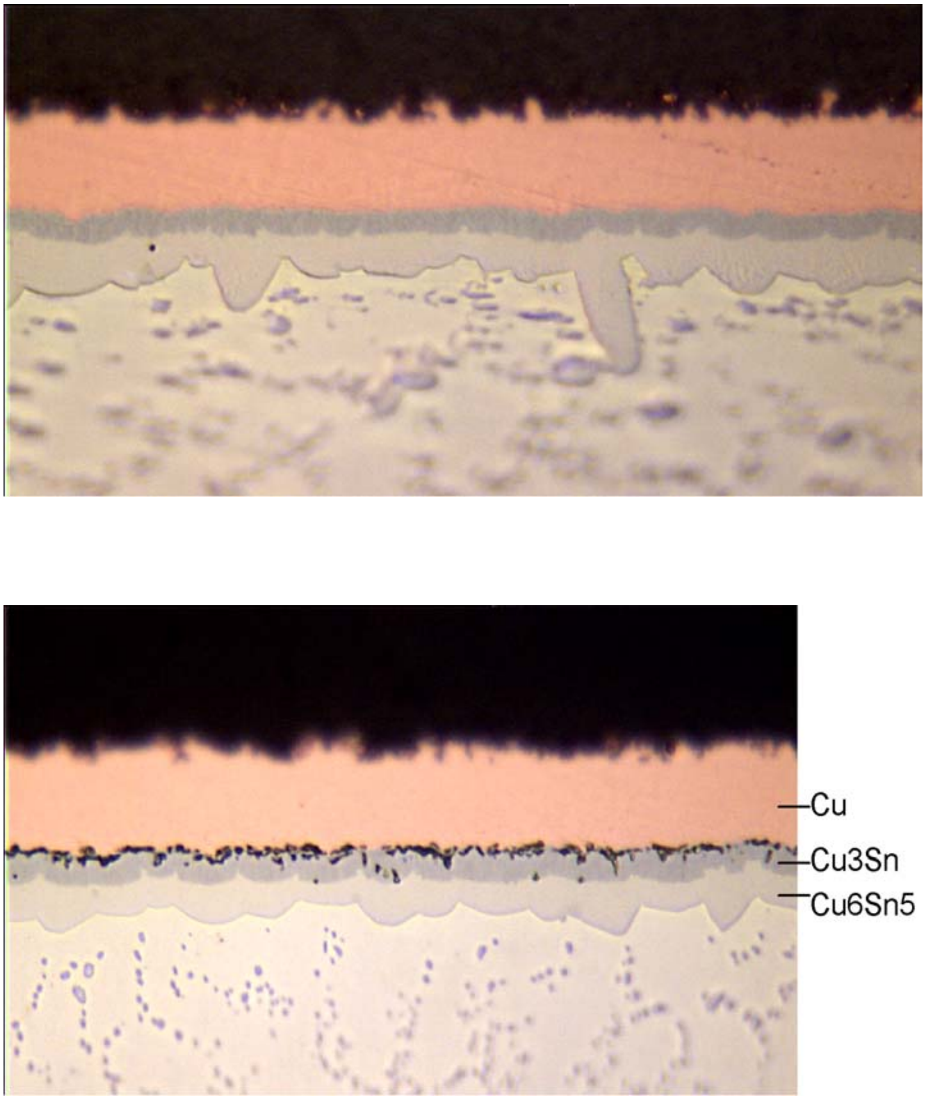

Figure 2: Interfaces between Sn-Ag-Cu solder balls and Cu pads on identically aged samples (1000 hours @ 150°C) from different lots.