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A Period of Adjustment: The Effect of Lead-Free Electronic Assembly on the Semiconductor Industry

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The Inevitable Shift to Lead-free Electronic Assemblies

With the arrival of the twenty-first century, the shift to lead-free electronic assembly appears to be a certainty. Barring unforeseen developments, the production and importation of leaded solder and electronic components will be banned in Europe in 2004. In Japan, the electronics industry is voluntarily removing lead from its products. Each company has set its own goals with some, like Sony, planning to be completely lead-free by 2001, and most planning to become lead-free between 2002 and 2005.

As of now, there has been no discussion of banning imports containing lead from the Japanese market but, given the environmental issues driving the shift, this issue will surface eventually. In the United States the situation is more ambiguous. While it appears unlikely that there will be any legislative efforts to ban lead in the American electronics industry, there are other issues that make it probable that the American electronics industry will follow the European and Japanese lead.

The Situation as of January 2000

In the past year there was some uncertainty in the United States as to whether the European directive would be implemented. It is now certain that the European WEEE (Waste Electrical and Electronic Equipment) will be implemented. This has been recognized by the major American trade associations. Following IPC Works99, an International Summit on lead-free Electronics Assemblies, there can be little doubt that lead-free is not just coming, but is here. Participants at IPC Works99, held in Minneapolis in late October 1999, included major electronics manufacturers and assemblers, most solder paste manufacturers and representatives of the automotive industries electronics subsidiaries. Papers were presented that covered all aspects of the shift to lead-free assemblies, including legal, marketing and technical issues.

The Current Legal Situation

Japan: Japan has a severe problem with solid waste — all available landfill space is projected to be filled by 2007. The Japanese are also very concerned with removing toxins from their environment, and want to remove lead from waste to prevent leaching into ground water. In 1998, the Japanese Electronics Industries Association made the decision to voluntarily eliminate lead from electronic assemblies. The goal of the association is to have half of Japanese electronics production lead-free by 2002 and to be completely lead-free by 2004.

Europe: The final draft of the WEEE (Waste from Electrical and Electronic Equipment) Directive is expected to be completed in January 2000. The document is still changing, but it is certain that electronic assemblies containing lead will be banned from the European Union as of January 2004. The motivation behind this ban is that electronic waste is growing a rate three times greater than other solid wastes, and this huge increase in the amount of electronics waste has raised concerns about lead leaching into water supplies.

United States: Ironically, the initial impulse for lead-free electronics originated in the United States. Following the ban on leaded plumbing solders in the early 1980s, electronic assembly was seen as the next logical from which industry to remove lead. The Reid Act of 1992, an omnibus environmental bill, would have done that, but was defeated. Currently there is no legislation proposing a ban on leaded solder, but there are some legal threats on the horizon. The main one is that the EPA may reduce the regulatory limit on lead as a hazardous material from 10,000 pounds per year to 10 pounds per year, making almost every user of leaded solders subject to EPA regulation, reporting and inspection. There is very little chance that leaded solders will be banned in the United States in the near future, but there are many compelling reasons that will cause the majority of American electronics assemblers to go lead-free.

International: One further issue that is of concern to all electronics manufacturers is that the European ban and the potential for a Japanese ban may touch off trade disputes. To anyone who has followed the disputes over relatively insignificant products like bananas, the prospect of a major trade war involving one of the world's largest and most critical industries is something to be avoided.

Marketing Advantages

Many prognosticators on the adoption of lead-free solders feel that the legal issue is a moot point, and that marketing considerations alone will force a change to lead-free electronics assemblies in the near future.

Japanese electronics manufacturers have taken the lead in "green" marketing. Panasonic's lead-free mini disc player, packaged with a green leaf environmentally safe symbol and released in October 1998, has gained significant increases in market share, moving from 4.7% to 15% of the mini disc market. In the United States, Ford Motor Company has launched what is perhaps the largest "green" marketing campaign to date. Ford has gone on record that its electronic assemblies will be lead free by 2002, and vehicles, aside from batteries, will be lead-free by 2004. Green marketing is viewed as becoming a powerful and effective marketing tool, and many electronics manufacturers are looking to take advantage of it by going lead-free.

Selecting a Common Alloy — the Next Hurdle

Controversy over lead-free solders has shifted from whether they are adequate replacements for traditional Lead/Tin solders to which of the hundreds of possible replacement alloys will be selected as a new standard. This will be critical. Currently, electronic assemblies can be repaired worldwide with standard leaded solder. There are numerous solderability and wetting issues between lead solders and lead-free solders — lead-free solders wet poorly to components with leaded leads, for example.

Further muddying the water are compatibility issues between various lead-free alloys. It is imperative that the global electronics industry settle on a single standard alloy to ensure that assemblies can be repaired expeditiously and reliably. Another downstream issue is recyclability of assemblies — a single standard alloy will make it much more feasible to recover and recycle the base metals in these assemblies.

As of this writing, most paste manufacturers and many electronics manufacturers have developed proprietary alloys. Obviously, it is in the best interests of the holders of these patents to have their alloy selected as the standard, and an enormous amount of research is being done to establish a winner. There are many alternatives that are unpatented, but the most of the promising alloys are.

The alloys that appear most likely to become the industry standard are Sn/Ag/Cu (Tin/Silver/Copper) and Sn/Ag/Bi (Tin/Silver/Bismuth). In the choice between the two lies a trade-off. Sn/Ag/Cu provides solder joints that are more reliable than the current Pb/Sn alloys and has liquidus temperatures around 217°C. The Americans and Europeans favor an Sn/Ag/Cu alloy as the standard because of its greater reliability and lower cost, but acknowledge that the higher process temperatures these alloys require present a challenge for electronics assemblers.

The Bismuth alloys provide solder joints that are inferior to those provided by current leaded solders, mainly due to a phenomenon know as "fillet lifting," and have liquidus temperatures that range from 206 to 213°C. (Bismuth alloys are considered to provide adequate reliability for consumer applications.) Bismuth alloys are preferred by some because they are the closest thing to a "drop in" replacement for leaded solders, are favored by the Japanese and are currently used in the lead-free electronic assemblies that are on the market. The Bismuth alloys are more expensive than Sn/Ag/Cu alloys and there are concerns that the world's current Bismuth resources are inadequate to fulfill the entire market's needs.

Both Bismuth alloys and Sn/Ag/Cu alloys have been extensively tested and will be used in volume production by 2000. An additional factor affecting the choice of a standard alloy is that the Sn/Ag/Cu alloys are favored by the automotive industry, as their higher melting points will give better reliability in under-hood applications. The more robust joints will also be favored for military and aviation applications.

The Effect of Lead-free Electronics Assembly on the Semiconductor Industry

The move to lead-free electronics assembly presents component manufacturers with a three-part challenge: they must remove lead from their products; they must develop leads that are compatible with lead-free solders and, eventually, they will need to develop components with higher temperature tolerances. The first two tasks must be completed in order to successfully assemble products which meet the European standards. This leaves the question as to whether component manufacturers will be able to raise their temperature tolerances in the short term. In the longer term, the question will be whether raising the process temperature limits of components will be economically justifiable or even necessary.

The chief technical problems associated with the adoption of lead-free electronic assembly are:

Component lead solderability issues. There are serious issues with solder joints between leaded leads and lead-free solders. Alternative lead finishes have been developed, mostly palladium-based. The fallout on this issue will be mostly economic, involving the costs associated with developing and implementing new processes, as well as the greater expense of more costly lead finish materials. (There are several papers on alternative lead finishes in the IPC Works99 proceedings.)

Alloy selection: It is critical that a common replacement for Sn63Pb37 leaded solder be agreed on by the worldwide electronics industry. The IPC is aggressively pursuing agreement on a common alloy — this will be discussed at the IPC Winter meeting and also at APEX. The goal is a short list of potential standard alloys by April 2000.

The effect of lead-free assembly on sophisticated modern ICs, such as BGAs, etc. The main issues are the effect of higher reflow temperatures on IC package substrates and the reliability of lead-free solder joint reliability — specifically, shear strength and intermetalic growth. While research is currently being done by the majority of the semiconductor industry's major players, very few of their findings have been made public.

Higher SMT and wave solder process temperatures. Lead-free solders reach liquidus at temperatures 20 to 50°C higher than the lead-based solders currently in use. It is projected that IC packages will have to be redesigned to withstand temperatures of 260°C. The main concerns are the effects that higher process temperatures will have on substrates and the MRT levels of plastic packaging materials.

The Lead-free Soldering Process Window

The primary challenge that lead-free solders present to electronics assemblers and IC manufacturers is higher process temperatures. The currently accepted limit on the peak temperatures that IC packages can withstand in the course of the thermal process is 235-240°C. The lower limit is generally set at 200-205°C, which is the minimum temperature required to reflow leaded solders reliably. These high and low process limits provide a Delta of ~30°C — wide enough that a carefully monitored process can be expected to produce a low defect rate and high yield with little fear of defects caused by process drift.

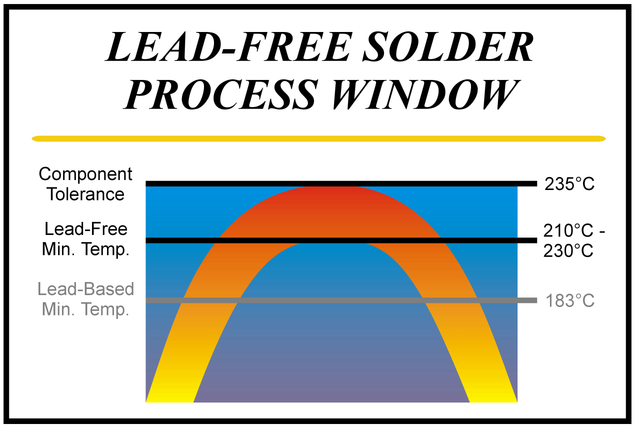


Figure 2: Replacing lead-bearing solders with lead-free formulations shrinks the thermal process window dramatically.

With lead-free assemblies, the process window shrinks dramatically (Fig. 2). With the Bismuth alloys favored by Japanese assemblers (206-213°C liquidus), the window shrinks by 1/3, to a Delta of ~20°C. Using the more reliable Sn/Ag/Cu alloys (217°C liquidus), the window is reduced by 2/3 to a Delta of 10°C. Given that few assemblers want to get within 5°C of their control limits, the true process window with Sn/Ag/Cu alloys is extremely small. One obvious solution to this problem is to widen the process window by raising the temperatures that IC packages can withstand. Another solution, one that has often been overlooked, is to increase and optimize the capability of the soldering process.

Real-time Thermal Management

A potential solution to the decreased thermal process window, and one that many engineers and managers in semiconductor manufacturing may not be aware of, is real-time thermal management. For more than a decade, the key to a reliable and repeatable thermal process has been real-time continuous thermal management, which allows electronics assemblers to obtain and analyze live data on their soldering process by continually monitoring process temperatures in the reflow oven.

Real-time thermal management can detect critical process temperature variations that oven control thermocouples cannot, and reveal these temperature drifts and their location immediately on the user's PC screen. Thirty thermocouples embedded in two slim stainless steel probes are permanently mounted just above or below the conveyor (Fig. 3). The probe thermocouples monitor process temperatures continuously, taking readings as frequently as every five seconds. These temperatures are dsplayed as "Process Profiles" on the furnace controller's PC screen. All data is recorded permanently to the hard drive, giving users the ability to review process data from any previous production date.

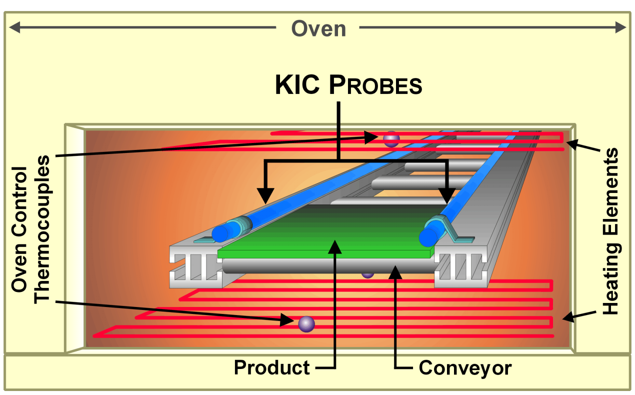
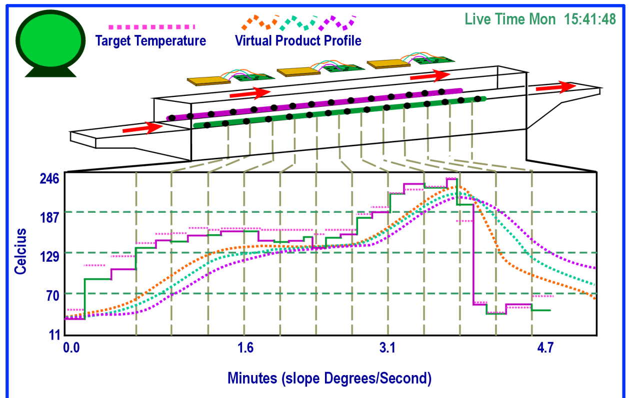


Figure 3. Probe thermocouples mounted at the conveyor level track process temperatures accurately and consistently, for real-time thermal management.

By creating a mathematical correlation between product profile, as measured by a pass-through profiler, and process temperature, as measured by the thermocouple probes, real-time thermal management provides a product profile for every board processed. This "Virtual" product profile is calculated every 30 seconds, and Virtual Profile statistics such as peak temperature are also calculated and updated continuously. The Virtual Profile allows users to monitor their processes accurately, automatically, continuously and in real-time (Fig. 4).



	Peak	Min	Max Rising Slope	Max Falling Slope	Time Between 130/160	Total Time Above 183	Total Time Above 200
VP[01] U3B1	219.2	24.7	2.24	-1.99	134.63	57.36	33.42
VP[03] BOARD	266.4	25.2	2.96	-2.99	141.30	57.21	42.31
VP[05] U2G1	210.5	25.1	1.95	-1.20	118.10	59.70	27.06

Figure 4. Virtual profiling allows thermal parameters to be tracked on-screen in real-time, and saved for future reference and analysis.

Automated Profile Prediction

The first automated profile prediction program was released in 1997. At the time, the technology was capable of formulating more than a hundred potential profile recipes per second, then evaluating and ranking the recipes. This tool was capable of finding optimum oven setups that would yield a profile in the center of the process window, as well as the recipe with the highest possible conveyor speed to maximize throughput. It was the first program that enabled users to know they had found an optimal thermal profile for a given product.

One issue with the original automated program was that it required an expert operator. With a ten-zone oven, there are literally billions of possible combinations of zone setpoints and conveyor speeds. To search all of them would take several days, so the operator was required know enough about thermal profiling to be able to tell the program which range of combinations of zone setpoint and conveyor speed to search in order to get a solution within a reasonable time.

The latest release of the tool offers several significant improvements. It is now capable of searching the entire range of possible recipes automatically, in less than a minute, so operators no longer need to set search parameters. The software package also includes a comprehensive database of solder paste specifications, including data for the new lead-free solder pastes from all major manufacturers. The operator selects the solder paste being used from a drop-down menu, enters any non-solder paste related process limits, runs a profile, starts the automated prediction tool and, within seconds, has an optimal profile that is custom-designed for both the oven and the product. Running a pass-through profile confirms that the oven settings are correct and that the oven is ready for production. Because the improved automated prediction tool has searched the entire range of possible oven setups, users are assured of finding the most productive profile.

The automated prediction tool is designed to center the profile in a process window defined by the solder paste specification and the user-defined input process limits. This is done by ranking potential process profiles with a "Process Window Index" (PWI). The Process Window refers to how well a given profile "fits" the critical process statistics. The index goes several steps beyond telling the user whether the profile is merely in or out of spec. The PWI uses the input process limits to rank profiles numerically, based on how well they fit the user-defined process window (Fig. 5).

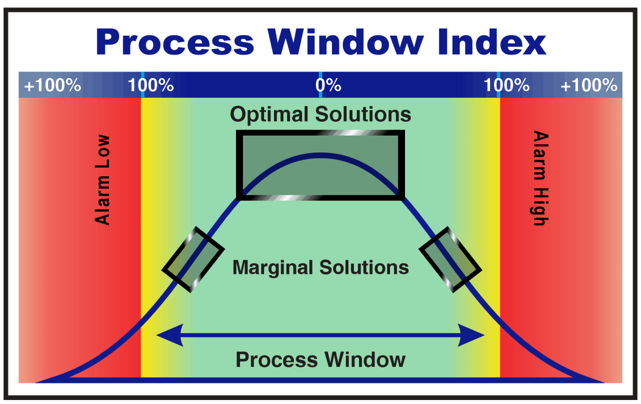


Figure 5. A Process Window Index enables users to optimize the thermal profile for any solder paste and set of processing parameters.

A PWI of 100 or more indicates that the profile will not process product in spec. A PWI of 99 indicates that the profile will process product within spec, but at the very edge of the Process Window. A PWI of less than 99 indicates that the profile is in spec and tells users what percentage of the process window they are using: for example, a PWI of 70 indicates a profile that is using 70% of the process spec. Most users seek a PWI below 80 and, with the improved automated prediction tool, profiles with a PWI between 50 and 60 are commonly achieved (if the oven is sufficiently flexible and efficient).

Temperature-sensitive IC packages provide an example of how the improved automated prediction tool functions. If the IC package can't withstand temperatures above 240°C, but requires peak temperatures above 230°C to reflow the lead-free solder properly, the automated prediction tool will find the optimal profile and center it between the high and low process limits, giving users the most robust profile their oven is capable of achieving.

Conclusions

While the shift to lead-free electronic assembly presents the semiconductor industry with significant challenges, technology exists to meet the most significant challenge. The higher minimum soldering temperatures required by lead-free solder alloys require that temperature-sensitive IC packages need to be soldered much more carefully than in the past, but the use of existing and proven technology demonstrates that the packages can be soldered to the electronic assembly successfully. The use of real-time thermal management and an improved automated prediction tool will allow most existing IC packages to be attached using lead-free solders without requiring modifications to increase their thermal tolerances.

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For further references and up-to-date information, go to www.lead-free.org

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