Lead (Pb)-Free Packaging Strategy 2000–2003

JUNE 2000 (DECEMBER 2001 Update)

JAMES HAYWARD

NOTE ON USAGE

It is a peculiarity of the English language that the words “lead” (as in package lead) and “lead” (as in the metallic element) are homographic; that is, they are spelled the same, although they have different pronunciations. In this document the chemical symbol “Pb” will be used whenever there is a reference to the metallic element. The word “lead” will be restricted to its meaning as in package lead unless a contrary usage is obvious.

Lead (Pb)-Free Packaging Strategy 2000–2003

Executive Summary

The use of lead (Pb) in electronic products is a concern to some environmental groups. Imposition of a ban on this use has been threatened in the past, but such a ban has never been implemented due to serious technical concerns. While it is not clear when, or even if, outright bans on the use of Pb may come into effect, a number of large electronic manufacturers believe that a *de facto* ban may occur in some markets in the near future. Many of these manufacturers are our customers, so we must understand the issues and problems of eliminating Pb from our products, and we must develop plans to address potential customer requirement that we do so.

The use of Pb has been banned from plumbing, paint, and other common applications for many years in the USA and Europe. The most significant new regulatory activity is proposed directives on Waste in Electrical and Electronic Equipment (WEEE) and Reduction of Hazardous Substrates (ROHS) now before the Parliament of the European Union (EU). The draft ROHS directive states that: “Member States shall ensure that the use of Pb, mercury, cadmium, hexavalent chromium, PBBs and PBDEs is substituted by 1 January 2006.” The proposed directive has elicited strong opposition from industry organizations. A few other countries have enacted, or are proposing to enact, legislation regarding disposal of electronic equipment, but none of these proposals explicitly bans the use of any materials. <u>There is at present no legislation anywhere that explicitly bans the use of Pb.</u>

Many electronic manufacturers view the elimination of Pb from their products as an advantage to product marketing. However, under a legislative regulation “Pb-free” would be explicitly defined, for market-driven action “Pb-free” is a much more elastic term. A number of “Pb-free” products have been introduced by, for example, Panasonic, Toshiba, and Nortel. Other companies, including Hitachi, NEC, Matsushita, and Sony, had announced plans for conversion to Pb-free assembly during 2000–2001. Many of our customers in the telecommunications and automotive sectors have programs for development of Pb-free processes and are querying their suppliers regarding availability of Pb-free compatible components.

The issues for components suppliers such as AMD can be summarized as follows:

- There is no exact replacement alloy for eutectic tin/lead (Sn/Pb) solder.
- The most likely replacement alloys have melting or liquidus temperatures that are 30–40°C higher than eutectic Sn/Pb (183°C).
- There is no single best choice of replacement alloy. Industry is slowly converging on a tin/silver/copper (Sn/Ag/Cu) alloy. Usage of this material may be limited by patent restrictions.
- Board assembly reflow temperature profiles will increase to ≅ 260°C to accommodate the replacement alloys.
- A change in package contact metallurgy (*e. g.* BGA solder balls) will not necessarily be compatible with conventional Sn/Pb reflow processes.
- Existing moisture-sensitivity data is invalid with respect to the new reflow profiles.
- Existing board-level reliability data is invalid with respect to new solders alloys and reflow profiles.
- Compatibility of existing package construction and materials to higher temperature reflow is not well understood.
- The effect on device structures of internal package stresses caused by a higher temperature reflow is not well understood.
- Changes in package materials to accommodate a higher temperature reflow will require new package qualifications.

A three-part strategy to address the above issues is proposed. During Part 1 we will evaluate the limits with respect to higher reflow temperatures of existing package materials and construction; we will also evaluate available options for lead finishes and BGA solder balls. During Part 2 we will complete development of new materials where necessary and the processes for new lead finishes and solder ball metallurgy, and demonstrate a capability for qualification of Pb-free packaged devices. Part 3 will comprise production implementation. Completion of Part 3 will be in conjunction forecasts of the actual need for shippable product.

Lead (Pb)-Free Packaging Strategy 2000–2003

Introduction

The electronics industry uses a wide range of materials in manufacturing processes that have been dubbed hazardous. At various times the use of these materials has been the focus of regulatory activity, and the industry has responded by developing safer means of using these materials or by reducing or eliminating their use. The use of Pb in electronic products has been of concern to some environmental groups. The threat of a Pb ban for electronics has arisen before (in the US, most recently in 1991), but the threat dissipated under pressure from the industry. Action currently proposed by regulatory agencies is driven by consumer perception that Pb in any form is a dangerous material.

While it is not clear when, or even if, outright bans on the use of Pb will come into effect, many electronic manufacturers believe that a *de facto* ban will happen in some form within the foreseeable future. Since some of these manufacturers are significant customers for AMD products, we must understand the rationale for, and problems of, eliminating Pb from our products and develop plans to address any possible customer requirement that we do so.

Legislative Incentives for Eliminating Pb in Electronics

The hazards of Pb in the environment and its effect on humans are generally accepted. The use of Pb in plumbing, paint, and other common applications has been banned in developed countries for many years. In the US, such bans were established in 1991 via Congressional legislation, although the Pb accumulated in the environment by that time continues to cause health problems. Virtually all such legislation to date in the US and elsewhere has exempted electronic products from regulation either explicitly by name or implicitly by usage levels. <u>There is, at present, no legislation anywhere in the world that directly regulates the use of Pb in electronic products</u>. The lack of regulation on Pb content can probably be attributed to the low usage level in electronics (<1 percent). However, the regulatory environment has been changing in recent years.

<u>European Regulation</u>

The spotlight of international environmental, health, and safety initiatives has focused sharply on electronics since 1998. Of major concern for AMD and our customers are initiatives incorporating chemical bans or restrictions and product "take-back" requirements. The most significant such international action is the directives on Waste in Electrical and Electronic Equipment (WEEE) and Reduction of Hazardous Substances (ROHS) proposed within the European Union (EU). Introduced in May 1998 by Directorate General XI, the Environmental Directorate of the EU Commission, the fourth draft of the WEEE proposal was distributed in May 2000. At the time of introduction to the European Parliament in October 2000, the original draft document was split into the current WEEE and ROHS draft directives. (WEEE includes the recycling and take-back provisions and ROHS includes the material bans.) Among its other provisions, the ROHS draft proposal states that: "Member States shall ensure that the use of Pb, mercury, cadmium, hexavalent chromium, PBBs and PBDEs is substituted by 1 January 2006." Product categories such as household appliances, networking and communications equipment, control instruments, electronic tools and toys, and medical equipment are covered by the proposal; integrated circuits and other components are included in the definition of electronic equipment. Automotive electronics are exempted from the directive implicitly by omission of this category from the listing of types of equipment covered by the regulations. Numerous other specific exemptions are included in one of the annexes to the document.

The WEEE and ROHS proposals follow from proposals originating in several of the EU member countries. Principal among these was a sweeping proposal introduced in Denmark. The Danish proposal was severely criticized on technical grounds by the Scientific Committee on Toxicity, Ecotoxicity and the Environment (CSTEE) in a report dated 5 May 2000. Many of these technical criticisms probably apply to the WEEE and ROHS proposal as well. The draft WEEE and ROHS directives have also elicited strong opposition from industry organizations such as the American Electronics Association (AEA) and Electronics Industry Alliance (EIA) in the US, and the Printed Circuit Interconnect Foundation (PCIF) and ORGALIME in Europe. Publication of a final regulation in the year 2002 is likely although the final form is difficult to determine at this time. The draft proposals were presented to the European Parliament in October 2000. The first reading and vote on the proposals occurred in May 2001.

Parliament members added numerous amendments to the documents that are now being resolved in the Environmental Committee. The year for enactment of the provisions (either 2006 or 2007 at this time) is a major point of discussion. A second reading and vote will likely occur in the 2001-2002 Parliamentary session. Approval of the directive proposals by the European Parliament will then require the member states of the EU to establish national regulations that implement the provisions of the directive in each country.

Of the substances to be banned by the ROHS directive, Pb is by far the most significant to AMD. Pb is present in our products in the solder balls on Ball Grid Array (BGA) and Fine-Pitch Ball Grid Array (FBGA) packages, the external plating on leadframe packages, and the C4 bumps used for flip-chip assembly. The ROHS draft in its present form will ban such uses, as well as the use of Pb-based solders for board-level assembly of components by our customers. The proposal includes exemptions to the ban such as:

- Pb as an alloying element in steel ($\leq$0.3%), aluminum ($\leq$0.4%) or copper ($\leq$4%);
- Pb in electronic ceramic parts (e.g., covers the use of Pb oxide in passive chip components);
- Pb in the glass of cathode ray tubes, light bulbs, and fluorescent tubes;
- Pb as radiation protection.

The document allows for additional exemptions in the future if the European Commission judges the use of a material “unavoidable”. While the draft does not now include any specification of allowable threshold concentrations, it does require that “as necessary” the Commission may establish maximum concentration levels for specific components and materials in the future. The initial allowable levels are left to the member states to determine and identify in their implementation legislation. The procedures for setting the allowable limits and for defining future exemptions are not defined.

The WEEE Directive proposal also includes take-back provisions that would affect AMD customers. Manufacturers and importers must set up systems to collect and treat waste electronic equipment from holders other than private households, and absorb the costs of collection, treatment, and disposal for private households. Distributors supplying new products must offer to take back similar equipment. Manufacturers may require that such costs as are incurred from these take-back provisions be reflected in the prices that they are willing to pay for components.

The WEEE and ROHS Directives are significant because they would affect a market that consists now of 15 member states, 4 associated states, and an unknown number of future EU members. The provisions of the directive will govern not only products produced in the EU, but also those sold in the EU regardless of origin. Since the Directives are not yet approved and in force, a major question for AMD is whether the proposed ban on Pb will remain as written in the final legislation. However, some EU legislation will eventually incorporate Pb bans or restrictions, or require an end-of-life solution (*i.e.,* removal of Pb at product end of life). The result of the legislation, in whatever form it finally appears, will be increased pressure to remove Pb entirely from production processes.

Additional bans have been proposed at various national levels. In 1998 Denmark proposed a ban on the import, sale, and production of most products containing greater than 50 ppm Pb; Pb used in electronic equipment was exempted until “further notice.” In 1998 and 1999 Sweden and Norway also identified Pb as a material they will target for further restrictions in the future. The WEEE/ROHS directives would supersede these national bans if they come into effect.

<u>Other Countries</u>

Most European countries, Japan, and Taiwan have enacted electronic take-back regulations that require manufacturer recycling or recovery of materials at product end of life. In 1998, the government of Japan published a Bill on Recycling of Specific Household Appliances, covering such “major” appliances as refrigerators, washing machines, and televisions. Extension of this regulation to include all electronic appliances has been proposed. While this type of “take-back” regulation does not explicitly ban the use of Pb, it does mandate the recovery of Pb contained in the specified home electronics, and is an indirect incentive to Japanese manufacturers to avoid the use of Pb entirely. A legislative ban on the use of Pb in Japan has been discussed, but it is not clear in what form or when this might occur.

US initiatives affecting manufacturers of electronics have to date focused on community reporting, recycling, waste restrictions, and product labeling. In August 1999, the U.S. Environmental Protection Agency (EPA), under the Emergency Planning and Community Right to Know Act, proposed stricter community reporting requirements for all industries that use Pb compounds. EPA has labeled Pb a persistent, bioaccumulative and toxic (PBT) chemical posing a high risk of danger to human health. While present usage reporting thresholds are 25,000 and 10,000 pounds, the proposed change would require reporting of releases and off-site transfer of greater than 10 pounds of Pb compounds.

Rationale for Pb Bans

The basis for the above legislative activity is to curtail the disposal of hazardous materials in landfills. This is a particular problem in Europe and Japan, since the availability of areas for landfill is extremely limited. The argument in the case of Pb is that elemental or compounded Pb can be leached by percolation into lower level ground water sources, and then be consumed by humans from drinking water or by uptake by edible plants. Although there has been considerable study of the mechanisms for the leaching of Pb, the science is far from definitive on the subject. Leaching processes have been identified, but there is uncertainty if these processes occur naturally. Regulatory agencies generally wish to err on the side of conservatism where even a remote possibility of hazard is involved.

Market Incentives for Eliminating Pb in Electronics

Aside from the pressure of legislative activity, many electronic manufacturers are viewing the elimination of Pb from their products as an advantage to product marketing. With concern for environmental damage due to industrial activity continuing to rise in the general world population, labeling of products as being more “green” is on the rise as well. However, under a legislative regulation “Pb-free” would be explicitly defined, whereas for market-driven action “Pb-free” is a much more elastic term. Although a degree of mythology has arisen around the issue in regard to activity such as that in Japan, market forces may have more long-term impact than any legislative action.

Japan

In fact, some Japanese electronic companies are now marketing Pb-free products or have announced plans to do so. These product and plan announcements have generally been presented in the trade press in oversimplified form, but it is clear that these companies are at least making a commitment to the appearance of being truly Pb-free.

The most frequently cited example of an actual product is a mini-disk player produced by Panasonic. Although the product is not completely Pb-free, it was assembled using a Sn/Ag/Bi solder alloy, and many of the components had Pb-free lead finishes (no BGAs were used). This product has reportedly allowed Panasonic to gain some market share for this product line, although hard data confirming this claim is not readily available. Other Pb-free products reportably available in Japan include a Panasonic television, a Toshiba laptop computer, and other consumer products.

A number of Japanese companies, including Hitachi, NEC, Toshiba, Matsushita, and Sony, had announced plans for conversion to Pb-free assembly during 2000–2001. Although few of these plans have been accomplished as originally announced, the fact of their publication indicates the intent of the issuing companies. The method announced by Sony for this conversion is instructive in that Sony is taking account of the fact that it will be very difficult to convert to Pb-free all at once. Sony has developed their own Sn/Ag/Bi/Cu/germanium alloy that they intend to use initially in one model in each of their sales categories. However, they will be satisfied if one component type in each of those models is completley Pb-free. In 2000, they will use the Pb-free solder for a minimum of one component type in all domestic products (i.e., those sold in Japan). In 2001, they will use the Pb-free solder for a minimum of one component type in all products sold worldwide. In briefings given to their suppliers, Sony recognized that the major obstacle to moving beyond these immediate goals would be the ability of components from all their suppliers to withstand the higher processing temperatures needed for their chosen solder process.

At least one Japanese semiconductor manufacturer, Matsushita Electronics Corp, announced a program to supply Pb-free integrated circuits (ICs). The announced program was originally restricted to leaded packages, and palladium and Sn/Bi alloy plating are specified as lead finishes. All “new packages to be produced from April 1999” will conform to Pb-free specifications. Other products will be converted as needed with “approval,” but conversion will be completed by the end of fiscal 2000 (i.e., calendar 2001). However, resistance to higher reflow temperatures will be treated “separately with each package.” The date for complete conversion has since been adjusted to fiscal 2002.

Europe

There have been few actual product announcements outside of Japan. But one such product was the Nortel Meridian desk telephone. This phone was assembled using a Sn/Cu solder paste screened on an organic solder preservative (OSP)-Cu printed circuit board (PCB). The lead finish on the components was either tin or palladium. This product was not intended to be a high-reliability telephone, but it apparently functioned well in the home/office environment for which it was designed.

In private communications most of AMD's major customers in Europe (Siemens, Nortel, Ericsson, *etal*.) have indicated that they have internal programs for the development of Pb-free solder processes. The extent and status of these programs is not completely clear, but these companies are clearly driven by both the WEEE/ROHS directive proposals (that they expect to gain final approval at some point) and the threat of Pb-free products imported from Japan. There have been few, if any, public announcements regarding plans from European companies, although general knowledge of their intentions is widely assumed. Product introductions in 2002 are very likely. Requirements are beginning to be defined in general component specifications. A notable development is the acceptance by one major European OEM of "Pb-free process compatible" components that are not themselves Pb-free; that is, components that can withstand the elevated process temperatures of Pb-free assembly processes.

United States

Pb-free development in the US has been sponsored primarily by automotive electronics suppliers such as Ford Visteon and Delphi-Delco Electronics. The interest from the automotive electronics sector, in both the US and Europe *(e.g.,* Siemens and Bosch), is driven to a large extent by a desire to raise the operating temperature of their products. Since a weak link in the reliability chain for higher temperature operation is the eutectic Sn/Pb solder joint, converting to a higher temperature solder material is desirable. That such materials are basically Pb-free and, hence, environmentally friendly is a side benefit. But validation of reliability and transfer of designs into production in the automotive business is a time consuming process, and it is not likely that changes will come rapidly. However, the automotive electronic suppliers will likely spur development activities by their suppliers in order to be ready to make the conversion to Pb-free assembly when they need it.

Other US manufacturers, such as Motorola and Lucent, have made public expressions of support for environmentally friendly manufacturing. And Lucent has used Pb-free solder processes in a few submodules, such as power convertors.

Industry-Wide Activity

In addition to individual development activity, many suppliers and OEMs are working with various trade organizations in all three geographic areas (US, Europe, and Japan) on Pb-free roadmaps and processes. In the US, the IPC and National Electronic Manufactures Initiative (NEMI) have attempted to take a leadership role by organizing conferences and initiating consortial development projects. NEMI is including implementation of Pb-free assembly for US manufacturers in its biannual technology roadmap. The High Density Packaging Users Group (HDPUG) has initiated a consortial project with European and US manufacturers. NEMI and HDPUG are coordinating their respective projects to avoid unnecessary duplication of effort. In Europe, the International Tin Research Institute (ITRI), based in England, has set up a Pb-free soldering research consortium under the name SOLDERTEC that has 45 member companies and wishes to be the premier such consortium in Europe. The European national governments and the EU itself have funded other research activities. The Japan Electric Industry Development Association (JEIDA) and the Japan Institute for Interconnecting and Packaging Electronic Circuits (JIEP) have been developing roadmaps for Pb-free manufacturing by Japanese companies. The New Energy and Industrial Technology Development Organization (NEDO) was established in 1998 to coordinate the activities of JEIDA, the Japan Welding Society (JWS), and the Electronic Industries Association of Japan (EIAJ); NEDO had a budget of ¥350 million for two years of operation. In 2001 JEIDA and EIAJ merged their respective organizations into the Japan Electric Industry Technology Association (JEITA) in order to enhance their presence as a representative of Japanese industry.

Alternatives to Pb in Solders

In all the discussions about elimination of Pb in electronic products, the principal question is what will be the replacement. The usage of Sn/Pb solders dates back some 6000 years. Sn/Pb solders have been the primary interconnection material in the electronics industry for the last 100 years. One of the great successes of the industry has been that for joining technology the same material is used in very similar ways for almost all applications. The large body of knowledge that has been developed regarding the properties and behavior of Sn/Pb solders would become irrelevant if the alloy were significantly changed.

Manufacturers that have begun programs to develop Pb-free assembly processes have until recently worked independently, and as a result a variety of alternative solder alloys have been developed. Many of these alloys are the subjects of issued patents or pending applications. While sorting out the claims of intellectual property is not an insurmountable obstacle to the adoption of an alloy, it will be an additional factor in the selection process.

Pb Alternatives

The number of elements that can be substituted for Pb in solders is limited. A number of metals with desirable properties are either in limited supply (germanium, Ge) or of equal or greater toxicity than Pb itself (antimony and cadmium). The short list of metals includes the following:

- Tin (Sn): readily available, very low toxicity, easily workable, 232°C melting point;
- Silver (Ag): limited availability, expensive, low human toxicity but potentially harmful to aquatic animals and plants, oxide is conductive, easily workable, 962°C melting point;
- Copper (Cu): very abundant, inexpensive, very low toxicity, easily workable, 1084°C melting point;
- Bismuth (Bi): readily available, a byproduct of Pb smelting, low toxicity, low ductility and difficult to work, 272°C melting point;
- Zinc (Zn): readily available, inexpensive, low toxicity, easily oxidized, 420°C melting point;
- Indium (In): limited availability, low or unknown toxicity, very ductile, 157°C melting point.

It is generally assumed that tin will form the basis metal for any solder replacement alloy since the other possibilities (bismuth and indium) are not sufficiently plentiful. Tin forms eutectic alloys with all of the above metals with melting points in the range of 118°C (Sn/In) to 227°C (Sn/Cu). With additions of third, fourth, or fifth metal components to the alloys, a very wide selection of alloys with melting or liquidus points within the 118–227°C range (whether or not of eutectic composition) is possible.

Table 1: NCMS SOLDER SELECTION CRITERIA

Property	***Definition***	***Limits***
Liquidus Temperature	Temperature at which solder alloy is completely molten.	< 225 °C
Pasty Range	Temperature difference between solidus and liquidus temperatures. Represents the temperature range where the alloy is part solid and part liquid.	< 30 °C
Wettability	A wetting balance test assesses the force resulting when a copper wire is wetted by molten solder. A large force indicates a good wetting, as does a short time to attain a wetting force of zero, and a short time to attain the two-thirds of the maximum wetting force.	Fmax > 300 µN t0 < 0.6 s t2/3 < 1 s
Area of Coverage	Assesses the coverage of the solder on Cu after a typical DIP test.	> 85%
Drossing	Assesses the amount of oxide formed in air on the surface of molten solder after a fixed time at soldering temperature.	Qualitative scale
Thermomechanical Fatigue (TMF-1)	Cycles-to-failure for a given percent failed based on a specific solder joint/board configuration, as compared to the eutectic Sn/Pb.	> 75%
Coeff. of Thermal Expansion (CTE)	Differences in thermal expansion behavior between alloys might create differences in thermal stresses.	< 29 ppm/°C
Creep	Stress required at room temperature to cause failure in 10,000 minutes.	> 500 psi
Elongation	Total percent elongation of material under uniaxial tension at room temperature.	> 10%

Comparative Studies

The National Center for Manufacturing Sciences (NCMS) in the US and the Brite-IDEALS project in Europe independently undertook extensive evaluations of solder alloys based on the above metals, with and without additional alloying metals. The most extensive compilation of data on solder materials is that published by the NCMS in 1998. This consortium of 11 US manufacturers and research organizations evaluated 79 solder alloys based on toxicology, economics, and material properties. This evaluation resulted in a short list of alloys that were subsequently evaluated for manufacturability and reliability.

Table 1 shows the primary characteristics that NCMS used to select candidate alloys. The consortium was primarily looking for alloys that became liquid below 225°C and have small pasty ranges. (Eutectic alloys have a distinct melting temperature at which the alloy goes directly from the solid to the liquid state. Non-eutectic alloys have a temperature at which some phase begins to melt and another at which all phases have melted; the two temperatures are the solidus and liquidus temperatures respectively. The range between the solidus and liquidus temperature is the “pasty” range in which the material is a mixture of solid and liquid phases.) Since the list of candidate materials does include non-eutectic as well as eutectic alloys, the size of the pasty range is of concern. A smaller pasty range allows for easier control of the solder processing temperature. The alloys in the final NCMS list, as well as Sn/37Pb, are shown in the Table 2. Although none of the materials on the list can truly be said to be drop-in replacements for the eutectic Sn/Pb alloy (Sn/37Pb), the materials on the short list do have many characteristics that may be in fact better than the standard alloy. One particular eutectic alloy that had interested several companies (Sn/0.7Cu) is probably not practical due to the melting point of 227°C. The listed Sn/Ag/In alloy is also probably not a viable candidate due to the limited availability and cost of indium. Nevertheless, the alloys on this list are generally similar to those under evaluation by various companies.

Selected Pb-Free Alloys

Composition	**Melting/Liquidus Temperature (°C)**	**Alloy Type**	**Companies Evaluating or Using**
Sn-37Pb	183	Eutectic (Standard)	
Sn-3.5Ag	221	Eutectic	Siemens
Sn-0.7Cu	227	Eutectic	Nortel
Sn-58Bi	139	Eutectic	Matsushita
Sn-3Ag-0.5Cu	217	Non-eutectic	Siemens,Nortel
Sn-3Ag-2Bi	220	Non-eutectic	Fujitsu
Sn-2.6Ag-0.8Cu-0.5Sb	211	Non-eutectic	Sony (+ Ge)
Sn-3.4Ag-4.8Bi	210	Non-eutectic	Matsushita
Sn-2.8Ag-20In	187	Non-eutectic	
Sn-3.5Ag-0.5Cu-1Zn	221	Non-eutectic	NEC

In board-level reliability tests using surface-mount and chip components, several of the listed alloys appeared to perform better than the control Sn/Pb eutectic due apparently to higher mechanical strength and/or ductility. The final recommendation of NCMS was that three of the listed alloys warranted further study. Under the NCMS criteria the Sn/Bi eutectic would be acceptable for consumer electronics, and both the Sn/Ag/Bi and Sn/Ag/Cu would be suitable for telecommunications, automotive, and aerospace applications.

Individual Studies

In addition to the NCMS list, other alloys are being investigated or implemented by various companies in Japan and Europe. Showa Denko claims to have solved the problem of using zinc-containing alloys and is producing materials with eutectic (Sn/9Zn, 199°C melting point) and non-eutectic (Sn/8Zn/3Bi, 197°C liquidus) compositions; NEC is reported to have adopted the Showa Denko process. Sony developed a Sn/Ag/Cu/Bi/Ge alloy with a 220°C liquidus. Other Japanese companies are working on variations of Sn/Bi or Sn/Ag/Bi compositions. Nortel has worked primarily with the Sn/Cu eutectic, but is evaluating variations of the Sn/Ag/Cu class. Additionally, researchers at Iowa State University developed and patented a series of alloys based on Sn/Ag/Cu, and Flip-Chip Technologies (FCT) developed and patented a Sn/Ag/In/Cu alloy (Sn/3.1Ag/10In/1Cu, 200°C liquidus) for direct chip attach (DCA) applications. In Europe and the US, where the production of high-reliability equipment for telecommunications and networking constitutes a high percentage of electronic manufacturing, there is a trend toward the use of the Sn/Ag/Cu alloy possibly with additional alloying metals.

Evaluation Issues

Evaluation of many of these new solder alloys is difficult because reliable information about the mechanical properties and phase constituents of these materials is lacking. Mechanical properties of many of these materials remain to be determined. Construction of phase diagrams for materials with the addition of third or fourth constituents is practically impossible and can only be done via thermodynamic modeling methods; construction of phase diagrams for binary alloys has proven difficult enough. Sn/Bi-based alloys exhibit a specific example of the subtleties of phase structures. When these alloys are used with components that still have Pb-bearing contacts a Sn/Pb/Bi eutectic phase (96°C melting point) can be formed. This phase would melt at any temperature above 96°C causing a solder joint to become pasty and the mechanical strength of such solder joints could be severely degraded. At least one automotive manufacturer has stated that they will not use any solder containing bismuth due to this phenomenon,

Most discussions about solder replacement have focused on the external contacts on packages and the means for connecting packages to boards. However, Pb-bearing solders are essential materials for flip-chip assembly processes used for connecting die in packages. The well-known IBM C4 process, of course, uses not only a Pb-based solder but also a solder that contains mostly Pb. No acceptable alternatives to the Pb/3Sn eutectic (318°C melting point) and related alloys used in this process have been identified. A good argument has been made that C4 contributes only a very small portion of the Pb contained in present-day electronic equipment and C4 applications have been granted exemption in the current version of ROHS. Flip-chip processes that use solders with lower Pb content (non-C4 assembly processes) would probably not be exempted from regulation. But even if flip-chip-in-package applications are exempted from regulation, the solder used for the flip-chip connection would have to be compatible with the elevated temperatures required by the board-level assembly process. There will be a problem if the melting temperatures of the flip-chip solder, or the liquidus temperatures, are below the board assembly temperature. For either of these cases, the flip-chip solder joint may melt or become soft during board assembly, and the reliability of that joint may be reduced.

Packaging Issues Resulting from the Elimination of Pb in Solders

The issues for packaging that derive from a change to Pb-free solder assembly can be broken into several groups:

- Metallurgical: selection of a compatible lead finish or solder ball alloy;
- Temperature sensitivity: compatibility of existing package materials and construction with elevated board assembly process temperatures;
- Reliability: evaluation of the solder joint reliability of the new solder/lead finish system;
- Cost: evaluation of the cost of converting manufacturing processes;
- Schedule: managing the conversion to Pb-free processes.

The metallurgical issue of compatibility with the chosen material for board assembly is both an easy and a difficult one for the component supplier. The easy part is that to a large degree customers will dictate the choice of materials. The difficult part is that different customers may choose, for very logical reasons in each case, different solder systems that they wish to use in their manufacturing. Selecting an alternate to Sn/37Pb solder is an engineering problem for the OEM that does not have a unique solution. The component supplier may have the difficult task of supporting multiple lead finishes or developing a package solution that is compatible with a variety of solder systems. The choice is driven by external events that the component supplier may have little control or influence over. Although industry organizations throughout the world are attempting to foster agreement to a single or limited number of replacement alloys for board assembly, this effort is not yet complete.

For leaded packages the list of possible lead finishes is short. Plated tin (electrolytic or electroless), plated silver, nickel/palladium (several variants), and nickel/gold have been suggested. Evaluation of these and other less likely finishes have begun, but no clearly superior finish has been demonstrated. All have specific drawbacks: nickel/gold and nickel/palladium may be too costly; tin has the problem of whisker growth; silver has the problem of electromigration; etc. Any of these problems can be overcome, but successfully demonstrating the accomplishment may require a substantial effort.

Lead Finish Issues

During the transition to use of non-Pb solders for board assembly, leaded packages with Sn/Pb finishes may continue to be utilized. The solder finish on the package lead is thin, and it is only intended to ensure wettability of the lead during assembly. The majority of the solder in the joint comes from solder paste screened on the board or from solder plated on the board. So, the integrity of the solder joint is influenced only to a small extent by the lead finish. However, with BGA-type packages the solder ball contributes most of the material in the joint. If a non-Pb solder paste with a higher melting temperature is used on the board, then the Sn/Pb solder ball on the package may melt during assembly before the solder paste melts. The lower melting Sn/Pb solder will alloy with the tin-rich solder paste forming a non-eutectic alloy of indeterminate composition that will likely freeze before the solder paste would have melted. In effect, a “cold” solder joint will be formed that may have low fatigue resistance. Thus, the Pb-bearing solder balls on BGA packages will have to be replaced in most Pb-free applications.

For BGA-type packages not only the solder ball material but also the solder attach pad material on the package substrate are of interest. Raw solder balls used in BGA package assembly can be manufactured of any desired alloy. However, if the solder ball material is changed, then the interfacial characteristics at the substrate are likely to change as well. Without a clear understanding of the metallurgy involved, predicting the results of a different interface condition is difficult. Research organizations must be encouragement by industrial partners to obtain the necessary metallurgical knowledge. Otherwise, the strength of the solder ball to substrate joint can only be evaluated on an empirical basis.

Similar considerations apply also to packages assembled with flip-chip processes. Although C4 assembly is likely to be exempted from regulation, non-C4 processes (those using low Pb content solders) will be included in the regulation. The solder used for the flip-chip joint needs to be compatible with the elevated process temperatures of the new board assembly solders. Melting or significant softening of the flip-chip joint during board assembly is very undesirable and may degrade the reliability of that joint. Thus, solders with melting points or solidus temperatures below 260°C should not be used. Packages that are attached to boards only with sockets are not be effected by board assembly processes, but may still need to avoid the use of Pb solders to ensure that the final product falls within the scope of regulation. Any change in the flip-chip solder alloy may require a change in the barrier layer metallization or the solder bump structure as well. The same issues apply to passive chip components used in packages or assemblies; contact metallization and stability after high temperature reflows have to be evaluated.

Assembly Issues

A potentially more difficult problem for the component supplier comes from an increase in the board assembly processing temperature that comes with a change to Pb-free solders. Most replacement solder alloys have melting or liquidus temperatures that are higher than Sn/37Pb by as much as 20°C. There are several factors that determine the processing temperatures for Sn/Pb assembly, and they also determine the processing temperature for any other solder. Current board assembly process temperatures are from 40°C to 50°C above the melting point of 183°C for the eutectic Sn/Pb. This temperature difference is necessary to ensure that all components going through a reflow furnace reach temperatures where the solder liquefies and wets the component leads. The process temperature must account for variations in board size in a given manufacturing line, and for varying thermal masses of components on the board, in order to satisfy throughput requirements. The process temperature must also compensate for the fact that often the composition of material at the solder joint is not exactly at the eutectic composition. Material contributed by the board finish, solder paste, and lead finish may all deviate by ±5 percent from the eutectic composition, and such deviation increases the melting (now liquidus) temperature. In an actual assembly the liquidus temperature may be as much as 10°C above the stated melting point of 183°C because of the variation (intentional or not) in solder composition. For non-Pb materials the same situation will exist; manufacturing variation will result in compositions that deviate from the specified composition, and the actual liquefaction temperatures will deviate as well. For all these reasons, processing temperatures up to 260°C can be expected for alloys with melting points up to 220°C. And in order to maintain assembly throughput without adding significantly to the size of reflow furnaces, heat-up and cool-down rates may be higher than those used at present. It must be noted that for BGA packages, the above considerations apply to the ball attachment process as well.

Temperature Effects

Higher assembly process temperatures affect packages in several ways. If the package contains absorbed moisture, then the elevated temperature of the reflow process and the ramp to that temperature can cause the moisture to desorb from the package rapidly with a high risk of crack formation or fracture. This is the classic “popcorn” effect. Current test methods to determine the susceptibility of packages to this problem specify peak reflow temperatures of 225°C (or 240°C for thin packages). The tests are empirically derived, and there is no method to extrapolate the results to higher temperatures. Thus, the susceptibility of packages to moisture-driven damage at higher processing temperatures cannot be predicted.

In addition to the moisture-driven effects, higher temperatures can also degrade the package integrity by directly effecting the adhesion at interfaces, and by stressing the structure as the temperature goes ever farther above the glass transistion temperature (Tg) of the materials. Some of these effects can be modeled by use of finite element analysis (FEA), but a thorough understanding of the material properties and the interfaces is necessary both to construct adequate models and to interpret them. In the case where package functionally survives the non-Pb assembly process (that is, the electrical performance of the device does not degrade as a result of the assembly process), a reduction in the useful life of the component due to incipient defects initiated by the assembly process would remain a concern. Reduction in adhesion may result in an earlier onset of catastrophic delamination; development of harmful intermetallics at wirebond interfaces may be initiated; and harmful residual stresses may be induced that lead to early thermo-mechanical failure. Mold compounds, die attach adhesives, underfill adhesives, and substrate materials may all exhibit significant temperature-driven degradation; whether such degradation occurs is very difficult to demonstrate except by extensive testing. Clearly, if it is necessary to develop or adopt new materials to prevent such degradation, then the time required to implement a conversion to Pb-free manufacturing may be dramatically increased.

Reliability Effects

Changing the material used for the solder joint also changes the thermo-mechanical behavior of the joint. The mechanical properties of the solder alloy contribute significantly to the strength of the joint. Many of the non-Pb materials seem to be stronger or more ductile than Sn/37Pb, and the microstructure of these materials also appears to be immune to the grain-coarsening process that Sn/37Pb exhibits. Increased strength and ductility should result in stronger, more fatigue-resistant solder joints, and the absence of grain coarsening should result in solder joints with greater stability. But the increase in solder joint strength may also result in higher levels of strain at the interfaces between the solder joint and the package lead or substrate attachment pad. Thus, the quality of this interface becomes more critical to board-level reliability. The level of residual stress generated at the temperature at which the solder joint solidifies also affects the reliability of the solder joint. The full range of mechanical properties with respect to temperature for most of the alternate solders has not been well characterized; adequately modeling the solder joints using FEA techniques is not possible without this material characterization. Therefore, the solder joint reliability must be determined experimentally.

Implementation Costs

The cost of converting to Pb-free manufacturing comes from the implementation of new processes, development of new materials, and qualification of the resulting products. The implementation of the new processes has an expense associated with both the new process itself (equipment, materials, facilities, etc.) and running the new process in parallel with older processes during any transition period. The duration of the transition period is difficult to determine until clear plans for conversion on the part of customers are defined. However, it is safe to assume that the conversion of customers will not be well synchronized. The component supplier will have to maintain the parallel process lines for an indefinite period, or demonstrate that the new lead finishes are sufficiently compatible with conventional Sn/37Pb solder processes. And, in the absence of explicit regulation, some OEMs may never convert to Pb-free assembly for part or all of their product lines. In that case, separate component process lines will be permanent installations. Such parallel process lines increase the cost both of conversion and of continued component production.

The cost of qualifying products is potentially much more than establishing the necessary new processes. As a minimum, families of packages will need to be requalified for moisture sensitivity under a revised version of the standard test method for preconditioning. (A proposal for modifying the existing JEDEC preconditioning standard is about to be submitted to the JC-14 committee.) If new materials or assembly processes are needed to make the packaged component more resistant to temperature, then complete product qualification will also be needed. For component suppliers with extensive catalogs, the cost and time required to do such qualifications may exceed any other cost incurred.

Implementation Plan

In responding to requirements for components compatible with Pb-free assembly, two extreme positions are possible. The first is to do nothing, wait to see what happens, and address the problem at the time customers demand Pb-free components. The second is to rush into a program to change lead finishes and put Pb-free components on the market as quickly as possible. Either approach is a defensible option that comes with associated problems. The danger in the first approach is that the company would not be able to respond in time to customer requirements and would potentially lose business. The danger in the second approach is that the company would ignore the reliability and manufacturing issues outlined above, commit excessive resources to the program, and convert our manufacturing processes ahead of the time that business would naturally support. The newly installed manufacturing capacity may stand idle for an indefinite time.

AMD must find a reasonable middleground between these extremes that allows us to fully understand the problems and the solutions, and to map whatever manufacturing conversion is needed against the business plan. It is ultimately to our advantage that the development process be undertaken methodically and efficiently, and that any conversion process be an orderly addition to current manufacturing capabilities. Additionally, our development and/or conversion must be coordinated with our family of subcontractors. All of this implies that we begin our development process as early as possible.

Because of the package-related issues described earlier, AMD cannot make a commitment to produce Pb-free components without having completed certain initial evaluation projects. The evaluation projects require cooperation between Sunnyvale and the offshore sites in Singapore, Penang, Bangkok and Suzhou. The strategic program should consist of three phases of which the first will be an evaluation of existing packages and potential replacement materials.

1A Evaluate the sensitivity of current package materials and assembly methods to the elevated temperatures necessary for the new reflow profiles. This program would begin by selecting a representative group of production packages, including leaded and BGA types, and subjecting these packages to our standard qualification tests with the higher temperature reflow profiles used for the pre-conditioning steps. The packages would be examined in detail during the tests in order to determine the onset of additional defects beyond those expected from the standard qualification procedures. (Our standard qualification procedure would be the control for this evaluation.) The results of the evaluation will determine the extent of our jeopardy with regard to higher processing temperatures, and be the basis for subsequent evaluation of new materials and assembly methods. This evaluation should also be the basis for evaluation of board-level reliability for new lead finishes and solder alloys.

1B Evaluate the impact of higher package and board assembly temperatures on device performance. We need to determine the effect of exposure to higher processing temperatures on device performance. Issues such as Flash memory data retention above 250ºC and mechanical stability of new fab processes using organic dielectrics must be included in the evaluation.

1C Evaluate lead finish options for leaded packages. We must evaluate metallurgical, process, and cost parameters of alternative plated finishes in order to determine the optimum replacement process.

1D Evaluate solder ball options for BGA and FBGA packages. We must evaluate metallurgical, process, and cost parameters of alternative solder ball alloys. We will need to consider possible changes in the solder pad finish on the BGA substrate as well. This part of the evaluation includes an investigation of solder joint reliability.

The second part of the program will extend the work of phase 1 to a development phase in two parts:

2A Pb-free process compatible packages. A selection of package types will be modified though changes in materials or construction as recommended by the work in phase 1 in order to achieve the required moisture sensitivity level with a 260°C preconditioning profile. The modified packages will undergo a complete qualification process to demonstrate achievement of this requirement. No change will be made to lead finish or solder ball composition.

2B Fully Pb-free packages. A selection of package types will be modified though changes in materials or construction including lead finish and solder ball composition as recommended by the work in phase 1. The modified packages will undergo a complete qualification process to demonstrate the required moisture sensitivity level with a 260°C preconditioning profile. Board-level testing will be performed to demonstrate the reliability of the new lead finish and solder ball composition.

Phase 3 of the program will be production implementation of the solutions developed in phase 2. The timing and target devices for this phase will depend strongly on market forecasts and business plans formulated by the effected product lines. Consultation between manufacturing and these product lines will be required to do the capacity planning and any necessary equipment conversion in the assembly sites.

During the course of this strategic program certain additional activities will take place:

1 **Establish a program manager for all Pb-free activities.** Since these activities cross over boundaries with customers and with internal organizations, the establishment of a directing body, whether a specific individual or a group, is needed to oversee the activity within MSG and coordinate with outside groups.

2 **Select a set of specific customers with whom we wish to engage in cooperative development activity.** Such development will include reliability and compatibility evaluations. Candidates such as Nortel Networks, Delco-Delphi, Siemens, and Compaq Computer would be appropriate.

3 **Select specific industry consortial organizations with which we will engage in development activity.** This action serves to lend our weight to encourage the worldwide industry to converge on a single solder replacement, or at least a very limited number of such alloys. The most important candidates are the High Density Packaging Users Group (HDPUG), the International Tin Research Institute (ITRI), and the Japan Electronic Industry Development Association (JEIDA) or EIAJ.

4 **Encourage our subcontractors to participate in the above activities or incorporate them as partners explicitly.** We cannot depend on our subcontractors to develop conversion plans consonant with our needs independently. We must help them choose materials and processes, and validate those choices.

5 **Work with AMD's product groups to perform an official survey of customers to determine both the need and the requirements for specific AMD products in Pb-free form.** The product groups will need to develop business plans based on this information as justification for MSG to formulate subsequent conversion plans.

6 **Develop an in-house expertise in the metallurgy of solders.** Understanding the applicability of any particular lead finish or solder ball attach process requires an understanding of the metallurgy of interfaces at the package (for BGAs/FBGAs) and at the board.

7 **Establish a website for information on our Pb-free program.**

Completion of phases 1 and 2 outlined above requires in itself a significant commitment of resources by MSG and other divisions of the company. The goal for the first phase evaluation should be to define by Q4, 2001, the extent of any problems with existing package materials and construction and propose solutions to these problems that will be the basis for the phase 2 projects. This goal should be accomplished by Q4, 2001.

The phase 2 projects, as well as implementation as manufacturing processes in phase 3, will be a longer-term program extending into 2002.

Acknowledgments

Thanks are hereby given to Donna Sadowy and Fumio Namba of AMD, and to Brian Swiggett and Neil Moskowitz of Prismark, for their assistance in gathering the information necessary for this document. Thanks are also due to many of my AMD colleagues for assistance during visits to customers throughout the world. In addition, thanks are due to John Hunter who encouraged this study.