Adaptation to scientific and technological progress under Directive 2002/95/EC

Joint response from EICTA, AeA Europe and EECA ESIA to the general and specific questionnaires

relating to exemption 7b

31 March 2008

<u>Content</u>

General questionnaire

1. For which substance(s) or compound(s) should the requested exemption be valid?	Lead (in Tin-Lead soldering alloy)
2. What is the application in which the substance/compound is used for and what is its specific technical function?	The application in which lead is required is lead in solder used in Server, Storage and Storage Array systems, Network Infrastructure Equipment which provides switching, signaling, transmission and network management functions in high reliability telecommunications networks. Its function is to make reliable mechanical and electrical connections between components and Printed Wiring Boards (PWB). In addition to these interconnections, leaded solder is also used in Server applications for solder joints or interconnections within components such as flip chip modules (flip chips, capacitors, other devices), power modules, cooling technologies such as Small Gap Technology to solder pistons within a multi-chip module and vapor chamber heatsinks, as well as high performance board-terminated cable connectors.
3. What is the specific (technical) function of the substance/compound in this application?	The specific function of lead in this application is to provide a solder alloy having known, well characterized, and predictable fatigue life and shock performance characteristics when used to make electronic interconnections (electrical and mechanical interconnection between components).
4. Please justify why this application falls under the scope of the RoHS Directive (e.g. is it a finished product?	Pb containing solder is used in the systems which are shipped as finished products required for very high complexity/reliability products until the lead-free alternative alloys have been optimized and qualified for this use.
- Is it a fixed installation?	NO
- What category of the WEEE Directive does it belong to?).	3 – IT and Telecommunications Equipment
5. What is the amount (in absolute number and in percentage by weight) of the substance/compound in:	
i) the homogeneous material[1]	35 – 45% Lead by weight of a single solder joint as part of an SnPb alloy
ii) the application, and	This varies greatly depending on product. It may range from 0.5% to 5.0% by weight of product.
iii) total EU annually for RoHS relevant applications?	An estimated 5000 tonnes of lead as per attached. This estimation may not take into account the large number of lower complexity server components and PWBs that are already transitioning to lead-free solders as technically feasible. (Please see attached document). C:\Documents and Settings\asalemink\De
6. Please check and justify why the application you request an exemption for does not overlap with already existing exemptions respectively does not overlap with	*Not applicable – this is only for new exemption requests*

exemption requests covered by previous consultations.	
7. Please provide an unambiguous wording for the (requested) exemption.	Maintain the current wording as is: "lead in solders for servers, storage and storage array systems, network infrastructure equipment for switching, signaling, transmission as well as network management for telecommunications"
8. Please justify your contribution according to Article 5 (1) (b) RoHS Directive whereas:	See answers to questions in the specific questions area and ANNEX 1
• Substitution of concerned hazardous substances via materials and components not containing these is technically or scientifically either practicable or impracticable;	Long term reliability of the end products with Pb-free solder is not yet completely understood. While it is possible to substitute lead-free soldering alloys in some applications, a variety of technical issues specific to the entire range of high-end electronics applications have demonstrated that this exemption cannot be totally eliminated without risk of increased failures. Please refer to the specific questionnaire and ANNEX 1 for further details. Many of the technical and reliability challenges that remain to be solved are a direct result of the elevated assembly temperatures required by lead-free solders. The magnitude of these challenges scales directly with the complexity and thermal mass of the printed circuit assembly. More massive, higher end server PWB assemblies demand ever more temperature robustness across the full PWB assembly Bill of Materials to tolerate the required process exposures. These higher temperatures can have detrimental affects on temperature sensitive components and/or the PWB, as further described in the responses to specific questions 1 and 4, and the Annex. The industry is working very diligently on this issue and converting products to lead-free as soon as possible. However, for mission-critical "24-7" products, the new solder alloys and supporting components have not yet been qualified for all applications.
• Elimination or substitution of concerned hazardous substances via design changes is technically or scientifically either practicable or impracticable;	While it is possible to redesign some applications to enable the use of lead-free solders, the complexity of the required changes to the electrical and mechanical design for the entire range of applications requires further study and invention before elimination of this exemption can be executed. Pb-free alloys, such as SAC, require new design changes to nullify shortcomings of SAC alloy properties. Several design modifications using lead-free solder are being evaluated and long term reliability impacts are still partly unknown, thus further time is needed to develop reliable alternatives. With additional development, it is very likely that the new alloys can be optimized and meet the necessary reliability goals. Please refer to the specific questionnaire and ANNEX 1 for further details.
• Negative environmental, health and/or consumer safety impacts caused by substitution are either likely or unlikely to outweigh environmental, health and/or consumer safety benefits thereof (If existing, please refer to relevant studies on negative or positive impacts caused by substitution).	The original study performed by ERA (Annex 1, ref (1) outlined the risks of critical system failures caused by unexpected interconnect failures. SAC alloy has been widely used to replace Pb/Sn in solder. However, as stated above, the long-term reliability properties of SAC and other Pb-free solders are not fully known. Reliability of network infrastructure equipment is critical for the safety, security and health of modern societies. Long term reliability of network infrastructure equipment in applications such as commercial and government finance, health care and hospitals, local and national security and other applications are critical to the health & safety of consumers, countries and the global community. Therefore a more thorough testing and simulation together with additional real-life experience is needed before the exemption can be completely removed. Early retirement of computer systems caused by use of lead-free solders that fail to perform their function will generate waste unnecessarily.

	Please refer to the specific questionnaire and ANNEX 1 for further details. While the amount of lead introduced annually on the EU market based on this exemption is significant, the actual negative environmental impact caused is relatively low since the equipment covered is used in non-household settings only whereby recycling of End of Life products is a well established practice.
9. Please provide sound data/evidence on why substitution / elimination is either practicable or impracticable (e.g. what research has been done, what was the outcome, is there a timeline for possible substitutes, why is the substance and its function in the application indispensable or not, is there available economic data on the possible substitutes, where relevant, etc.).	Current candidates for the substitution of Sn/Pb solder are not completely proven to be practicable in all applications. Over the past four years, the electronics industry has been actively pursuing a conversion to lead-free soldering technology. Over this time, a number of new lead-free failure mechanisms have been uncovered that may impact some applications. These failure mechanisms are outlined in detail in question 1 of the Specific Questionnaire as well as in ANNEX 1. While the industry has been converting a great deal of the PWB assembly volume to lead-free solders, it is clear that not all PWB assemblies used in critical server and telecommunications applications can be converted at this time. We therefore propose that the current exemption remains in place while more data is developed and additional practical experienced is gained regarding the long term reliability of substitute solders. A review of the technical papers (see Annex 1, references) from any electronics conference concerned with manufacturing or reliability will quickly show the reader that many companies are working hard to generate lead-free solutions. However, that same review will also highlight many of the technical challenges facing high-reliability manufacturers in the lead-free soldering field.
10. Please also indicate if feasible substitutes currently exist in an industrial and/or commercial scale for similar use.	Lead free substitutes exist (eg. SAC alloys, matte tin) for some applications, but have not yet confirmed sufficient reliability for the full range of products under this exemption. Please see the Specific Questionnaire as well as ANNEX 1. We have high confidence that the new alloys can be optimized and meet our standards for all products in the future.
11. Please indicate the possibilities and/or the status for the development of substitutes and indicate if these substitutes were available by 1 July 2006 or at a later stage.	Some of these substitutes were available by 1 July 2006. They were not fully qualified for the complete range of applications covered by this exemption. This qualification process is still ongoing. The electronics industry needs time to continue to investigate the reliability of the SAC alloy and needs to study the new design practices for this new alloy. As a very early assessment indicated, the design practice needed for SAC alloy may be quite diversified, which means it depends on the complexity of the electronics and how the electronics will be used.
12. Please indicate if any current restrictions apply to such substitutes. If yes, please quote the exact title of the appropriate legislation/regulation.	For applications with known lead-free substitute solders, no additional restrictions exist. Since acceptable substitutes for all applications have not yet been invented, it is not possible to predict if other restrictions would be applicable.
13. Please indicate benefits / advantages and disadvantages of such substitutes.	From a cost and technical standpoint, there is no benefit to the new lead-free solder alloys. There is an increase in power consumption during soldering process. While remaining questions about reliability of SAC solder joints will be answered by ongoing studies clarity is lacking regarding the impact of Tin whiskers on long term reliability that is likely to continue through the transition.
14. Please state whether there are overlapping issues with other relevant legislation such as e.g. the ELV Directive that	We are not aware of any conflicting legal requirements.

should be taken into account.	
15. If a transition period between the publication of an amended Annex is needed or seems appropriate, please state how long this period should be for the specific application concerned.	Once proven technology is available, a transition period of three years is required to manage the transition to new materials such that safety, health, security and environment of consumers and societies are protected.

Specific questionnaire

1. Please describe the current status of **lead-free soldering** in applications covered by exemption 7 (b).	Since failure of any NIE network element (individual application), from the simplest to the most complex, can cause unscheduled down-time in telecom networks expected to operate with 99.999% reliability or 5 minutes of downtime per year, customers expect data to prove that equipment can fulfill these requirements. After the fact remediation provided by an extended warranty or penalty clauses is not an acceptable substitute. While one can make logical arguments sufficient to defend the reliability of some lead-free NIE assemblies today, the case by case nature of these arguments makes it impossible at present to define in any practical manner classes of NIE products that can be produced lead-free and classes that cannot. Trying to limit the scope within NIE is today not possible or would require such a complex definition that it would create a large gray area and therefore be impractical. Similarly, a typical Server utilization capability is 24 hours per day, seven days a week, for a period of up to 10 years or more with a total downtime of 4 hours or less over the entire operational period. That equates to an operational percentage of 99.9985% over the 10 year field life of 87,600 hours typically expected of mainframe systems (or 30 years Mean Time Between Failures – MTBF). Servers also are expected to remain functional during most repair actions. Over the past four years knowledge of, and experience with lead-free soldering technology has grown significantly due to experience gained in assembly of non-exempt products and completion of a significant number of technical/reliability studies. While many issues remain, this evolving experience has provided sufficient insight into lead-free assembly and reliability to enable an increasing number of NIE (Network Infrastructure Equipment) products falling under exemption 7(b) to be delivered to customers with completely lead-free assembly. This has only been possible due to limited assembly complexity coupled with ~~designs~~ constraints in choice and placement of Pb-free components. Similarly, lower complexity Server printed wiring board assemblies are beginning a transition to lead-free assembly. An example of an early qualification of an entry Server complexity PWB assembly to meet a specific customer requirement has been documented in an industry paper [1]. This product was however released to the field with largely unknown long term reliability performance. PWB assemblies targeted for lead-free soldering will be limited in board thickness, component and connector bill of materials (BOM) and end-use requirements. In addition to these advances in PWB assembly technology, some cable assemblies have been qualified with Pb-free solder including: Soldering of wires directly to terminals, Solder cup terminals, Soldering of braid and drain wires for ground connections. Also, feasibility work is in progress to find a substitute lead-free solder for the Small Gap Technology used to solder pistons in the cooling assemblies for complex high-end mulit-chip modules. Overall, the industry continues to face two opposing forces. The first, driving towards completely lead-free soldered products, comes from a supply chain that is rapidly moving to provide only lead-free parts due to overwhelming demand from the largest segment of the electronics industry whose products are not included in the scope of the exemption. The second, pushing to maintain the status quo, results from the need to have proven capability to forecast the long term reliability of lead-free Server, Storage and NIE products to meet the stringent requirements of telecom service providers and Server / Storage system customers. Although assembly issues remain for complex lead-free PWB assemblies, the main concern today continues to be long term reliability of lead-free solder joints and the potential impact of Tin whiskers. Completion of numerous research programs in this area has improved the understanding of lead-free solder, but knowledge as essential to long term reliability as an acceleration factor relating lead-free solder fatigue test results to field performance is still under development [2]. Moreover, while providing some answers, the ongoing research programs have also uncovered additional, unanticipated factors (e.g. solder aging [3][4], microstructural, grain orientation and alloy effects [5][6][7][8][9]; etc.) that may impact long term reliability. It has found from the industry that the aging of SAC alloy can reduce the shock resistance and its fatigue performance. Without further understanding of the impact of the aging characteristics on solder joints reliability, this

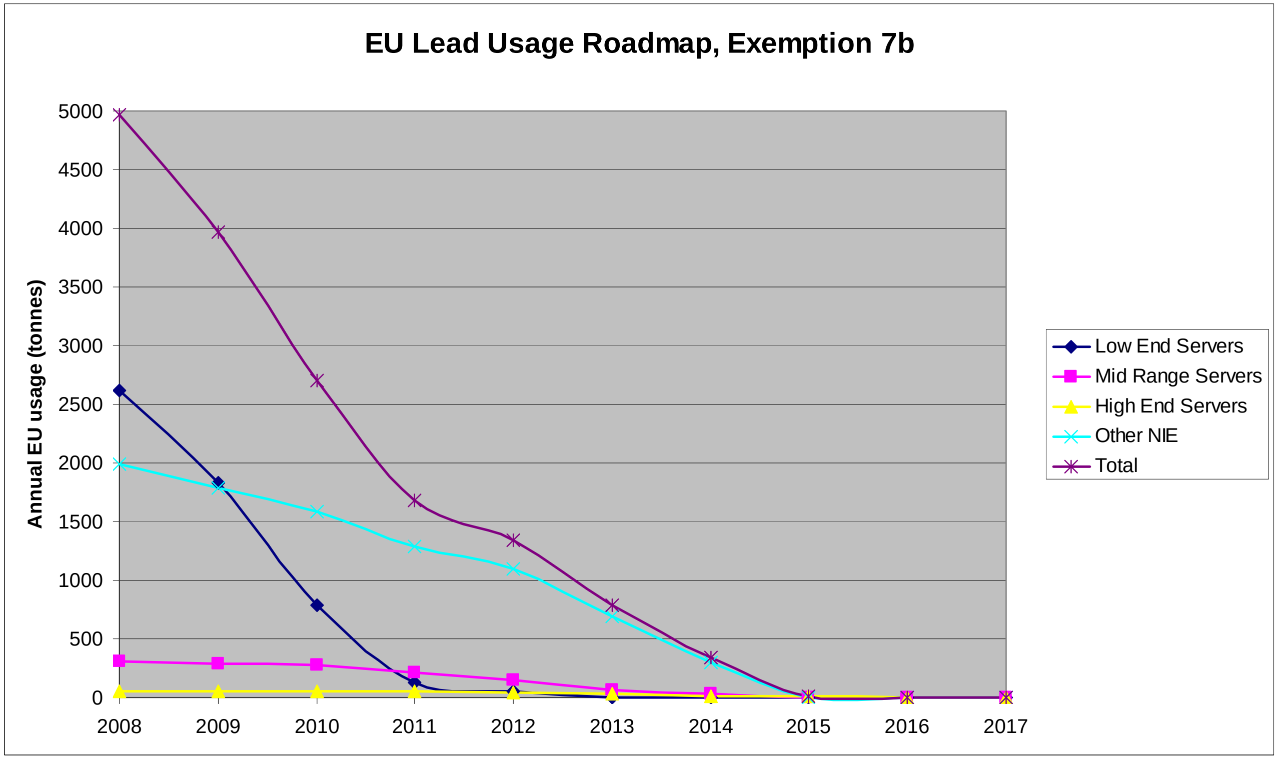
	factor is still a concern for Pb-free solder long-term reliability for some applications. These issues must be resolved through further technical effort. In addition, experience gained from assembly of non-exempt products over the last few years has also uncovered additional concerns (e.g. mechanical shock resistance) with the existing and most widely studied lead-free solder alloys. This has resulted in a proliferation of new lead-free solder alloys formulated to resolve these problems but still uncharacterized for long term reliability and assembly performance. Continued changes in lead-free solder paste formulations over the past four years (with the intent to improve them) and identification of new physical phenomena that may potentially impact reliability have served to further complicate our ability to develop acceptable models of solder joint fatigue failure critical to establishing their long term reliability as a function of use environment. The impact of low temperature on solder joint fatigue life and mechanical properties is still unknown. The effect of high humidity and corrosive/contaminated gas environment on SAC alloy material properties, mechanical properties and field life are also not completely known. Further complicating these problems are indications that the Sn-grain orientations might be factors that will affect the Ball Grid Array (BGA) solder joint's fatigue life [10]. Without knowing further details, it is still a potential concern to the solder joint reliability for certain applications. With these issues in mind companies have expanded already comprehensive internal R&D programs and are actively supporting major consortia programs to help answer the numerous technical questions that currently prevent the industry from being able to consistently quantify the long term reliability of Pb-free solder joints and Pb-free assemblies in general. In addition to these concerns directly related to the lead-free solder alloys, there are other challenges that remain related to the processing required by these higher temperature alloys including: • Printed Wiring Board (PWB) robustness for 245C reflow temperature compatibility has only been proven for PWBs with limited thickness (below 22 layers), below that required for high end servers. As these qualifications have progressed, new failure modes have been discovered and must be thoroughly understood. The need for thicker cards, large arrays of fine pitch vias, low loss tangent materials, 2 oz copper and other complexities in construction increase the challenges in qualifying PWBs for Server applications. In addition, thicker PWBs will likely increase the temperature exposure closer to 260C. For this higher temperature compatibility, no PWB suppliers have demonstrated the reliability required for Server applications. [11]. • PWB surface finish: questionable extension of Organic Solderability Preservatives (OSP) to complex Pb-free applications; technical issues with and manufacturing immaturity of new lead-free capable materials such as immersion silver (galvanic corrosion, poor resistant to corrosion in certain environments) and Pb-free Hot Air Solder Level (HASL) (consistent thickness and flatness of solder thickness) • Wave solder and PTH rework: excessive PTH copper dissolution[Annex 1, Figure 4], inadequate hole fill resulting in unreliable solder joints • Temperature Sensitive Components and Connectors: Still today, some cannot withstand Pb-free reflow profiles for complex and larger PWB assemblies without impact to electrical function or long term reliability. Industry standard J-STD-075 needed to identify, classify, and handle Non-Integrated Circuit Temperature Sensitive Components won't be released until mid-2008 at the earliest. [12] • Mechanical assessment requirements on a per product basis given that Pb-free solders are more susceptible to mechanical fragility. • Solder interconnection reliability: new failure modes / earlier failures than for SnPb solder have been found for components such as Thin Small Outline Packages (TSOP), Quad Flat No leads Packages (QFN) and Ceramic Ball Grid Array (CBGA) packages through reliability testing of Product Vehicles • Reflow equipment for higher complexity assemblies is not available at all suppliers – 10 or 12 zone ovens, vapor phase requirements for the complex assemblies used in mid-range and high-end Servers may be required • Multi-chip module applications: component and capacitor joining for high reliability and to maintain a solder hierarchy is still dependent on high melting temperature, high Pb solders, which may have compatibility issues with SAC solders. • Thermal applications: Small Gap Technology and vapor chamber heatsinks have complex assembly and performance requirements and are only starting to be developed with Pb-free solders

	• High performance board-terminated cable connectors – issues have been identified with light crimp and solder and soldering wires to cards for high performance cable assemblies. There is an impact on both reliability and performance with Pb-free solders. Additional examples of the technical limitations of lead-free solders can be found in ANNEX 1.
2. Please explain whether and in which **applications** covered by exemption 7 (b) the exemption for lead-solders is still necessary, and in which applications it has become obsolete.	The exemption for lead-solders is still necessary for Server, Storage and NIE applications. As discussed in (1) above, for Server, Storage and Network Infrastructure Equipment the ability to discontinue use of SnPb solder in general can not be considered in a meaningful way as a function of the particular application. For Server, Storage and NIE, an application may be comprised of as few as one but usually several PWBs each with its own level of assembly complexity and wide range of electronic component types. While one or more constituent PWBs may be of sufficiently low complexity to have no Pb-free assembly issues it is likely that others will be large, thermally massive PWBs common to NIE and currently known to have assembly issues. Moreover, whether individual PWBs that comprise the application are simple or complex, each board will have a large array of different component types whose lead-free solder joints must be proven capable of surviving the particular use environment without fatigue failure for the service life of the application. There is still insufficient capability to forecast the long term (10 years and longer) reliability of Pb-free solder joints as a function of device package type and use environment for many applications and the long term reliability impact of tin whiskers is not fully verified. The industry still needs additional time to minimize these risks. Hence, it is industry's belief that exemption 7(b) for lead in solder is still necessary for all products in the Server, Storage and NIE category until there is a more complete understanding of the long term reliability of Pb-free solder joints.
3. What is the **amount of lead** per application, the lead content in the homogeneous material, the annual production volume as well as the number of applications related to exemption 7(b) put on the EU market annually.	"Please see answer to Q5. General"
4. When can lead solders be substituted by lead-free solders or other RoHS-compliant materials or designs in specific applications? Please provide a **roadmap** or similar evidence with activities,	As explained in (2) above, a lead-free transition roadmap can not be formulated for specific Server, Storage and NIE applications but, rather, must be developed for Server, Storage and NIE industry as a whole. This roadmap, currently under development, and roughly outlined below, considers 1.) the evolution of lead-free assembly technology, 2.) availability of a full and complete set of thermally compatible components/materials, and 3.) the availability of sufficient data to determine solder joint fatigue life as a function of electronic device package style and use environment. Each of these three areas will have their own timelines but all three must be complete to build lead-free Server, Storage and NIE applications/products of known long term reliability. The system level timeline will thus be a strong function of the complexity of the system board in question. Large mass, high complexity, applications will necessarily drive higher and more prolonged assembly process temperatures onto the component set and therefore require ever more robust and temperature tolerant supporting technologies. While this roadmap will estimate the earliest time that NIE products in general can complete the transition to fully lead-free assembly

milestones and timelines towards the replacement of lead in these applications.	with known and acceptable reliability, as indicated in (1) above there are an increasing number of cases in the interim where individual PWB assemblies and/or products will be able to transition to lead-free earlier as the growing body of test data provides sufficient insight to address reliability of the specific components on that PWB/assembly/product. We estimate that it will take approximately 2 years for research and characterization of lead-free materials to better understand the impact of new materials on lead-free products and their long term reliability, additional 2 years to establish reliable supply chain for temperature tolerant components and transition into production. Please note that it may take longer time to establish long term reliability and hence conversion to lead-free of our high end products for mission critical applications. The experience available today clearly establishes that the application of lead-free technologies requires changes to PWB (layout) designs. These changed requirements are increasingly taken into account whenever a new product is designed or when an existing PWB is undergoing a redesign. However, the Server, Storage and NIE industry faces long term delivery demands of products (up to 15 years after first introduction) from their customers which require the manufacturers to maintain a large base of very complex legacy products each containing between 10 to 300 individually designed PWBs. In the transition to lead-free technology each of these PWBs will have to be redesigned before lead-free technology can be applied. In many cases the required redesigns will be of sufficient extent to require lengthy requalification to telecom industry standards before they can be offered to customers. It is not unusual for such redesign and requalification/recertification to take as much as a year or more for very complex products. The number of legacy PWBs requiring redesign, coupled with the time required supports the need for a significant transition period after lead-free technology is accepted for general application. Allocating insufficient time to this transition before eliminating the exemption could result in service providers unable to obtain the legacy products they require to keep their networks fully functional. The roadmap for the complete elimination of lead-based solder by the Server, Storage and NIE industry should therefore consider sufficient time for proving the technology (which may be dependent on PWB complexity (number of layers, thermal mass) and use of specific critical components (such as ceramic BGAs) for its reliable application until the completion of existent product redesign or withdrawal from the market (for which customers demand notification and leadtime of up to two years). <u>Lead-in-Solder Usage Reduction Roadmap</u> 1. System level Assembly Process Technology Qualification : · Partly complete today (for select, low complexity, entry level server and NIE product) · Expected release for all low to mid complexity applications between now and 2012 2. Availability of Supporting Technology: · temperature tolerant, server class PWB laminates: 245C, 3.0 mm thick std-loss available now · temperature tolerant server class PWB laminates: 260C, 4.0 mm thick std-loss by 2010 · temperature tolerant server class PWB laminates: 260C, 4.0 mm thick, low-loss by 2012 · 260C tolerant active device components available now (per J-STD-020C). · 260C / 40-50 sec time above 217C liquidus /capable passive components (electrolytic and polymer-tantalum capacitors) by 2010 · 260C / 90 sec time above 217C liquidus /capable passive components (electrolytic and polymer-tantalum capacitors) by 2012 3. Technology Application / Field Reliability Knowledge Base : · Applied today (2008) for some designs (depending on complexity/components used) · Consider for system upgrades and redesigns (individual PWBs, complete products) after 2011 · Expand scope of product introduction as field reliability experience grows from 2008 through 2012

	· Apply new technology to all new entry level and mid-level complexity designs by 2012 · Additional time required for redesign or phase-out of legacy low to mid-complexity products until 2014 · Maintain exemption for high end servers through 2016 · Maintain spare parts supply chain for Pb-bearing products installed base (i.e. repair as produced). According to this proposed reduction roadmap, lead usage in Server, Storage and NIE shipped to the EU can be approximated as shown in the figure below where most volume is driven by low end Servers and other NIE.

Lead Usage (in tonnes)	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Low End Servers	2620	1834	786	131	52	0	0	0	0	0
Mid Range Servers	307	292	276	215	154	61	31	0	0	0
High End Servers	51	51	50	48	41	31	15	8	3	0
Other NIE	1985	1787	1588	1290	1092	695	298	0	0	0
Total	4963	3963	2700	1685	1338	787	344	8	3	0



5. Please propose a new **wording** limiting the current exemption	Lead in solders for servers, storage and storage array systems, network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunications.

to those applications where substitution is technically not feasible.	
6. Assuming the current exemption will be given an **expiry date**, what date do you think is technologically feasible for industry?	It is anticipated that Pb-free assembly issues such as reliability and availability of components/PWBs/connectors that can withstand the high process temperature will continue to be the gating issue for the coming years. It is considered unlikely that solutions will be fully in hand before 2012 to enable its use in Server, Storage or NIE applications. Even though over the coming years an increasing range of Server, Storage and NIE products will become available as lead-free, 2014 is the earliest feasible expiration date foreseen for the exemption. Where technical challenges still remain some subset of equipment may require additional time.

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ANNEX 1 – Exemption 7b Technical Details

The exemption for lead in solder for servers and telecommunications equipment was originally granted on the basis of risk to consumer safety should these systems fail unexpectedly. This equipment is employed to run critical communications systems and financial institutions where an unexpected failure could have catastrophic results. At the time the original exemption was granted, there remained many unresolved questions about the long term reliability of lead-free solders. Specifically, SAC alloys result in fundamental changes of materials composition and grain boundaries for which the long term reliability is not fully understood. Whether new designs in electronics should be implemented to compensate the SAC alloy performance is not understood. In addition, the design of complex servers presents design challenges that are not found in consumer products

In the original EU report from ERA (1), Table 1 was used to highlight the different interconnect requirements between servers and most consumer products.

Characteristic of "typical" PCBs	Mobile phone PCB	Desktop computer PCB	Server or Network PCB
PCB thickness	0.5 mm	1 – 2 mm	Up to 10 mm, typically 2 – 4 mm
Number of layers in PCB	4 – 6	~12	>18 – 52
PCB size	30 cm^2	~900 cm^2	Various, up to 6200 cm^2
Types of components	Small low thermal mass	Mix of small and medium with a small number of large	Includes many larger high thermal mass components
Component density	High	Medium	High
SMT Reflow temperature required	235°C (used by Motorola)	~245 – 250°C (estimated)	260°C (sources: IBM, Lucent)

Table 1 Characteristics of typical PWBs (1)

The thicker and denser PWBs for servers present a number of unique challenges that are much more difficult to solve for lead-free soldering processes. Some of the biggest challenges are related to the additional stress placed on the solder joints by a stiffer board as the product experiences temperature cycling due to power on/off cycles, or due to environmental conditions. Stress in the solder joint is increased by limited bending of the PC board. Since board stiffness is a function of the cube of the board thickness, the thinner boards in consumer products will bend much more readily than a thicker board. Using the examples above, a typical 3 mm thick server board will be 27 times stiffer than a typical desktop computer board with 1mm thickness.

To compound the issue of increased board stiffness, the IC packages used in server products tend to be much larger and denser than those found in consumer products. The increased size of the package results in larger CTE-mismatch strains at the corner solder joints of the package, which increase roughly linearly with the distance from the center of the component. These linear increases in strain accelerate thermal fatigue exponentially during server or component on/off cycles as they are accommodated by creep and cyclic damage within the solder joint.

In addition to inherent mechanical differences between servers and consumer products, there are many indicators that the lead-free soldering technology is not yet mature and lacks demonstrated reliability. During the past 4 years, the industry has been working to understand the new failure mechanisms associated with SAC solders. Efforts to develop predictable accelerated life tests and predictive models have not yet resulted in validated methods having widespread acceptance and availability.

One of the indicators of an immature technology is the continued proliferation of solder alloys(4)(5)(6)(7)(8)(9)(11)(12)(13). While the majority of the consumer electronics industry has converged upon tin-silver-copper (SAC) alloys, there is still considerable variation in the percentage of each element. Although not fully understood, it appears that low silver alloys may have better resistance to shock failures, while higher silver alloys may have better thermal fatigue resistance. Variations in silver concentration impact board assembly processes, creating reliability risks if not properly managed. There are also a number of experiments (5) indicating that alloys containing minute amounts of other elements (such as nickel or bismuth) may be beneficial. A full assessment of the impact of these elements and their effective concentration ranges has not been completed.

In order to assure the long term fatigue life of a solder joint, it is necessary to have a mathematical model to predict solder joint fatigue life from the results of accelerated stress testing. For tin lead solders, the most widely used equation to model fatigue life is the modified Coffin-Manson equation. This model was fully developed over a period of 20 years (1969-1989) and the industry has decades of experience in its use.

When one considers the relatively recent adoption of lead-free solders, combined with the proliferation of different materials, it is little surprise that the electronics industry has yet to agree on a suitable model to predict the long term life. To date, there are at least five different acceleration models that are under discussion (22)(23)(26)(27)(29)(30)(31). A wide range of industry associations have been working toward convergence of these models. Some of the models under discussion include the Solder Creep-Fatigue Equation, the Cyclic Damage Assessment, and modified versions of the Coffin-Manson model (21). The importance of having accurate life prediction models for lead-free servers cannot be over stated. These models are critical to design and component selection. Poor models could lead to poor choices that could lead to reliability degradation.

Thermal fatigue reliability of Pb-free solder joints does not appear to be a significant issue for the simple and mid size PWBs already in production with tin-silver-copper (SAC) solders. In fact, SAC joints may be superior to SnPb joints in many thermal fatigue situations. However, concerns remain for the case of complex PWBs due to the thick, stiff boards, high operating temperatures, and especially the use of large, high strain, components such as ceramic packages. These characteristics lead to large strains per thermal cycle, which as shown by Clech (24), degrade thermal fatigue reliability of SAC joints relative to SnPb. Hillman et al. (23) also have noted that the often-cited superiority of SAC solder joints in thermal fatigue may not hold in all circumstances, potentially being significantly worse than Sn-Pb for joints with inherently low reliability (e.g., large ceramic BGAs used in servers and NIE). It is also noteworthy that the iNEMI consortium has a project team investigating potential "early" failures in SAC solder joints that could be of significant impact for high reliability equipment. Concerns center around the unusual microstructure of SAC solder joints (25). Therefore, it is prudent for these issues to be worked out prior to using Pb-free solder joint technology in critical equipment.

Figure 1 shows a compilation of results from a number of different laboratory thermal cycle tests made on area array devices (BGA/CSP (Chip Scale Package)). To better indicate system field behavior, these accelerated test data have been adjusted to longer thermal cycle dwell times and extrapolated to 1% failure rates (23). The big variations in result shows that although the reliability for SAC can be as good as that for SnPb, there are difficulties still to overcome. This is especially apparent for those SAC BGA/CSP components shown having early life (1%) failures at cycle counts less than half of their SnPb counterparts. (19, 23).

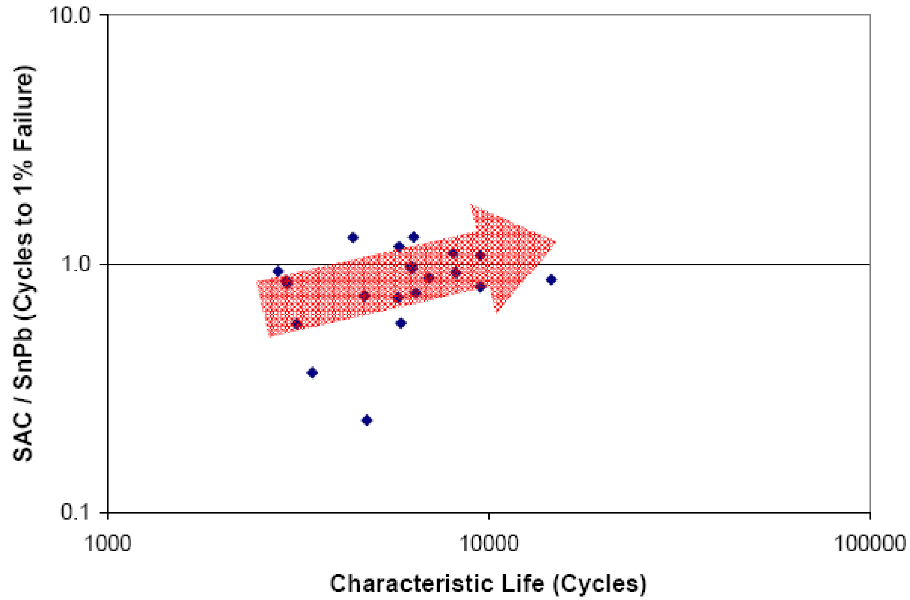

Figure 1 Ratio of SAC/SnPb cycles to 1% failure for area array devices as a function of characteristic lifetime of the SAC solder component. (Experimental data adjusted to simulate eight hour dwells at thermal cycle temperature extremes.) (23)

While there are indications, including the data presented above, that lead-free solders may exceed the fatigue life of tin lead alloys, a number of troubling new failure mechanisms have been uncovered in recent years. One of these is the reduced resistance to bending strain.   Lead-free solder alloys have higher strength and stiffness than tin-lead, creating high joint stresses during mechanical bending or shock. Bend tests show that these materials have a 30% reduction in acceptable bend strain when compared to tin-lead solders.   The reduction in allowable bending strain can sometimes require new test fixtures, and in some cases, a change of the system mechanical design. Lower bending strain also increases the risk of damage in the field when repairs or upgrades take place, due to handling and component/card insertion.

Because of the mechanical properties of high-Tg board materials, a shock event can also cause the PWB pad to fail by "pad cratering", as shown in Figure 1. Pad cratering occurs when the solder joint exerts sufficient stress to the PWB to cause bulk failure of the epoxy laminate.   Prior to the use of lead-free materials, this type of failure was rare. Again, the high strength and stiffness of lead-free alloys creates higher joint stress than for tin-lead for the same amount of board flexure.

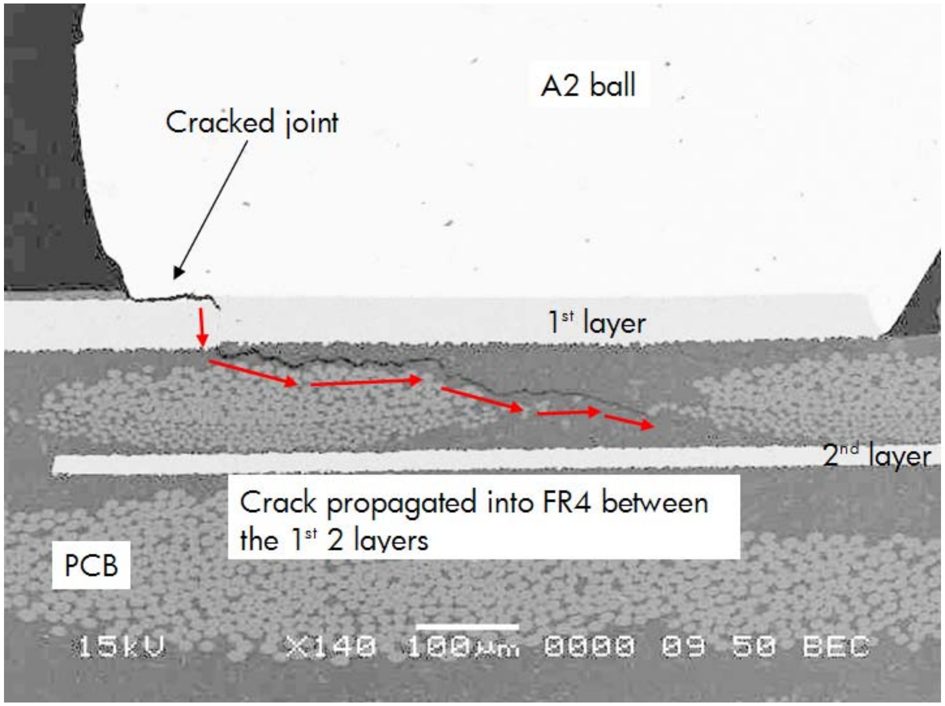

Figure 2 Pad Cratering on Lead-Free PWB

A number of studies have identified another failure mechanism sometimes referred to as "sporadic brittle fracture" (18)(19)(20)(21)(22). While these failures can occur on OSP boards (Figure 3), they appear to be even more pronounced on nickel plated PWBs. These failures are characterized by a planar fracture that occurs within the intermetallic layer joining the solder to the pad on either the package substrate or the PWB. Such fractures can occur at very low loads and have a sporadic nature that makes study of them difficult. While the exact mechanism(s) involved are still being debated, it appears that sporadic brittle fracture is due to several features of lead-free joints that are not present in tin-lead:

- High strength and stiffness of the alloy
- Changes to the intermetallic layer composition and crystal structure relative to that formed with tin-lead
- High levels of undercooling during solidification of the joint, creating a small number of large Sn grains within the joint.

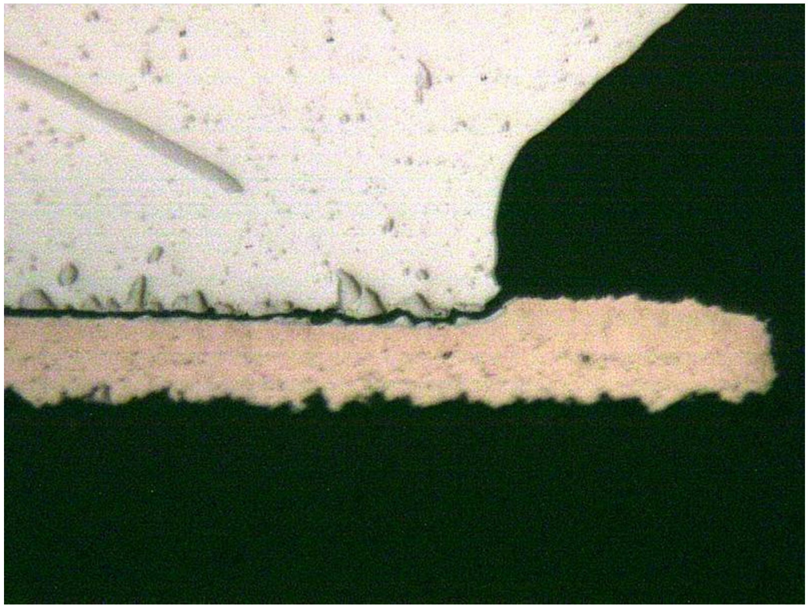

Figure 3 Typical BGA brittle intermetallic fracture with SAC alloy on copper pad.

Rework Issues

Because of the complexity and cost of boards for servers and telecommunication equipment, rework is frequently required during the manufacturing process. Because of the higher temperatures and the materials involved, the lead-free rework process can be more damaging to the PWB materials than the tin-lead process. In SAC soldering processes, the copper pads and vias of the PWB are much more prone to erosion because of the affinity for copper to go into solution in the high Sn solder. Figure 3 also shows evidence of the early stages of SMT pad dissolution after just one reflow cycle. The worst cases of copper dissolution occur when reworking through-hole components (28). Figure 4 shows an example of complete copper removal at the corners of a through-hole barrel during the rework process.

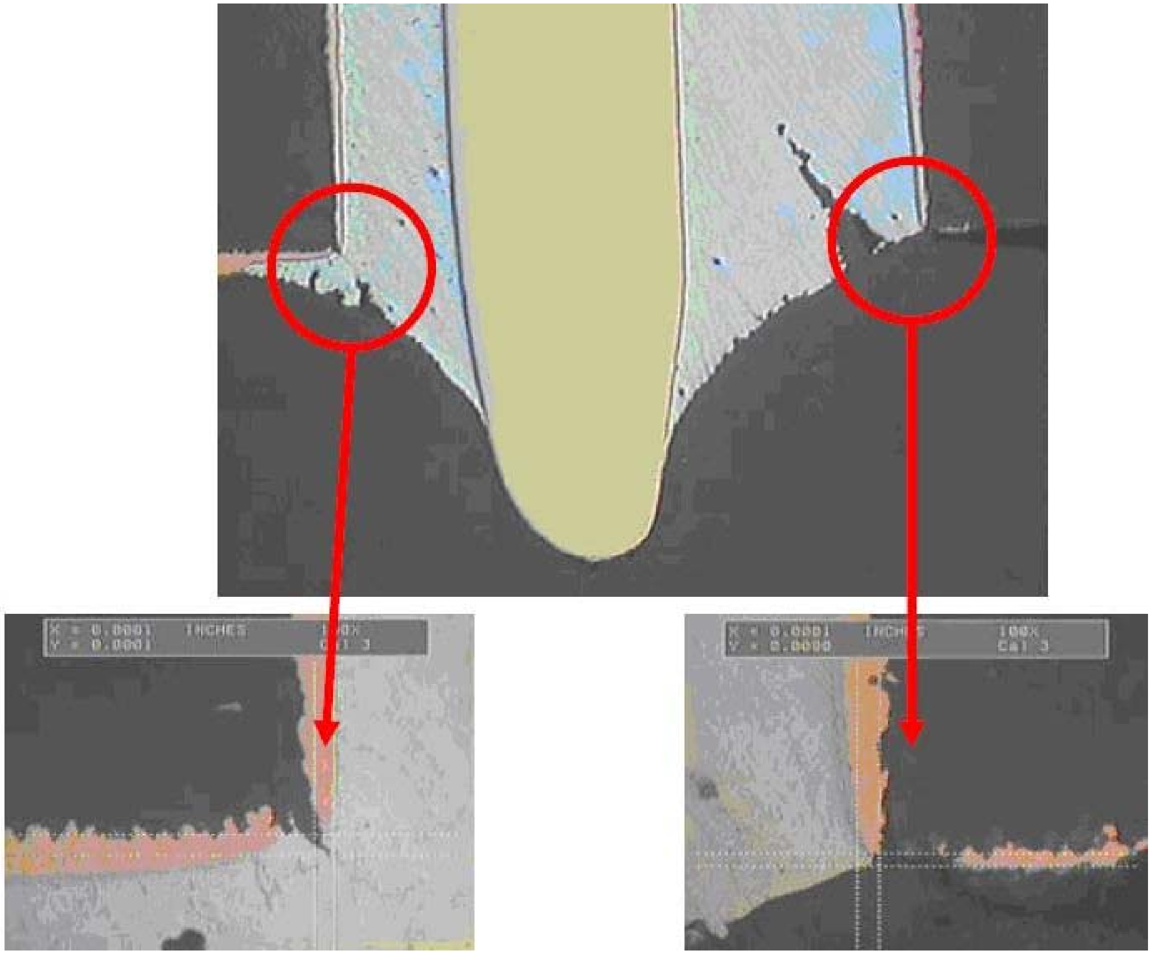

Figure 4 Complete copper erosion during rework of a through-hole device (courtesy Intel Corp)

Although PWB barrel cracking is a well known issue, the higher temperatures involved in lead-free processes have increased the severity of this problem, especially during rework processes. An example of a cracked PWB routing via barrel can be seen in Figure 5. Because of the increased density and board thickness in server products, this is much more of an issue than typically experienced in consumer products.

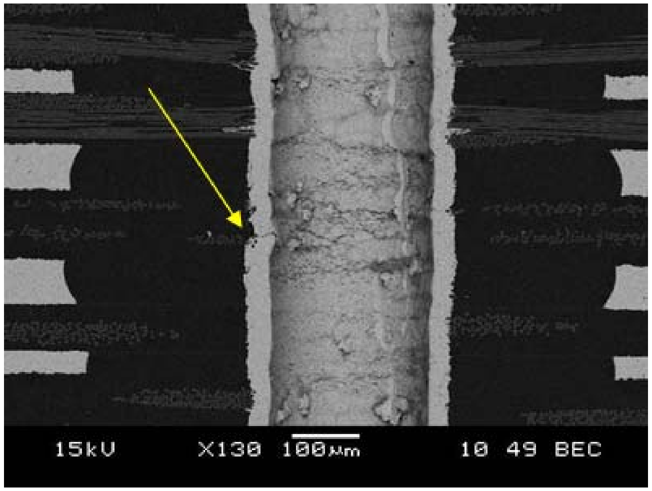

Figure 5 Cracked copper barrel in PWB

Corrosion Issues

Another failure mechanism with lead-free products is increased corrosion of printed circuit board metallization. HP and other companies have discovered this issue to be especially critical when immersion silver plated PWBs are operated in a corrosive environment. Expanding markets in China and India have been found to have highly corrosive environments due to the air pollution caused by the use of high sulfur coal. Figure 6 and Figure 7 show examples of related corrosion reported by Dell (25) and observed by HP. Within the EU such severe conditions are uncommon and may exist only in limited industrial applications. However, the fact that such failures have occurred so quickly in high pollution environments (even inside data centers with climate control) indicates the possibility of failures of silver plated PWB´s in more benign environments to occur over longer periods of time. Thus, this failure mode for silver plated boards may pose a risk for long life, mission critical equipment installed in the EU. Even if this proves not to be the case, the problems encountered with Pb-free, immersion silver platings illustrate a general concern on the part of producers of high reliability equipment. Changes to basic materials for which the industry has decades of experience sometimes leads to unexpected problems.

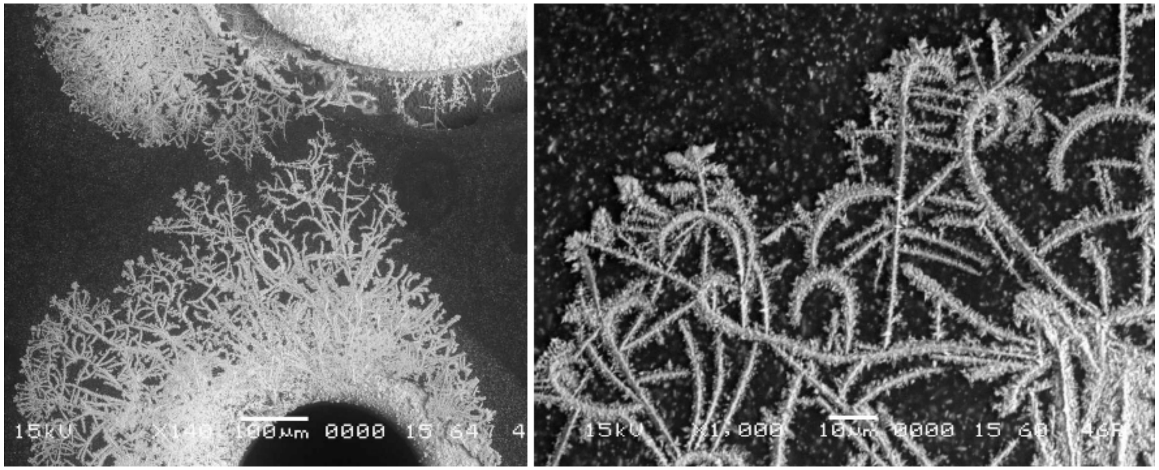

Figure 6 Corrosion on lead-free PWB (courtesy Dell)

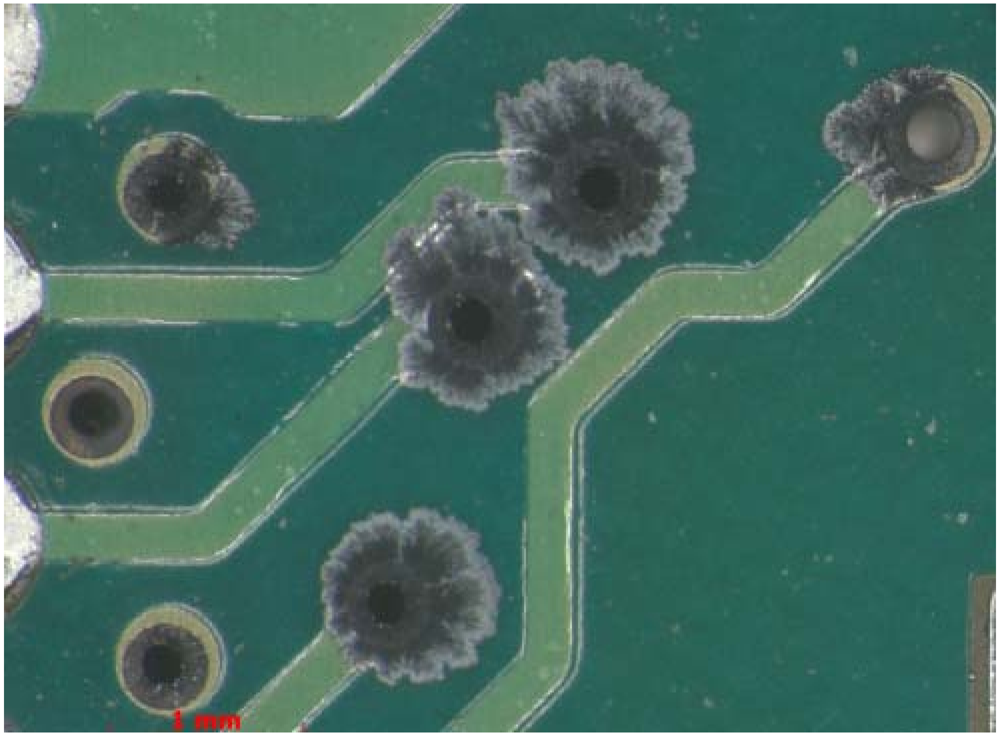

Figure 7 Corrosion on an immersion-silver plated PWB (courtesy HP)

A primary driving factor in corrosion is the galvanic reaction between silver plating and the copper traces on the PWB. Figure 8 shows the mechanism identified by Dell. This failure mechanism is not observed with traditional tin-lead solders and plating. In severe cases, the corrosion byproducts have caused the PWB assembly to fail by creating an electrically conductive path between adjacent conductors.

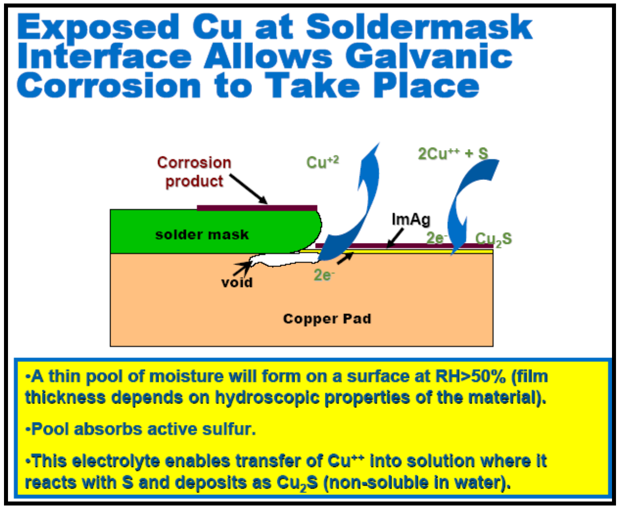

Figure 8 Mechanism for PWB corrosion (courtesy Dell)

Microvoiding

When using immersion silver plating for solder pads, another potential failure mechanism of lead-free products that has been recently discovered is known as "micro-" or "champagne-" voiding. To date, the industry is not in total agreement as to the cause of micro-voiding. Potential causes include micro-roughness of the plated surface or the plating chemistry. Electronics manufacturers do agree that excessive micro-voiding can weaken the solder joint to a degree that will shorten both the fatigue life and the shock resistance of the component. Figure 9 shows a BGA solder joint with severe micro-voiding.

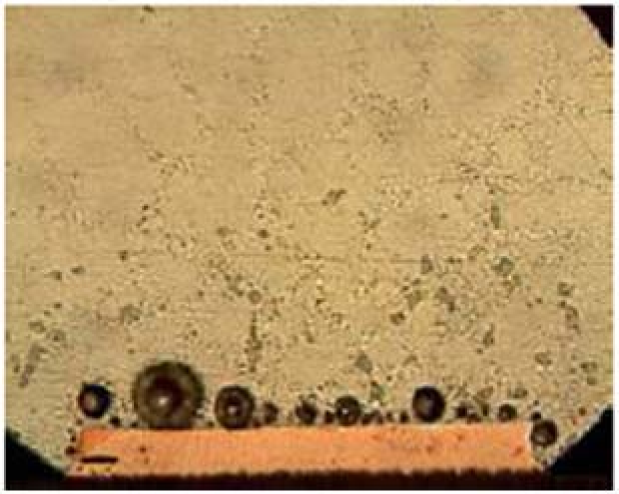

Figure 9 Immersion Ag / SAC Solder joint with micro-voiding

Kirkendall Voiding

Another interfacial voiding mechanism that can significantly weaken a lead-free solder joint is Kirkendall voiding (16). Kirkendall voiding is caused by solid state intermetallic reactions between the solder and the copper pad. The voiding is accelerated at high temperatures. Wide variations in the rate of void formation have been observed. While this mechanism did occur with tin-lead solders, it appears to be a more significant challenge with lead-free solders. Over time, Kirkendall voiding can weaken the solder joint to the point where the interface becomes susceptible to shock related failures. Figure 10 shows a severe case of intermetallic voiding in which the interfacial integrity of the solder joint has been compromised. Because of the higher operating temperatures and extended product lifetimes, server products are far more likely to encounter long-term issues with Kirkendall voiding than is the typical consumer product.

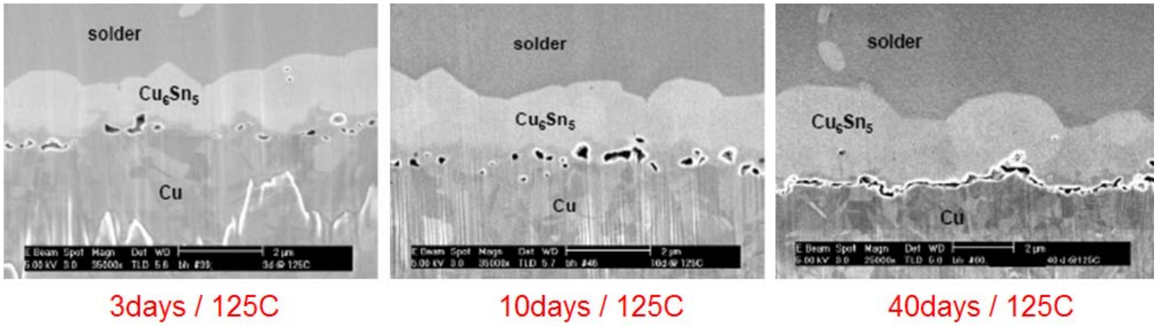

Figure 10 Kirkendall voiding in Cu_3Sn solder joint intermetallic layer

Snowman Failures

Thermal and solder process issues in Pb-free manufacturing have been solved for a large varity of electronic products. Manufacturers have been successfully shipping products using Pb-free solder for several years now. However, for massive, high complexity PWBs used in some servers and NIE equipment, a few issues remain to be solved. One such challenge is the manufacturing defect associated with lead-free soldering processes named the “snowman” or “head in pillow” defect (Figure 11). This problem can occur with large, ceramic BGAs, especially on thermally massive PWBs. One of the causes of this defect is warping of the component or PWB during the lead free reflow cycle. Mixed alloy soldering processes can also contribute to this defect (26). Because the reflow temperature profile is dynamic, relative coplanarity of component and PWB can change throughout the soldering process. If relative movement occurs during a critical phase of the solder joint formation, the result can be the snowman solder joint. While this defect was sometimes observed with tin-lead solders, it is exacerbated by the higher reflow temperatures of the lead-free process for high complexity PWBs. These defects are of particular concern for some of the second generation lead-free alloys that have melting points 5 – 7 °C higher than those in widespread use until recently [9].

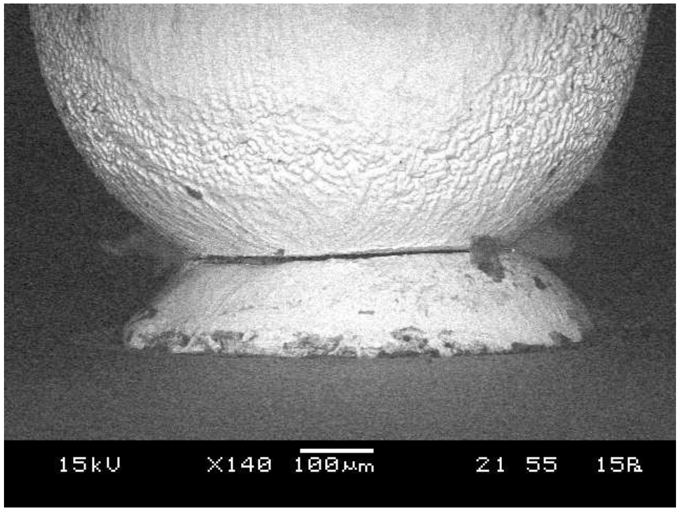

Figure 11 "Snowman" defect (courtesy HP)

Tin Whiskers from SAC alloys

During the last exemption review, tin whiskers were identified as a potential reliability concern. While whiskering of component plating was the primary concern, there is also some evidence that tin whiskering can occur in SAC solders. The first case was documented by the iNEMI Tin Whisker Test Group, which studied voltage bias effects on various components assembled using SnPb and SAC solders. It found tin whiskers of length of 70 to 100 μm after 3000 hours at 60°C, 87% RH (relative humidity). Moreover, these whiskers were found at the foot and shoulder of the component leads in regions wetted by SAC solder.

The second case was reported in CALCE (Center for Advanced Life Cycle Engineering) Tin Whisker Symposium 2006 at University of Maryland (34). Numerous long whiskers (some over 1mm) were found on a Pb-free (SAC) assembly after 20 days of life testing at 65°C and 25% RH, with cyclic load applied. During the tests, these whiskers were found to cause intermittent shorts and triggered system reset. At present, the root cause for such rapid whisker growth remains unclear and requires further investigation. This incident raises concerns about SAC solder's long term reliability and whether it is a suitable replacement for SnPb solder for the high reliability electronic systems.

Component Temperature Tolerance

Lead-free solder assembly of complex, thermally massive PWBs poses thermal challenges not evident in the lead-free assembly of less complex PWB assemblies. The extended times and temperatures required for satisfactory lead-free reflow of densely populated, thick PWB assemblies drive up the peak temperature exposure of the smaller passive components. While the packaging technologies for most semiconductor components have been satisfactorily upgraded to survive elevated lead-free soldering temperatures, some non-semiconductor (passive) componentsstill encountered significant difficulties at high temperatures. Thesepassive components are now recognized by the industry as being Temperature Sensitive.This subset of components poses severe challenges for lead-free solder assembly of complex and thermally massive PWBs. Temperature Sensitive components include, among others, crystals, oscillators, fuses, inductors, and a wide array of capacitor types. Some temperature induced damage, such as delamination, dimensional instability and local melting, is immediate and captured in the manufacturing process. Of greater concern are the time dependant failure modes. These are not detectable in the manufacturing process but can lead directly to system failures in the field. Examples include: damage to the can seals of aluminum capacitors (Figure 12) leading to early dry-out and electrical degradation; increased loss tangent in polyester capacitors at high frequencies (Figure 13), intermittent shorts in inductors due to cracks in the lacquer coil coating, and shifting of resonant frequencies in crystal oscillators. This is but a partial list of known temperature induced component damage mechanisms that will not be evident at the time of lead-free card manufacture. The industry recognizes the need for added component temperature robustness to service a lead-free server and NIE market but the materials challenges involved have proven difficult. JEDEC is now establishing a passive component Temperature Sensitivity rating system (J-STD-075) to assist in managing this assembly challenge.

Figure 12 100μF Electrolytic Capacitor after Pb-free reflow. Bulging indicates temperature induced internal damage with field reliability consequences. (M. Wickham, *et al.*, 2003. (35))

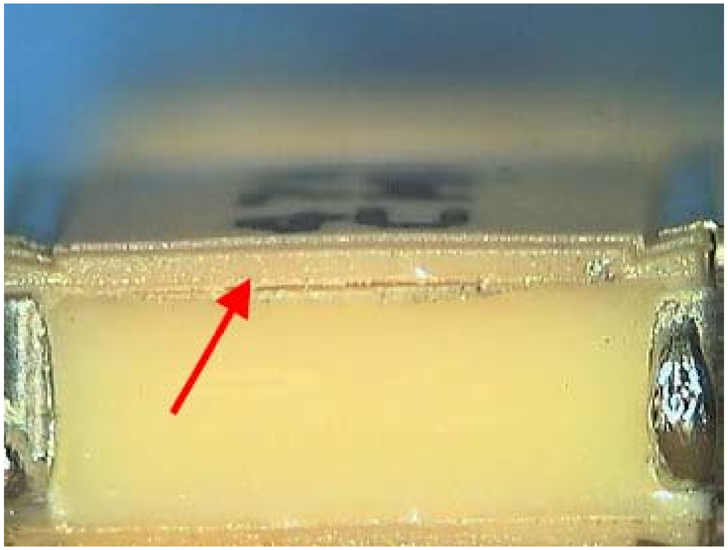

Figure 13 Assembly temperature induced cracks in a Polyester Capacitor (M. Wickham, *et al.*, 2003. (35)).

Pb-free Reflow-Induced Laminate Cracking

PWBs with certain design features that are fabricated with any of a number of different laminates and marketed as being compatible with lead-free soldering temperatures have a propensity to develop cracks within the laminate structure on exposure to these higher temperatures (Figure 14). These internal cracks, which increase the likelihood of electrical opens and shorts, occur within the resin and/or at the glass-to-resin interface.

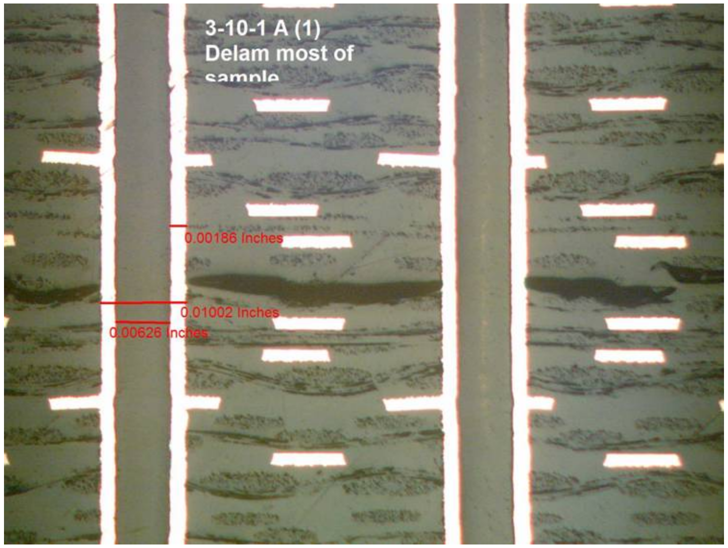

Figure 14 Internal Laminate cracking after high temperature reflow. (courtesy IBM)

Depending on copper plane thickness and location, these laminate cracks may be located at or near the deepest layers of the PWB. The likelihood of finding indications of the presence of these internal cracks through observations of the outer card surfaces decreases with increasing PWB thickness. The propensity for formation of these internal cracks generally increases with increasing peak reflow soldering temperatures and possibly with increasing temperature ramp rates. Formation of these internal cracks is highly dependent upon PWB attributes, tending to be more likely with increasing PWB thickness, decreasing via-to-via pitch and possibly with increasing concentrations of power plane-to-via connections (36).

Summary of Reliability Arguments

Although considerable progress has been made in understanding the reliability of lead-free solders over the last 4 years, there are many indicators that this is not yet a proven technology with sufficient long term reliability for critical applications. As can be seen in many of the illustrated failures, the possibility exists to ship devices with defective conditions that will pass the factory electrical test and visual and X-ray inspection. Over time, these defects are likely to cause an electrical failure that can result in system failure.

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Total EEE volume in EU 27 (2007)		9606510	Oekopol study on The Producer Responsibility Principle of the WEEE Directive	http://ec.europa.eu/environment/waste/weee/pdf/final_rep_okopol.pdf
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Cat III EEE covered by exemption in EU 27		354480	(calculated from above)	
% Pb in Cat III EEE	1,4		Arcadis Ecolas Study of the RoHS Directive	http://ec.europa.eu/enterprise/environment/reports_studies/studies/draft_rep_stu
Pb in solder in EEE covered by exemption		4963	(calculated from above)	

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