RELIABILITY AND FAILURE ANALYSIS

Technical adaptation under Directive 2002/95/EC (RoHS) - Investigation of exemptions

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Executive Summary

The RoHS[1] Directive allows electrical equipment manufacturers to use restricted substances for specific applications where there are no alternatives and these are listed in the Annex to the Directive. This report is a technical review of three of the applications listed in Item 10 of the Annex.

2. "mercury in straight fluorescent lamps for special purposes",
3. "lead in solders for servers, storage and storage array systems, network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunications (with a view to setting a specific time limit for this exemption)",
4. "light bulbs",

and eight proposed new exemptions:

5. "compliant pin VHDM (Very High Density Medium) connector systems",
6. "lead as a coating material for the thermal conduction module C-ring",
7. "lead and cadmium in optical and filter glass",
8. "optical transceivers for industrial applications",
9. "lead in solders consisting of more than two elements for the connection between the pins and the package of microprocessors with a lead content of more than 85% in the proportion to the tin-lead content (exemption until 2010)",
10. "lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85% lead) and any lower melting temperature solder required to be used with high melting temperature solder to complete a viable electrical connection",
11. "lead in solders to complete a viable electrical connection internal to certain integrated circuit packages (Flip Chips) (exemption until 2010)",
12. "safety equipment for fire and rescue services".

The first application in item 10 of the RoHS Directive Annex is decabromo-diphenyl ether which would be No. 1 but is not included in this study. All of the exemptions except for decabromo-diphenyl ether have been investigated and the technical reasons why these exemptions have been requested are explained. Most of these exemptions apply to technically complex components and equipment and to determine whether these exemptions were justified, in-depth investigations have been carried out by ERA. This has included extensive consultation with leading researchers working in these fields as well as consulting the scientific and patent literature.

Conclusions

Exemption Reference		Conclusion
2	Mercury in straight fluorescent lamps for special purposes	There are no alternatives for some applications of these lamps. For some applications, alternative lamp types could be used but these have disadvantages, for example they use more energy, are large or produce coloured light.
3	Lead in solders for servers etc.	There is a risk to consumer safety should these systems fail unexpectedly. The reliability of lead-free solders is being researched using accelerated testing. It is not yet known, however, how to extrapolate accelerated test data to predict field performance and this will not be possible until lead-free solders have been in widespread use for at least five years.
4	Light bulbs	There are no technical reasons why filament light bulbs should not fall within the scope of the RoHS directive. One request for an exemption for a linear incandescent lamp has been reviewed. This is a type of decorative lamp which is similar in appearance to fluorescent lamps. This application uses lead to bond a silicate coating to the glass and there appear to be no substitutes for lead.
5	Compliant pin connector systems	Some connector manufacturers have stated that there is no need for this exemption but users who manufacture high reliability equipment are concerned that the alternative tin coatings may be susceptible to tin whiskers which is, as yet, not well understood.
6	Lead as a coating material … C-ring	Lead is used to obtain a high vacuum seal and there is no alternative material which achieves the required performance. Lead will eventually be eliminated from this application by a complete redesign but this will take until 2009 to complete.
7	Lead and cadmium in optical and filter glass	Most optical glass currently used in electrical equipment is now lead-free but there are certain specific applications where a combination of properties are required and these can be achieved only with lead.
8	Optical transceivers ….	There is insufficient technical justification for this proposed new exemption.
9	Lead in solders consisting of more than two elements for the connection between the pins & the package of microprocessors ….	One microprocessor manufacturer uses a lead solder to attach pins to the package carrier. This alloy gives very high yields whereas a lead-free alternative (which contains antimony) gave poor results when these components were originally developed. Their competitor, however, is able to use this lead-free solder. The applicant would experience poor yield and high wastage if forced to use the lead-free alloy until they have developed techniques to improve yields whereas, as an alternative, they plan to eliminate these solder bonds and the pins by development of a different package design which will be available by 2010.

Exemption Reference		Conclusion
10	Lead in high melting temperature type solders …	Both proposed exemptions are intended mainly for lead in the internal electrical connections within flip-chip packages. These are very varied and complex devices and at present some types cannot be made without lead. Flip-chip manufacturers are able to replace the external electrical connections with lead-free solders and so an alternative wording has been suggested which clearly allows an exemption for lead in "Level 1 bumps" but avoids the possibility of misinterpretation that appears to be a possibility with the original description.
11	Lead in solders …. (Flip Chips)	
12	Safety equipment for fire and rescue services	There is insufficient technical justification for this proposed new exemption.

Several of the proposed exemptions have wording that is unclear. The risk with unclear wording is that it could be misinterpreted or used as a loophole. Alternative wording has been suggested for some of these exemptions. Proposed exemptions 10 and 11 could be combined as both relate to the internal connections within flip-chip packages and manufacturers have stated that they are able to use lead-free solders for the external connections.

The RoHS Directive permits the use of spare parts for the repair and upgrade of equipment put onto the market before 1st July 2006. Equipment put onto the market after this date but within the scope of one of the exemptions (and so, for example, may use lead) will also need to be repaired and upgraded. In many cases this will require spare parts containing restricted substances which would be permitted only while the exemption is extant.

Several applicants have provided dates by which they would no longer expect to require exemptions. Exemptions with expiry dates would cease to apply after these dates unless they are extended by the Technical Adaptation Committee (TAC). All exemptions will be reviewed every four years and defining expiry dates in most cases would seem to be unnecessary.

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Abbreviations List

Bi	Bismuth
CAF	Conductive anodic filaments
CPU	Central processor unit
CRT	Cathode ray tube
DCA	Direct chip attach
EPA	Environmental Protection Agency (USA)
IC	Integrated circuit
K	Dielectric constant <u>or</u> stress optical constant
LCD	Liquid crystal display
LED	Light emitting diode
LGA	Land grid array
NEMI	National Electronics Manufacturing Initiative Inc.
Pb	Lead
PCB	Printed circuit board
PTH	Plated-through-holes
RI	Refractive index
RoHS	Restriction of the use of certain hazardous substances
SAC	Tin, silver, copper (solder)
Sb	Antimony
Sn	Tin
TCE	Thermal coefficient of expansion
TCM	Thermal conduction module
VHDM	Very high density medium

1. Introduction

The RoHS Directive[1] allows electrical equipment manufacturers to use restricted substances for specific applications where there are no alternatives and these are listed in the Annex to the Directive. Item 10 of the Annex is being reviewed by the European Commission. This includes the flame retardant deca-bromodiphenyl ether, (exemption 1) which does NOT form part of this review and three other items which have been included in this study. These are:

2. "mercury in straight fluorescent lamps for special purposes",
3. "lead in solders for servers, storage and storage array systems, network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunications (with a view to setting a specific time limit for this exemption)",
4. "light bulbs".

Eight proposed new exemptions have been requested and are also assessed in this investigation. These applications (original wording) are:

5. "compliant pin VHDM (Very High Density Medium) connector systems",
6. "lead as a coating material for the thermal conduction module c-ring",
7. "lead and cadmium in optical and filter glass",
8. "optical transceivers for industrial applications",
9. "lead in solders consisting of more than two elements for the connection between the pins and the package of microprocessors with a lead content of more than 85% in the proportion to the tin-lead content (exemption until 2010)",
10. "lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85% lead) and any lower melting temperature solder required to be used with high melting temperature solder to complete a viable electrical connection",
11. "lead in solders to complete a viable electrical connection internal to certain integrated circuit packages (Flip Chips) (exemption until 2010)",
12. "safety equipment for fire and rescue services".

The precise wording used for each exemption must be clear and it should not be possible to misinterpret their intentions. Unfortunately some of the existing exemptions in the RoHS Directive Annex are unclear and one, "lead in high melting temperature solders…", is discussed in this report as some of the new proposed exemptions relate to this.

1.1 Grounds for granting an exemption

Article 5 1b states the basis on which the Technical Adaptation Committee may accept exemptions and so the technical issues that have been considered in this investigation are:

- The existence of alternatives that do not contain the six restricted substances
- Whether changes to alternative technology is practical
- Whether alternatives have a negative impact on the environment or human health or consumer safety
- Impact on reliability that may create an increased risk to consumer safety
- Health hazards of alternative materials

Also considered were:

- Impact on global warming
- Release of toxic materials into the environment
- The existence of patents that may restrict manufacturer's options
- Potentially excessive cost increases

1.2 Methodology used for assessment of exemptions

The procedure used in this study to investigate proposed exemptions was as follows:

- Gain a clear understanding of the application. Determine the reasons why the restricted substance is currently used and establish essential characteristics.
- Assess possible alternative materials that could be substitutes for the restricted substance. Determine how substitution affects essential characteristics and performance, for example the appearance, reliability, manufacturing yield, etc.
- Determine whether alternative materials have a negative environmental impact, they are harmful or could pose a risk to consumer safety for example due to an unexpected premature failure.
- If no suitable replacement materials are available, then the possibility of using an alternative production procedure was reviewed.
- Different product designs that perform the same function could be viewed as alternatives and these were also assessed in this study.

Many of the applicants provided information of the quantity of restricted substance that the application would use, the potential impact on the environment and commercial issues such as the affect on employment. These have been taken into account as secondary issues but the Technical Adaptation Committee will use the criteria defined in Article 5.1 b as described above in section 1.1.

An exemption is not required if the application is for equipment that falls outside of the scope of the RoHS Directive. However these applications may have an impact in some cases. For example, lead optical glass of certain types is used in relatively small quantities. Some of the applications may be within the scope of RoHS and others are outside of the scope. The market size may be too small for manufacturer of the glass to be worthwhile if the applications within the scope of RoHS were to cease thereby preventing its use in all other applications.

A variety of sources of information were used in the course of this investigation. These included:

- The scientific and patent literature was reviewed for all of the exemptions in this study. This proved to be very limited in some areas, but extensive in others, for example, there is extensive research currently into tin whiskers and as a result a large number of technical publications.

- Consultations with applicants of the exemptions

- Discussions with leading experts. Research into substitutes for lead and other restricted substances is being carried out mainly by component and equipment manufacturers and this is frequently not published. Therefore the technical experts who are carrying out this research were identified and interviewed, usually by conference call (many are located outside of the EU), but also with face-to-face meetings. This provided a lot of data that was valuable for assessment of the technical issues and characteristics of potential alternatives.

- Other experts and others who wanted to contribute towards this study were also consulted. ERA contacted Trade Associations and issued a press release to encourage anyone with an interest to contribute towards the study.

Typically, discussions would take place with the applicants and others with an interest in each exemption. As a result of initial contact, ERA identified the most appropriate experts in each organisation for further more detailed technical discussions. In some cases, additional questions were asked at a later date and in one case the applicant decided to carry out a reliability study to obtain the necessary supporting data to justify their request for an exemption. In parallel, the information provided by manufacturers was assessed by comparison with independent research publications where these were available.

1.3 Background to the proposed exemptions

The three exemptions included in item 10 of the Annex which form part of this review are:

- **2 - Mercury in straight fluorescent lamps for special purposes**

  The Annex includes four exemptions for different types of mercury lamps but only "mercury in straight fluorescent lamps for special purposes" is to be reviewed. This review establishes:

  - What are "special purposes"?
  - Is this exemption required?

  Note that if a mercury lamp is not mentioned in items 1 – 3 of the Annex, it will be covered by item 4 as this applies to "mercury in other lamps not specifically mentioned in this Annex". Therefore, if any restrictions apply to mercury in straight fluorescent lamps for special purposes, these lamps need to be identified.

- **3 - Lead in solders for servers, storage and storage array systems, network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunications (with a view to setting a specific time limit for this exemption)**

  This exempts lead in solders only and <u>not</u> lead in other materials <u>or</u> the other five restricted substances. The scope of this exemption is unclear and whether expiry dates are needed and what they should be needs to be defined.

- **4 - Light bulbs**

  The scope of the RoHS Directive (Article 2.1) includes "light bulbs and luminaires in households" but the Annex states that "light bulbs" are to be reviewed. In this investigation, it is determined whether is possible to manufacture filament light bulbs without the six restricted substances. The study also investigated one application for a type of filament light bulbs where an exemption had been requested.

Eight possible new exemptions are investigated. The European Commission received these requests before publishing the tender invitation for this project. (More exemption requests have been received since, however these are not considered here unless they are within the scope of those being studied.)

- **5 - Compliant pin VHDM (Very High Density Medium) connector systems**

  Compliant pin or press-fit connectors are used in a variety of electrical equipment. VHDM is a trade mark from "Teradyne" who are one manufacturers of this type of connector. All types are considered in this study. Compliant pins have tin/lead alloy coatings and this exemption has been requested to allow the continued inclusion of lead in these coatings.

- **6 - Lead as a coating material for the thermal conduction module c-ring**

  Lead is used to create a hermetic seal in the central processing unit (CPU) of IBM top of the range main-frame computers.

- **7 - Lead and cadmium in optical and filter glass**

  A variety of glass compositions are used in optical components used in electrical equipment. Some contain lead. There are many lead-free glasses however, the characteristics may not be the same or suitable for all applications. Cadmium is used in optical glass filters.

- **8 - Optical transceivers for industrial applications**

  Most optical transceivers are used as part of telecommunications networks and so are covered by the exemption for lead in solders for Network Infrastructure equipment. However, a small percentage is used in industrial applications including audio and visual data transmission.

- **9 - Lead in solders consisting of more than two elements for the connection between the pins and the package of microprocessors with a lead content of more than 85% in the proportion to the tin-lead content (exemption until 2010)**

  This exemption request is from one microprocessor manufacturer which uses a specific alloy containing less than 85% lead. The Annex of the RoHS Directive includes an exemption for lead in high melting temperature type solders. This indicates that solder alloys with greater than 85% of lead are exempt although some clarification of what this existing exemption includes has been requested by several individuals and manufacturers.

- **10 - Lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85% lead) and any lower melting temperature solder required to be used with high melting temperature solder to complete a viable electrical connection**

  This exemption request is principally intended for flip-chip packages which use high melting temperature solder bumps which are attached to the carrier using a eutectic tin/lead solder. This exemption would also cover situations where high melting point solder balls, such as those used on ball grid arrays, are attached to printed circuit boards using lead-free solder.

- **11 - Lead in solders to complete a viable electrical connection internal to certain integrated circuit packages (Flip Chips) (exemption until 2010)**

  Flip chip integrated circuit (IC) packages are increasingly being used in electrical equipment. There is a very large variation in size and construction and there is no one standard “flip chip”. There are some “lead-free” flip chip already available but manufacturers are concerned because some of the more complex designs cannot yet be manufactured without the use of eutectic tin/lead solder or that their reliability if made “lead-free” is uncertain. This proposed exemption was requested to cover internal connections in flip-chip packages that currently use eutectic tin/lead solder bumps.

- **12 - Safety equipment for fire and rescue services**

  This request for an exemption was received by the Commission some time ago but they have no record of who requested it. However, this has been investigated.

1.4 Existing high melting point solders exemption

The Annex of the RoHS Directive includes (item 7.1) an exemption for “lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85% lead)”. As several of the new requested exemptions refer to “high melting temperature solders” the interpretation of this phrase is discussed here.

Some manufacturers have stated that, in their opinions, the wording used for this exemption is unclear. The wording implies that alloys that contain only lead and tin are within its scope and so other alloys containing > 85% by weight lead are not covered; however this may not be intentional and the original intention may have been that these alloys should be included. Soldertec has proposed a revised version which aims to provide an unambiguous wording and one which clearly includes all solders which contain more than 85% lead:

“Lead in high melting temperature type solders (lead-based alloys containing 85% or more lead).”

It is unclear now what was originally intended by the current wording. One view expressed is that it is intended only for lead-tin alloys (and so Soldertec’s suggested alternative version would be a new exemption request) but, as with some of the other exemptions, they are often worded to combine several similar exemption requests from several different applications. Unfortunately records no longer appear to exist which would clarify this issue.

Exemptions are acceptable if there are no alternatives to the use of a restricted substance. There are only a small number of lead-free solder alloys with a melting temperature between about 260°C and about 350°C. All of these, however, have significantly different physical properties to the alloys based on lead. Lead solders with >85% lead are ductile whereas all of the lead-free alternatives such as bismuth-silver, gold-tin and gold-silicon are hard, brittle materials and so unsuitable for many of the applications where high melting temperature lead-based solders are currently used.

Proposed new exemption ref. 9 (in the list in section 1) is for a solder which contains less than 85% lead although the lead : tin ratio is in fact >85%Pb : <25%Sn since this alloy contains a third element.

Proposed new exemption ref. 10 (in the list in section 1) is for a combination of lead-tin solder containing >85% lead (and so covered by the existing exemption – 7 in the RoHS Directive Annex) but with a low melting point solder (typically 37% lead). In combination, the material will contain <85% lead and so is not covered by the current exemption 7 of the RoHS Directive Annex.

It is worth noting that all concentrations expressed as percent in the RoHS Directive are intended to be weight percent. “Weight” (%) is specified in exemption 6 of the RoHS Directive Annex but not in the others. Weight percent is correct and is different to volume %, atomic %, etc. and so inclusion of the word “weight” would make this clearer.

2. Review of the proposed exemptions

2.1 Mercury in straight fluorescent lamps for special purposes

2.1.1 Definition of "special purposes"

Special purpose indicates lamps used for other than general illumination such as the purpose of the lamps covered by items 1 and 2 of the RoHS Directive Annex.

Examples include:

- LCD backlights
- Light sources in scanners, printers, photocopiers and fax machines
- Disinfection lamps
- Medical/therapy lamps
- Pet care lamps (such as those used within aquaria)
- Lamps for use at low temperature
- Extra long lamps which contain > 10mg of mercury
- Amalgam lamps

2.1.2 Alternative lamp types

The Annex includes four exemptions for different types of mercury lamps but only "mercury in straight fluorescent lamps for special purposes" is to be reviewed. This review will establish what are "special purpose lamps", whether this exemption is required and should there be a limit on the quantity of mercury in individual lamps? It is worth noting that if a mercury lamp is not within the scope of items 1 – 3 of the Annex, it will be covered by item 4 as this applies to "Mercury in other lamps not specifically mentioned in this Annex".

Various alternative types of lamps are available but all have different characteristics. Examples, including some newly developed lamps, are listed in Table 1.

There is no equivalent substitute for straight fluorescent lamps for some applications as all of the alternatives are different in one or more ways.

Table 1. Characteristics of existing straight fluorescent lamps and possible alternatives

	Lamp type	Lamp size	Light output efficiency (Lm/W)	Useful life (hours)	Characteristics
Existing	Straight mercury	From 2.4 mm diameter	90 – 100	18,000 (economical) 24,000 (average)	Can be made very thin
Potential alternatives	High pressure sodium (most contain mercury)	>30 mm	95 - 150	~40,000 hours	Light colour not equivalent to straight fluorescent but mercury free version available
	Low pressure sodium	>30mm	170		Yellow colour
	Planon[2] flat (xenon) lamp	10 mm thick	25 – 27	100,000 (maximum)	Proposed LCD backlight replacement but runs too hot. Not RoHS compliant as it contains lead solder
	Linex[3] (type of xenon lamp)	10 mm diameter	~30 – 50	2,000	10 mm diameter straight
	Short xenon lamps	>10 mm diameter	10 – 50 Perkin-Elmer Cermax = 19	Perkin-Elmer Cermax = 4,000 (average)	Long xenon (>20 cm) uncommon and low efficiency
	LED (white)	Very small	20 (50 by 2005)[4]	>50,000 (30% degradati on)	Not straight lamp but possible LCD backlight replacement

Most alternative types of lamp (including filament lamps) are less energy efficient so their use as alternatives to mercury fluorescent lamps would increase global warming. Mercury is emitted during power generation by oil and coal combustion and an EPA study[5] found that the quantity of mercury emitted during the life cycle of a CRT monitor was more than the mercury emitted and used in the equivalent life cycle of an LCD monitor.

Most xenon lamps also have much shorter lives (except for the new Planon lamp), they run too hot for some applications, are too large and are currently over 7 times more expensive. The performance and energy efficiency of LEDs are improving and are now used in some scanners and printers and for illumination of small LCDs. These applications require gradient index lenses (see section 2.6) which use a glass containing lead. At present LEDs are less energy efficient and more expensive than straight fluorescent lamps and, as they are point sources, they cannot be used for higher quality scanners, copiers and for large LCDs. Less energy efficient lamps are also unsuitable in battery powered products such as mobile phones and laptop computers.

Organic light emitting diode displays have recently been developed[6]. These can be used as an alternative to Liquid Crystal Displays (LCD) with mercury lamp backlights but currently are available only in small sizes suitable for mobile phone displays, etc.

2.1.3 Summary of the case for an exemption

There are alternatives to straight mercury lamps for special purposes for some applications but they have certain uses where there are currently no alternatives. Also, where alternative lamps such as Xenon lamps could be used, these are less energy efficient and so would have a negative impact on the environment.

2.2 Lead in solders for servers, storage and storage array systems, network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunications (with a view to setting a specific time limit for this exemption)

2.2.1 Reason for exemption

Manufacturers of equipment that would be covered by this exemption request are concerned that the long term reliability of their products made using lead-free solders is not known and may be inferior to products made using tin/lead solder.

"Servers" is a term currently used to include all large computation systems and includes mini and midi systems as well as main-frame and super-computers. This equipment is essential for the operation of most businesses, government departments, hospitals, and many other organisations. These systems usually run continuously for at least 10 years and may be in use for 30 years. Continuous operation without downtime to repair faults is essential for many users. The cost of downtime to a bank or insurance company can be many millions of euros per minute. Servers are also used in hospitals, by the emergency services, for traffic control, to control railway signalling and for air traffic control where an unexpected defect could pose a serious threat to consumer safety. Server manufacturers aim to build machines which have typically less than 4 hours downtime over a 10 years life (source IBM).

Network infrastructure equipment is also essential for normal life. Telecommunications (e.g. public telephone networks) relies on a reliable network which does not fail. Unexpected failures could pose a threat to consumer safety if, for example, communications with the emergency services is not possible due to a break down within the system. This risk would occur if the failure was to the public network or in the private network at a fire station, doctor's surgery or hospital department.

There clearly could be a threat to consumer safety if the use of alternative lead-free solders were to result in Servers or Networks failing prematurely. The aim of this investigation, therefore, is to determine if premature failures are likely to occur and when manufacturers are likely to be able to use lead-free solders.

2.2.2 Definition of the scope of exemption

A definition has been produced in collaboration with manufacturers covering the following:

- servers, storage and storage array systems
- network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunications
- definition of "solders"
- spare parts for repair, upgrade and re-use

2.2.3 Alternatives to lead in solders and concerns with the affect on reliability

Many different lead-free solders have been developed and several types are used in electrical equipment. A lead-free solder must contain metallic elements that are:

- Non hazardous
- Non reactive
- Not in very limited supply or very expensive
- Contain elements with melting point of about 1000°C or less

Only a very limited number of combinations of elements can fulfil all of these requirements.

Researchers have formulated and tested several hundred different alloys but all are different to standard tin/lead and there is no one alloy that can be used as a direct replacement that has identical properties. The main difference is that they have higher melting point but they are also harder, less ductile materials and solder wetting tends to be inferior. Some alloys contain zinc and have similar melting point to tin/lead but these are susceptible to corrosion. The addition of bismuth lowers melting temperature and improves wetting but causes difficulties with recycling, is difficult to repair or rework and can produce weak solder joints if lead is also present.

Some electrical equipment, mostly consumer electronics, is now being produced using lead-free solders but the types of PCBs used in Servers or Network equipment are larger and more complex and so more difficult to produce and are likely to be more susceptible to defects if all of the failure mechanisms are not understood and well controlled by the producer. In normal use, consumer electronics equipment is not used continuously for over 15 years without downtime unlike the equipment covered by this exemption request. Equipment manufacturers need to be aware of the differences between tin/lead and lead-free solders to avoid early failure of their products and modify production processes to compensate for these differences. This is more difficult with large, thick, very complex PCBs than with simpler types. The characteristics of PCBs from three types of electrical equipment are summarised in Table 2.

Table 2. Characteristics of PCBs

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)

Component damage

Many electronic components have a limited upper temperature. While these are suitable for use with tin/lead solders, most lead-free alloys require a higher processing temperature which will damage some types of components. Tin/lead solder melts at 183°C whereas the lead-free solder most frequently recommended as the alternative is tin/silver/copper which melts at 217°C, which is **34°C higher**. This results in the temperature becoming much hotter during soldering processes which may exceed some components upper temperature limits.

Equipment manufacturers are able to minimise soldering temperatures to some extent by careful control of soldering conditions, the use of modern soldering equipment and ensuring that all surfaces to be soldered are clean and oxide free. However, the temperature of components on a PCB will depend on the characteristics of the PCB. Thin laminate with few layers and having only small, low thermal mass components such as in a mobile phone can successfully be manufactured, with state of the art ovens, at a temperature of 235°C. This is only 15 – 20°C higher than is normally used for tin/lead PCBs and at this temperature most components survive undamaged. However, when large, high thermal mass components or thick, multilayer PCBs. which also have a high thermal mass, are required, the board and components will need to be heated to up to 260°C. At this temperature, many components will be damaged.

Damage to plastic connectors and many other types of components will be obvious as connectors will be distorted and, if components are destroyed, the equipment will not function. However, some damage is not immediately apparent and failure occurs only after a period in service. Electrolytic capacitors lose electrolyte if over-heated which will shorten their life. Multi-layer ceramic capacitors are brittle and crack due to strain from thermal mismatch between board and component or if the PCB warps due to over-heating. This is not uncommon with tin/lead soldering but is likely to be more common with the higher temperatures needed for lead-free.

Component manufacturers are currently working to increase the upper temperature limit of their products and some new more heat resistant components have recently become available. However, it is likely that there will be some components used on the most complex Server and Network PCBs that cannot at present withstand the higher soldering temperature required for this type of PCB. Some manufacturers of Servers and Networks report that they have produced some types of PCBs with lead-free solders under laboratory conditions but have not been able to produce lead-free PCBs in a production environment, which would be essential for long-term reliability trials, partly due to the unavailability of heat resistant components.

PCB damage

The UK's National Physical Laboratory[7] has carried out research on the effect of soldering temperature on damage to PCBs. Their results showed that delamination and warping of PCBs increases with temperature. They also showed that failure of PCBs by a process called conductive anodic filaments (CAF) becomes increasingly more likely as the temperature increases. CAF is very uncommon with tin/lead solders.

Research also shows that damage to plated-through-holes (PTH) becomes more likely as the temperature increases. PTH are used to create electrical connections between layers within the PCB. These are made of copper which has a much smaller coefficient of thermal expansion than the laminate material itself in the z-axis (the direction of the PTH through the thickness of the board) and therefore strains are set up in the materials as the temperature changes.

Thermal fatigue

The temperature of circuit boards in most types of electrical equipment changes repeatedly during its life. This can be due to ambient temperature changes but this would not be the case for Servers which are used in air-conditioned and temperature controlled rooms. However, many components themselves produce heat and so when these are functioning, their temperature changes. Changes in temperature due to internally produced heat occur when components become active even when equipment is already switched on. Servers and Networks are usually required to run continuously but temperature changes occur due to the activation and deactivation of individual components. These temperature changes may occur a very large number of times during the life of a Server or Network PCB. These temperature changes are a problem because the TCE (thermal coefficient of expansion) of most components is different (and usually smaller) to that of the circuit board to which they are attached.

Temperature changes result in repeated cyclic strain on the solder bonds which can eventually cause it to produce cracks leading to an open circuit. This effect, illustrated in Figure 1, is called "thermal fatigue". Real examples of thermal fatigue failures are shown in Figure 2.

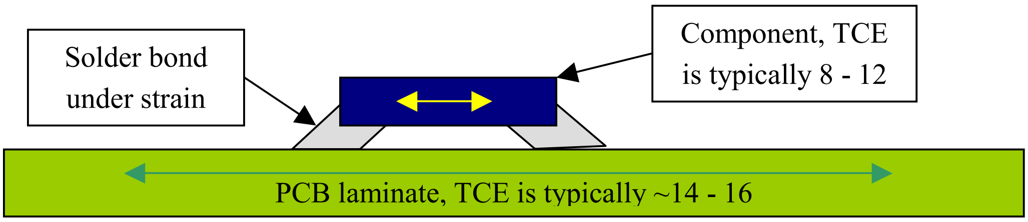

Figure 1. Schematic cross-sectional diagram of a component mounted on a board showing how temperature changes produce strain in the solder bonds.

Tin/lead solders have been used commercially in electrical equipment for many decades and their thermal fatigue properties are well understood. It is possible to carry out accelerated life tests on equipment made with tin/lead solders to determine the likely field life. This is possible because manufacturers have many years of experience with their products in the field so that accelerated tests can reliably predict field lives of tin/lead soldered products. It is not possible, however, to estimate field life expectancy from accelerated tests with lead-free solders because these solders have been used in mass produced electrical equipment for only a few years.

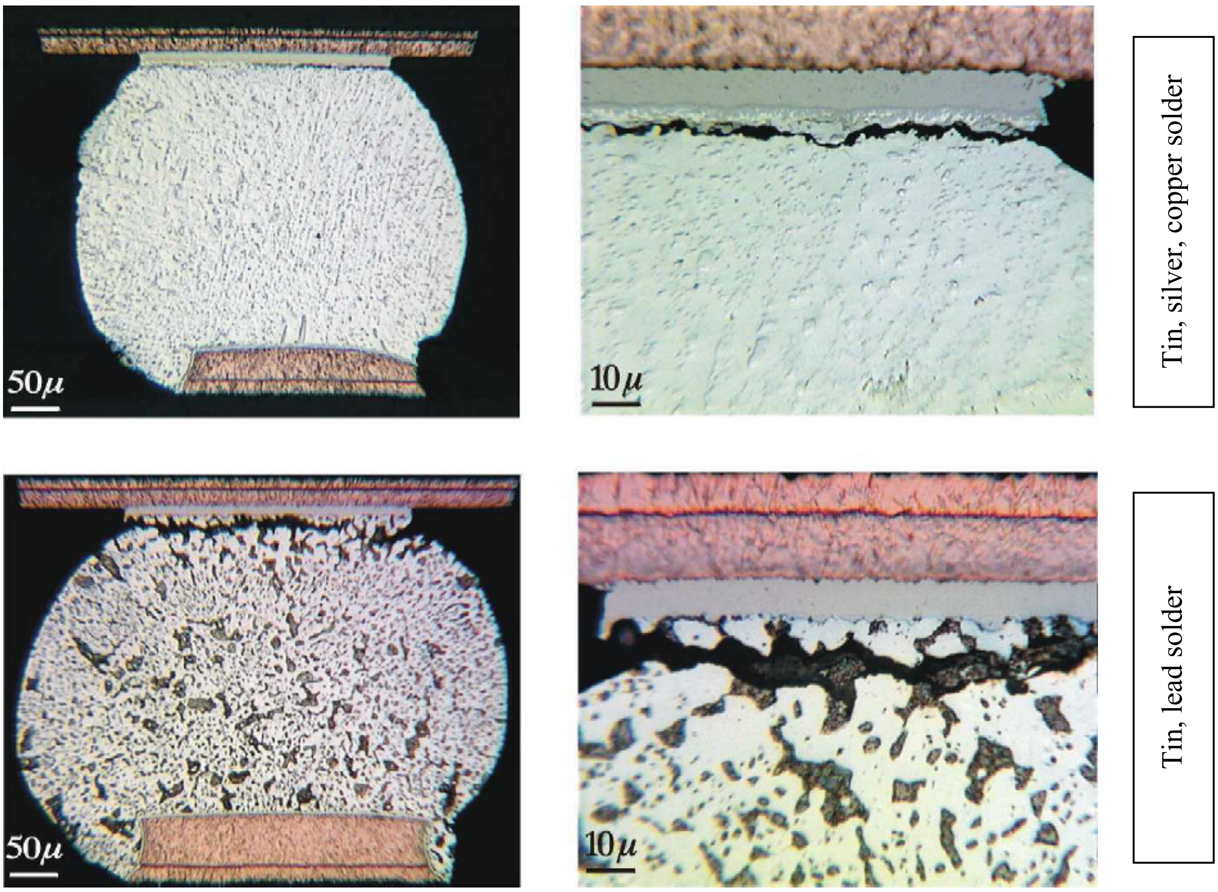

Figure 2. Ball grid array solder bonds that have failed by thermal fatigue. (Image from Cookson Electronics)

Accelerated life testing has been carried out with lead-free solders, however, and the results compared with tin/lead solder. Data from many investigations has been published and appears to show:

- Where there is a high strain, lead-free solder bonds fail after fewer cycles than bonds made with tin/lead solder.
- Where there is a low strain, lead-free solder bonds fail after more cycles than bonds made with tin/lead solder.

These results indicate that if high strain bonds can be avoided, reliability will be better with lead-free solders but the relationship between these accelerated tests and field conditions is unknown. High strain situations cannot be avoided, particularly with Servers and Networks which have large components soldered to PCBs. Therefore, if lead-free solders are used, there is an unquantified risk of premature failure due to thermal fatigue.

Comparison of accelerated test results from tin/lead and lead-free solders may be incorrect as the microstructure and creep behaviour of these alloys are different so that they cannot be directly compared. Accelerated tests use relatively short dwells to shorten the test time. It is during the upper temperature dwell that most creep occurs. It is known that creep of eutectic tin/lead is 10 – 100 times faster than lead-free solders and it is possible that these tests under-estimate the risk of thermal fatigue with lead-free solders[8].

To quantify this risk, equipment manufacturers will need to wait for field data to be received from a statistically meaningful number of pieces of equipment which has been in use for sufficient years in service. This data will enable them to determine the relationship between lead-free accelerated life test data and field life and establish whether lead-free soldered Servers and Networks can be used safely.

Tin whiskers

Tin whiskers have been known to occur on electroplated tin coatings for many years and have caused some well-publicised and expensive failures[9] (http://nepp.nasa.gov/whisker/failures/index.htm). Tin whiskers can cause short circuits in electrical equipment leading to either complete failure or intermittent faults. This potential problem was avoided in the past by using tin/lead coatings instead as tin because lead added to tin significantly reduces the susceptibility to whisker formation and, although tin/lead whiskers do occur, they are usually very short, so are not likely to cause a short circuit.

Causes of whiskers

It is fairly certain that tin whiskers are caused by stress within electroplated tin coatings. The exact mechanism is not well understood and there may be several underlying causes. It was at one time thought that "bright" tin was much more susceptible to whisker formation than "matte" tin coatings. Bright electroplated coatings usually do have more stress partly due to incorporation of organic compounds used to brighten the coating but recent research has shown that it is possible to produce bright tin with a low susceptibility and some matte tin coatings have been found to readily produce many long whiskers.

Tin deposited onto copper will form an irregular tin/copper intermetallic layer. As this grows, some research has indicated that this increases the strain in the tin coating which eventually causes whiskers. Some manufacturers now always electroplate tin onto a nickel barrier layer. Tin and copper form an intermetallic much more slowly and so whiskers are much less likely to form.

Humidity, voltage bias, tin thickness and the effect of heat (i.e. pre-baking or soldering) all influence whisker formation and growth and some of these variables are not fully understood.

Prevention of whiskers

NEMI[10] have published methods to prevent tin whiskers. One important characteristic of whiskers is their length. It is normally only long whiskers that cause short circuits and, frequently, whiskers are very short and would not cause a defect. NEMI's recommendations include:

- Use nickel/gold or nickel/palladium coatings instead
- Ensure that tin is electroplated over a nickel barrier layer (porosity free nickel has a thickness of a minimum of 1.27µm) of 2µm thickness.
- Hot dipped tin and electroplated tin that has been melted is not normally susceptible however these surfaces have inferior solder wetting properties and the high temperature can damage some components. Immersion tin is also not susceptible.
- Tin-plating bath chemistry is important. Generally matte tin is less susceptible than bright tin. However, some claim that bright tin coatings can be produced which have a low susceptibility. Also, some matte tin coatings can produce many long whiskers. Unfortunately there is currently no quick test for whisker resistance (the NEMI tests take 6 months).
- Tin plating on low TCE materials such as Alloy 42 and Invar is much more susceptible to tin whiskers due to the strain caused by the TCE difference between materials. It is best to avoid tin plating these materials.
- Tin-bismuth has a reduced tendency for whisker formation, especially after reflow, due to its lower melting temperature. The bismuth content should be $<3\%$ and thickness <8 µm if used with SnPb. It is best to avoid this composition if used with SnPb reflow as Bi may build up in solder pot.
- Tin thickness – NEMI recommends a thickness of $>$ 8µm (without a nickel under-layer). Recent research has found that, with nickel, relatively thin tin coatings are preferable.
- Compressive stress is the cause of whiskers and so tin plating in tensile stress is preferable to tin in compression. Do not bend tin plated parts as this will cause compressive stress.

- Bias voltage is known to be detrimental to tin whiskers but the reason is unknown.

Effect on Servers and Networks

Equipment that incorporates components, which have electroplated tin coatings, is potentially susceptible to tin whiskers. Tin whiskers are generally 100 – 150 µm in length but can be much longer. Fine pitch components are the most at risk and many of these are used in these types of equipment.

NEMI have proposed accelerated tests for whisker susceptibility but these take six months and so cannot be used for quality control. Also, as with thermal fatigue, the relationship between these tests and field life over 30 years is not yet known.

Component manufacturers will endeavour to produce components with coatings that do not produce whiskers by careful control of tin electroplating bath conditions. However, as no rapid test is available, if an error occurs this could not be detected (by the six month test) until these components have been incorporated into equipment and is in use. Most component manufacturers use sub-contractors to tin plate lead-frames and so are not in an ideal position to control the plating process.

2.2.4 Exemption expiry dates

Equipment

Most manufacturers of Servers, Storage, Storage Arrays and Network equipment have stated that, in their opinions, they should have sufficient life data to be confident in the use of lead-free solders by 2010, although some Network equipment manufacturers have requested an expiry date of 2012 as long as these solders do not prove to be unexpectedly unreliable. Those Network manufacturers who have requested a later date manufacture products that use the largest and most complex PCBs. In this time, experience will be gained with other lead-free products such as personal computers and, if production of these start in 2005 as planned, there will be 5 years of field data available by 2010. Reliance on only five years field data may be relatively optimistic for products that can have a field life of up to 30 years but will at least show if the reliability predicted by accelerated tests is much worse than expected.

Spare parts for repair, upgrade or reuse

There is an additional issue concerning spare parts for repair, upgrade or reuse. Many of these will have been made at the same time as the original equipment and so will contain lead solders. Lead-free versions will not be available after 2010 or 2012 as many components will have become obsolete. Consequently, lead containing spare parts will have to be used after 2010 or 2012, as shown in Figure 3, to extend the life of these products. If this is not possible, the quantity of waste produced will be increased which contrary to the aims of both the WEEE and RoHS Directives as well as being very expensive for manufacturers and users.

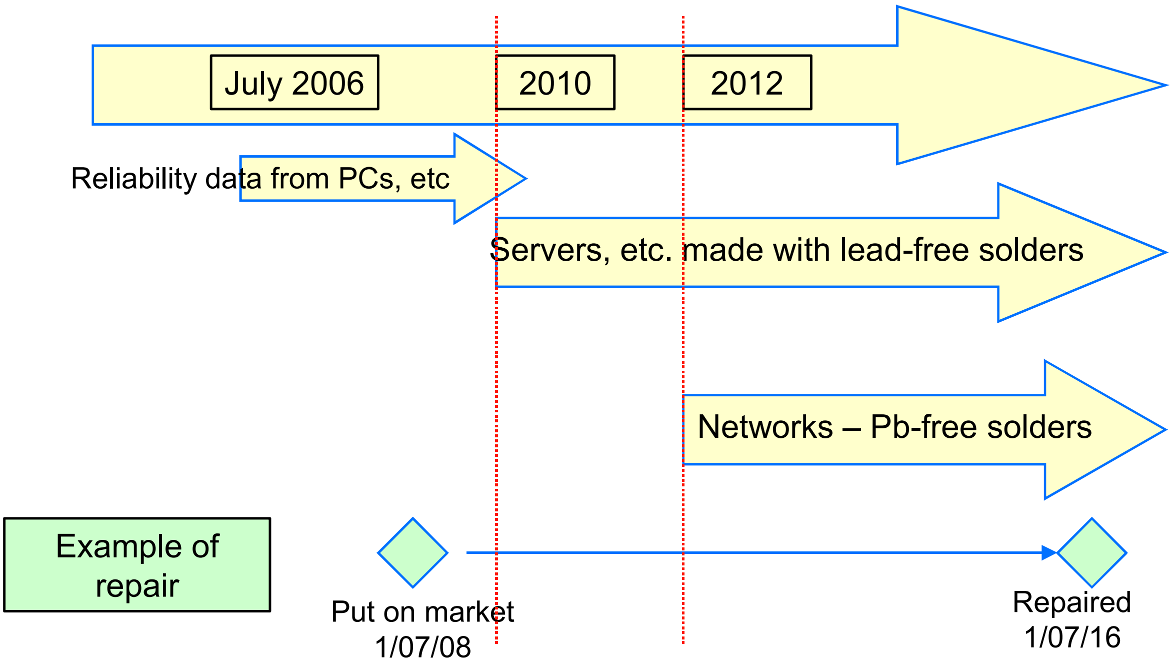

Figure 3. Road map for implementation of lead-free solders in servers, storage and storage arrays, and telecommunications networks

An alternative approach, which would get round this difficulty, is as follows:

1. Set no expiry date on this exemption.
2. Review this exemption again at least every four years as required by the RoHS Directive and so the next review should be no later than December 2008.
3. If this review finds that lead-free solders have been shown to be sufficiently reliable then terminate the exemption at this point. Otherwise, if reliability is still uncertain or frequent failures are encountered, then the exemption could continue - to be reviewed at least every four years until satisfactory reliability is achieved.

2.2.5 Definition of products covered by this exemption

A definition has been prepared, initially by manufacturers of these products and this has been amended in consultation with ERA to avoid potential loopholes. This definition, given in Appendix 1 of this report, covers those products that are currently on the market that should be included by this exemption and excludes those where it is not justified. There is a small risk that some manufacturers will design new equipment, such as desktop computers or telephones, to comply with this definition in order to avoid the need to use lead-free solders. Therefore this definition will need to be regularly reviewed.

2.2.6 Summary of the case for an exemption

Servers, storage and storage arrays and telecommunications equipment have characteristics which are different to most other types of equipment:

- their PCBs are larger, more complex and so more difficult to produce,
- the equipment is intended to operate continuously, often for over 10 years, without down-time,
- unexpected failures could create a risk to consumer safety.

Lead-free solders are available but they have been in use commercially for a relatively short time and the long-term behaviour in the field is unknown. Comparative accelerated test data for lead-free and tin/lead solders is available but there is uncertainty whether this can be relied on as lead-free solders and tin/lead solders have different micro-structures.

Manufacturers will have confidence that lead-free solders could be used in Servers, etc. when consumer equipment that will be produced with lead-free solders has been in use for five years without unacceptably high rates of early failures.

2.3 Light bulbs

This review applies to filament light bulbs which are excluded from the WEEE Directive. Filament lamps are used for general illumination in households and businesses as the light source in some types of luminaries. They are also used in a wide range of electrical equipment, for example in torches (tools), within illuminated switches and as indicators in consumer, IT, and other types of equipment. They are produced as relatively large bulbs such as the example in Figure 4 and as small (miniature) lamps, which can be attached to equipment by various means such as by soldering to PCBs by surface mount technology.

2.3.1 Inclusion of filament lamps within the scope of the RoHS Directive

Many filament lamps are currently made with lead-free glass and either lead-free or high melting temperature solders (>85% lead) and so there is no reason why these should not be within the scope of the RoHS Directive. Some lamp manufacturers are in the process of changing their product range.

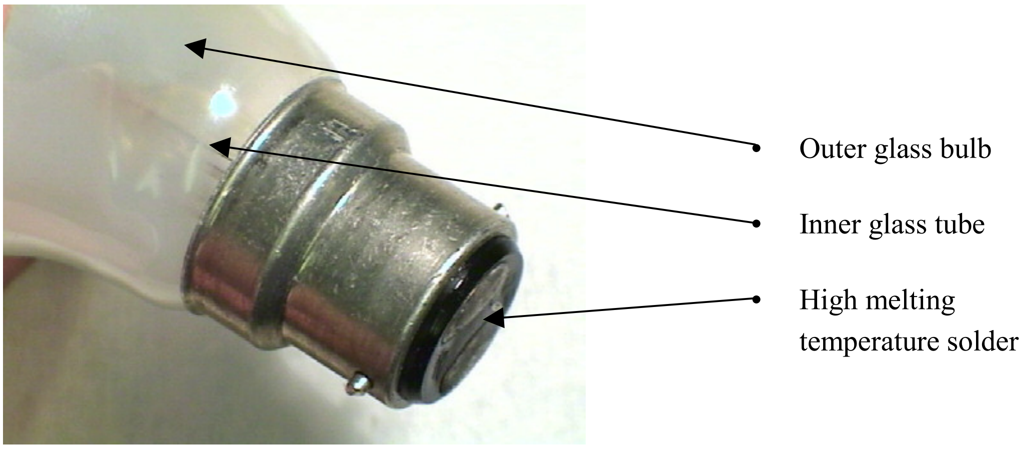

Figure 4. Filament light bulb

Standard filament or incandescent light bulbs can be made using lead-free glass. The composition of the glass used for the outer bulb is lead-free and the inner glass tube, which is used to create the low pressure atmosphere within the lamp and to support the filament wires is also lead-free but has a different composition, frequently with a high barium content. Barium is classified as “harmful” but is generally regarded as less harmful than lead:

- Occupational Exposure Standard for barium = 0.5 mg Ba/m^3. (8 hour time weighted average)
- Maximum Exposure Limit for Lead = 0.15 mg Pb/m^3. (8 hour time weighted average)

High melting temperature solders (>85% lead) are used on lamps which operate too hot for a lead-free solder although some lamp types now use lead-free solder.

Fluorescent and mercury lamps are covered by separate exemptions (for mercury within lamps and for lead in fluorescent tubes only), but there are some special lamps which use lead for other applications and manufacturers have asked for six new exemptions for these types. Only one of these is for a type of filament lamp and this is reviewed here.

It is clear that there is no technical reason why filament lamps should not be within the scope of the RoHS Directive. There is an issue over the adequacy of supply of the special glass used inside the bulbs but this should be resolved by the 1st July 2006 deadline. However, lamp manufacturers have not known with certainty that filament bulbs would be within the scope of RoHS because of the requirement for the European Commission to review light bulbs in item 10 of the RoHS Directive Annex and so some may have delayed converting production processes to “lead-free”. They should be able to convert to lead-free production before the 1st July 2006 but stocks of lead-containing slow-moving bulb types may remain after 1st July 2006. Some of the older lamps made with lead will not have been incorporated into new products put onto the market before the RoHS deadline and after this date these cannot be used in products that are made for the EU market. These can however be used as spare parts in equipment that is put onto the market before 1st July 2006.

2.3.2 Request for exemption for linear incandescent lamp with silicate coated tube

An example of this type of lamp and a typical application are shown in Figure 5.

Figure 5. Linear incandescent lamp and typical application

These lamps have been manufactured for over 65 years. They are a decorative lamp which provides a white light as a result of the silicate coating attached to the inside of the soda lime glass tube. This coating is attached to the glass with a material containing lead. The silicate powder has a high melting temperature and is attached to the glass by melting the lead-containing bonding material. The bonding material must fuse and form a good bond at a temperature below the glass melting temperature. Lead oxide was originally used as a constituent of the glass as it produces glass which is colourless and has a low melting temperature. It forms glassy materials with a wide range of other oxides which is why it bonds well to the glass tube and the silicate coating. Lead oxide, therefore, is the ideal choice of material for this application and is why it was originally used.

There are now many glass compositions which are lead-free. These alternatives have different compositions to lead glasses and it is not usually possible simply to replace lead with another element and retain all of the glass characteristics. Commonly used oxides in lead-free glass include those of barium, bismuth, zinc and titanium. Most of these alternatives give a glass with melting temperatures significantly higher than can be achieved with lead and so are not suitable for this bonding application. Bismuth is often used as an alternative to lead but tends to produce glass with a yellow colour and can reduce transparency to visible light. Lamp manufacturers have also evaluated zinc oxide compositions for bonding. This gave poor non-uniform bonding, a yellow colour and reduced light transmission by about 20%.

Lead is technically the only material currently available that can be used to produce this type of lamp. This is consistent with the bonding materials used in cathode ray tube production. Lead is used as an essential component of the glass frit to form a bond between the front and the cone - an application which is exempt under the RoHS Directive.

Alternative lamps have also been considered as an alternative to this application. Linear incandescent lamps are in some ways similar to fluorescent tubes; both have similar dimensions and produce white light. However there are differences:

- Fluorescent lamps have metal end caps so do not provide the same decorative effect as shown in Figure 5.
- Fluorescent lamps have higher light output efficiency, clearly an advantage where the lamp is used for long periods although this is less significant in applications where the lamps are on for short periods.
- Fluorescent lamps require additional electrical equipment such as choke coils, ballasts, etc. These are not required for incandescent lamps.

2.3.3 Summary of the case for an exemption

Most types of incandescent light bulbs are already produced with lead-free glass and either lead-free solder or solder containing >85% lead and so exempt from the RoHS Directive. Therefore, there are no technical reasons why incandescent light bulbs should not fall within the scope of the RoHS Directive.

Other types of lamp are already within the scope of this Directive. Filament light bulbs are used as components within other products that will be required to comply with the RoHS directive and so stocks of lead–containing bulbs will need to be used well before the RoHS deadline, this will leave those manufacturers who have not already switched to lead-free, little time to develop alternative products.

One exemption request for a particular type of straight incandescent lamp has been reviewed. This lamp uses lead in a material used to bond a white silicate coating to the inside of the glass tube. Technically, this appears to be the only material that provides a good bond, is colourless and allows maximum light transmission. These lamps are used for their decorative affect. Fluorescent tubes have similar visual characteristics and have better energy efficiency but require additional equipment to function.

2.4 Compliant pin VHDM (Very High Density Medium) connector systems

2.4.1 Introduction

Compliant pin or press-fit connectors are used in a variety of electrical equipment. VHDM is the trade-mark of one manufacturer but all types are being considered under this exemption request. Compliant pins have tin/lead alloy coatings and this exemption has been requested to allow the continued inclusion of lead in these coatings.

Several of the larger compliant pin connector manufacturers have stated that there is no need for this exemption as tin can replace tin/lead coatings. This change of materials will increase the insertion force but connector manufacturers and users disagree whether this should be overcome by a small increase in the hole diameter (not always feasible) or decreasing the pin size.

The main concern of users is tin whiskers, for the reasons discussed in section 2.2, but also because these coatings are not heated in the soldering process. There is evidence that soldering heat reduces the stress in coatings which in turn reduces the risk of whiskers being formed. The compliant pin connector manufacturers believe that they can produce tin coatings that are not susceptible to tin whiskers and so the risk is small, however their customers, who produce high reliability products such as Servers and Networks, are concerned that there is a small risk as this issue is not fully understood and so are asking to be able to continue to use tin/lead coated compliant pin connectors in their products until 2010.

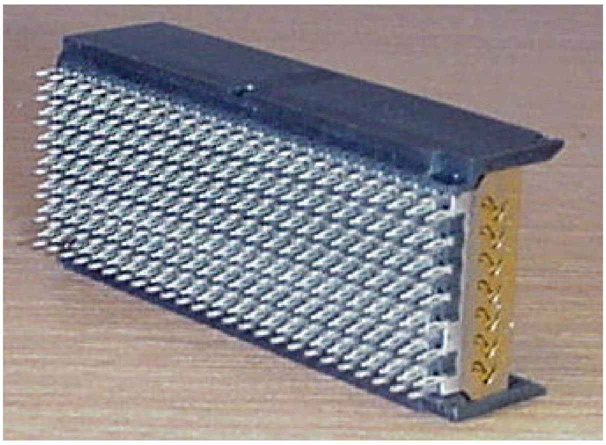

Figure 6. Example of a typical compliant pin connector (length 50 mm)

2.4.2 Construction

These connector systems generally have a large number (hundreds) of closely spaced pins. These compliant pins are inserted into holes in the printed circuit board. These connectors were developed to avoid the difficulties encountered in soldering such a large number of closely spaced pins because the total thermal mass would be so large that it was difficult to achieve the correct temperature throughout the connector for the solder to flow and wet the surfaces. (The situation would be even more difficult with lead-free solders due to their slower wetting and higher assembly temperature). These connectors can be extracted and reinserted several times for repair or to change PCBs (upgrade or repair). As solder is not used, smaller pads can be used around each pin, so that they can be placed closer together. The connectors can also be inserted from both sides of the board, which is a major advantage in backplanes.

The compliant pins have a controlled degree of flexibility, allowing them to be forced into the holes, while clearing away any oxides on the surfaces and then applying sufficient outward force to maintain a good electrical contact. The insertion force is mainly dependent on the hole size with only a secondary dependence on the plating on the pin and the internal hole coating. The retention force is also dependent on the hole size, but much more dependent on the coating composition than in the case of the insertion force. Compliant pin manufacturers claim that average insertion force is increased by about 8 –10% when changing from tin/lead to matte tin (it would be reduced if bright tin were used). Some users find similar or slightly higher figures, up to 15% but these are average figures and one manufacturer has found an increase of 30% for one particular application. The insertion force could be reduced by increasing the hole size but users claim that this is not always possible due to space limitations and in some cases would require a re-design. Users would prefer connector manufacturers to slightly reduce pin diameter.

There are several designs of pins available from different manufacturers. One common type is called "Eye of a Needle" as it looks rather like the end of a sewing needle. The Tyco version is called an "Action Pin" and each side of the eye is bent slightly away from the plane of the pin in opposite directions. Winchester Electronics uses an approximately "C" shaped cross section. The shapes are distorted as the pins are pushed into the board.

2.4.3 Properties required

Compliant pins should:

- be sufficiently flexible to deform as they are inserted into the holes without an excessively high force that might damage the plating in the holes,
- be extractable for repair without damage to the board.

The tin-lead plating on the pins contains only about 10% lead and is only about 1.5 microns thick. It is required to:

- provide lubrication while the pin is inserted and withdrawn,
- have an oxide that can be displaced during insertion,
- ensure good electrical contact once the pin has been inserted.

2.4.4 Alternatives

The request for this exemption is solely for tin/lead plating on the compliant pins. Even though it is used in servers and networks, it is not used as part of a solder joint, as the tin/lead does not melt to form a bond.

Alternative coatings for compliant pins include matte and bright pure tin, and gold. Gold is not suitable for PCBs as it is too hard and increases the insertion force significantly although it is used in applications where very high frequency signals are used.

Tests by Tyco Electronics[11] and other connector manufacturers with pins pressed into PCB holes of a range of sizes with a range of coatings gave good performance. They found that the insertion force was mainly dependent on the hole size and the plating type was a secondary factor. The retention forces depend on the coating on the pin due to the static friction at the points where the metals are in contact. IBM and other users contend that:

- the tests were made only on thinner boards (2.36 mm as against the 3.175 mm used in IBM back planes),
- the tests used only a single layer board compared to IBM's boards of about 30 layers,
- the insertion forces with tin coated pins are on average 15% higher,
- there has been more damage to the plating of the holes,
- there is the possibility of tin whiskers.

At present compliant pin manufacturers and users have not been able to resolve concerns over insertion force. It seems reasonable that by July 2006, this should be resolved by small changes in the design of pins and in some cases, where practical, a small increase in PCB hole size. This would not allow users sufficient time to qualify new connector designs, however, as, they claim, this takes over 2 years and the RoHS Directive comes into force in only 18 months.

The main long-term risk is tin whiskers. This is discussed in detail in section 2.2 and is unlikely to be resolved by 1st July 2006. There has been research as well as informal observations from a variety of manufacturers who are evaluating lead-free production that any tin plated component that is reflowed, has a low susceptibility to whiskers in accelerated tests whereas the tin coatings that are not soldered suffer from a much higher risk of whisker formation. It therefore is a concern that this type of component with tin coatings is more at risk than soldered components.

2.4.5 Future plans

Equipment manufacturers are continuing to examine and test alternative types of compliant pins as they become available but, in many cases, their tests have found that these are unsuitable for their requirements.

2.4.6 Summary of the case for an exemption

There are genuine concerns from manufacturers of high reliability equipment that tin plated compliant pin connectors will have a risk from whiskers. Until this is well understood and a shorter reliable test that is known to reflect field conditions becomes available, this concern will remain.

There is also concern over the potential for damage to holes due to the increased insertion force. Research by the connector manufacturers has identified the causes of increased force and there is no reason why this cannot be resolved by a combination of small modifications to pin diameter and hole diameter.

Connector manufacturers and their customers are already discussing these issues but it seems unlikely that they will be fully resolved before 1st July 2006.

2.5 Lead as a coating material for the thermal conduction module C-ring

Lead is used as a coating material on a sealing ring used in a module at the heart of IBM's highest performance main-frame "super-computers", which are called the "Z Series". These are not used in IBM's lower specification machines or in machines made by IBM's competitors.

This exemption is requested solely by IBM as the highest performance computers made by other manufactures use different designs to make their products. IBM claims that their design has several unique advantages in speed and performance.

2.5.1 Design of equipment

The most important part of an IBM main-frame computer is an array of high performance microprocessor chips and memory chips which are mounted on a glass-ceramic substrate. To ensure the fastest signal transmission between the central processing units (CPU) and the associated memory, these devices are mounted as bare chips as close together as possible in an array with an area of 150mm square.

Figure 7 shows how the components are arranged on the substrate. The processor and memory chips generate a significant amount of heat, typically 1.4 kW. These must be cooled efficiently as the computer would cease to function if it over-heated and this is achieved by the Thermal Conduction Module (TCM). Cooling of the bare silicon chips is achieved by conduction of heat through a thermally conducting paste into a liquid cooled copper "hat". Figure 8 shows the "hat", glass-ceramic and C-ring.

IBM's latest versions contain about 16 semiconductor chips. The electrical contacts to the silicon chips are formed by hundreds of thousands of fragile solder interconnections on the active faces as Land Grid Arrays (LGA). These chips are mounted face down (i.e. flip chip) onto a glass-ceramic interconnection board at the base of the module. To ensure that the use of space is maximised and heat can be efficiently conducted away, the silicon chips are not encapsulated. As a result, the module as a whole has to be hermetically sealed to protect the active surface of the chips, to ensure that the grease does not dry out and to prevent oxidation of the bumps, silicon and chip circuitry. This is achieved with a high vacuum, which is maintained by the lead coated C-ring seal. This is a unique design used by IBM which they claim gives the best performance for their machines.

The very complex high performance chips cannot be adequately tested until they have been mounted in the module. On most of the assembled modules a small number of the chips need to be replaced to ensure the performance required. Therefore, it is necessary to replace defective chips and this means that the modules have to be dismantled, sometimes several times. The C-ring seal is inserted between the upper and lower plates of the modules to enable a demountable but sealed system.

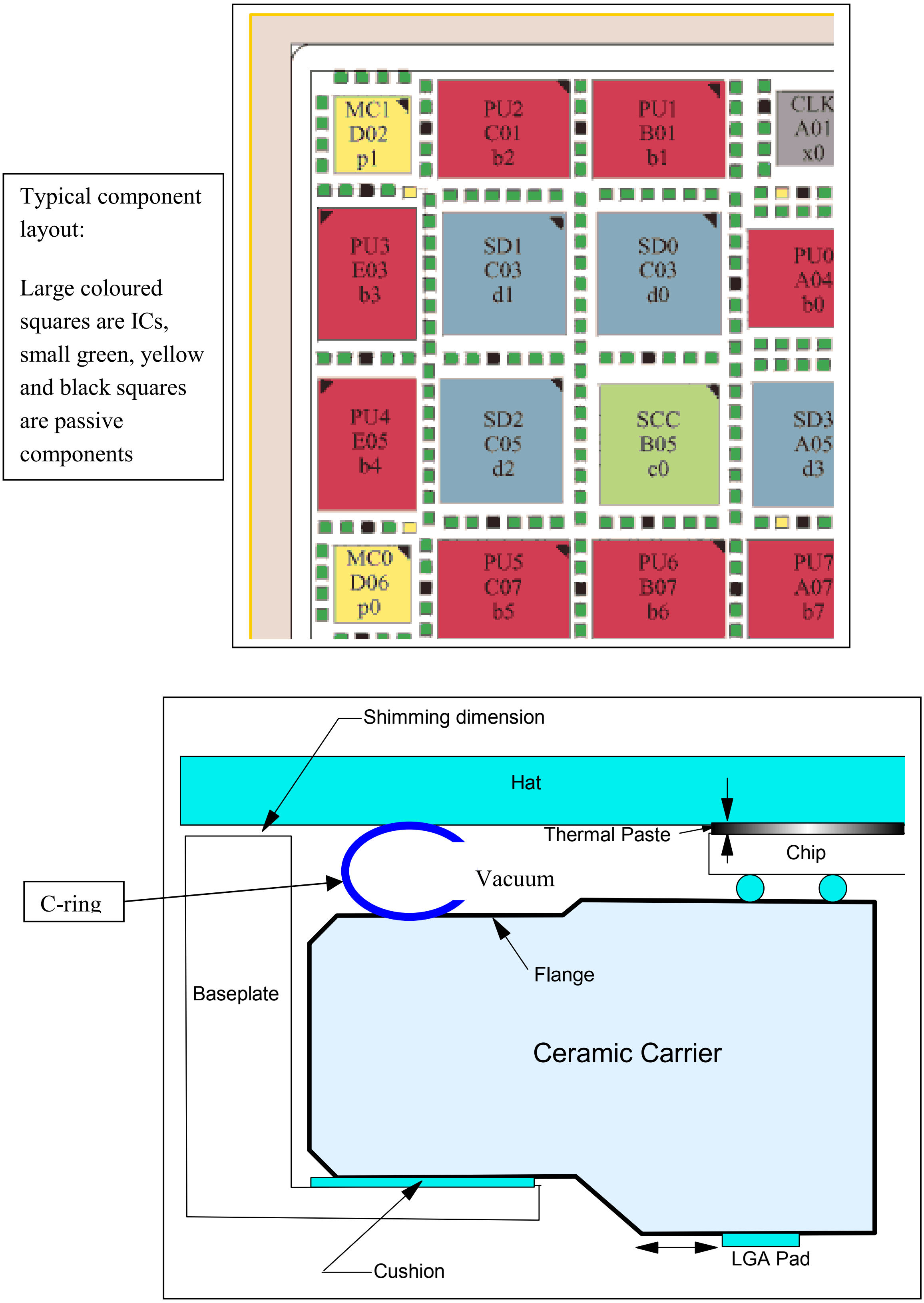

Figure 7. Thermal Conduction Module, component layout and schematic cross-section

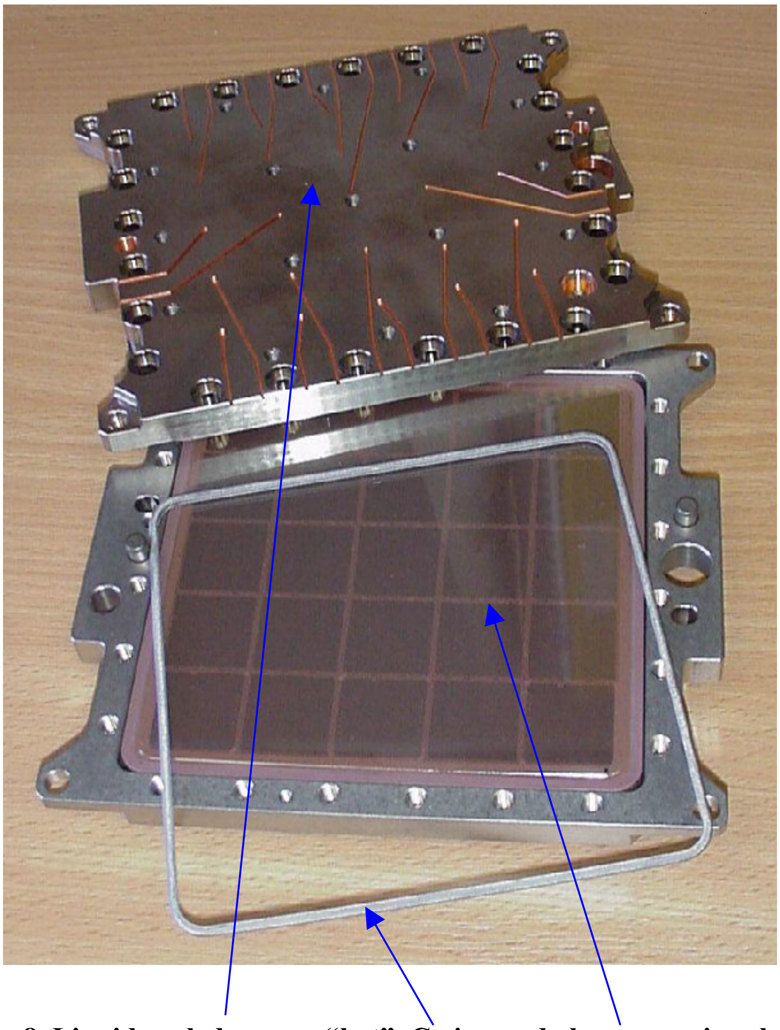

Figure 8. Liquid cooled copper "hat", C-ring and glass-ceramic substrate

2.5.2 Properties required

The sealing ring has to provide:

- A high-grade seal against air ingress – better than 10^{-8} atm-cc/sec. These are the levels used in aerospace grade semiconductor devices in individual packages. A vacuum must be maintained for up to 30 years.
- Sufficient flexibility to accommodate the spread of heights in the devices and to allow for changes in spacing between the plates due to differences in thermal expansion coefficient of the materials, while the module heats and cools during use.
- There is a large difference in TCE between the copper "hat" and the glass ceramic. The TCE of copper is 16 ppm/°C whereas the glass ceramic is designed to match silicon at about 2.5 ppm/°C. This results in significant sideways movements as the temperature changes and it is essential for the lead surface to slide across the surfaces during these movements without breaking the hermetic seal. This performance must be maintained over tens of years without significant wear.

- As there are many die in each module and these cannot be pre-tested, it is essential that any faulty die can be replaced after testing and the module re-assembled while maintaining the position of the parts.
- Construction of modules must be straightforward, as complex procedures tend to cause a larger proportion of defective product.

The C-ring seal is square with rounded corners, where the cross section of each arm is a “C” shape. C-rings are a common type of seal for retaining high vacuum and are available commercially with a variety of coatings. The “C” shape allows for compression without large lateral movement. The material of the IBM seal is Inconel, which is electroplated with pure lead which provides the seal against the upper and lower plates. The lead is coated with a mixture of waxes to assist the sealing and sliding. The lead has a thickness of 63 to 115 µm with a total average amount of lead of 3.1 g per seal. The total consumption of lead in this application by IBM is estimated to be about 10 kg per year. This includes about 150 g of lead per year (world-wide) on seals used for repair.

2.5.3 Alternatives

During development by IBM, many other plating materials were evaluated. Those examined and their disadvantages include harder and softer materials. The harder metals were:

- Gold - too hard and did not retain the vacuum in tests by IBM.
- Silver - prone to tarnishing and also did not retain a vacuum.
- Lead-tin - harder than pure lead. Also, tin suffers from fretting, where the surface, freshly exposed after each movement, oxidises. The tin oxide builds up to an irregular layer, which disrupts the hermetic seal.

The softer material examined was indium, which makes a good seal initially but is deformed more than lead so that it did not retain a vacuum. Indium under pressure will adhere to a glass or ceramic surface which will prevent sliding during temperature changes. It is also prone to corrosion especially in the presence of traces of chlorine.

IBM also examined other sealing materials, which included:

- Elastomer O-rings
- Metal O-rings
- Elastomer gaskets
- Metal gaskets
- Composite gaskets
- Plated elastomers.

All of these failed to meet the full set of requirements due to high gas leak rates, low initial yield, aspect ratio limitations, tolerance control, high wear rate, poor thermal cycling performance, and loss of normal force, which balances the pressure to the Land Grid Arrays to ensure electrical contact to the semiconductor devices. It is well known that all polymers are porous to gases and so will not permanently retain a vacuum and so can be used only if continuous pumping with a vacuum pump is used which is not practical with these modules as well as significantly increasing the energy used.

Only IBM use C-ring seals in their multi-chip modules for their “high end” systems. Their competitors use completely different designs in their equivalent products. It should be noted that only modules that generate very large quantities of heat require the complex designs that maximise cooling. Most computers produce less heat so that vacuum seals are unnecessary.

The top of the range computers are very complex devices which take many years to develop and, clearly, each manufacturer will use their own proprietary designs and each will believe that theirs are the “best” but IBM’s competitor’s designs do not require lead coated C-rings. IBM claim to have about 70% of the market for high-end computers and this indicates that the design they have developed is successful. It is very unlikely that IBM would be able to identify an alternative coating to lead and its elimination could be achieved only by significant design changes, which will take many years of research bearing in mind how long the current design took to develop.

2.5.4 Future plans

IBM is already carrying out research into its next generation of Z Series computers. This will take many years of research but IBM are planning to replace their computers that use the TCM modules (which use the lead coated C-ring) with new Z Series computers some time in 2009. After that date there will be a common architecture over the IBM 1, P, X and Z Series computers. These will use far fewer semiconductors chips which is possible because new much more complex chips will replace the functionality of several chips that are currently used. This is a continuation of the trend that has been progressing for many decades. Originally the Z Series TCM had 133 chips but in 2004 this has fallen to only 16. Since far fewer chips will be incorporated into the TCM from 2010, there will not be the same packaging and rework constraints and IBM should be able to phase out the C-ring in future designs.

IBM will need to continue to supply lead coated C-rings after 2009 for repair of machines built before this date. The RoHS Directive allows the use of spare parts containing restricted substances for the repair of equipment put onto the market before 1st July 2006 but this would not automatically apply to products put onto the market after this date but which contain an exempted component (such as the C-ring) and so this exemption request is for the use of lead coated C-rings in new computers until 2010 and lead coated C-rings after this date for the repair of equipment put onto the market until 2010.

2.5.5 Summary of the case for an exemption

Lead provides a unique combination of properties for this application by IBM. No alternative material has been found despite extensive research. This exemption can expire at the end of 2009 when IBM plan to have phased out lead-coated C-rings by a change in module design. The request for the exemption is made on the assumption that this includes the allowance for repair of computers with this material after 2010.

2.6 Lead and cadmium in optical and filter glass

2.6.1 Introduction

Most optical glass and optical filters do not require lead or cadmium. Almost all camera lenses are now made using lead-free lenses. However, there are a small number of specific applications for which there are no lead-free or cadmium free alternatives. In many cases all of these can be achieved with a lead-free formulation but, in a few specific applications, no alternative matches all of the characteristics. Some examples of applications for optical glass which contain lead include:

- There are no alternatives to lead optical glass for projectors (described below)
- Certain types of lenses such as those used in surveying equipment and certain professional camera lenses
- Some types of gradient index lens (e.g. Selfoc).
- Micro-lithography equipment
- Certain types of high quality printers
- Other applications currently outside of the scope of the RoHS Directive, i.e. Medical Devices and Monitoring and control Instruments.

Table 3. Some characteristics of lead glasses

Characteristic	Lead- glass	Lead-free glass
High refractive index (R.I.). Useful for minimising lens size	Easily achieved	Achieved by use of certain oxides but it is not possible to make gradient index lenses without lead.
Abbe number, ideally low	Important characteristic	Possible to match high refractive index, and low Abbe number of lead glass BUT cannot match other optical properties.
"Blue" wavelength light transmission (light appears "orange" if this is low)	Typically 95% transmission at 450nm	Typically 70% transmission at 450 nm (with same glass thickness), even if R.I and Abbe number are matched (for high R.I. glass).
Stress-birefringence (distortion of glass causes poor image quality)	Can be very good with lead glass	Can be achieved but other characteristics such as TCE cannot be matched so cause distortion.

Other important optical glass properties include chromatic aberration, partial dispersion, thermal coefficient of expansion and many others. It is often possible to match one or more of the optical characteristics of a lead glass with a lead-free glass but there are certain applications where it is not possible to match all of critical characteristics that can be achieved with a lead glass.

Cadmium and lead are used in coloured glass filters. It is possible to produce coloured glass or plastic filters without these metals but in some circumstances, a very sharp wavelength cut-off (~100% to

~0% transmission over a small wavelength range) is required and in these cases, cadmium and/or lead are essential.

2.6.2 Characteristics

Blue- wavelengths light transmission

Lead-free optical glass can be produced which transmits a very high percentage of light of all wavelengths unless high refractive index is also required. Lenses for high magnification can be made with less material and so are lighter and smaller if they have a high refractive index. It is possible to produce high refractive index lenses without lead but, in these types of glass, blue light transmission is inferior to the lead-types and causes a yellowing of the image, particularly where thick lenses are required. Figure 9 shows a comparison of optical transmission through a lead-containing glass with an equivalent lead-free glass of the same dimensions.

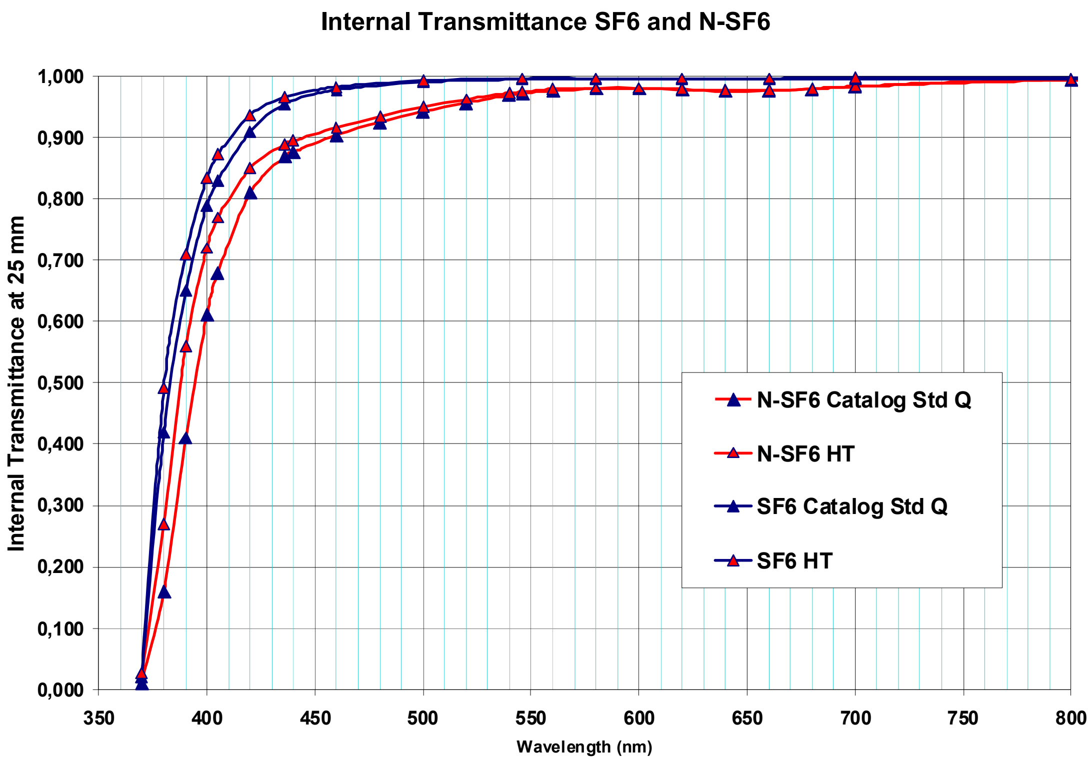

Figure 9. Comparison of light transmission through lead glass (SF6) and equivalent lead-free glass (N-SF6) from Schott Glass.

Stress-birefringence

Optical glass beam splitters are used in projectors and backlit televisions. These products use four beam splitters in total; one each for blue, red and green light and one to recombine these colours to produce the image. The beam splitters are designed to either transmit or reflect light depending on the angle of polarisation, which is switched electronically and scanned to produce the image. The glass used for the beam splitters must have a combination of properties and although each individual property could be met by a lead-free glass, the combination of properties can be achieved only with glass containing lead. The important properties are:

- High light transmission – for high refractive index glass at blue wavelengths high transmission is possible only with lead
- Low TCE – possible with lead free glass unless low stress birefringence also required
- Robustness
- Ease of fabrication – lead glass is easier to fabricate
- High refractive index – possible with lead-free but with limitations
- Low stress birefringence – very few glass types have very low stress optical constants, of these most include lead. The very few without lead have high TCE.

Stress is applied to the beam splitter as a result of heat from the projector lamp but can also result from the way it is mounted. Stress to beam splitters affects the image obtained from the projector as shown in Figure 10 which compares the images obtained in tests with two types of glass. The image is supposed to be a perfect black but the glass with high stress birefringence is distorted giving a coloured image.

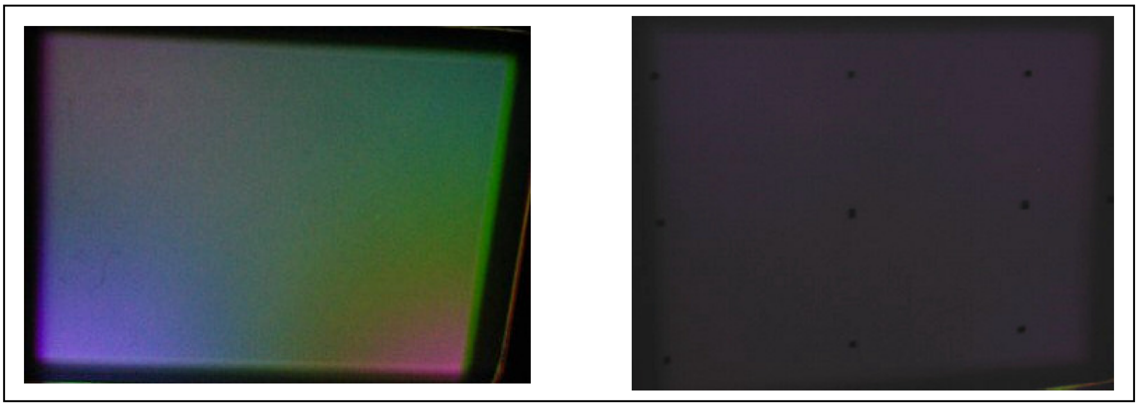

Figure 10. Stress birefringence test images. The left image is lead-free glass (K = 2.77), the right is lead-glass (K = 0.06)

Gradient Index glass

Gradient index (GRIN) lenses are cylindrical glass rods that are used for optical telecommunications and in printers, copiers, scanners and fax machines. They have a gradient of ion concentration from the outer surface to the centre and this gradient is matched by a refractive index gradient. They are produced from glass containing pairs of alkali metals such as caesium, potassium, sodium and lithium. The glass rods are treated with molten salts containing one of the pair so that ions are exchanged for the other (ion exchange). This reduces the concentration of one of the pair at the outer edge and produces a parabolic concentration gradient as shown in Figure 11.

Lead-free glass is used in lenses used for telecommunications but lead is required for applications where a clear image is required. The purpose of lead is mainly to control the ion exchange process so that a smooth concentration gradient is achieved. This gives lenses which produce a clear image whereas without lead, the gradient is less precise resulting in distortion to the image although lead-free glass is suitable for telecommunications applications where an "image" is not required. As with all types of optical glass, lead increases the refractive index and lowers melting point.

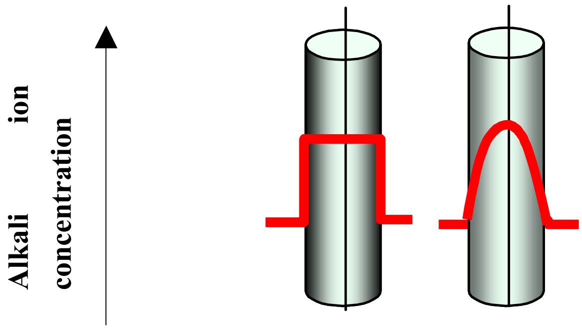

Figure 11. Alkali metal ion concentration gradient (equivalent to the refractive index) before (left) and after (right) ion exchange

<u>**Literature survey on lead-free optical glass**</u>

The scientific and patent literature has been reviewed. There are publications on many types of lead-free glass where lead has been replaced by barium, titanium, bismuth or another material. Where lead is added to obtain a high refractive index, lead-free alternatives are available. For example, US patent application publication US2003/0191006 A1 9th October 2003[12] discloses glass compositions with refractive index of 1.9 to 2.07. The compositions are however slightly yellow as two essential ingredients, bismuth and cerium oxides, are both yellow compounds and so this will reduce blue light transmission. These formulations are useful for certain applications but will not be suitable for all of those where lead glass is currently used.

2.6.3 Optical Filters

Glass filters are "coloured" by adding various materials. These materials need to be thermally stable, as they become part of the glass. Both lead and cadmium are used to obtain particular colours. These filters are made in relatively small quantities but have a wide variety of uses although many of these are in medical devices, monitoring and control instruments and military equipment. Examples of applications which would be covered by the RoHS Directive include:

- Runway lighting
- Lighting for infra-red security cameras

- Professional camera filters
- Television cameras
- Bar code reader
- Projectors

One important characteristic of these light filters shown in Figure 12.

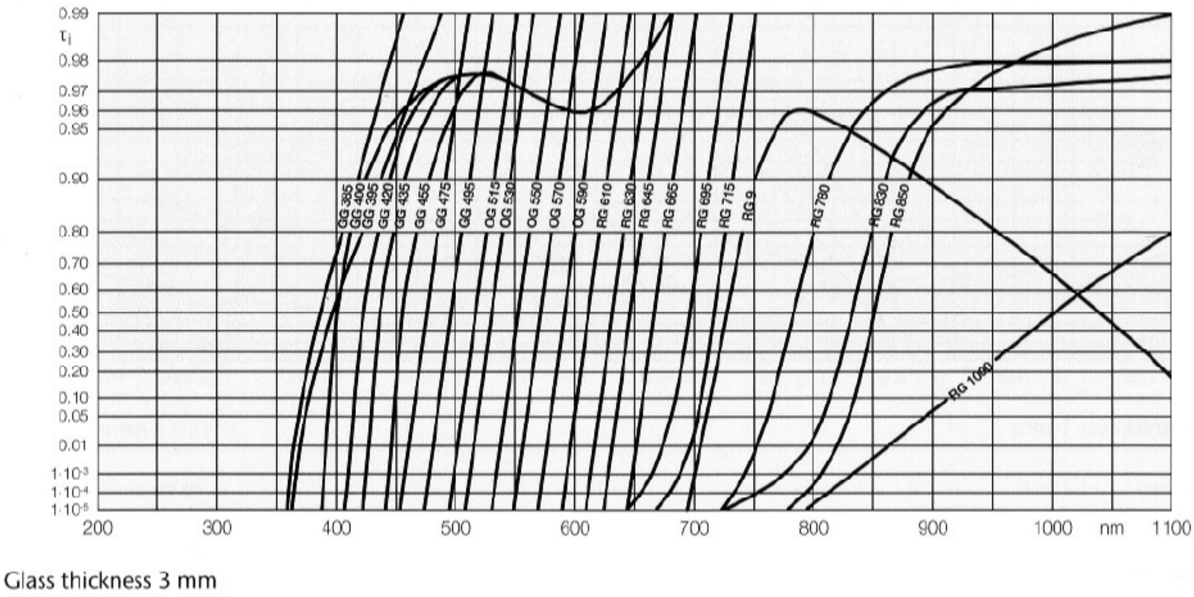

Figure 12. Light transmission plotted against wavelength for optical filters

The red/orange/yellow filters contain cadmium and some of the dark blue filters contain lead. Cadmium filters have a sharp “cut off”. For example, many of those shown in figure 12 transmit 0% of light at one wavelength and 100% at a 50 nm higher wavelength. Being able to achieve a sharp cut off over a small wavelength range is important for some applications. A literature search for cadmium free optical filters has identified a small number of possible alternatives but all have disadvantages which make them unsuitable for at least some of the applications where cadmium is currently used.

Alternatives

A search of the scientific literature identified very few alternatives to cadmium based glass filters. The following options have been identified but none are suitable as alternatives for all applications:

1. Red glass coloured by gold. This has been used for centuries for stained glass windows however the cut-off slope is much less steep than can be achieved with the red cadmium filters

2. US Patent Application Publication US 2003/0123167 A1 3rd. July 2003[13]. Describes “steep edge filters” which uses, for example, $CuInS_2$ (copper indium sulphide) as the semiconductor material as a

substitute for cadmium compounds however there are significant differences that limit the applications of this alternative technology:

- $CuInS_2$ and the related compounds added to glass are thermally unstable and a large proportion is lost by evaporation.

- The technique proposed in this patent application is to deposit a thin coating of these materials on a glass surface. Thin films coatings are more easily damaged than solid glass filters.

- The data provided in the patent application for one example shows that transmission at 100% to 0% occurs over a wavelength range of over 100nm which is about double that possible with cadmium.

3. US Patent 4,228,349 14th Oct. 1980[14]. Uses a thin plate of a III-IV semiconductor such as indium/gallium arsenide. These must be very thin, are very fragile and suitable only as filters in optical telecommunications.

4. Plastic filters. Plastics can be coloured with organic pigments that have similar, although not identical, characteristics to cadmium glass filters. However, these are unstable and darken at elevated temperature and bleach under UV and sunlight.

5. Interference filters. These are glass filters which can be used to transmit a narrow wavelength range of light. The wavelength (colour) depends however on the viewing angle and so these are unsuitable for some applications.

2.6.4 Summary of the case for an exemption

The majority of optical glass in current use does not contain lead or cadmium. Most of the individual properties of lead glass can be matched by a lead-free alternative but there are a small number of very diverse applications which require a combination of critical characteristics that cannot be matched by a lead-free glass. There are also certain applications where there are no alternatives to filter glass containing cadmium.

2.7 Optical transceivers for industrial applications

The main use of optical transceivers is in the telecommunications network infrastructure which falls within an existing exemption for lead in solders (although being reviewed by this study). However, they are also used for other applications, some of these are within the scope of the RoHS Directive.

The functions of optical transceivers are:

- to convert optical signals to electrical signals by connections between optical fibres and photo-diodes,
- to convert electrical signals into optical signals by connection of an optical fibre to a laser diode or light emitting diode chip,
- to perform both functions of the latter functions in some cases.

The photodiode, light emitting diode and laser diode are very small semiconductor chips and precise alignment with the end of the optical fibre is essential. These are aligned and then held in position with special optically transparent epoxy adhesives. The latter can be deformed by excessive heat, for example during soldering processes, and if there is any movement that causes misalignment between fibre and photocell the device will not function. Movement of less than 1µm is sufficient to lose over 95% of the signal intensity.

With the present assembly technique the optical cement must:

- be optically transparent,
- hold the source and fibre in the correct position. Movement of less than 1 µm would cause the device to not function,
- maintain that accuracy over the temperature range and life-time of the equipment.

2.7.1 Alternatives

The applicant has already developed optical transceivers that contain circuitry made using lead-free solders. After assembly of the transceivers, these are attached to printed circuit boards, usually by wave soldering and in preliminary trials using lead-free solders for PCB attachment; the applicant found that the device was damaged.

In the course of this investigation, the data sheets of some of the optical transceivers currently on the market were reviewed. For example, Infineon produce optical transceivers principally for telecom applications. The data sheet for their OmniPort SFF BiDi - transceiver indicates that they are able to withstand a wave soldering temperature of 260°C for up to 10 seconds[15]. This implies that this device can be attached to PCBs by wave soldering with a lead-free solder without damage. In the wave soldering process, the pins that pass through the PCB are dipped into molten solder and heat is conducted through these into the device. The temperature inside the optical transceiver will be significantly less than the solder temperature unlike with reflow soldering surface mount devices in which components are heated for longer periods in an oven and so internally will reach much higher temperatures. The heat sensitive epoxy resins used in optical transceivers will be distorted by temperatures above their glass transition temperatures, which are typically 160°C.

As it appeared that one of the applicant's competitors could produce optical transceivers that can withstand lead-free wave soldering conditions, a programme of reliability trials was initiated as the data that was available was insufficient to justify this exemption. The results of these trials showed that the temperature reached by the epoxy resin was lower than expected and to date, the reliability of the transceivers do not appear to have been affected significantly although these tests are continuing.

One alternative to soldering transceivers to the PCB is to plug the transceiver modules into sockets on the printed circuit board. Some companies, such as Bookham Technology, who manufacture transceivers only for telecommunications network infrastructure use this approach already and at least one other manufacturer plans to introduce plug in devices.

A second request for an exemption for lead in solders for a different design of optical transceiver was received in the course of this study from another manufacturer. At present, this transceiver does not need a separate exemption as these are used only in telecommunications networks which are already covered by exemption 3 (see the list in section 1 of this report). These transceivers are hermetically sealed units which are constructed using a sequence of several different solders which have different melting points. Each solder used has a lower melting temperature to the previous solder so that a bond is created without melting the solders already used. There are a large number of solder compositions which can be formulated to melt at almost any temperature between 80 and 360°C but most of these include lead, cadmium or both. Without these two metals, the choice of solder is very limited and there are only a small number of alloys that can be used to obtain a sequence of melting temperatures. As these transceivers are used only in telecommunications network infrastructure, an exemption is not currently required but this will need to be investigated in the future when the exemption for network infrastructure equipment terminates.

2.7.2 Summary of the case for an exemption

At present, there is no evidence that supports the need for an exemption for optical transceivers. The original applicant has, as a result of this study, carried out a programme of reliability testing which has indicated that lead-free solders can be used to attach the devices to PCBs by wave soldering without damage. The internal circuitry in the transceivers can also be produced with lead-free solder. This applicant has asked for their request for this exemption to be withdrawn. Several other optical transceiver manufacturers were also consulted. It appears that their components are either suitable for wave soldering with lead-free solders, can be attached without solders by use of plugs and sockets or, as they will be used in network infrastructure, are covered by another exemption.

Optical transceivers should not require an exemption in the future but sequential soldering, which is used for a variety of applications including one type of optical transceiver, may need to be considered in a future study of new exemptions.

2.8 Lead in solders consisting of more than two elements for the connection between the pins and the package of microprocessors with a lead content of more than 85% in the proportion to the tin-lead content (exemption until 2010)

This exemption request is from the microprocessor manufacturer AMD that uses an alloy containing <85% lead. These ICs have up to 939 pins and if one is bent or damaged, the component becomes waste. The sockets are attached to computer motherboards, which can also be damaged resulting in the PCB becoming scrap.

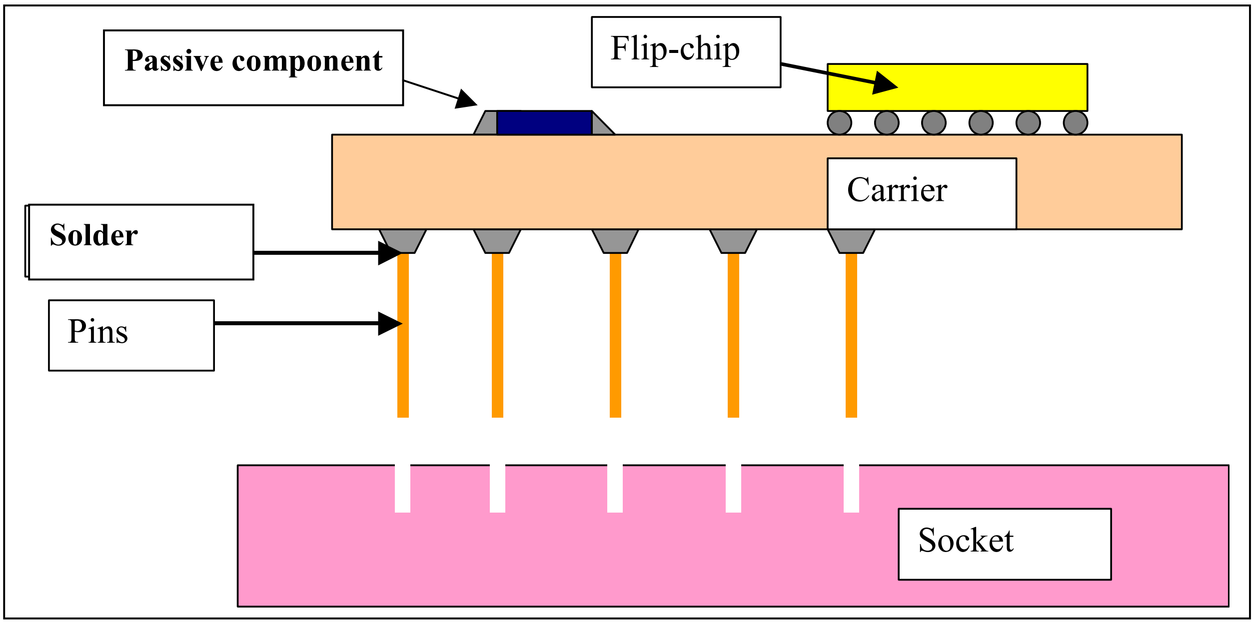

Figure 13. Diagram showing parts of pin grid array microprocessor package

Three alternatives have been considered:

1. Alternative solders.

2. Building microprocessor packages in a different way. This is not possible as the pins are attached first by a sub-contractor.

3. Alternative design.

The pin attachment solder must have a specific range of properties for maximum reliability:

- Melting point higher than the solder used to attach other components.
- Melting point lower than the decomposition temperature of the polymer carrier
- Should be an eutectic alloy to prevent grain growth during subsequent soldering steps that would reduce the strength of the solder.

- Should not be susceptible to electromigration (see section 2.9) or dendrites (silver is susceptible to this).
- Provide minimal wetting of gold plated pins. If solder flows too far along pins there is a risk that this solder be forced into socket holes causing a blockage which cannot be removed so that the socket has to be replaced or in some cases the PCB will become waste.
- Solder must have high strength to prevent pins from bending and this strength retained after three reflow cycles.

2.8.1 Possible alternative solders

Sn5%Sb (tin with 5% antimony) was evaluated but gave a lower bond strength than the lead solder. Pins attached by solder with low bond strength would be more easily bent or broken resulting in a high scrap rate. In AMD's tests, bond strength was measured after three soldering steps and the number of packages with pins damaged during trial production and testing were monitored. The bond strength after three reflow steps was significantly reduced and a statistically significant number had very weak bonds whereas, with the lead solder, the bond strength was significantly higher. In trial production, an unacceptable level of scrap packages was obtained with packages having less pins than are used in AMD's current products. Currently, some AMD packages have over 900 pins which would result in a much higher rate of defective packages based on these test results. A further disadvantage with Sn5%Sb solder is that antimony is detrimental to PCB recycling processes. It is difficult to remove and many recyclers will not accept PCBs containing even small quantities of antimony.

However, Intel has stated in its response to the Stakeholder Consultation that Sn5%Sb can be used for attachment of pins and is reliable. There have been news reports that Intel's customers have experienced difficulties with bent pins on Intel's microprocessor packages however there is no evidence that this is a serious problem and damaged pins may be due to careless handling of what clearly are fragile, very fine pins.

Clearly the experiences of these two competitors, Intel and AMD, have differed. The technical data provided by AMD shows that Sn5%Sb is a lower strength solder than AMD's current lead solder and so, unless procedures are developed to avoid damage to pins, defects that result in scrap components would be statistically more likely with a lower strength alloy. AMD has used the lead solder for many years and so has not developed the procedures required to avoid problems whereas Intel has many years experience with Sn5%Sb and would have developed during this time proprietary techniques to avoid pin damage during manufacture. Intel provides detailed instructions on their website for its customers to avoid pin damage during use.

Sn10%Sb was evaluated by AMD and gave less defects in tests than Sn5%Sb but many more than the lead-based alloy currently used. Also the presence of 10%Sb would increase melting temperature and create more difficulties with recycling.

Tin/silver/copper – the melting temperature of this alloy is too low; pins would drop off when the flip chip is attached.

Solders with >85%lead. AMD did not evaluate these alloys when these products were originally developed as the solder with less lead was found to give almost no defects. Solders containing >85% lead are not eutectics and so would theoretically give weaker bonds after attachment of the flip-chip and passive components. Also, the melting temperature is higher and so could damage the polymer carrier. The use of an increased lead content, although permitted as these solders are exempt from the RoHS Directive, would have a negative environmental impact as more lead and more energy would be used.

2.8.2 Alternative package design

AMD are developing a new package design that avoids pins using "land grid arrays". These were recently introduced by Intel as an alternative design. AMD prefer to pursue this approach to the elimination of the lead solder rather than changing to Sn5%Sb solder in the interim period and have to resolve problems with poor yields, and potentially damage to their customers products. AMD and its customers plan to change to this design by 2010.

2.8.3 Summary of the case for an exemption

AMD originally developed pin grid array microprocessor packages using a higher melting temperature eutectic solder although this contains <85 weight % lead. In their original trials, this gave much better yields than other alloys including lead-free alternatives. Their only competitor, however, uses a lead-free solder and claims good reliability. Intel now has many years experience with the lead-free alloy and so will have developed techniques to obtain a high yield.

AMD now has two options. If they change to the lead-free solder, their yields would initially be poor creating waste components and equipment until techniques are developed to improve yields. Their preferred alternative, which was originally planned prior to the introduction of the RoHS Directive, is to develop land grid array packages which avoid the need for pins and solder. AMD intends to have changed to land grid array packages by 2010.

The wording of this exemption is not clear, a possible alternative would be:

"Lead in solders consisting of more than two elements for the connection between the pins and the package of microprocessors with a lead content of more than 80% and less than 85% by weight."

ERA TECHNOLOGY

2.9 Lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85% lead) and any lower melting temperature solder required to be used with high melting temperature solder to complete a viable electrical connection" and "Lead in solders to complete a viable electrical connection internal to certain integrated circuit packages (Flip Chips) (exemption until 2010)

These two exemption requests are both principally for internal connections within flip chip packages although the first of these could have other applications. Unfortunately the first request does not specify the applications to which it is intended to apply. This creates a risk that it could be used for applications for which a lead-free alternative exists or that it may be misinterpreted for widespread use of any low melting point solders.

Electrical connections are made to most silicon ICs using very thin gold wires attached to circuitry on the silicon surface. These are attached to pads at the periphery of the silicon chip. Chips are becoming more complex, however, with a need for an increasing number of electrical connections and to have connections from locations other than the chip's periphery. Also, semiconductor chips have become larger and the packages around them smaller, so to meet these requirements, an alternative means of electrical connections was required. This has been achieved by replacing the gold bond wires with raised metal "bumps" attached to pads across the surface of the silicon. These "bumped" chips are then "flipped" over (hence the name flip chip) to make electrical connections between the chip and the "chip carrier" which is essentially a small circuit board which acts as an interface between the chip and the PCB. Some flip chip are attached directly to the PCB without a carrier, these are called direct chip attach (DCA).

It is now possible to have hundreds or thousands of connections to the silicon chip, which may be up to 25 mm along each side. The solder joints between the chip and the carrier are called "Level 1" interconnections. There is another layer of solder connections between the carrier and the printed circuit board called "Level 2" interconnections.

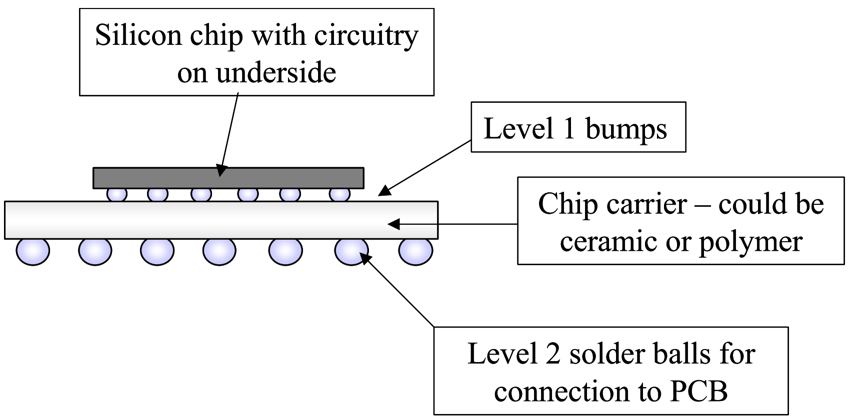

Figure 14. Schematic diagram of interconnection levels from silicon chip to PCB

The Level 2 connections are outside the device and manufacturers are working to convert these to lead-free solder. These joints are generally much larger than those at Level 1. The term flip chip covers a wide range of components and this variation is summarised in Table 4.

Table 4. Characteristics of flip-chip packages

Characteristic	Variety
Silicon chip	Varies in size from less than 2 mm up to 20 mm along one side. Circuitry built up on surface with various materials and complexity. Most advanced flip chip use copper circuitry and many layers.
Bumps	97%Pb3Sn, 90%Pb10%Sn, 63%Sn37%Pb, SnAg, Sn3.5%Ag0.7%Cu (SAC), gold, copper are all used
Attachment of bumps to carrier	Method depends on bump material and substrate. 63Sn37Pb currently used for 97%Pb3%Sn bumps High Pb content solder can be soldered to ceramic at 350°C but low melting point solder is needed for polymer carriers. 63%Sn37%Pb, SnAg and SAC can be soldered directly onto ceramic and organic Gold and copper bumps can be attached using thermocompression bonding or with anisotropically conducting adhesive.
Chip carrier	Ceramic or polymer. There are various types of both of these materials which have different characteristics and so are suitable for different applications.
Level 2 connections	63%Sn37%Pb, SnAgBi, Sn3.5%Ag0.7%Cu (SAC)
Underfill	The gap between the chip and the carrier may be filled by underfill materials. These are adhesives which prevent damage to the bumps and the chip that would otherwise result from the strain imposed by thermal cycling. These need to be compatible with choice of soldering flux (new fluxes are used for lead-free) and adhere to the surface layers on the chip after soldering

Flip-chips range from very small ICs with a small number of bumps and Level 2 interconnections to devices with a large silicon chip and thousands of Level 1 bumps. The technical challenges to change to lead-free flip chip are much greater for the larger more complex flip chip than the small and simple components. Some lead-free flip chip devices are already available commercially from several manufacturers. Most of these are relatively small with few bumps and are used in low power applications where thermal cycling is minimal.

2.9.1 Level 1 connections

The Level 1 connections need:

- High fatigue resistance to survive large numbers of thermal cycles, where there is significant difference in coefficient of thermal expansion between the chip and the chip carrier. Lead is known to provide this fatigue resistance.
- Electromigration resistance[16]. Electromigration is the (slow) movement of the elements of an electrical conductor under the action of an electrical current. The effect becomes more serious as the dimensions of the parts shrink.

- Known long term reliability.

Thermal Fatigue

The coefficient of thermal expansion (TCE) of silicon is very low in comparison with the polymers used for carriers and the PCB. The TCE of ceramic carriers is intermediate between that of silicon and most polymers:

Table 5. Comparison of the thermal coefficient of expansion of package materials

Material	TCE ppm/°C
Silicon	~ 2.5
Ceramics	~ 7
Polymer carriers and PCBs	~ 14

As a result of the differences in TCE, when the temperature changes, a strain is imposed on the bumps, the silicon and the circuitry on the chip surface.

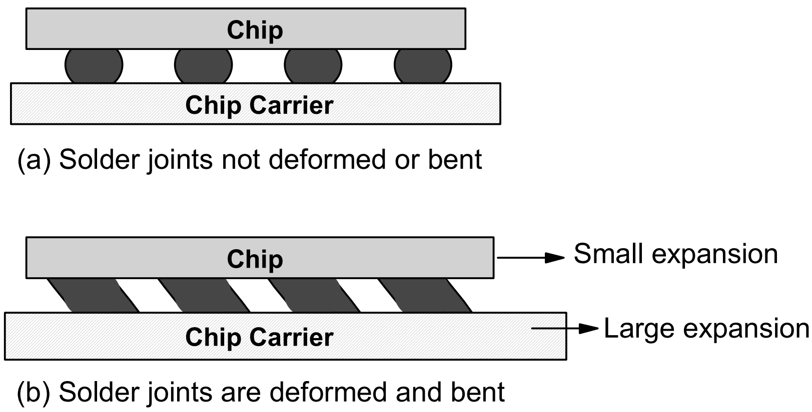

Figure 15. Schematic diagram of interconnection levels from silicon chip to PCB

This strain can cause damage to the silicon (cracks), damage to chip circuitry (particularly the fragile dielectric layers) or cracks within brittle intermetallic layers which tend to be thicker, and so more prone to damage, in lead-free bonds than in tin/lead bonds.

Thermal cycling occurs with most electrical equipment and this can result in thermal fatigue of solders. The thermal fatigue behaviour of lead solders is well understood as these have been used for decades and so both accelerated tests data and field data are available. No field data is available for lead-free solders. High lead content solders are frequently used for the larger size silicon chips because of its superior thermal fatigue life, which is approximately double to three times that of eutectic tin/lead. The difficulties with prediction of field life of lead-free solders from accelerated tests data is discussed in section 2.2.3. Larger silicon flip-chips attached to polymer carriers present a high strain situation and so test data obtained with lead-free solders would indicate that performance would be inferior to eutectic tin/lead and high lead content alloys. In the course of this investigation, several flip-chip manufacturers provided data which they had obtained with flip chip packages using accelerated testing. In general, smaller die with tin/silver/copper bumps passed test criteria but the field life is of course unknown. However, tests with the largest die caused cracking after very short test periods and this alloy could not be used. In one case, a manufacturer may be forced to change from a solder with 37% lead to a high lead content solder (already exempt from RoHS).

Electromigration

Flip chips with relatively high power requirements use high lead solder bumps because eutectic tin/lead cannot be used due to degradation by electromigration. Electromigration can occur to the thin conducting tracks on silicon chips as well as to the very small solder bumps on flip-chip and is a failure process in which the flow of electrons through the conductor causes the movement of atoms. Different metals move differently and their movement is affected by temperature. At temperatures below 100°C, tin/lead can be separated into tin at one end of the bump and lead at the other but at above 100°C, tin moves in the opposite direction. This makes acceleration of this process very difficult. The movement of atoms eventually leads to the formation of voids or gaps which, under strain, cause cracking and eventually bond failure. As voids form and the bump contact area decreases, the current conduction path is constricted which increases the current density. This can increase the rate of electromigration and also increases the temperature.

Research into electromigration is on-going but results are frequently contradictory. The main obstacle is that it is very difficult to accelerate this process as the main method, increasing temperature, changes the basic electromigration behaviour of metals. High lead content solders are known to be superior to eutectic tin/lead, in one series of tests, by a factor of 100 times (see Figure 16, from Freescale Semiconductors).

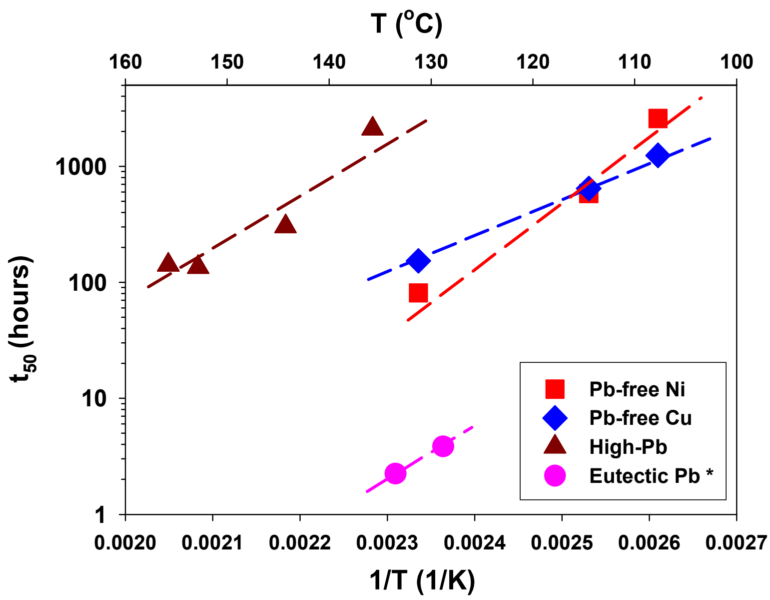

Figure 16. Accelerated electromigration test results (Freescale Semiconductors). Predicted reliability for three alloy types Pb-free is SAC on either copper or nickel

Results obtained with lead-free solders are often contradictory but it appears to be inferior to high lead content solders although it may be superior to eutectic tin/lead but, again, this is not yet certain. Lead-free solders such as tin/silver/copper contain intermetallic crystals which are poor electrical conductors. As a result, the flow of electrons is diverted around these particles which could in theory cause voids to form where current crowding occurs, severely shortening the bond's life.

Research into high lead solder bumps attached to carriers with lead-free solders has not been carried out yet. This would add silver and or copper to the high lead alloy which theoretically would increase electromigration due to intermetallic crystals.

Intermetallics

Eutectic tin lead and high lead content solder such as 97%Pb3%Sn do not contain intermetallic crystals and as a result are ductile materials. The most commonly used lead-free solders contain silver and copper but both form intermetallic crystals and as a result, these alloys are harder and less ductile. Intermetallic crystals are relatively small in comparison with the size of solder joints made between components and PCBs. However, solder flip-chip bumps are typically 60µm diameter and intermetallic crystals can grow to become a significant proportion of these bumps. Ag3Sn intermetallic crystals are needle shaped and so are relatively long (see Figure 17). The length of intermetallic crystals will depend on the temperature and flip chips that operate at higher temperatures may grow relatively large intermetallic crystals. As these crystals are hard and in many cases brittle, if they become relatively thick or occupy a significant volume of the bump, then these may cause cracking and failure if a high strain is applied such as that due to thermal cycling. Manufacturers are currently investigating this to determine what are the limitations that intermetallics will impose. Research should be able to define conditions where intermetallics are not a serious problem and those where they are likely to cause premature failure and hence using these solder alloys would be inappropriate.

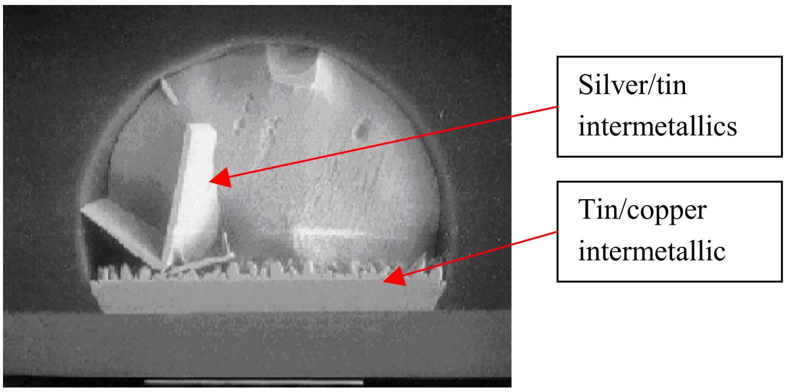

Figure 17. Etched cross-section through SAC bump showing large Ag3Sn intermetallic crystals (from Texas Instruments)

Another concern with very small solder bumps is the formation of voids at the intermetallic / solder interface due to "Kirkendall voids". This effect is known with tin/lead solder but recent studies have shown that this is worse with lead-free solders. However this defect is apparently intermittent and although could be viewed as another reason to exempt lead in solders, this was not highlighted as a serious concern by any of the flip-chip manufacturers who were consulted.

Damage to Dielectrics

There is an on-going trend with the most advanced flip-chips to use dielectric layers with lower dielectric constant (K). These layers are the insulators between conductor tracks and pads and as the clock speeds of these chips increase, the K values need to be reduced. Air has a very low K and so the low K dielectrics are produced with minute air bubbles as "foam". These materials are relatively fragile, however, and cannot withstand a high strain. Lead-free solders, gold and copper bumps are all harder than eutectic tin/lead and high lead content solders and so will transfer more strain to these layers during assembly and thermal cycling. Damage is seen as cracks or as delamination and both result in failure of the flip-chip.

2.9.2 Alternative bumps

1. Some flip chip packages currently use high melting point solder bumps which are attached directly to ceramic carriers by melting these at 350°C. These alloys are exempt and so this approach can continue. However this is possible only with certain types of flip-chip and ceramic carriers and cannot be used with all types of ceramic. The choice of carrier is complex and depends on many variables but in particular depends on the function of the device.

2. High melting point bumps cannot be attached directly to polymer carriers as the high temperature required to melt the solder would destroy the carrier and therefore a low melting point solder is used. 63%Sn37%Pb solder is used by many of the flip chip manufacturers as reliable bonds can be produced. Figure 16 shows a cross-section through a bond made in this way (from IBM).

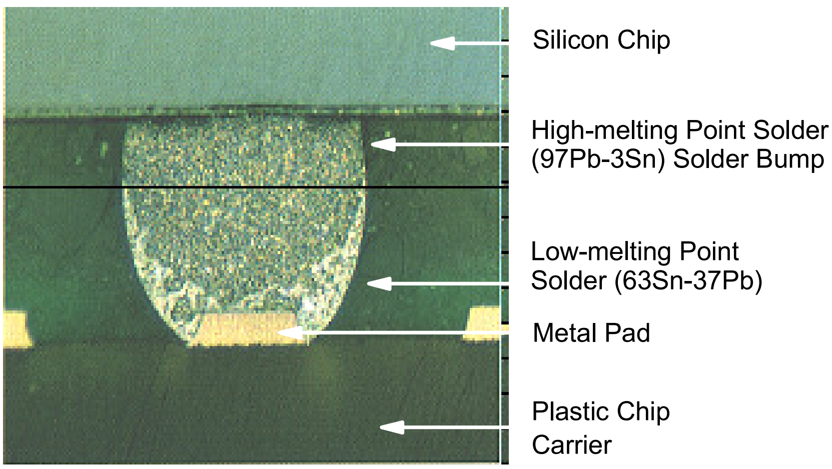

Figure 18. Cross-section through solder bump

The use of 63Sn37Pb solder is not permitted by the RoHS Directive and so, without an exemption, an alternative alloy would be required. Also, the lead content of each bump after bonding the high lead content solder with eutectic solder would contain <85% lead and so may be considered not to be covered by the existing exemption included in the RoHS Directive Annex.

Manufacturers have considered the use of, for example tin/silver/copper lead-free solders to attach the high melting point solder bumps to carriers as an alternative approach. However, this would produce a combination of elements that is new, with no research data available. Also, there is no field data on the long term reliability of these bonds. Without this data, there is a potential risk to consumer safety when these components are used in safety critical equipment. The addition of silver would produce intermetallics as well as hardening the material, both of which could potentially reduce reliability.

3. Several manufacturers currently use 63Sn37Pb bumps but have been evaluating tin/silver/copper (SAC) bumps as an alternative material. One flip chip manufacturer uses tin/silver bumps. Both of these alloy bumps are used in commercially available flip chip packages but the thermal fatigue reliability is not known for the reasons discussed in this report and may be poor, particularly for larger more complex devices.

   Chip size is an important variable. Unpublished research data which was provided by two manufacturers showed that, in accelerated thermal fatigue tests, silicon die of 11 – 15 mm along each side bonded with SAC bumps did not fail the test whereas silicon die of side 20 mm rapidly failed due to thermal fatigue.

4. Gold bumps are used by a few flip chip manufacturers but all of these devices have relatively small numbers of bumps. Gold bumps are produced using the same technique as is used to attach wire bonds to ICs and is a very reliable process. Attachment of a gold bumped chip to the carrier is relatively new technology and, although it is possible where there are a few bumps only, this may not be straightforward where the number of bumps is large as the technique used to create the bond applies force and ultrasonic energy which has the potential to damage the fragile dielectrics on the chip surface, particularly with the more complex devices which have many layers. Also, long term reliability is unknown for this relatively new approach.

   There is a significant cost disadvantage. Solder bumps can be applied to each silicon wafer simultaneously, one wafer may produce 1000 die each with typically 5000 bumps and therefore 5,000,000 bumps can be produced within a relatively short period of time whereas each gold bump is attached one at a time and it is estimated that application of gold bumps to a wafer would take at least 20 times longer and so would require 20 production lines instead of 1 for the same productivity. This would require a very considerable investment. The cost of gold is also a consideration but on simple flip chip is not very significant. Research has been carried with copper bumps and flip chip using relatively small numbers of copper bumps have been successfully produced on a laboratory scale. Much more work is required however to develop a reliable manufacturing process. This is analogous to the use of copper for wire bonds which, although it can be achieved on a small scale, is not widely used as production yields are lower and fine copper wire is susceptible to corrosion.

2.9.3 Level 2 connections

Some semiconductor packages use high melting point solder spheres or columns to make electrical connections to the printed circuit board (PCB). The advantages of this type of connection are:

- Many more connections can be make to one package than if connections are made only at the periphery.
- High melting point solder is ductile and has a very good resistance to thermal fatigue damage. Repeated temperature changes result in stress/strain cycles because of the thermal coefficient of expansion differences between package and substrate which causes thermal fatigue.
- When the package is soldered to the PCB using a standard solder, which could be a lead-free solder, the high melting point solder does not melt maintaining the gap between the package and PCB. This is an advantage because sideways movements due to temperature changes and TCE mismatch will cause less strain with a large gap between PCB and package.

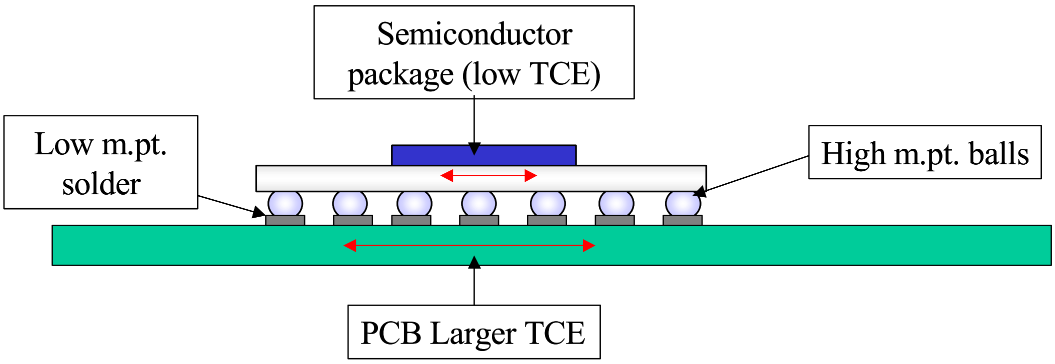

Figure 19. Attachment of Level 2 high melting temperature solder balls to PCB with a low melting temperature solder

In this application, the high melting point solder balls or columns (such as 95%Pb5%Sn) contain >85% lead and so are exempt from the RoHS Directive. A lead-free solder such as Sn3.5%Ag0.7%Cu could be used as the low melting temperature solder which would also be acceptable for the RoHS Directive. However, when the low melting point solder melts, there will be some local melting of the solder ball or column at the interface and some mixing and diffusion of metals so that the metal composition in the vicinity of the interface will contain <85% lead.

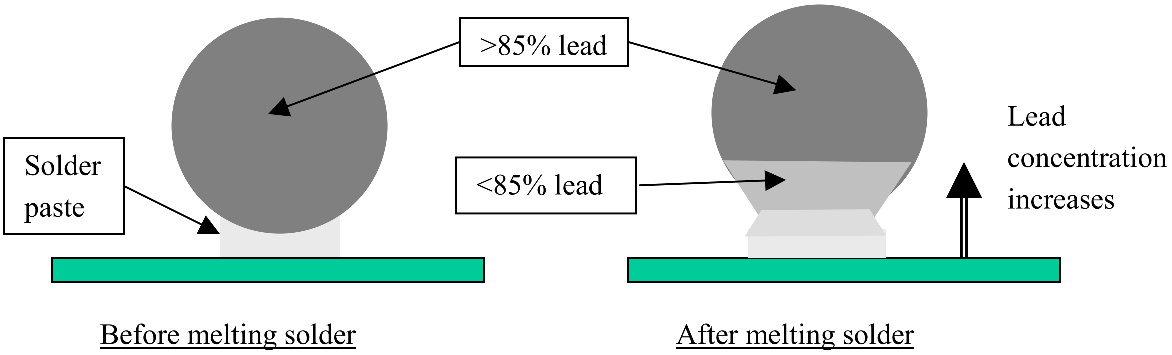

Figure 20. Composition of Level 2 solder ball before and after assembly

In this process, two materials – high lead content solder and lead-free solder have been used, both of which are compatible the RoHS Directive. However, if the alloy composition were to be analysed during market surveillance, the solder bond would be found to contain lead at a concentration of approximately 60 – 70%. The enforcement authority may conclude from this result that the equipment does not comply with the RoHS Directive but it is unclear whether this requires an exemption as two acceptable materials are used.

2.9.4 Alternatives for level 2 connections

One alternative connection technology for semiconductor packages having large numbers of electrical connections would be to use lead-free solder instead of the exempt high melting point solder. These would fully melt during the reflow which could significantly reduce the distance between the chip carrier and the PCB and as explained above, this could be affect long term reliability.

All flip-chip manufacturers who were consulted during this study were asked what their plans were for level 2 connections. Most of the flip-chip manufacturers have developed lead-free level 2 connection technology, although there are a small number of package types where high melting temperature solder cannot yet be replaced. Alternatives include tin/silver/copper balls and, although these melt during reflow, the stand-off height can be achieved in some cases by modification of ball and pad dimensions. IBM has developed an alternative to lead alloy column arrays which are replaced by copper columns[17].

Packages with electrical connections at the periphery are the other alternative as these "lead-frame" (NB "lead" does not mean Pb in this context) components are connected to the PCB with lead-free solders. However, to achieve the same number of electrical connections, the package size would need to be increased significantly, even with a very fine pitch, which may be susceptible to tin whiskers (see section 2.2.3). A larger component size would occupy a larger area of the PCB; this may not be possible in compact equipment and require the use of more materials and generate more waste, some hazardous, during production and at end of life.

2.9.5 Summary of the case for an exemption

Two exemptions have been requested for flip chip packages. One, with no proposed expiry date is for higher power flip-chips that need to use high lead content solder bumps to prevent electromigration in combination with eutectic tin/lead solder. The second exemption request is for lower power flip chip connections which currently use eutectic tin/lead bumps and the original exemption application has a suggested expiry date of 2010.

Higher power flip chip – currently there is no lead-free alternative and lead based alloys may be the only viable option as no other known materials meet all of the essential requirements.

Lower power flip chip – tin/silver/copper and tin/silver may be suitable in some applications but there is no long term field data available and it is not yet known whether accelerated test results can be extrapolated reliably. One manufacturer who produces the largest flip chip die on the market has evaluated tin/silver/copper and tin/silver bumps but, due to the high stress that results from the very large die size, both solder alloys are unsuitable as cracks rapidly form within these lead-free bumps and it appears that a lead-free alternative may not be found for all types of lower power flip-chip package currently on the market.

The wording of the first exemption would also covers level 2 connections of flip-chip and other package types. Manufacturers use high lead solder balls and columns to attach various types of devices to PCBs (Level 2 connections). Most have found that they are able to reliably replace lead solders with lead-free solders and a few have been selling these components for over a year. Clearly a lead-free alternative is possible for most, and probably all level 2 connections.

If a high melting temperature solder ball were to be soldered to the PCB using a lead-free solder such as tin/silver/copper and a reliable joint produced (as found by at least one BGA manufacturer), two acceptable materials would have been used to produce the solder joints and although there will be material with <85% lead and >0.1% lead at the interface, it is unclear whether a separate exemption is needed for this.

2.9.6 Possible alternative wording for proposed new exemptions 10 and 11 (from list in section 1)

The wording used for these two exemption requests would be satisfactory but their interpretation is unclear and could be misleading. Therefore an alternative is suggested for level 1 flip chip connections:

Flip chip Level 1 connections only

“Lead in solders to complete a viable electrical connection between semiconductor die and carrier within integrated circuit Flip Chip packages”

It is possible that no substitute for lead can be found and so no exemption expiry date is suggested although the Commission should review all exemptions at least every four years.

Level 2 connections for Flip chip and certain other package types may not require an exemption as most of the manufacturers consulted have already developed lead-free alternatives. Possible wording to cover the connections between high melting temperature solders and lead free solders could be:

> **"Lead in component external connections made from high melting point solder containing >85% lead and a lead-free solder containing <0.1% lead"**
>
> This reworded exemption is for situations where a manufacturer combines an exempt high melting point solder with a lead-free solder which will create a bond which may have <85% lead, however most flip-chip manufacturers expect to have replaced high melting point solder balls (ball grid arrays) with lead-free alternatives before the 1st July 2006.

2.10 Safety equipment for fire and rescue services

Although the European Commission received this request for an exemption, they have no records of who the applicant was and no original supporting documentation. This was included in the Stakeholder Consultation, however, but only one comment was received which was a request for assurance that lead-free equipment would be reliable.

The main concern is likely to be that the equipment used by fire and rescue services should be reliable as an unexpected failure could pose a safety risk. It is for this reason that lead solders are permitted in vehicles (these are exempt from the End of Life Vehicles Directive) and medical devices and monitoring and control instruments are outside of the scope of the RoHS Directive. Also, lead in solders is permitted in servers, telecom network infrastructure, etc.

The types of equipment that might be included in the scope of this proposed exemption would be:

- Radio equipment - clearly within the scope of RoHS but no radio manufacturer has consulted the authors with information to support this exemption. National emergency services frequently use dedicated commercial telecommunications networks, such as Tetrapol and Airwave, which would be covered by the Network Infrastructure exemption except for end terminating equipment such as two-way radios. It is likely that radios used by these services are made for a wide variety of applications and manufacturers are already developing lead-free products and may not want to also produce lead-based radios for a small percentage of their market.

- Gas sensors to detect toxic gases – outside of the scope of RoHS (monitoring and control instruments).

- Tools for cutting, etc. (specialist fire service equipment is usually air driven and so not electrical equipment).

- GPS equipment – The same equipment would be used for many other purposes, fire and rescue services do not appear to use specially made GPS equipment. Manufacturers of GPS equipment have requested that all GPS equipment should be exempt from the RoHS Directive due to the risk to safety if it were to fail prematurely.

- Fire alarms and call points - Manufacturers have stated that this is monitoring and control instrumentation although some are currently developing lead-free equipment.

The exemption for lead in solders for servers, storage, storage arrays and network infrastructure is discussed in section 2.2. The reasons for this exemption are clear but the two types of equipment that would be covered by an exemption for fire and rescue services are different in several ways.

Table 6. Comparison of characteristics of fire and rescue service equipment and servers, networks, etc.

Characteristic	Fire and rescue service equipment (two-way radio and GPS)	Servers, Networks, etc.
Typical frequency and period of use	Intermittent, usually for a few hours at a time with periods not in use. Life not known, likely to be > 10 years	Usually continuous for at least 15 years
Environment	Potentially harsh with extremes of temperature, moisture and sometimes corrosive. Could increase risk of failure	Usually in buildings, some air-conditioned. Temperature will cycle from internally produced heat due to demand from system
Circuit boards	Relatively standard. Portable GPS similar to mobile phone PCBs. Soldering temperatures likely to be lower than for servers, etc. Impact of board design on risk of failure likely to be less than for more complex server or network PCBs	Large, complex and difficult to manufacture, increases risk of failure
Maintenance	Could be checked before each period of use	Very complex equipment which has built in redundancy to cope with a certain level of defects

The justification for Servers, Network infrastructure, etc has been discussed in section 2.2. Some of the causes of potential poor reliability, whiskers, thermal fatigue and an increased risk from latent defects caused by the higher soldering temperature are similar in both product categories. However, there are issues affecting fire and rescue service equipment that need to be considered.

- Most importantly, there has been no request for an exemption since the original request from an unidentified applicant and as a result no supporting data has been provided.
- Most fire and rescue equipment is outside of the scope of the RoHS Directive.
- Radio manufacturers may not want to make both tin/lead solder and a lead-free versions of their products and so are likely to produce only the lead-free types. GPS equipment manufacturers are in the same situation and will not make two identical product ranges using the two types of solders. It would be very difficult to manage two separate production lines in practice, mainly to avoid the wrong parts being used in each product type but also this would significantly increase costs.
- As with servers, etc., it is only lead in solders that is of concern. If other concerns exist, these have not been reported to the authors during this investigation.

It has been suggested that there should be an exemption for lead in solders in safety critical equipment. This could include any fire and rescue service equipment that is made specifically for this application, and so would be practicable to make with lead solders, but this could also include aerospace equipment, GPS equipment and any other products which would pose a safety risk if they were to fail prematurely as a result of the reliability of lead-free solders. This would be a much broader exemption that fire and rescue services equipment and is outside of the scope of this study. It would however include several of the exemption requests received by the European Commission since this study was launched and could cover any medical device and monitoring and control instruments if these categories are brought within the scope of this Directive. It would be essential to clearly define "safety critical equipment" to avoid free-riders and loopholes. This may prove to be very difficult or impossible.

2.10.1 Summary of the case for an exemption

The case for this exemption has not been proven nor have any substantive representations been made for such an exemption. Although premature failure due to defects caused by lead-free solders would potentially pose a risk to safety, there is doubt whether an exemption for this category of equipment would be of any value to manufacturers and users in practice. Most manufacturers will not want to operate two production lines, one using lead solder and another using lead-free solder, and so, unless the equipment category itself is exempt, then it is likely that only lead-free products will be produced.

An exemption for "safety critical equipment" could be considered in a future study but it will be essential to clearly define the scope of these products.

3. Conclusions

Eleven exemptions have been reviewed. Technical data and other information have been obtained from the scientific and patent literature as well as from discussions with experts from manufacturers. In general, all applicants of exemptions believed that their requests were justified and they were not simply trying to avoid investment in alternatives.

1. Light bulbs

There are no technical reasons why filament light bulbs should not fall within the scope of the RoHS Directive. One exemption for a particular type of filament lamp was investigated. In this latter decorative application there is no alternative to lead as a material to construct this type of lamp. Fluorescent lamps might be seen as an alternative but these require additional equipment to function although they are more energy efficient.

2. Optical transceivers

The proposed exemption for optical transceivers does not appear to be required at present. Additional testing carried out by the applicant since the start of this investigation has shown that these components can be attached to PCBs using lead-free solders without damage to the transceivers and circuit boards within these devices can be made with lead-free solder.

3. Fire and rescue services equipment

No information was received to support the request for an exemption for fire and rescue equipment. It is likely that an exemption for the limited types of products used by these services would be impractical although it is suggested that an exemption for safety critical equipment is investigated in a future study. One important aspect would be to define “safety critical”.

4. Other exemptions

There are good technical reasons why the other proposed exemptions are justified. In some cases, there are no alternatives and in others, the potential alternatives do not provide adequate performance or there is a possible risk to consumer safety because of uncertainty over long term reliability.

5. Alternative wording

The descriptions of the exemptions needs to be clear and it should not be possible to misinterpret them as this would provide loopholes that could create unfair competition. It is important that these are correct as these will be used in an amended Annex to the Directive and in national legislation. Guidelines are useful but it is preferable that the descriptions are clear. Several could be reworded:

- **Lead in compliant pin connectors** – note that VHDM is a trade mark.

- **Lead in solders consisting of more than two elements for the connection between the pins and the package of microprocessors with a lead content of more than 85% in the proportion to the tin-lead content**

  This is unclear and could be amended to: …"more than 80% lead and less than 85% lead".

- **Lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85% lead) and any lower melting temperature solder required to be used with high melting temperature solder to complete a viable electrical connection**

  This is intended to primarily apply to internal connections within flip chip packages. This wording is however incorrectly being misinterpreted to imply that any solder (with lead or cadmium) may be used if a high melting temperature solder is also used. Therefore a simpler wording, which would also cover exemption 11, is suggested:

  "Lead in solders to complete a viable electrical connection between semiconductor die and carrier within integrated circuit Flip Chip packages".

  The original wording covers other applications such as some types of Level 2 connections but all of the component manufacturers who were consulted have already developed lead-free alternatives. Attachment of high melting temperature solder balls to PCBs with lead-free solders would create a thin zone with an intermediate lead content at the interface but this should not require an exemption as acceptable materials would have been used.

6. Expiry dates

There has been much discussions of expiry dates. If an exemption defines a specific expiry date, it will expire at this date unless the TAC chooses to extend it. This the TAC could do, but in most cases it is likely to do so to only after an investigation. It is possible that an exemption may expire by default if no action is taken.

Manufacturers are aware that, where an expiry date is not defined, all exemptions will be reviewed every four years and the default situation is that the exemption will continue until a decision is made to end it. Expiry dates have been suggested for several of the exemptions included in this study; most are 2010 but these will be reviewed by this date whether an expiry date is imposed or not.

7. Spare parts

The exemptions for lead in solders in servers, etc. and for lead coated C-rings should not be required beyond 2010. However the equipment covered by these two exemptions and put onto the market after 1st July 2006 may need to be repaired after 2010 with spare parts which would contain lead. The RoHS Directive permits the use of spare parts for the repair and reuse of equipment that is put onto the market only before 1st July 2006. This creates a problem for equipment that is covered by an exemption after the exemption has expired as it could prevent these products from being repaired or upgraded reducing their lifetime.

4. Proposed guidelines to define the scope of exemptions

The following sections provide clarification of the scope of each exemption.

4.1 Mercury in straight fluorescent lamps for special purposes

Straight fluorescent lamps not intended for general illumination. Examples include:

- LCD backlights
- Light sources in scanners, printers, photocopiers and fax machines
- Disinfection lamps
- Medical/therapy lamps
- Pet care lamps (such as those used within aquaria)
- Lamps for use at low temperature
- Extra long lamps which contain > 10mg of mercury
- Amalgam lamps

4.2 Lead in solders for servers, storage and storage array systems, network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunications

A proposed definition of the scope has been produced by equipment manufacturers with input and some amendments by ERA. This is given in Appendix 1. Equipment that is covered by this exemption is of the type which is intended for continuous use for at least 10 years and has a high reliability. Personal computers, laptops, telephones, etc. are not covered by this exemption.

4.3 Light bulbs

This refers to filament or incandescent light bulbs. These can be included in the scope of the RoHS Directive. An exemption for one type of filament lamp has been reviewed. These are straight filament lamps that use lead to attach a silicate coating to the interior of the glass tube.

4.4 Compliant pin connector systems

This title has been rewritten since "VHDM" is a trade mark and this exemption request is for all types of compliant pin and press-fit connectors. Compliant-pins are used as connections in multi-way connectors. The compliant pins are of various designs and have electroplated tin or tin/lead coatings which are inserted into a matching array of plated through holes in printed circuit boards to make an electrical and mechanical connection. These connectors are designed to make multiple reliable connections to PCBs without soldering but which can be removed and re-inserted without damage to the connector or the PCB.

4.5 Lead as a coating material for the thermal conduction module C-ring

Thermal conduction modules are the central processor units used in the Z-Series main-frame computers produced by IBM. The C-ring is the seal used between the glass-ceramic circuit and the liquid cooled copper plate, which is used to remove heat from the semiconductor chips.

4.6 Lead and cadmium in optical and filter glass

Optical components used in electrical equipment such as glass lenses, optical filters and prisms where no lead-free alternative is suitable. Lead in the glass of electronic components is not included in this exemption as this is covered by item 5 of the Annex of the RoHS Directive.

4.7 Optical transceivers for industrial applications

This exemption request was made to cover optical transceivers and the solder connections made to the PCB to which they are attached. Optical transceivers convert optical signals into electrical signals using glass-fibre connected to a photosensitive semiconductor, convert electrical signals into optical signals using a laser diode or LED attached to an optical fibre or one device may contain both functions.

4.8 Lead in solders consisting of more than two elements for the connection between the pins and the package of microprocessors with a lead content of more than 85% in the proportion to the tin-lead content (exemption until 2010)

A lead-based solder with a melting point higher than standard lead-free solders and eutectic tin/lead but containing <85% lead which is used to attach pins to the carriers of microprocessor packages. This alloy is not covered by the exemption listed as item 7.1 of the Annex of the RoHS Directive which is for solders which contain >85% lead (see section 1.3).

4.9 Lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85% lead) and any lower melting temperature solder required to be used with high melting temperature solder to complete a viable electrical connection

This exemption is intended for internal (Level 1) connections made between the semiconductor die and the carrier in flip-chip packages which have higher power consumption and currently use high melting temperature solder bumps (>85% lead) which are connected to the carrier with eutectic tin/lead (~37% lead). The bump composition will have <85% lead. This exemption would also include situations where high melting point solder balls (e.g. on ball grid array packages) are attached to a PCB with a lead-free solder. It is <u>not</u> intended to permit the use of solders containing lead for making electrical connections to PCBs unless the low melting point solder is attached directly to the high melting temperature solder. Although the description states "all low melting temperature solders", this is not intended to include cadmium based solders.

4.10 Lead in solders to complete a viable electrical connection internal to certain integrated circuit packages (Flip Chips)

For internal (Level 1) connections made between semiconductor die to carrier in flip-chip packages which have lower power consumption and currently use eutectic tin/lead solder bumps. Currently eutectic tin/lead solder (37% lead) bumps are used.

4.11 Proposed alternative flip-chip exemption titles

As the previous two proposed exemptions are intended primarily for Level 1 connections in flip chip packages and information received during this study has shown the first of these is being misinterpreted, two alternative descriptions have been suggested:

- **Lead in solders to complete a viable electrical connection between semiconductor die and carrier within integrated circuit Flip Chip packages**

  This refers to lead in solder used for internal Level 1 interconnections within most types of flip-chip packages.

- **Lead in component external connections made from high melting point solder containing >85% lead and a lead-free solder containing <0.1% lead**

  Where an external connection to a component (flip-chip and others) uses a high melting point solder containing >85% lead is connected to a PCB using a lead-free solder. This combination of materials produces a solder composition at the interface containing <85% lead. This is used to maintain the stand-off height of components to reduce the risk of damage by thermal fatigue from thermal cycling but most component manufacturers who have been consulted have stated they have developed lead-free alternatives and so this exemption may not be required.

4.12 Safety equipment for fire and rescue services

Equipment used by fire and rescue services, in the field, that would otherwise be within the scope of the RoHS Directive. This would include telecommunications and GPS equipment.

APPENDIX 1. Scope of 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

1. Definition of "Solders"

Alloys used to create metallurgical bonds between two or more metal surfaces to achieve an electrical and/or physical connection. The term "solder" also includes all materials that become part of the final solder joint, including solder finishes on components or printed circuit boards. This exemption applies to alloys containing tin and/or lead used as "solder", as board coatings and as component termination coatings.

2. Definition of "server" product for the purpose of RoHS exemption:

A "server" is defined as a computer that meets one of the technology criteria set out in section (a) below, and one or more of the functional criteria set out in section (b) below.

(a) Technology Criteria For Server

Designed and placed on the market as a Class A product per EuroNorm EN55022:1994 under the EMC Directive 89/336/EEC (whereas a Class B product is intended primarily for use in the domestic environment) and designed and capable of having a single or dual processor capability (1 or greater sockets on board).

Or

Designed and placed on the market as a Class B product per EuroNorm EN55022:1994 under the EMC Directive 89/336/EEC and designed and capable of having a minimum dual processor capability (2 sockets on board).

(b) Functional Design Criteria For Server

i. Designed and capable of operating in a mission-critical, high-reliability, high-availability application in which use may be 24 hours/day and 7 days/week, and unscheduled downtime is extremely low (minutes/year).

Examples of typical server functions are given in items *ii* to *ix*:

ii. Designed and capable of operating in a multi-user environment in which access to the computer or accompanying storage or storage array is not required of the user; or

iii. Designed and capable of operating as an intermediate step to process information, i.e. takes input from another system, processes that input, and passes it on to another system for further processing; or

iv. Designed and capable of operating to provide network infrastructure services, (e.g. archiving); or

v. Designed and capable of operating to provide gateway or switching services; or

vi. Designed and capable of operating to host data on behalf of multiple users; or

vii. Designed and capable of operating to allocate or manage user id's that can be used for remote logons, i.e. where physical access to the system is not required by the user; or

viii. Designed and capable of operating to run a server-capable operating system (e.g. Windows NT, Windows 2000 Server, OS/400, OS/390, Linux, Unix and Solaris); or

ix. Designed and capable of operating as a web server.

The exemption applies to the whole of the computer and its components including processors, memory boards, power converters, power supplies, enclosed housings, modular power subsystems and adapter cards. It also applies to the components as integrated into the whole computer or as sold separately for use in an exempt server. Cables and cable assemblies, and all connectors and connector assemblies used to provide interconnections for the server are also covered.

It should be noted that this exemption does not apply to parts or components that are peripheral to the server, nor does it apply to parts or components when they are used other than in an exempt server, storage or storage array system or networking product.

3. Definition of storage and storage array systems

EICTA recommends that "storage and storage array systems" be defined as any device or subsystem that meets at least one of the functional criteria (a) and one of the technology criteria (b) as set out below. The exemption applies to the whole of the device or a subsystem, including, but not limited to disc drives, disc arrays, tape drives/libraries and automated management.

(a) Functional Design Criteria for storage and storage array systems:

i. Designed and capable of operating in a mission-critical, high-reliability, high-availability application in which use may be 24 hours/day and 7 days/week, and unscheduled downtime is extremely low (minutes/year).

Examples of typical storage and storage array functions are given in items ii through iv:

ii. Designed and capable of operating in a multi-user environment in which access to the storage or storage array is not required of the user; or

iii. Designed and capable of operating to provide network infrastructure services, (e.g. archiving); or

iv. Designed and Capable of providing long term data archival storage such as regulatory and/or compliance records as required by US and EU laws.

(b) Technology criteria for storage and storage array systems:

Designed and placed on the market as a Class A product per EuroNorm EN 55022:1998 under the EMC Directive 89/336/EEC

Or

Designed and placed on the market as a Class B product per EuroNorm EN55022:1998 under the EMC Directive 89/336/EEC and designed and meets one of the following criteria:

1. Any storage device or storage management device capable of accepting direct or switched input from more than one computer. As examples, but not limited to, fibre channel and SCSI devices allow for direct or switched input from more than one computer or

2. Any storage fabric or switching device for interconnecting storage devices to server products.

4. Definition of Network Infrastructure for the purpose of RoHS

In the Annex of Directive 2002/95/EC the use of lead in solders for telecommunication network infrastructure equipment is exempted. In order to define the boundaries of the telecommunication network infrastructure a number of manufacturers have taken the initiative to provide a recommendation as included in this document.

We recommend that the equipment falling under the "network infrastructure equipment" for telecommunications exemption would be defined according to functionality of the product. Telecommunication network infrastructure equipment can be located well beyond the service providers' network demarcation points. As such, the lead-free exemption for network infrastructure equipment under RoHS should be based on long-term capital investment, reliability, availability and operability issues that must be addressed by all operators (service providers and private companies).

Network infrastructure equipment is defined as *professional equipment* used for the provision of *telecommunication* services between a number of locations, where

The term "*professional equipment*" is defined as equipment, which has been designed primarily to serve high-reliability and availability public and business applications and which meets at least one of the two following criteria:

- Any system used for routing, switching, signalling, transmission, network management or network security in telecommunication applications;

- Any system which can simultaneously enable more than one end-user terminating equipment to connect to a telecommunication network;

And any system in a network **except** for end-user terminating equipment such as voice terminals, personal computers, facsimile machines, mobile phones, personal digital assistants, consumer-type modems and routers, and TV set-top boxes.

This includes all components, power supplies, display devices and similar electronic units that are incorporated into network infrastructure equipment. It also includes all cables and cable assemblies and all connectors and connector assemblies use to provide interconnections for telecommunication network infrastructure equipment.

The term "*telecommunication*" is defined as information transfer according to agreed conventions by means of wires, radio, optical or other electromagnetic systems. Any transmission, emission or reception of signs, signals, writing images and sounds or intelligence of any nature by wire, radio, optical or other electromagnetic systems. (Source: IEC 60050-714).

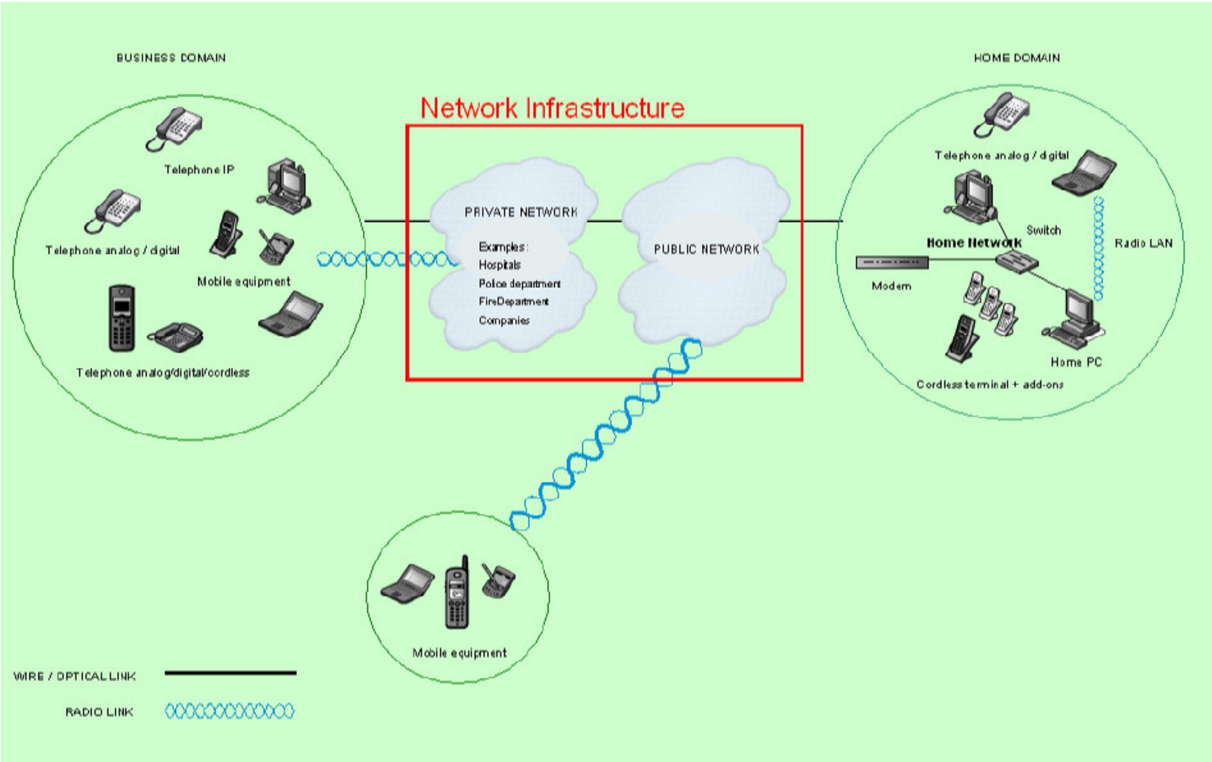

Figure 21. Boundaries in a typical telecommunications network for RoHS exemption

5. Parts for repair and upgrades

Equipment covered by this exemption (listed above in 2 – 4) and put onto the market after 1/07/06 will, at some time in the future, require repair using identical parts to the those types that were originally used to manufacture the product and which may contain lead in solders. This will be required for the normal lives of these products, which are at least 10 years and up to 30 years. Repairs and upgrades extend the life of these products whereas the alternative option of disposal would have a negative impact on the environment as well as being very costly for users.

Consistent with Article 2 of the Directive, spare parts for the repair, upgrade or to the reuse, of equipment covered by this exemption (listed above in sections 2, 3 and 4) and put onto the market after 1/07/06 are also exempted.

Appendix 2. Companies consulted or providing input to this study

- 3M
- Alcatel
- Agilent Technologies
- AMD
- American Electronics Association
- Apple
- Areva
- Bombardier transportation
- Carl Zeiss AG
- Cisco
- Dell Inc.
- EICTA
- EMC
- Epson
- Ericsson
- FCI
- Hewlett Packard Company
- IBM
- Intel Corporation
- JVC
- Lucent
- Motorola Freescale Semiconductors
- NEC
- Nippon Sheet Glass
- Nortel Networks
- Olympus UK Ltd
- Philips
- Photo Imaging Council
- Photoindustrie-verbande e.V.
- Samsung
- Schott AG
- Seagate
- SLI
- Sun Microsystems Inc
- Texas Instruments
- Tyco Electronics
- Xerox
- Xilink

5. References

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[3] Sylvania website, http://www.sylvania.com/BusinessProducts/LightingForBusiness/Products/Lamps/PhotoOpticSpecialty/OSRAMLINEX.

[4] Lumileds Lighting website, http://www.lumileds.com.

[5] Design for the environment study of CRT and LCD monitors funded by the US EPA http://www.epa.gov/opptintr/dfe/projects/computer/

[6] Kodak website, http://www.kodak.com/eknec/PageQuerier.jhtml?pq-path=1473/1481&pq-locale=en_US

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