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An Analysis of the Current Status of Lead-Free Soldering

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Approved on behalf of the Managing Director, NPL, by Dr C Lea, Head of Centre for
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EXECUTIVE SUMMARY

Lead (Pb) is a major constituent of solder which is used extensively within electrical and electronic equipment and there are environmental concerns over the amount ending up in land-fill. As a result attention has been increasingly focused on the potential of Pb-free soldering which can also provide improved reliability and mechanical strength. Some major companies are already using the green image of Pb-free products to promote their products successfully.

The publication in 1998 of the second draft of a proposal for an EC Directive on WEEE (Waste from Electrical and Electronic Equipment) has brought about a sharp focusing of attention. Although principally about recycling, the draft contains clauses aimed at banning the use of Pb in certain categories of electrical and electronic equipment. There is also a proposal to ban halogenated flame retardants used in the manufacture of the bare circuit boards and equipment housings.

The drive to reduce the level of use of hazardous materials is not new of course. For example lead in domestic water pipes and plumbing solders, petrol, paint and fishing weights etc has long been the centre of environmental and green pressures.

Printed circuit boards (pcbs) pervade every form of electronic equipment and are therefore vitally important for a vast range of products. Any change in soldering technology to Pb-free materials, would therefore have major implications for the industry, not only in the UK and Europe, but world-wide, involving many sectors including computers, white goods, brown goods, telecommunications, and other electronics.

The possibility of a change to Pb-free soldering has highlighted a whole series of questions relating to awareness and dissemination of existing information, materials availability, soldering technology, implementation of any new technology, added costs, and competitiveness not only within Europe but world-wide, especially with the US and the Pacific Rim countries. Moreover the timescales involved leave little room for manoeuvre. Japanese companies are now beginning to market lead-free products, and many intend to convert to lead-free technologies within the next two years. Furthermore, the proposed EC legislation mentions a phase-out of lead before 1.1.2004.

Clearly the first step in evaluating the implications of any change to Pb-free solders, is the accumulation, evaluation and dissemination of as much relevant data as possible, irrespective of where they have been generated, whether they are related to aspects of materials, technology, timescales, finance, competition etc. It is sensible that this step is taken quickly as the essential first stage in providing the help anticipated by the industry.

This report covers a short, two months, project commissioned by the DTI for NPL and ITRI to collaborate on a data gathering and preliminary dissemination exercise. Of necessity the project has been short and quickly implemented. Hence it is unlikely to be complete, but it is expected to provide a substantial basis on which to build, as and when other information, views, legislation etc become available.

The main objectives of this project were:

- (a) *to gather as much relevant information as possible within the timescale*
- (b) *to review and analyse the information, and generate a report to be submitted to the DTI*
- (c) *to undertake the first steps in dissemination e.g. by generating summaries suitable for widespread dissemination via existing NPL and ITRI dissemination routes*
- (d) *to suggest the nature of any necessary further steps required by the UK industry to enable it be able to respond and comply with any proposed legislation*

The main activities have been a desk-top study, discussions with key industry/technology experts (individually and corporately), to determine the current

industry status vis-à-vis Pb-free soldering issues arising from the proposed legislation, and the preparation of reports for widespread distribution.

The project was divided into eight sections:

General Level Of Awareness

This section was geared towards assessing the general level of awareness currently exhibited by UK companies, especially the SMEs, in the affected sectors. The primary vehicle used was a questionnaire sent to over 4000 people. Where possible and appropriate, the questionnaire was supplemented with a telephone contact to obtain additional or explanatory information. A full analysis of the returns is included in the report.

R&D Projects

In this section the work was directed at ascertaining what relevant R&D projects have been, or are being carried out in the UK, and where possible, in non-UK countries. Clearly confidentiality considerations have been taken into account. The names of major sponsors of the R&D projects together with summaries of key projects have been incorporated in the report.

Pb-free Materials Availability

The origin, sourcing and availability of potential lead-free solders and their constituent elements have already been the subject of ITRI work. That work has been updated especially regarding information on lead-free solder availability in all forms that will be required (wire, bar, paste etc), and on listings of lead-free board coatings' suppliers and any information on component suppliers. Comments on the properties of various alloys and availability of low and high temperature alloys are included.

Pb-free Soldering Technology

The work has focused on lead-free processes aimed at a direct replacement for the mainstream (63/37 or 60/40) SnPb alloys. Ascertaining what technology exists, its maturity, its wider applicability, is a non-trivial exercise, and in such a short project the information is of necessity far from complete. But efforts have been made to highlight the issues surrounding implementation of each technology, the cost implications in changing the technology (solder materials costs, equipment modifications, qualification exercises etc). Particular implementation issues discussed are technology, logistics, availability, inspection, rework/repair, design for the environment, reliability, and recycling.

Legislation

Since legislation, if enacted, will be a key driver for the change to Pb-free soldering, it is vitally important to know what the current UK and EC legislation is, what changes are planned and in what timescales, and what regulations apply in other areas and

countries around the world. The latter is crucial for issues of competition. The views and results of initiatives taken by EMIF members (e.g. PCIF) have also been included.

Halogenated Flame Retardants

The uncertainty surrounding the future use of pcbs containing brominated flame-retardants is not strictly a Pb-free issue, but it is highlighted in the second draft proposal of the EC WEEE Directive. Hence information has been sought on the availability of pcb materials which do not contain brominated flame retardants, and of associated issues such as compatibility, temperature tolerance, likely costs.

International Perspective

The project has sought to ascertain some (but non-exhaustive) information relating to “who is doing what” around the world, as a means of determining some idea of the trends and developments in the technology, and the breadth of applications of new technologies. The reasons for certain alloy choices by manufacturers already trialling Pb-free alloys have also been investigated.

Preliminary Dissemination.

The gathering pace in the drive to reduce the use of lead, means that time is of the essence, and there will be a need to deliver information to the UK industry as quickly as possible. Moreover, if the legislation is confirmed in the EC Directive, the need for such dissemination will be significantly enhanced. Hence the first steps of this dissemination have been implemented and/or planned.

The main conclusions from this study are:

Lead-free soldering is technologically possible, but key implementation issues need to be addressed:

- in most cases, higher process temperatures are required than for SnPb solders, and this may be incompatible with *some* materials, components and equipment.
- equipment and processes will have to be modified in many cases to accommodate the higher soldering temperatures. More flexible reflow ovens provide a relatively easy way to switch to lead-free solder use. More difficulties may be experienced with IR ovens.
- the process windows for Pb-free soldering are narrower than for SnPb,
- careful optimisation of the soldering process is required with wave soldering to eliminate fillet lifting defects, especially with Bi-containing alloys and components with Pb-containing terminations. A simple diagram illustrating fillet lifting is shown in Appendix 5.

- the changeover to lead-free technology is more straightforward for reflow than for wave soldering due to a reduced probability of fillet lifting.
- in the case of wave soldering the preferred changeover sequence is to Pb-free boards and components BEFORE Pb-free solders, due to the problems associated with fillet lifting. The changeover sequence for reflow soldering is not as critical because of the much lower risk of fillet lifting.
- criteria for visual and X-ray inspection methods may need to be modified.
- problems of fillet lifting and poor reliability may occur with boards which have been initially soldered using lead-free technology, but which are subsequently repaired/reworks using lead-containing solders. Appropriate labelling should reduce the problem.
- in some cases, cleaning processes may have to be modified.

Many lead-free alloys are readily available, however there has been no universal drop-in replacement identified so far.

- Some specific alloys may be dropped into specific processes without significant problems.
- At the moment one of the most promising alloys for general purpose soldering appears to be that based on Sn-Ag-Cu. Other alloys with potential are Sn-0.7Cu, Sn-3.5Ag and Sn-Ag-Bi.
- No viable alternatives for the high lead, high temperature alloys have yet been identified.
- The availability of Pb-free solders and board finishes is not an issue, and can be sourced within Europe. Solders are available in all forms required, and whilst certain alloys are patented, other attractive alloys are available for free use. Many lead-free boards are in widespread use, and there are not expected to be any compatibility problems between these coatings and lead-free alloys.
- The availability of components with Pb-free finishes, generally supplied by the multi-nationals into a global market, may pose a problem, particularly in the short term. Some components are already available with lead-free coatings but supply is currently limited. Some sectors of industry are already moving towards the use of Pd-Ni terminations for reasons other than lead-free compatibility.
- All necessary fluxes are available, although it appears that little or no change in flux chemistry will be required.

- Indications on reliability so far are that joints made with the proposed replacement Pb-free alloys are at least as good as those made with SnPb.

The main barriers to implementation of lead-free soldering are;

- lack of information on any necessary equipment and process modifications.
- poor understanding within the SMEs of the issues and implications of changing to Pb-free technologies
- the availability of components with Pb-free finishes,
- absence of sufficient in-depth R&D results in the public domain.
- lack of information on the reliability of complex devices such as BGAs, μ BGAs, flip-chip attachments, etc.
- there are other related factors, which although not strictly barriers to implementation, do need to be taken into account, eg the lack of co-ordination of R&D effort into lead-free soldering, and cost, in the absence of restrictive legislation.

There is a huge variation in awareness between OEMs and SMEs.

- the apparent awareness of the SMEs is only superficial and not supported by detailed understanding of the issues, timescales and implications involved. Even with OEMs, whilst the awareness may be high at the technical level, senior management understanding, commitment and activity, are often surprisingly low.
- trade organisations, the trade press and scientific meetings appear to offer the most efficient channels for dissemination.

The two main drivers for a change to lead-free technology remain the “green” activities in Japan and the proposed EC legislation.

- many multi-national companies intend to change to lead-free technologies earlier than the WEEE Directive proposes. This change is not dependant on the EC legislation being enacted and will impact on sub-contractors and suppliers.

Alternatives to halogenated flame retardants are available.

- higher loadings of some of these compounds are required to achieve the required safety standards.
- these alternatives are expected to increase cost and may degrade other properties.

1 INTRODUCTION

Lead (Pb) is a major constituent of solder which is used extensively within electrical and electronic equipment and there are environmental concerns over the amount ending up in land-fill. As a result attention has been increasingly focused on the potential of Pb-free soldering which can also provide improved reliability and mechanical strength. Some major companies are already using the green image of Pb-free products to promote their products successfully.

The publication in 1998 of the second draft of a proposal for an EC Directive on WEEE (Waste from Electrical and Electronic Equipment) has brought about a sharp focusing of attention. Although principally about recycling, the draft contains clauses aimed at banning the use of Pb in certain categories of electrical and electronic equipment. There is also a proposal to ban halogenated flame retardants used in the manufacture of the bare circuit boards and equipment housings.

The drive to reduce the level of use of hazardous materials is not new of course. For example lead in domestic water pipes and plumbing solders, petrol, paint and fishing weights etc has long been the centre of environmental and green pressures.

The electronics manufacturing industry relies almost entirely on the use of tin-lead (63Sn-37Pb) for the attachment of individual components into, or onto, the surface of pcb assemblies. However, although electronics manufacturing accounts for only 0.6% of annual consumption of lead, hardly any is recycled. Some six million electronics products are dumped each year in landfill sites in the UK alone, and there is a concern that lead will leach into ground water. Hence there is a move to reduce the use of lead in electronics manufacturing. Pcb's pervade every form of electronic equipment and are therefore vitally important for a vast range of products. Any change in the soldering technology to Pb-free materials, would therefore seriously impact many sectors including computers, white goods, brown goods, telecommunications, and other electronics..

The possibility of a change to Pb-free soldering has highlighted a whole series of questions relating to awareness and dissemination of existing information, materials availability, soldering technology, implementation of any new technology, added costs, and competitiveness not only within Europe but world-wide, especially with the US and the Pacific Rim countries. Moreover the timescales involved leave little room for manoeuvre. Japanese companies are now beginning to market lead-free products, and many intend to convert to lead-free technologies within the next two years. Furthermore, the proposed EC legislation mentions a phase-out of lead before 1.1.2004.

Clearly the first step in evaluating the implications of any change to Pb-free solders, is the accumulation, evaluation and dissemination of as much relevant data as possible, irrespective of where they have been generated, whether they are related to aspects of materials, technology, timescales, finance, competition etc. It is sensible that this step is taken quickly as the essential first stage in providing the help anticipated by the industry. Of necessity this first stage must be short and quickly implemented. Hence it is unlikely to be complete, but it is expected to provide a substantial basis on which to build, as and when information, views, legislation etc become available.

This report covers a short, two months, project commissioned by the DTI for NPL and ITRI to collaborate on a data gathering and preliminary dissemination exercise. The short timescale meant that a collaborative effort between NPL and ITRI would be more effective way of completing the exercise with the partners working in parallel. The two establishments are geographically close, both have established substantial track-records of working in this and related areas, and have appropriate data acquisition and dissemination vehicles which have been put to immediate use. Just as importantly, the combination has brought together groups of expertise which are largely complementary.

2 OBJECTIVES

The main objectives of this project were:

to gather as much relevant information as possible within the timescale on all aspects of Pb-free soldering

to review and analyse the information, and generate a report to be submitted to the DTI

- (c) to undertake the first steps in dissemination e.g. by generating summaries suitable for widespread dissemination via existing NPL and ITRI dissemination routes
- (d) to suggest the nature of any necessary further steps required by the UK industry to enable it be able to respond and comply with any proposed legislation

3 APPROACH ADOPTED

The main activities in this study have been:

- a) A desk study in order to:-
 - determine the current industry status vis-à-vis Pb-free soldering issues arising from the proposed legislation
 - study the availability of Pb-free solders, components and boards with Pb-free finishes
 - highlight possible replacement soldering materials and processing technologies, and identify any implementation issues.

assess the implications on possible materials compliance issues on the pre-assembly design activities (i.e. DfE, Design for the Environment)

Discussions with key industry/technology experts (individually and corporately) in order to:-

- validate observations on current status, barriers, possible replacement technologies etc.
- ascertain the levels of awareness regarding the possible implications of restrictions on the use of lead
- ascertain nature, extent and success of any trials or pilot production of Pb-free soldering technologies
- determine the stance of relevant trade organisations, and of any initiatives generated by them

(c) Preparation of a report in order to:-

- summarise the outputs of (a) and (b) above

identify areas in which further steps may be required by UK industry to ensure compliance with any future legislation (including both technological and dissemination activities).

- define the focus and scope of such projects.

The project has been divided into eight sections; the contributions of ITRI and NPL being shown respectively on the diagram below.

General Level Of Awareness

This section was geared towards assessing the general level of awareness currently exhibited by UK companies, especially the SMEs, in the affected sectors. The primary vehicle used was a questionnaire sent to over 4000 people. Where possible and appropriate, the questionnaire was supplemented with a telephone contact to obtain additional or explanatory information.

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Halogenated Flame Retardants

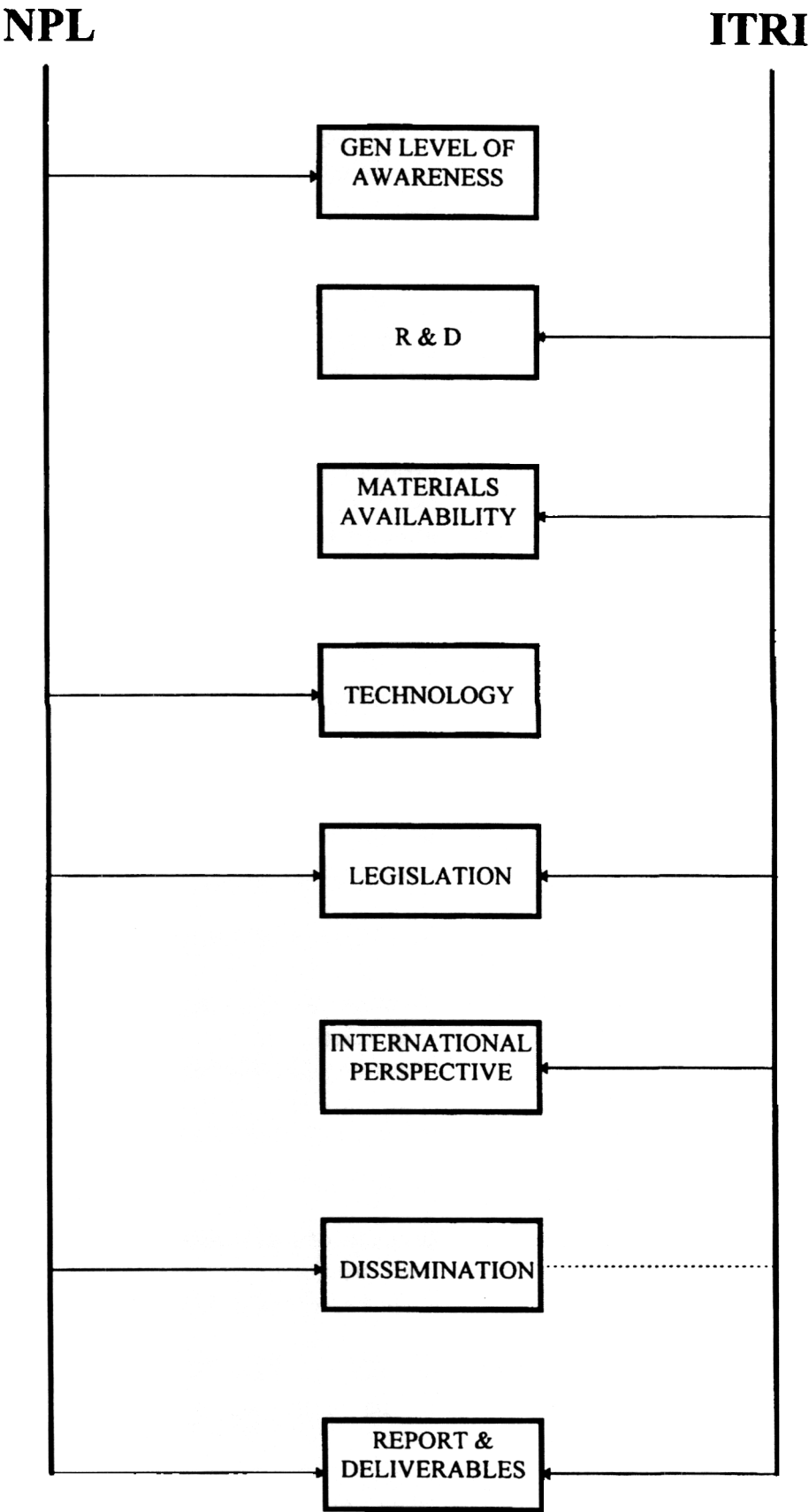
The uncertainty surrounding the future use of pcbs containing brominated flame-retardants is not strictly a Pb-free issue, but it is highlighted in the second draft EC WEEE Directive. Hence information has been sought on the availability of pcb materials which do not contain brominated flame retardants, and of associated issues such as compatibility, temperature tolerance, likely costs.

International Perspective

The project has sought to ascertain some (but non-exhaustive) information relating to “who is doing what” around the world, as a means of determining some idea of the trends and developments in the technology, and the breadth of applications of new technologies. The reasons for certain alloy choices by manufacturers already trialling Pb-free alloys have also been investigated.

Preliminary Dissemination.

The gathering pace in the drive to reduce the use of lead, means that time is of the essence, and there will be a need to deliver information to the UK industry as quickly as possible. Moreover, if the legislation is confirmed in the EC Directive, the need for such dissemination will be significantly enhanced. Hence the first steps of this dissemination have been implemented and/or planned.



4 BACKGROUND

Moves to reduce the use of lead in pipes for domestic water, in petrol, in paint, or in fishing weights have long been the centre of environmental considerations. Further moves to reduce the use of lead in a variety of applications is gathering pace. In the electronics industry the technological requirement for stronger joints, higher reliability etc, has generated interest in moving to lead-free solders for pcb interconnections. Moreover, the Japanese are beginning to implement Pb-free soldering technology for commercial advantage. Such moves have prompted an acceleration of research into the development of Pb-free soldering technologies. This move to eliminate lead in solders has also been given added impetus by currently proposed EC legislation. It is therefore only relatively recently that attention has been focused on lead in *electronic products*, and hence the industry response is relatively immature.

In 1991 the US Senate proposed a Bill ('The Reid Bill' S.391 *Lead Exposure Reduction Act* - one of whose sponsors was the now Vice-President Al Gore) which, among other lead-containing materials, posed restrictions on lead solder, banning some and in others limiting the lead content to less than 0.1%. A sister Bill (S.729 *Lead Exposure Reduction Act*) emerged in 1993. The consequential furore and lobbying by the US manufacturing industry, resulted in the legislation being moth-balled awaiting a "better day" for environmentalists. However, a number of companies, individually and collaboratively took heed of the situation and initiated R&D exercises into alternative Pb-free soldering technologies.

The first indications in 1990 that use of universally employed Sn-Pb solders might be restricted caused many people to consider the possible consequences. Sensing what might emerge in the future many companies and institutions world-wide immediately began investigations into the feasibility of Pb-free solders (see section 8).

Indeed, in the UK, a two-year collaboration between GEC, BNR Europe, Multicore Solders and ITRI was supported by the DTI in 1991 to undertake a short project aimed at assessing alternative solders for electronic assemblies. Following this UK project a European collaboration was formed in 1994 to undertake a related investigation into aspects of processing associated with any implementation of Pb-free soldering regimes. This project is nearing completion. In addition, other large UK companies (e.g. Nortel and Motorola) have investigated the feasibility and issues associated with Pb-free soldering technologies.

Abroad there have been other projects and associated studies carried out in several countries and by a number of private organisations. The direction of their work and their success is evidenced by a series of publications and trade press articles over the past decade. Indeed, some companies are using the fact that they now sell "green" (i.e. lead-free) products as a marketing tool. In addition, many others have Pb-free product out for test under normal service conditions, but are not describing them as Pb-free. However, as indicated above, the awareness of these new technologies, the driving legislation, the business implications etc are at best varied, at worst absent.

The attack on the use of *brominated flame retardants* in pcbs is new. However, it does follow the trend of restrictions (or bans) on the use of halogen-containing materials, notably ODSs (ozone depleting substances) - particularly cleaning solvents such as CFCs, HCFCs and 1,1,1 trichloroethane - fire suppressants (halons), dielectric fluids (e.g. polychlorinated

biphenyls used in transformers) and certain plastics (e.g. PVC used for cabling, packaging etc).

The possible restrictions on the use of brominated flame retardants (BFRs) was first mentioned in the second draft proposal for an EC WEEE Directive, being an unexpected addition from the first draft. The industry was largely taken by surprise and is currently considering the implications and possible replacement technologies. It is seeking information on pcb materials which do not contain halogenated materials, and of associated issues such as compatibility, temperature tolerance, likely costs etc.

5 GENERAL LEVEL OF AWARENESS

In order to give a clear indication of the general level of awareness within companies involved in microelectronics assembly, in particular amongst the SMEs, a questionnaire survey designed to yield a rapid response within the timeframe of this study was carried out by NPL. The questionnaire was formulated in consultation with DTI; a copy and detailed analysis of the results can be found in Appendix 1.

The survey was distributed to over 4000 recipients through the mailing lists of the NPL Soldering Science and Technology Club (SSTC), Microelectronics News, ITRI, PCIF and FEI. Copies were also given for distribution to site visitors at Marconi Communications and TWI. In addition the SMART group posted the questionnaire on the SMART-e-link electronic mail forum and the equivalent IPC TECHNET forum. It should be noted that non-UK responses were not analysed as part of the general awareness exercise, but were used to give a wider view on the international perspective.

The response from SMEs (<250 employees) was high and constituted over half the responses received. This is encouraging since the SMEs are likely to be most vulnerable to changes in technology brought about by legislation. All major sectors of the microelectronics industry were represented in the survey, with a majority engaged in PCB assembly, the activity which will be most affected by any change over to lead-free technology (Figs 1 and 2.)

The response from the questionnaire revealed that awareness of lead-free solders as an issue *per-se* is high with virtually all respondents answering yes to this question (Fig. 3). However, subsequent answers indicated that this level of awareness is superficial, and that detailed awareness is actually poor. Although a relatively high percentage (~75%) stated that they were aware of the implications of changing over to lead-free soldering, the awareness of impact on specific activities within the microelectronics assembly industry was at a much lower level (~35% see Fig.4) . ***Clearly one can gauge from this fact that although most respondents felt they were aware of the issue, only a minority were actually aware of the technological implications of a changeover to lead-free soldering.*** A majority (~60%) of respondents were aware of legislation to restrict the use of lead in soldering, although this question is not limited to the WEEE directive exclusively.

Further questioning of selected respondents via telephone and/or visits, indicated that whereas the large multinational OEMs are very aware of both technological and legislative issues, the detailed awareness amongst SMEs is generally very poor, in particular regarding the banning

of lead and timescales of current proposed legislation. This observation is in broad agreement with findings from a recent study entitled *Materials Compliance Issues in the Design, Assembly and Recycling of Printed Circuit Assemblies (PCA)* carried out on behalf of the DTI, and also from a survey of TWI members.

The survey also addressed the current activities of UK industry in lead-free soldering (Fig. 5). As expected the majority of activity in the UK is centred around information gathering, involving approximately 50% of all respondents. Some tests/trials are being carried out by nearly 25% of respondents and a very small minority are engaged in pilot processing/production. It should be noted that of those companies involved in the latter activity, almost all are solder material suppliers. ***Not surprisingly the majority of companies engaged in activities other than information gathering are large OEMs (>250 employees).***

Some indication of the availability of lead-free materials can also be gauged from the survey (Fig. 6). Clearly lead-free solders are relatively easy to source with nearly 60% of respondents claiming to be able to do so. The awareness of the available lead-free board finishes is not as high as one might expect given that there are many already on the market, with only 30% of respondents knowing where to source them. However, one of the key issues to come out of the survey is that only a very small percentage know where to source lead-free components.

It is clear from the responses to the survey (Figs. 7-9) that ***the most effective ways of raising awareness of such issues within the industry is through the trade press. Almost as equally effective, scientific meetings and trade organisations*** were also cited as good platforms for raising awareness of such issues. Therefore any awareness raising activity which results from this study should take into account these three routes as the most effective channels for communicating to the microelectronics industry.

An interesting result of the survey was that the majority of companies stated that they would go to trade organisations for advice regarding lead-free soldering (Fig. 10). Since most of the technical information regarding lead-free soldering resides with large multinational companies, RTOs and Universities, it would seem imperative for the UK microelectronics industry, that the trade organisations are provided with *the right information in the right format* by these bodies and that a *co-ordinated* effort is made by the trade organisations to disseminate this information as widely as possible.

In addressing the questionnaire returns, it should be remembered that the findings may be coloured by the distribution mechanism employed for the questionnaire, and by the percentage returns.

In summary, the main conclusions of the questionnaire survey of awareness are;

- Superficial awareness of lead-free soldering issues is high across the industry.
- Awareness of the impact on specific technological issues is low in the SMEs but not surprisingly higher in the large multinational OEMs.
- Current activity within the industry is limited mainly to information gathering, with certain significant exceptions.

- Lead-free components are much more difficult to source than lead-free solders.
- Trade press, trade associations and scientific meetings are good awareness raising channels.
- Trade associations are seen as the major source of advice on lead-free issues within the industry and therefore will need to be provided with appropriate information by RTOs, universities, collaborative projects (or to refer enquiries to the relevant organisations).

6 LEAD-FREE MATERIALS AVAILABILITY

6.1 SOLDER MATERIALS

A large number of lead-free solders have been developed and applications have been made for over 100 patents on various alloy compositions. Although not all these alloys are commercially available there is still a wide range to choose from. The question of which lead-free solder is the 'best' is often asked but is difficult to answer since there is no absolute drop-in replacement for tin-lead with identical melting temperature, cost, wetting and strength properties.

The most convenient way to separate the available lead-free alloys is first to consider their melting temperature. Most fit into one of the following categories; low melting temperature (below 180°C), melting temperature equivalent to the tin-lead eutectic (180-200°C), mid-range melting temperature (200-230°C), and the high-temperature alloys (230-350°C). By considering the service temperature that the alloy will experience, together with any maximum temperature limitations of the components or other items to be joined, an alloy of suitable melting point can be found.

It should be noted that while the eutectic (single melting point) temperatures of simple binary alloys are relatively easy to establish and have been known for some time, there is invariably disagreement between parties quoting melting temperatures of alloys with pasty ranges. This is a particular problem with some bismuth and indium containing alloys.

6. 1 Low Temperature Alloys

Low temperature alloys have been in use for some time for specific sequential soldering operations. These solders are based on tin with relatively large additions of bismuth or indium. The tin-bismuth and tin-indium eutectic alloys are the most obvious examples but others are also shown in Table 1. It is not expected that alloys with low melting temperatures would be able to provide reliable joints at higher service temperatures. The supplies of bismuth and indium are also limited to an extent where the eutectics could not be offered for large soldering markets. The current price of indium is also prohibitive for a general soldering market.

Table 1: Examples of lead-free solder alloys melting below 180 °C

Alloy System	Composition (wt%)	Melting range (°C)
Sn-Bi	Sn-58Bi	138 (e)
Sn-In	Sn-52In	118 (e)
	Sn-50In	118-125
Bi-In	Bi-33In	109 (e)

Sn-Pb Equivalents

As the soldering industry has been built on the use of the tin-lead eutectic the obvious choice for a replacement lead-free alloy is for one with similar melting characteristics i.e. as close as possible to 183°C. Some alloys are available which fall into the temperature range between 180-200°C, and in general are based on mixtures of tin with elements such as zinc, bismuth and indium. The tin-9%zinc alloy is the only eutectic in this range, melting at 198.5°C, but other ternary alloy examples are shown in Table 2.

Table 2: Example of lead-free solder alloys melting 180-200 °C

Alloy System	Composition (wt%)	Melting range (°C)
Sn-Zn	Sn-9Zn	198.5 (e)
Sn-Bi-Zn	Sn-8Zn-3Bi	189-199
Sn-Bi-In	Sn-20Bi-10In	143-193

Unfortunately all these alloys possess certain notable problems. Alloys with significant levels of indium are very expensive, and can also be subject to the formation of a low temperature phase in the alloy (melting in the region of the tin-indium eutectic at 117°C) which produces cracking in soldered joints. Alloys containing zinc are subject to rapid oxidation, and not much work has been carried out to examine potential corrosion problems which may be associated with this metal.

6.1.2 Mid-range Melting Temperature Alloys

Most of the best known lead-free solders, as well as those which have been developed more recently with complex quaternary or quinary composition definitions, fall into the mid-temperature range. Most of these compositions are combinations of the base metal tin with copper, silver, bismuth and antimony. Examples of the most popular of these alloys are shown in Table 3. Although their melting temperatures are slightly higher than that of the tin-lead alloy, and therefore they cannot be described as absolute drop-in replacements, it is alloys from this melting temperature range that will be used as general purpose lead-free solders. Marconi Communications with experience of use of SnAgCu have described the alloy as a virtual drop-in replacement for reflow soldering due to the limited changes required to their soldering process.

Table 3: Examples of lead-free solder alloys melting 200-230 °C

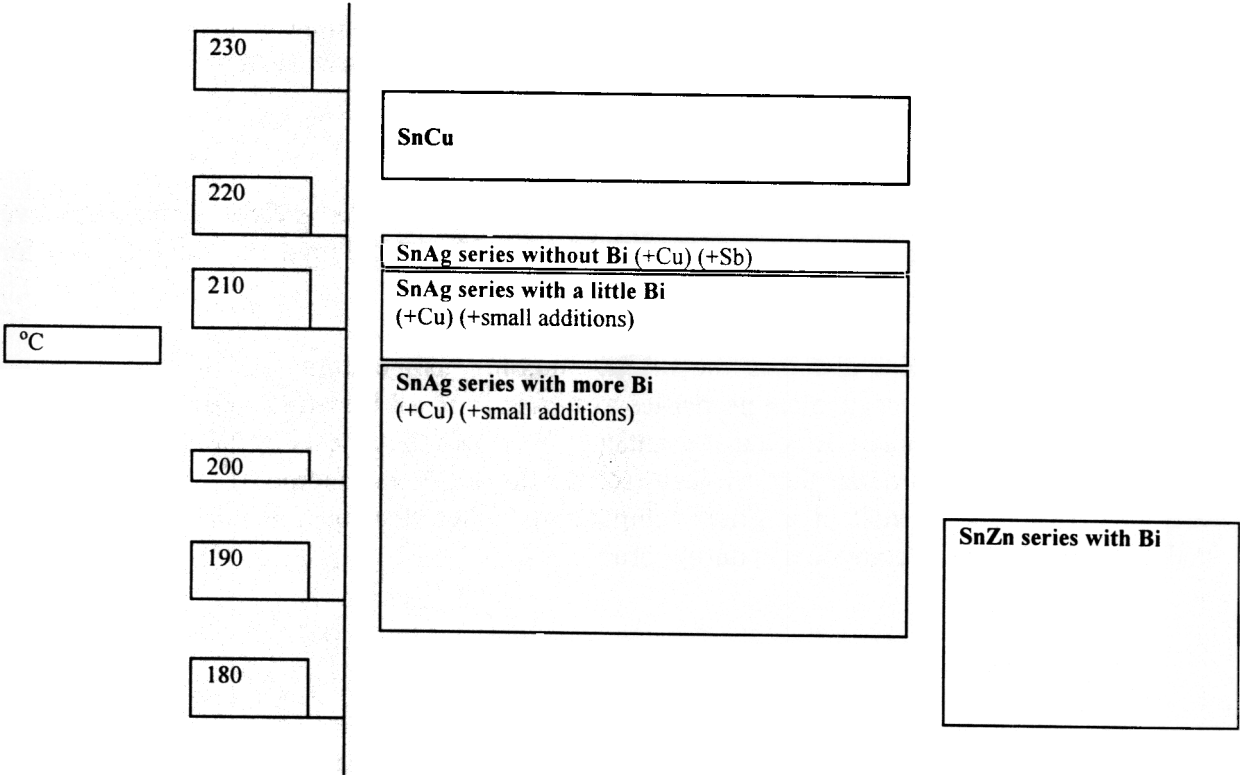
Alloy System	Composition	Melting range (°C)
Sn-Ag	Sn-3.5Ag	221 (e)
	Sn-2Ag	221-226
Sn-Cu	Sn-0.7Cu	227 (e)
Sn-Ag-Bi	Sn-3.5Ag-3Bi	206-213
	Sn-7.5Bi-2Ag	207-212
Sn-Ag-Cu	Sn-3.8Ag-0.7Cu	217 (e)*
Sn-Ag-Cu-Sb	Sn-2Ag-0.8Cu-0.5Sb	216-222

* Several other compositions around that quoted also claim to be the eutectic alloy

The alloys in Table 3 can be divided into better defined ranges of temperature by the use of a diagram adapted from the Japan Electronics Industry Development Association Lead-Free Solder Roadmap.

The diagram indicates differences in melting range which can be used for advantage for certain electronic products. The importance of using the correct bismuth content of an alloy is evident. The use of bismuth lowers the melting temperature of solders allowing lower process temperatures to be used, but it also brings with it certain difficulties, particularly fillet-lifting (or hot tearing), which need to be carefully considered.

Possible lead replacement alloys



High Temperature Solders

The last group of alloys are those which can be classed as high temperature solders melting above 230°C. This is the temperature region in which high lead solder alloys have typically been used, and where there is a limited number of choices for lead-free replacements. Examples are shown in Table 4. Various diffusion dependent techniques are being proposed to solve the problem of the lack of lead-free alloys with melting temperatures above 230°C, but these are not yet been developed sufficiently for general use.

Table 4: Examples of lead-free solder alloys melting above 230 °C

Alloy System	Composition (wt%)	Melting range (°C)
Sn-Sb	Sn-5Sb	232-240
Sn-Au	Au-20Sn	280 (e)

While a limited number of alloys have been mentioned in this text there are also numerous others available of slightly varying composition. However, these are all variations on the same type of alloys series mentioned with no clear benefits in processing or service performance. The Sn-Sb alloy does not melt at sufficiently high temperature for most applications, and the cost and mechanical properties of Sn-Au limit its use.

Lead-free alloys: A comparison

By looking at the range of alloy types shown in the previous section and the lead-free solder selection diagram, it can be seen that there is a choice of 5 alloy groups from which to select. As with tin-lead, each lead-free alloy has particular properties that are outlined below.

(i) SnCu

Tin-copper is one of the cheapest lead-free alloys available. As such it is an attractive proposition for many companies particularly when considering filling a wave solder bath for the first time.

On the downside, SnCu also has the highest melting temperature (227°C eutectic) and probably the ‘poorest’ mechanical properties available from all lead-free solders, although in some cases this is not necessarily a disadvantage. Thermal fatigue tests by Nortel have shown that SnCu can perform better than tin-lead (see Sections 7, 8 and footnote)*. Eutectic alloys are preferred as they melt at a single temperature rather than over a temperature range, reducing movement of components during processing.

* It must be emphasised that some general concern has been expressed over taking fatigue test data at face value. In order to understand (and certainly compare) such data, it is essential to know the history, full test conditions and full test data etc.

(ii) SnAg

Tin-silver is a reliable alloy with the longest previous history of use of the lead-free alloys. It has good mechanical properties and better solderability than the SnCu alloy. It is also a eutectic, melting at 221°C. Thermal fatigue testing of the SnAg alloy has often shown improvement in reliability over SnPb and has been used for “years in certain electronic applications”.

There is a limited difference between SnAg and SnAgCu and so the choice between the two may depend on supply and price as much as anything else.

(iii) SnAgCu (Sb)

The tin-silver-copper ternary eutectic composition has been developed more recently as an improvement on the basic SnAg alloy. It was not generally known until around 4 years ago that SnAgCu produced a ternary eutectic melting at a lower temperature (217°C) than SnAg. The exact composition for this is still a matter of debate.

The Sn-3.8Ag-0.7Cu alloy was recommended for general purpose use by the Brite-Euram project (see sections 7 and 8) and has been found to have better reliability and solderability than other alternatives such as the SnAg and SnCu.

Antimony additions (0.5%Sb) were made to the SnAgCu alloy during the Brite-Euram project, particularly for wave soldering purposes, to strengthen the alloy further.

The SnAgCu alloy is therefore suited to both general purpose soldering and for applications seeing high service temperatures. The addition of Sb may also increase the high temperature reliability of the alloy to a certain extent. Both alloys perform better than SnPb in practically all thermal fatigue tests, certainly in all tests carried out during the Brite-Euram project.

(iv) SnAgBi (Cu) (Ge)

The lower melting temperature of the SnAgBi alloy is of vital importance and the alloy also provides good reliability. Alloys of various compositions, close to those in Table 3, melt in the range of approximately 200-210°C.

The solderability of SnAgBi based alloys is consistently found to be the best of a range of lead-free alloys and this is confirmed by Matsushita. The addition of copper and/or germanium to the basic SnAgBi alloy is for a general improvement of strength, and possibly wettability.

The greater inclination of SnAgBi to exhibit fillet lifting, compared to other lead-free solders, is altered by the addition of other elements. However, greater care is required with this alloy, especially if SnPb component finishes are being used.

(v) SnZnBi

Tin-bismuth-zinc alloys can be made with melting temperature very close to that of the SnPb eutectic, but, the presence of zinc causes many problems related to its reactivity;

- very short paste shelf life,
- requirement for relatively active fluxes,
- excessive drossing and oxidation,
- potential corrosion problems on the assembly.

Although both air and nitrogen reflow pastes are available their use cannot be recommended without much further investigation.

Products that can be defined in a high professional group (automotive, military) are likely to use the high performance SnAgCu alloy, with or without the addition of Sb depending on company preference. Those in the medium professional group (industrial, telecoms) are likely to use the SnAgCu alloy, or the SnAg binary eutectic. In the general consumer and low professional product grouping (TV, audio-video, office equipment) it is likely that a greater range of alloys will be involved, eg the SnAgCu(Sb) and SnAg groups, and additionally SnCu and SnAgBi solder use. The choice here is likely to be influenced by company preference, particularly relating to the use of Bi containing alloys.

6.1.5 Non-mainstream soldering temperatures

High and low temperature solder alloys may also be required to be lead-free and some consideration of the options is given.

Fusible or low melting point alloys melt between room temperature and around 150 °C. The main elements used in these alloys are tin, cadmium, lead, indium, bismuth and zinc and some examples of common combinations are shown below:

	Alloy	Melting Point °C
•	BiInPbSn	58
•	InBi	72
•	BiInSn	81
•	BiPbCd	92
•	BiPbSn	95
•	InSn	117
•	BiSn	138
•	SnPbAg	179

The alloys prohibit themselves from use within mainstream electronics as their melting points are below normal working and service temperatures. Certain InSn alloys are already used for specialist applications, for instance wetting and joining of ceramic components, but lead alloys are not generally used. Sn-58Bi has been used extensively for the last twenty years in high performance applications where low assembly processing temperatures are required and when ‘end of use’ temperatures are well below 100°C. However, this alloy is already lead-free.

High melting point alloys can be said to melt above around 230 °C. The main constituents of these alloys are tin, silver and lead. Examples are given below.

Alloy	Melting Point °C
• Pb-10Sn	302
• Pb-5Sn	320
• Pb-3Sn-2Ag	315
• Sn-25Ag-10Sb	365

There are two main areas of the use for the high lead, high melting point alloys within the soldering market today. These are for die-attach and BGA (Ball Grid Array) solder spheres.

The 90Pb-Sn alloy was traditionally used for die-attach although this is already being replaced with silver-filled epoxy resins, thus removing lead from the internal connections of components in most applications. The die-attach material has to be of a sufficiently high temperature to withstand normal working temperatures during soldering and also to be suitably conducting to transfer heat away from the device.

High lead alloys in die-attach are generally only being used by the power circuits industry where very high levels of conductivity are required. The high power devices generate a greater amount of heat and this cannot be sufficiently dealt with through conduction in a silver-loaded epoxy. The conductivity of solder alloys is in the region of ten times greater than silver-loaded epoxies. This type of power circuit is normally found in under bonnet automotive applications, due to the high current/low voltage produced by car batteries, and the high temperature within the engine area.

The lead-free J alloy (Sn-25Ag-10Sb) has been tried as a replacement for high lead alloys in die-attach with little success. The alloy has very low ductility and is therefore prone to thermal fatigue failure. Results of die-attach trials with alloy J have shown a reduction in thermal and mechanical fatigue life, to an unacceptable level.

For this particular high power, high temperature application it is not yet possible to propose a suitable lead-free alternative.

The high package density achieved with BGA is a factor in the mobile communications industry where size and weight are major design considerations. Currently, at carrier level, both high temperature and eutectic or near eutectic solders are used to form the connection. At board level only eutectic or near eutectic solders are used. High lead solder columns or spheres can also be used to produce a fixed stand off height between the chip package and the PCB, thus controlling reliability.

Lead-free BGA spheres made from Sn-In-Bi and Sn-Ag alloys are already available. These lead-free spheres have been shown to produce higher thermal fatigue reliability than with Sn-Pb, mainly due to the increased stand off between chip package and PCB. Other lead-free alloys can also be used to manufacture BGAs.

High lead spheres may still be required in high power applications similar to those discussed for die-attach, but lower temperature alloys would be sufficient in most other cases.

6.2 SUPPLIERS

Appendix 2 lists suppliers in the UK of the alloy types perceived to be of most importance to mainstream soldering;

Sn3.5Ag
Sn0.7Cu
SnAgCu
SnAgBi

Other alloy types available around the world are also listed but without details of each supplier. The Castin alloy (SnAgCuSb) is also seen as a lead-free alloy of importance but this is only available from one supplier (see Appendix 2) in the UK for patent/licence reasons.

Tables are also presented showing the availability of the alloys in the various forms required i.e. paste, bar, wire (cored if required). It is possible to manufacture any lead-free alloy in any form that SnPb has been manufactured using the same equipment. Suppliers may be limited at the moment but this is entirely due to the current low demand for lead-free alloys. As demand increases the number of suppliers will increase and any additional premium on the price of lead-free materials should reduce.

Solder manufacturers and users should be made aware of the patent situation of the lead-free alloys available, due to some potential legal restrictions on alloy use. The two eutectic alloys of SnAg and SnCu, and also compositions close to the eutectic, have been in use for many years and are therefore not patentable, and are available for manufacture and use by any company.

The situation with the SnAgCu alloy is more complex with patents in existence that cover various countries and compositions. Discussions also continue over the exact composition that represents the ternary eutectic of 217°C with several different compositions claimed. It is thought that the Sn4Ag0.5Cu composition will become the most widely used as this particular composition was claimed as the ternary eutectic in data published fifty years ago. Knowledge of this composition has therefore been in the public domain for some time and it is thought that it can be manufactured and used without patent or licence problems. This is not the case with other SnAgCu compositions.

The SnAgBi system is also affected by several different patents. However, it is thought that several are relevant only to other countries, such as Japan, and that the number of European patents is more limited. The legality of use of any SnAgBi composition should be checked independently before use. Unlike the Sn4Ag0.5Cu solder, there is no particular composition in this system thought to have been previous knowledge in the public domain.

As mentioned previously the Castin alloy (Sn2.5Ag0.8Cu0.5Sb) may be popular due to its good high temperature characteristics but this is patented and can only be produced under licence.

Major electronic equipment manufacturers have stated concern over the use of patented alloys since this effectively ties them to only one supplier. Companies may have one preferred supplier but they also often require alternative suppliers to be available. It is for this reason

that it is expected that many of the lead-free alloys used will be unpatented rather than proprietary alloys. However, any company considering the manufacture or use of a new lead-free alloy should make their own assessment of the legality of the situation.

6.3 FLUXES

Flux is required for the soldering process in order to chemically clean the surfaces being joined and to maintain the cleanliness of the surface so that sound solder joints can be achieved. In addition to the strength of the flux agent, fluxing kinetics are an important aspect of fluxing performance. The flux activation temperature and activation time during heating and soldering have to be designed to fit the process settings.

There are many types of flux being used in the current soldering/electronics industry, such as rosin based, water soluble and no-clean flux packages. However, development of new fluxes for lead-free alloys has concentrated on rosin-free, VOC-free environmentally sound products. Specially developed fluxes for lead-free pastes are commonly available in a no-clean version. Newly developed water soluble fluxes have also been developed for lead-free alloys and are commonly found.

Pastes are commonly available in all flux types; no-clean, water soluble and rosin. However, the rosin-based flux packages are those high temperature versions of products developed for SnPb and have not been designed specifically for the new alloy.

All the solder manufactures will supply pastes and solder bar with any type of flux system that is required by the customer. Most solder manufacturers make lead-free products to order as the demand for this type of product at present is very small. Some companies already have off-the-shelf products and prefer to supply a particular flux system for different reasons, normally cost and performance. The most common types of flux systems available are no-clean, and water soluble. The following supply off-the-shelf flux systems for solder paste:

Alpha Metals.	All alloys with no-clean.
Heraeus Silica & Metals.	All alloys with no-clean.
Indium Corporation of Europe.	No-clean and water-soluble systems recommended.
Mountstar Metal Corp.Ltd.	Water-soluble recommended.
Multicore Solders Ltd.	All alloys with rosin based RMA.
Turbo Braze(Europe) Ltd.	All alloys with rosin based RMA.
Warton Metals	All alloys with no-clean flux.

Wave soldering process temperature profiles have changed very little from that for Sn-Pb and so the use of lead-free alloys has not required any significant change in the type of fluxes used. The following supply preferred flux systems for lead-free wave soldering baths.

Alpha Metals.	Low Residue and VOC-Free Water Soluble fluxes
Heraeus Silica & Metals.	VOC-Free water based No-Clean fluxes.
Mountstar Metal Corp.Ltd.	No-Clean and RMA fluxes.

The same oxide (tin oxide) is formed on both lead-containing and lead-free alloys and therefore the same fluxes will work for both. It is only the slightly higher temperatures

required with lead-free soldering that mean some flux development has to be carried out to prevent the formation of black residues etc.

The compatibility between soldering temperature profile and chemical and physical properties of the specific flux or paste remains a critical point in achieving optimum soldering results and the highest level of cleanliness. Much development work has been carried out on all types of flux to improve their performance with lead-free alloys, and the pastes are now available in all flux types. No-clean VOC-free versions are also available that give good solderability.

6.4 PCB/COMPONENT FINISHES

Appendix 3 lists major suppliers of lead-free finished boards and component terminations.

Boards

The protection of substrates from corrosion or contamination is an important factor in any soldering process. Protective coatings are applied in order to preserve solderability and enable the use of mild fluxes. Coating methods such as plating, tinning and organic coating have been used for many years, as has HASL (hot air solder levelled; also referred to as HAL) solder coatings.

A wide choice of lead-free board coatings is available that are already in widespread use in the industry. The choice ranges from metallic based coatings (matte or bright tin, tin over nickel, gold over nickel, palladium, palladium over nickel, silver) to organic solderability preservatives (OSPs).

Even with the current SnPb solders wettability varies on different coatings and can also vary between boards from different suppliers of the same coating. The same is true of the wettability of lead-free solders on the board coatings available. Choice of coating is often a compromise between coating cost and performance.

Two manufacturers in the UK and USA have performed trials on lead-free HASL coatings. Both have confirmed that lead-free alloy coatings can be produced with no, or only slight, changes to the production process. Trials have been performed on both horizontal and vertical leveling equipment. The performance of lead-free HASL has been shown to be equivalent to that of SnPb HASL.

It is thought that around 70% of board finishes are currently SnPb HASL. Lead-free HASL boards are not yet available as standard due to low demand but could be produced upon request.

The performance of lead-free coatings and their solderability has been thoroughly investigated within the industry. Generally, lead-free alloys perform adequately on OSP coated boards, but have improved solderability on metallic coatings such as Sn, Ag or Pd.

In conclusion, it must be noted that when considering any soldering application it is important to choose the correct combination of solder/coating/flux for maximum performance.

Components

Lead-free component supply remains one of the main areas requiring further action during the transition to lead-free soldering.

Traditionally components have been “tinned”, that is a SnPb plated or dipped solderable coating (the component finish) is applied onto the leads before the soldering process. The coating is widely used throughout the soldering industry, to give good wetting while at the same time not affecting the composition and microstructure of the solder joint.

The main concern over the continued use of lead-free alloys with lead-containing component coatings is fillet lifting. However, it should be remembered that this phenomenon does not occur under all circumstances. The continued use of leaded components is possible in surface mount technology with all the main alloys mentioned, although awareness of the potential occurrence of fillet lifting with SnBiAg alloys is of utmost importance. Continued use of leaded components is also possible with wave soldering with any Sn/Ag/Cu/Sb type alloys but should probably be avoided with Bi-containing solders. The use of 90Sn10Pb components rather than 60Sn40Pb also reduces the possibility of fillet lifting in all circumstances.

There are many lead-free alternatives to tinning already used in all areas of the electronic industry. Current coatings used as lead-free finishes include;

- Dipped/plated lead-free solder alloys
- Ni/Pd
- Ni/Au
- Ag/Pt
- Ag/Pd
- Pt/Pd/Ag
- Ni/Au/Cu
- Sn
- Pd
- Ag
- Au

All these lead-free coatings are commercially available today and are being used as replacements for tin-lead solderable coatings. In most cases tinned coatings are being replaced to save money and/or to improve overall joint reliability, rather than for the environmental considerations.

Gold coatings have generally been used in military and space applications where cost is not an issue. Although gold is known to dissolve at a faster rate in high tin alloys it is not a concern for two reasons. First, gold coatings are applied at a limited thickness so dissolution rate has no effect on gold content in the joint. Second, Pb-free alloys can tolerate greater levels of gold without experiencing embrittlement problems associated with Sn-Pb alloys. The performance of Pd-coated components with lead-free alloys is equivalent to, or better than SnPb. This is due to the slightly greater dissolution rates of Pd in high tin alloys.

The IDEALS project (see sections 7 and 8) pinpointed some concern over the use of PdAg metallization due to the formation of voids in the joint during use since Ag diffuses into the alloy. However, the use of this coating is already being replaced by Sn/Ni. Other Ag-containing coatings such as PtPdAg and PtAg are not thought to exhibit this problem.

It can be seen that lead-free component coatings are now available and that many more will be produced in the near future. There are problems (see Section 7.3) associated with the change from tin-lead to lead-free solder use with the commonly used Ni/Pd alternative finishes. However, component suppliers still tend to lag behind other parts of the industry when it comes to consideration of the lead-free issue. Only large scale use and demand for lead-free finishes will encourage them to make a significant effort towards complete change over. It has been said by one company that it would be possible to produce a complete range of NiPd components within around 6 months if there were sufficient demand.

Aluminium electrolytic capacitors have been shown to be incompatible with higher temperature soldering required by most alloys. The normal maximum operating temperature for this type of component is 225 °C. The work that Nortel and Ford carried out using this type of capacitor showed that replacement was necessary. Tantalum based capacitors have been used as they have a much higher temperature threshold, to approximately 300 °C, but may have restrictions in terms of availability and cost.

6.5 COST/PRICING ISSUES

Current metal prices for solder constituents are shown in Table 5 together with data for prices at a similar time last year (metal prices have generally dropped over the last 12 months).

Table 5: Estimated costs and supplies for elements used in lead-free alloys

Element	Cost: 11/98 (US\$/t)	Cost: 11/97 (US\$/t)
Ag - silver	159,646	156,732
Bi - bismuth	7055	7385
Cu - copper	1598	1964
In - indium	275,000	300,00
Pb - lead	488	577
Sb - antimony	1325	1730
Sn - tin	5590	5570
Zn - zinc	952	1192

In the case of solder paste, metal cost is a fairly minor percentage of the product value. Any increase in metal cost is therefore diluted many times in the final paste price. It has been estimated that a 400% increase in metal cost would result in a paste price increase of 0-30%. A similar cost dilution would occur after use of the paste to form a solder joint and therefore even with a metal cost 4 times that of SnPb the cost of the final lead-free joint may be largely unaffected.

Currently, there can be huge differences between the cost of solder pastes due to market competition or other conditions. In particular, OEMs who use pastes of UK or European origin may pay more than consumer electronics manufacturers that are Japanese owned who tend to source from Japanese paste manufacturers.

As a comparison one manufacturer has quoted prices for 100 kg lots of two of the most common alloys. Sn63Pb37 is priced around £53 /kg where as an equivalent paste with the 62Sn36Pb2Ag alloy would be £55.50 /kg. Another European retailer sells paste at between £60 to £76 /kg irrespective of whether it is lead containing or lead-free.

Therefore for surface mount soldering the cost of the paste is likely to be almost identical to the current alloys used and will have little or no impact on the cost of the electronic product itself. This has been confirmed by discussions with paste suppliers.

The price of lead-free bar will be higher than that of SnPb due to the fact that suppliers sell product at a percentage over metal cost. This percentage is likely to remain the same whatever the alloy produced.

A standard wave solder bath would require around 300-400 kg to fill initially, but topping up would obviously not require such large amounts. Dross from the bath would be returned for reclamation as at present and some of the added metal cost of lead-free solder could be returned to the user at this stage.

Density should be taken into account when comparing costs of lead-free alloys with that of tin-lead. The volume of solder in a joint remains constant but the mass of lead-free solder is approximately 2/3 that of tin-lead due to density differences.

Current pricing of lead-free products are in some cases higher than would be expected. This is due to low current demand and prices will drop as soon as the interest increases. This has now begun with competition for the supply of SnAgCu pastes already lowering the price for its supply.

Cost savings are being continually made by large OEMs producing electronic equipment for the very competitive consumer market. Certain manufacturers have confirmed that this trend would continue and not be affected by the introduction of lead-free alloy use whether as paste or for wave soldering. Product re-design helps to achieve this aim.

Qualification of each new product has to be carried out to confirm to reliability and functionality requirements. Product qualification is already an inbuilt cost, therefore allowing sufficient time for the introduction of new products using lead-free alloys additional cost would be minimal. The typical development/qualification time for mobile phones, pagers etc, is in the region of 3-6 months, whereas that for an automotive product may be around 2 years.

7 LEAD-FREE SOLDERING TECHNOLOGY - IMPLEMENTATION ISSUES

Undoubtedly one of the most important questions facing companies changing over to lead-free soldering technology is 'How do I go about doing it?'. The answer to this question is not

straightforward since there are many issues within the microelectronics assembly industry which must be taken into consideration before effective lead-free soldering can be achieved. This report identifies several key areas of implementation in which issues will need to be addressed as detailed below.

7.1 TECHNOLOGY

The full range of technology issues which need to be addressed in lead-free soldering are far reaching and cannot be comprehensively covered in such a short study as this. However, from discussions with the few organisations who have had first hand experience of lead-free soldering in a commercial assembly environment, we have identified the key technological issues which companies changing over to lead-free soldering will have to address.

The first important point to note is that pilot lead-free assembly studies have already been carried out by a small number of companies such as Nortel Networks, Marconi Communications and others. These pilot studies have demonstrated that *lead-free soldering is technologically possible* albeit having been proved on very specific products and using particular production technologies.

Following the work in the DTI lead-free solders consortium, as part of the IDEALS programme, Marconi Communications have carried out production trials on a replacement for SnPb solders based upon commercially available SnAgCu alloys. They were able to drop this alloy into an existing assembly line using reflow soldering and predominantly surface mount technology, by modifying the reflow profile of their convection ovens. Products manufactured by this process are now out in the field and no significant reliability problems have been encountered so far. Based on the results of this study, Marconi Communications intend to commission a *fully operational lead-free production line* in the first half of 1999.

Also following the DTI sponsored investigation of lead-free solders, Nortel carried out their own mechanical/thermal cycling testing of SnCu and SnAg alloys. From these two alloys SnCu was selected for production trials based upon adequate mechanical and metallurgical properties and the cost and availability of Cu compared with Ag for wave soldering. A digital telephone was assembled using SnCu by a combination of both reflow and wave soldering carried out under nitrogen using commercially available no-clean fluxes. There are currently 150 of these telephones out in the field in the UK with no reported faults over a period of 2 ½ years. It should also be noted that a parallel exercise was carried out by Nortel in Canada using subcontractors for part of the assembly also with no reported problems.

From these and other studies the following technological issues have been identified

Higher process temperatures

The single most important technological issue that companies changing over to lead-free soldering will have to address is the need for higher process temperatures to provide an effective solder joint. The exact temperatures required will be dependent upon which alloy system is being used. For example, the peak reflow temperature used in the Marconi Communications study was 230°C whereas in the Nortel study a peak temperature of 255°C was used.

Higher process temperatures will impact existing soldering technology in three key areas;

(i) Materials stability/reliability.

Higher process temperatures will inevitably result in issues of stability and reliability of the board materials and components. This impact is expected to be less for wave soldering where the solder wave temperature is typically much higher above the melting point of the alloy than those experienced in reflow soldering. Some of the materials stability issues to come out of the above studies include;

- Electrolytic capacitors and other temperature sensitive components needed to be hand soldered after reflow. The long term solution to this is of course to design out such components where practically possible.
- Board laminates CEM-3 (and similar materials such as FR2) are generally unsuitable for reflow soldering at 255°C. However, no problems of board warpage with FR4 laminate were observed, albeit on relatively small size pallets.
- Soldering under nitrogen can increase the stability of organic materials such as plastics by up to 50°C where stability is a problem. However, this may add significant capital and overhead costs to the soldering process, particularly for the SMEs.
- No problems have been observed with active devices (ASICs, BGAs etc.) at the higher reflow temperatures so far despite concerns that the higher temperatures may cause an increase in the incidence of device failure. Since many of these failures are expected to be manifest as DOAs (Dead on Arrivals) rather than in-service failures, one may tentatively conclude that this problem may not be as critical as first thought. Most CMOS devices can withstand soldering temperatures up to 300 °C.

The conclusions to be drawn from these observations are that materials temperature stability issues do exist. However, many of these issues are not as serious as may have been first thought, and many can be addressed relatively straightforwardly. It should be noted that the experience so far is fairly limited and much more work needs to be carried out in this area before definitive conclusions can be drawn.

(ii) Equipment

Not only do most of the lead-free alloys require higher process temperatures than SnPb, but the process windows over which successful lead-free soldering can be achieved are narrower. This will have a severe impact on companies using Infra-Red (IR) based reflow ovens where variations in the temperature of the pca is not as tightly controlled as in more modern convection reflow ovens. It should be noted that replacing old IR ovens with convection ovens represents a significant capital expenditure for many SMEs where equipment turnover is relatively infrequent, compared to the larger OEMS and CEMs.

Two other concerns have been raised by the SME assemblers, both of which might result in the need to purchase new capital equipment, or at least to have modifications to the existing

equipment. Firstly, there may be a safety issue with reflow ovens. Many already “run hot”, and a higher operating temperature may require physical protective measures. Second, many of the ovens (and other equipment) are running on the limits of their capabilities, and may not be able to tolerate the required higher operating temperatures, hence incurring reliability problems. Moreover, SME manufacturers of ovens (in particular IR ovens) may well face a challenge in changing their product range. Some will not have the design and development resource to achieve the change.

(iii) Higher energy costs.

It should also be noted that higher process temperatures will inevitably lead to higher energy consumption and associated costs not only to the microelectronics assembly business but also indirectly to the environment through increased CO₂ production etc. At present we are not aware of any complete studies which quantify the specific impact of changing over to lead-free soldering on energy consumption and the subsequent environmental impacts. Some information from the IDEALS project may be available soon.

Materials compatibility

Another important technological issue is the compatibility of fluxes, board finishes and component finishes with lead-free solders.

(i) Fluxes

A wide range of fluxes has been developed by solder manufacturers for use with lead-free solders, requiring minor modifications from those traditionally used in SnPb soldering. Both the Nortel and Marconi pilot studies used commercially available no-clean fluxes, specified to rigorous customer standards, without any reported problems.

For reasons of reliability many pcbs are cleaned after soldering to remove flux residues etc which may compromise service performance. The choice of the particular cleaning regime, of which there are many, is geared towards efficient removal of the specific soils present by virtue of the particular soldering process, flux, activator etc, used. If new fluxes and pastes are required for the Pb-free soldering technologies, then there may be implications on the cleaning procedures used, and the change over may not be easy. Evaluation of the options, trialling, and final implementation are costly and time-consuming. It should be remembered that the changes in cleaning technologies brought about by the ban on ODSs has taken nearly 10 years to implement successfully. However, any problems regarding cleaning technologies are thought to be minor.

(ii) Board finishes

Again a wide range of lead-free board finishes is currently available commercially, and the evidence would appear to suggest that many of these are compatible with the lead-free solders. For example, the Marconi study has demonstrated that the SnAgCu alloy is compatible with Sn, Ag, Au and organic solderable preservative (OSP) finishes. The Nortel study also revealed that SnCu is compatible with OSP and Sn/Pb HASL finishes.

(iii) Components

As with Pb-Sn, the SnAgCu alloy is not compatible with Ag/Pd which exhibits very poor solderability. As well as the critical issue of lack of availability of components with lead-free finishes, there is also a technological issue to be overcome should a phased approach to removing Pb from the assembly process be adopted. Some studies have shown that if components with through hole SnPb terminations are wave soldered, a soldering defect known as hot tearing or fillet lifting occurs (Appendix 5), the exact cause of which is not known. This issue has yet to be fully addressed for wave soldering with SnAgCu, although the effect was not observed by Nortel, with SnCu. Initial trials with SnAgCu have not indicated any significant problems, but extra care is recommended.

The conclusion to be drawn here is that in the case of wave soldering, the preferred changeover sequence would be to move to Pb-free boards and components **BEFORE** changing to Pb-free solders. The change over sequence for reflow soldering is not as critical because of the absence of fillet lifting.

Work at Nortel has shown that the origin of lead in a traditional solder joint is apportioned as follows: 70% from the Sn-Pb solder, 25% from the HASL board finish, and 5% from the component terminations.

7.2 LOGISTICAL

One of the major concerns of industry is that although several lead-free alloys have been identified as suitable for specific applications, *no single drop-in replacement for general soldering has yet been identified*. However, for many purposes SnAgCu appears to be attractive and may become of general use. The lack of a single drop-in replacement has several implications as far as the logistics of actually implementing lead-free soldering are concerned. It should be noted that the overall trend of microelectronics industry is towards contract manufacture rather than in-house assembly. The consequence of this is that the contract manufacturers will have to address most of these logistical issues.

A particular concern is that, in the event of large customers specifying more than one alloy for their assemblies the contract manufacturer may be faced with having to have different assembly lines for each alloy. This is most applicable to wave soldering where emptying and refilling the solder bath is a non-trivial exercise. Clearly such an eventuality would result in a loss in competitiveness for the UK microelectronics contract manufacturing industry.

7.3 AVAILABILITY

The cheap cost and wide availability of SnPb solder and SnPb soldering finishes raises several issues relating to the availability of possible Pb-free alternatives.

Perhaps THE KEY ISSUE affecting the widespread implementation of lead-free soldering is the poor availability of components with lead-free finishes. This issue arises from the fact that a majority of component suppliers are large multinational companies, based outside the EC, operating in a high volume competitive global market. There is a concern within UK industry that if legislation is in place in Europe, but not the rest of the world, it may not be

economically sensible for the component suppliers to provide Pb-free versions of their products. Indeed one or two large component manufacturers have stated informally that they may consider pulling out of Europe in the event of a lead-ban. However, Europe is not the only region expected to implement lead-free policies. It should be noted that some suppliers are already changing to Pb-free terminations (eg Pd-Ni) - in some cases not for environmental reasons - and this change would increase following demand subsequent to legislation.

Such an availability problem does not exist with board materials, solders and equipment manufacturers as there already exists a local (European) industry which will accommodate the needs of their customers. Indeed, of the component manufacturers surveyed, most do not currently produce lead-free terminations and have stated that they will only do so at such a time when there is sufficient demand from industry.

Another equally important issue regarding availability is that of constituent elements in any Pb-free replacement for mass soldering. Although suitable for niche applications, alloys containing relatively scarce elements such as In will not be available in sufficient quantities without exhausting the world reserves of these materials in spite of an increase due to recycling activities. Indeed, if for example, the eutectic SnAgCu alloy were to be selected as a replacement for mass soldering, doubts have been expressed about the current spare Ag production capacity and the effects this may have on the price of the raw material. This analysis does not, however, take into account the recycling of Ag from the solder, which may be much more economically attractive than for Pb. Moreover, the Ag suppliers do not anticipate major supply problems.

7.4 INSPECTION

An important part of the microelectronics assembly process is the visual inspection of boards to pick up possible or potential defects and faults. The visual inspection process has been refined over many years experience with SnPb soldering to produce a set of simple guidelines which may be universally applied across the industry. Since the mechanical properties, physical properties and visual appearance of Pb-free joints may vary considerably from SnPb, there is a concern that new visual inspection guidelines need to be developed. Indeed, work at NPL for example, has demonstrated that the solder joint geometry and the visual appearance (the central criteria for inspectors) varies markedly depending on the materials present. The geometries associated with the combinations of Pb-free solders and Pb-free terminations, and of Pb-free solders and Pb-containing terminations, are both markedly different from the classic geometry exhibited by traditional Pb-Sn finished/soldered components.

The companies involved in pilot trials have been able to adapt existing inspection criteria to meet their requirements on an experiential basis. However there will need to be considerable work in this area if visual inspection operators currently working to the SnPb guidelines are to be successfully retrained to inspect Pb-free solder joints.

It should also be noted that X-ray inspection of Pb-free solder joints is possible, but requires greater care. Guidelines for the X-ray inspection of SnPb soldered joints will probably have to be modified depending upon the equipment and analysis software currently used.

7.5 DESIGN FOR THE ENVIRONMENT

Although considerable effort needs to be directed towards dealing directly with many of the implementation issues arising from lead-free soldering, perhaps a more radical and in the long term, economical approach is to address these issues at the design stage of the PCA. This approach, often termed beginning-of-pipe rather than end-of-pipe, may involve redesigning to avoid components which are known to be temperature sensitive for example. The benefit of this approach is that the assembly can be designed to fit best with the lead-free process being used, rather than trying to 'tweak' the process to accommodate the design. This approach, looking at the production of pcas "from the cradle to the grave", is beginning to find favour, especially with OEMs. However the disadvantage is that it may be costly in terms of both the initial design and development time, certainly for companies not used to the "front end" approach.

7.6 RELIABILITY

One of the reasons for the widespread use of SnPb solders in the industry at the moment is the high knowledge base, which has been accumulated over more than 50 years, relating to the long-term reliability of SnPb solder joints. Such a knowledge base, if it does exist, is not freely available for lead-free solders and indeed even with accelerated testing will still take many years to establish. While this may not be so critical for consumer electronics such as mobile telephones, with product lifetimes as low as 6 months, for other products which require service lifetimes from a few years to decades or more, this lack of knowledge is of real concern. However, SnAg has been used for several years and already has an established reliability record.

Early indications from accelerated ageing testing on SnAgCu alloys in the IDEALS programme would suggest that the *reliability of this alloy is at least as good as SnPb*. These studies have indicated a 50-100% increase in reliability under various conditions. However, much more work needs to be done to confirm this to be the case. Similarly, although Nortel have proven reliability of simple phones in the field and laboratory fatigue tests, a great deal of accelerated testing needs to be carried out before any conclusions can be drawn about the long term reliability of the SnCu alloy under a variety of conditions. Of prime concern is the lack of data on high lead-out devices such as BGAs and flip-chips. Although there is some evidence from TI to suggest that Pb-free BGAs are more reliable than the SnPb counterparts. It is anticipated that a great deal of work needs to be carried out in this area by organisations equipped to carry out these lengthy but essential studies. Certainly, many field studies are underway with few, if any, unexpected problems so far.

A major point to be recognised here, is that, in assessing and comparing the results of reliability tests, it is essential that the conditions of the test, the test regime etc are taken into account. Contradictory claims regarding reliability can arise from inappropriate comparison of the data, and misleading claims can be made using selected data.

7.7 REWORK AND REPAIR

Rework and repair of lead-free solder joints is another contentious issue which needs to be resolved. Rework of lead-free solder joints has been shown to be technologically possible, where issues with higher soldering temperatures have been thought to be of concern. These concerns are most likely to be manifest for rework of complex components such as BGAs which require a high level of background heat to remove and reflow effectively. However it appears that rework without damaging temperature sensitive parts of the assembly can be carried out *by carefully optimising the conditions used*. Essentially the same issues apply to rework as to general assembly in that good control over soldering temperatures are required.

Perhaps of greater significance are the issues arising from the fact that at this stage no single drop-in replacement for SnPb solder has been identified. Unless a suitable system of marking to indicate which solder was used during assembly is developed, it will be impossible for a rework operative to identify the alloy used and thus which alloy should be selected to carry out the rework. This should not be an issue for rework during initial assembly. But certain TOs have expressed the concern that there may be implications for rework and repair out in the field, where the absence of labelling and documentation, and/or problems of monitoring local soldering procedures, may give rise to incompatibilities between the different constituents of the rework alloy, component termination finish and original assembly alloy. However, it may be possible to use Pb-free solders without compatibility issues.

7.8 RECYCLING - SOLDER RECOVERY

Government regulations in many countries are becoming more stringent with regards to landfill and therefore companies are forced to find alternative methods for the disposal of their high-tech scrap, particularly following recycling. Printed circuit boards contain a great variety of metals in widely varying concentrations. Base metals such as iron and nickel are found in many electronic components, while most electrical connections contain significant quantities of copper. Solder is present on component leads and copper tracks. Many types of pcb scrap have sufficient concentrations of gold, silver and platinum group metals to ensure that the emphasis in most pcb recycling operations is currently on the recovery of valuable precious metals, rather than base metals like lead.

Current solder recycling process

A well-known method used to recover metals from pcb scrap is to use existing secondary copper smelting facilities. These can produce commercial grade copper from many different kinds of copper bearing scrap such as electric wire, piping and pcbs. Other metals contained in the scrap are separated from the copper in the form of oxides and slimes, which can be further refined by other metallurgical techniques such as hydrometallurgical extraction.

It must be noted that iron and aluminium, both abundant in electronic scrap are not recovered; they account for much of the slag produced in the early refining stages. It has been suggested that eliminating these metals from pcbs would significantly reduce the energy consumption of the smelting process. A reduction in use of aluminium electrolytic capacitors may therefore improve the overall recovery process.

Tin alloys are easily recycled. In one smelter almost 60% of tin coming into the group is in the form of tin-bearing residues such as solder dross, skimmings and metallic scrap, which in most cases also contain lead. The remaining tin input comes from copper-bearing materials where tin is also present such as brasses, bronzes, tinned copper wire and cable scrap. Elemental ingots of LME grade material are produced from this scrap.

As is the case for the refined metals, the scrap price of tin bearing substances remains significantly higher than those based on lead. Recycling often has to combat the problem that the transport and treatment costs of low value materials do not make the process economically worthwhile. The use of higher value tin based alloys, with the likely addition of silver, could make recycling of circuit boards more commercially viable.

The Sony solder recovery process

Sony has developed a circuit board recovery device in order to increase the separation, recovery and re-use of the solder used for electronic component connections. In particular, the technique was developed for television sets which use a relatively large amount of solder.

The circuit boards are removed from the television sets in the initial disassembly and pre-treatment phase of the operation, where the metal frames, resin mould frames, wiring and backing components are removed and crushed before the boards are passed through the solder recovery device. The solder recovery device contains a continuous conveyor passing the circuit boards through sets of heaters and brushes.

Solder recovery is easier to achieve from smaller components but it is particularly difficult in the case of components, such as tuners and heat sinks, whose construction requires good thermal dissipation. It is concluded that this is because the solder does not reach its softening temperature.

The equipment developed by Sony is capable of separating and directly recovering more than 70% of the solder from the circuit boards in question. The recovered solder contained little impurity and was capable of re-use as a soldering alloy. All tin-lead and lead-free alloys are suitable for recovery by this process apart from those containing zinc due to excessive drossing problems.

The treatment of small sized boards is likely to be more difficult to control and obviously produces a lower solder volume. Such treatment then becomes less economically favourable in comparison to shredding/landfill or other recovery treatments. Collection of small electronic goods and the separation of lead from these products before recycling treatments would be extremely costly.

7.9 COSTS

Perhaps one of the most significant barriers to a change to lead-free soldering in the absence of legislative pressure is that of cost. Some areas where cost is likely to have an impact on businesses assembling with lead-free alloys include:

Raw materials

Perhaps one of the most contentious cost issues: what will be the effect of increased demand on finite resources such as In, Ag, Bi etc. This is difficult to gauge from the current perspective. Some concerns have been raised about the effect on the price of Ag, for example, should the Ag-containing alloys be adopted as mainstream solders. However it should be noted that the raw material cost is only a tiny fraction of costs associated with a typical pcb product.

Soldering materials

As mentioned in section 6.5, analyses by solder suppliers have indicated that modest price increases can be expected for the solder pastes, with bar solder being more sensitive to raw material costs than pastes.

Equipment

Some older equipment, particularly for reflow soldering may not be adequate to achieve good results with lead-free solders. This may mean costly replacements or modifications to existing equipment, but more work needs to be done to establish what equipment is suitable and what modifications, if any, are required.

Energy Consumption

Both pca assemblers and component manufacturers have cited extra energy consumption as a cost barrier to changing over to lead-free technology (as well as environmental concerns).

Development time

This is expected to be the most significant one-off cost to companies changing over to lead-free technology in terms of both resources and time. This will be most critical for the SMEs where both time and resources are scarce; this cost could be significantly reduced by having the right information and help available to SMEs.

Retraining

It is anticipated that some retraining of process operatives/engineers will be required in production, inspection and rework. Again this could be minimised by having appropriate information available to industry.

Recycling

Some concerns have been expressed by recyclers about the costs of recovering certain alloying elements such as Bi from copper scrap. It should be noted that Ag can currently be recycled with a cost benefit, which may offset any anticipated problems with world supply and prices.

8 R&D PROJECTS

The world-wide concern of potential environmental effects and the recently proposed legislative restrictions on the use of lead-based solders, have prompted many research programmes in order to investigate the effects of producing lead-free electronic equipment.

8.1 INTRODUCTION TO SCOPE OF R&D

Many consortia have carried out research work on lead-free soldering. Most early programmes concentrated on the development of alloys, phase diagram determination and the assessment of basic properties such as toxicity of alternatives and some wetting or strength behaviour. Later programmes are concentrating on the five or so major alloy types such as SnCu, SnAg, SnAgCu, SnAgCuSb and SnAgBi, and are therefore able to carry out more detailed examination of fatigue properties, production behaviour and process optimisation.

Amongst the programmes set up to investigate lead-free interconnects are:

In the UK and Europe:

- **Lead-free Soldering**
1991-93 DTI part-funded project. The consortium consisted of GEC, BNR Europe (now Nortel), Multicore Solders and ITRI Ltd.
- **Solder Programme**
EPSRC funded project, Open University, Materials Engineering Department. Materials supplied by Alpha-Fry (Cookson Group) and Multicore.
- **Modelling of Solder Joint Reliability for Electronic Interconnects**
EPSRC funded project, Cambridge University 3½ year research programme
- **Loughborough University**
Fundamental characterisation of lead-free systems using DSC, TGA etc. Also involved with Motorola.
- **Wettability of Surfaces with New Solder/Flux Compositions**
TWI, 3 year research programme now in second year.
- **IDEALS (Improved Design Life and Environmentally Aware Manufacture of Electronics Assemblies by Lead-free Soldering)**
1996-99 a 36 month BRITE-EURAM funded project carried out by a consortium consisting of GEC Marconi, Multicore Solders, Phillips, Siemens AG, Witmetaal (Cookson Group) and NMRC Cork.
- **Integrity of Lead-free Solders**
Swedish Institute of Production Engineering Research (IVF). A multi-client research programme on 'Manufacturability, Failure Mechanisms and Reliability of Lead-Free Solders', Consortium work involving Promosol France, Volvo, ABB Automation Products and Ericsson Radio Systems, Sweden.

- **Helsinki University of Technology, Finland**
Predicting and investigating new alloy systems for lead-free solders.
- **Lead-free Solder Programme**
From 1991 to present. ITRI Ltd alloy development and assessment work funded by the tin industry and consortia members world-wide.
- **NPL - Lead-free Research Programme**
Visual Inspection, Compatibility, Solderability, Reliability, Rework and Repair, Conductive Adhesives.

In the US:

- **'Lead-free Solder Project', NCMS**
National Centre for Manufacturing Sciences four year project 1992-96 carried out by a consortium of: AT&T/Lucent Technologies, EMPF (the Navy's Electronics Manufacturing Productivity Facility), Ford Motor Company, GM-Delco Electronics, GM-Hughes Aircraft, NIST (the National Institute for Standards and Technology, Rensselaer Polytechnic Institute, Rockwell International Corporation, Sandia National Laboratories, Texas Instruments and Hamilton Standard, Division of United Technologies Corporation.

In Japan:

- **JIEP Project (Japan Institute of Electronics Packaging)**
Consortium work finished in 1996 included; Senju Metals, Harima Chemicals, Alpha Metals Japan, Nihon Handa, Ishikawa Metals, Uchibashi Estec, Speria Japan Solder Coat, Univ. of Tokyo, Osaka Univ, ICS, SC Lab, Tokyo Electric Univ. Tabai Espec, Mitsui Mining, Nippon Mining & Metals, Nippaku, Ishihara Chemicals, Tanaka Electronics Ind. Furukawa Electric Ind., TDK, Murata, Rubicom, Sony, Fujitsu, NEC, Hitachi, Toshiba, Panasonic, Fuji Electric and Omron.
- **Japan Welding Society**
Programme detail unknown.
- **Japanese Society of Mechanics**
Programme detail unknown.
- **Lead-free Soldering, NEDO**
New Energy and Industrial Technology Development Organisation. Consortium involved similar to JIEP project.
- **Japanese Universities**
Many universities are involved with the research and development of lead-free solders/soldering such as University of Tokyo, Osaka University, Yokohama National University, Shibaura Institute of Technology, Kohnan University, National Defence Academy.

8.2 SUMMARY OF KEY PROJECTS

'Lead-Free Soldering' UK. Industry - DTI funded

Work began on the research programme in 1991, involving GEC-Marconi, BNR Europe, Multicore, Solders and ITRI Ltd. and was part funded by the UK Department of Trade and Industry. The research was prompted by the world-wide concern over the use of lead and its ecological effects in old electronic equipment.

The consortium selected alloys with two criteria in mind: suitability for electronic assembly and supply potential. Thus, the following alloys were short-listed for trials:

- Bi-42Sn – eliminated due to poor mechanical properties and low melting point.
- Sn-9Zn – eliminated due to corrosion of the zinc phase
- Sn-5Sb – eliminated due to the melting temperature being too high.
- Sn-3.5Ag
- Sn-0.7Cu

After the initial work as part of the consortium, Nortel (formerly BNR Europe) continued working on the lead-free solders with the aim of obtaining some reliability data for the two remaining alloys. Three test boards were used for this work. Reflow trials in nitrogen were carried out using both tin-copper and tin-silver with a tin/lead control. Initial metallographic sections and mechanical pull tests showed that both alloys produced joints equal to that of tin/lead in their wetting behaviour and the initial mechanical strength was greater for the lead-free alloys. The remainder of the test boards were then put into accelerated thermal cycling ageing, using a cycle of 0-100°C with a fifteen minute dwell time at either end, and a fifteen minute ramp, giving a cycle time of one hour. All the 5,000 cycle thermally aged joints showed increased grain coarsening and significant surface cracking. However, sectioning showed that the cracks were only surface phenomena and did not penetrate through the thickness of the joint.

To test the validity of the lead-free soldering technology based on the tin-copper alloy in a manufacturing environment, 150 Meridian 8009 telephones were built at the Cwmcam factory in South Wales.

Nortel also carried out water leachate testing based on the US EPA TCLP methods to determine what difference would be made by replacing tin-lead with tin-copper soldering technologies. Both whole and 'shredded' boards were tested. The whole boards showed a x10 reduction in lead leachate in comparison to tin-lead and in the shredded form the reduction was increased to 30 times.

Nortel UK states that 'The universal adoption of lead-free solders by the electronics industry will probably be shaped by two factors – legislative action and competitive activity.'

Open University: The Solder Programme - Funded by EPSRC

There are a couple of factors which prompted the Open University research into lead-free solders. First, the environmental lobby for the elimination of lead, a toxic metal and a constituent of the vast majority of solders in current use. Second, due to more arduous

operating requirements and an increasing demand for smaller devices (surface mount technology), a solder joint must provide structural integrity and be efficiently designed.

The primary aim of the Open University programme is to develop knowledge and understanding with regard to the mechanical behaviour of lead-free alloys under the conditions likely to be found in service i.e. the life prediction of lead-free solder joints. It is hoped that a sound database will be compiled by the end of the programme with which candidate alloys may be compared.

The alloys under observation during this research programme are tin-3.5%silver, tin-0.5%copper and tin-3.5%silver-0.5%copper. The Open University quotes that the purpose of this work is “to establish a base of information and understanding relating to the behaviour of solder alloys, which perceive as essential to the fulfilment of our objectives”. The testing carried out on the lead-free alloys involved in the programme includes:

Mechanical testing	(tensile testing between -10 to 75°C)
Creep	(testing carried out at -40 to 130°C)
Fatigue	(at room temperature and at 75°C)
Metallography	

Initial results show that between strain rates of 10^{-1} and 10^{-3} s^{-1} , strain rate had a substantial effect on strength, with the tin-lead alloy being the most sensitive. Comparatively, the tin-copper solder alloy is usually the weakest and most ductile of the three alloys. Tin-lead is the strongest at room temperature, but with increasing temperature and slower strain rates it becomes inferior to tin-silver. Creep testing was performed between -40°C and 130°C with times to rupture of up to several thousand hours. Variations in creep ductility are profoundly influential on life during fatigue-creep when the dominant failure mechanism involves creep or stress relaxation processes. At 75°C the creep behaviour of the Sn-0.5Cu alloy is similar to that of Sn-37Pb. However, the tin-silver solder exhibits much greater creep resistance, which appears to increase at lower stress levels. The creep ductility at 75°C of the lead-free alloys is less than that for the eutectic Sn-37Pb, and that of the Sn-3.5Ag is the lowest at around 20% and appears to be insensitive to applied stress level.

Fatigue tests have been carried out on Sn-37Pb and SnCu alloys at room temperature and 75°C . Both alloys exhibit softening when subjected to strain controlled cycling. Incorporation of a dwell in the strain cycle causes a reduction in the number of cycles to failure in comparison to that measured during continuous cycling.

The initial phase of the Open University research programme focuses on the behaviour of the bulk solder alloys. It is quoted that “as data emerge it will be possible to evaluate both the conventional life prediction approaches and those more aligned to solder behaviour.”

The second part of the programme has been planned and funding/support is currently being sought from several potential sources. The extension of the programme is to incorporate thermal fatigue and include elementary joint geometries in order to give an insight into the extent of correlation between bulk and thin-layer behaviour.

Modelling of Solder Joint Reliability for Electronic Interconnects, Cambridge University - EPSRC funded

The aim of the research is to facilitate the development of both electronic devices and new solders by being able to predict, using computer simulation, the real life behaviour of soldered joints in area array devices. The ability to investigate rapidly the effects of altering materials, geometries of joints, fabrication methods and operating conditions would facilitate the development of new devices of higher reliability, smaller size and lower cost. Moreover, assurance can be given to the market that the new designs and materials will provide the long service lifetimes demanded commercially. Finite element analysis will be used to predict the strains that occur within solder joints due to thermal cycling; the data will then be combined with models of interactive fatigue-creep in order to predict lifetimes under given operational conditions. Simple experimental measurements will be an essential part of the programme in order to show the validity of the approach. An assessment of new solders will also be included since alternative alloys are being sought to replace currently used eutectic tin-lead solders.

'IDEALS' – Brite-Euram funded

The IDEALS programme has been carried out by GEC-Marconi, Philips, Siemens, Multicore Solders, Witmetaal and NMRC. The project runs for three years from 1996-1999. A presentation was made by Jim Vincent, representing the co-ordinating company GEC, at a seminar at NPL in October that outlined a number of conclusions;

- the optimum solders are based on Sn-Ag-Cu

Sn-3.8Ag-0.7Cu alloy was recommended for general purpose use, possibly with the addition of antimony
- Sn-3.8Ag-0.7Cu-0.5Sb, was recommended for wave soldering
- Sn-Bi-Ag could be used for single sided wave soldering
- the solders appeared to be compatible with existing paste and foam/spray flux systems
- the solders were compatible with many lead-free board finishes (Cu, OSP, Sn, Ag, Ni/Au, SnCu HASL) and even SnPb if no fillet lifting occurred. Caution was expressed over the use of Pd/Ni board coatings
- the solders were found to be compatible with most standard finishes including SnPb with the same proviso regarding lift-off, while there may be some questions over the use of Ni/Pd, and AgPd should be avoided
- reflow, wave and rework processes had been demonstrated with temperatures increasing only by 20°C in reflow and by 10°C in wave soldering

- the solders were found to be stronger than SnPb, and, more reliable in thermomechanical fatigue under all conditions
- the fatigue life assessment was carried out under a number of conditions; single chamber $-25 +125^{\circ}\text{C}$, liquid/liquid $-20 +125^{\circ}\text{C}$, gas/gas $-20 +100^{\circ}\text{C}$, gas/gas $-40 +125^{\circ}\text{C}$, power cycling ambient $+105^{\circ}\text{C}$, vibration up to 400g
- while the solders were said to hold promise for high stress application such as automotive to 150°C , this aspect had not yet been tested by the consortium

In summary, 'lead-free soldering is a practical proposition with direct and indirect benefits.'

No further details of this programme are available at present. The reservations over the use of Ni/Pd coatings do not spring from the IDEALS work itself, but the general opinion in the industry that the solderability and/or shelf life of Ni/Pd components are variable depending on supply. This comment does not depend on alloy type and is equally applicable to SnPb as lead-free solders.

AgPd coatings tend to result in the production of voids through diffusion of Ag into the joint during use. This type of coating is generally only found on capacitors and is now being replaced with Sn/Ni.

National Center for Manufacturing Sciences (NCMS) – industry funded

A consortium of 11 industrial corporations carried out the 'lead-free solder project' in order to evaluate alternatives to eutectic Sn-Pb solder. The project was initiated in response to potential legislation, which would ban or restrict the use of lead, and the goal of the project was to determine whether safe, reliable, non-toxic and cost effective substitutes existed for lead-bearing solders in electronics manufacturing. The project ran from 1992-96 and was therefore one of the early lead-free projects not having the benefit of examining previous work.

The choice of alloys was reduced by the elimination of:

- Candidates containing toxic elements.
- All but one of a family of candidates having very minor composition differences.
- Candidates falling outside certain manufacturability, reliability, economics, availability criteria established by project participants.
- Applying judgement criteria set forth in a weighted decision matrix for those alloys that passed the first three screenings.

Five alloys emerged from the down-selection as viable candidates to replace 80% of the currently used near eutectic tin/lead solder. Sn-58Bi and Sn-2.8Ag-20In were also retained as

selected alloys for manufacturability and reliability assessments even though they both failed economics/availability criteria. The Sn-2.8Ag-20In, theoretically rejected by the selection process, showed the poorest thermal cycling performance. It is known that this alloy has a pasty range of 12°C and a liquidus temperature of 186°C, but retains a measurable fraction of liquid phase that solidifies at 117°C as a result of segregation during cooling.

The solders were chosen to minimise liquidus temperature and pasty range whilst having no lower temperature melting phase detected by differential thermal analysis. The aim of this criterion was to prevent component movement caused by the use of an alloy with a large melting range and also to reduce fillet lifting (although this had not yet been defined by NCMS at the time). The criteria then limited the bismuth concentrations to less than 5% in high tin alloys, and should also have eliminated the In-containing alloys from the beginning of the study. However, certain members of the consortium felt that high Bi and In alloys should still be included so the initial elimination criterion was essentially ignored.

During the investigation, it was determined that indium-containing alloys interacted with certain flux packages and could therefore not be stored as pastes. Other problems relating to flux formulations suitable for the required reflow temperatures are mentioned throughout the report, as is the admission that reformulation would enhance the soldering performance of the lead-free alloys. Much flux development has been carried out since this time and lead-free compatible fluxes are available in all types, including VOC-free, no clean versions which have been particularly difficult to develop.

It was found during the NCMS project that Sn-58Bi eutectic, Sn3.4Ag-4.8Bi and Sn3.5Ag eutectic solders performed substantially better than the eutectic SnPb in certain surface mount applications. The project also showed that Sn-58Bi and Sn3.4Ag-4.8Bi had fatigue lives comparable to or better than eutectic SnPb, showed similar bulk properties at room temperature, as well as very high tensile and yield strengths combined with moderate to high elongation. The combination of high strength and ductility is desirable in a solder alloy because strength is a measure of the materials ability to withstand stress in tension, and ductility provides resistance to creep failure, which is the primary source of solder failure under thermo-mechanical loading. Sn-58Bi has been used extensively for the last twenty years in high performance applications where low assembly processing temperatures are required and when 'end of use' temperatures are well below 100°C.

Another section of the NCMS work was a report on the fillet lifting effect. Low melting ternary or quaternary eutectics may form when Bi and/or In is mixed with SnPb. For example, SnBiPb with a melting point of 98°C can be formed increasing the likelihood of fillet lifting. Two alloys were tested, the SnAg and a SnAgBi, both with additions of lead. Although, it is not specified in the report, it is thought that the components used were originally SnPb coated from which the alloy had been stripped prior to use. It is not known if any lead remained on the components that may have effected the fillet lifting results.

It must be remembered that this phenomenon almost only occurs in through hole joints and is not seen in surface mount assemblies unless there is a particularly unusual mixture of Bi and Pb. In any case, tests have been carried out that have shown a certain amount of lifting does not impact to any significant level on the reliability of the joint. Minor lifting is only a problem if the appearance of the joint is not acceptable to inspectors.

Table 6 summarises the findings of the NCMS report. The most surprising result is the apparent lower fatigue life of SnAg at the -55 to +125°C cycle as SnAg has been used in the past to improve product reliability at such service temperatures.

Table 6: Conclusions of NCMS

Alloys	Liquidus and Solidus Temperatures	Industry Sectors	Evidence for Recommendation
Sn-58Bi	139 °C (eutectic)	Consumer Electronics Telecommunications	Simple two-component eutectic alloy but low eutectic temperature restricts maximum use temperature. Surface Mount Technology: Better fatigue life than eutectic tin-lead for both thermal cycling ranges; less fatigue damage than eutectic tin-lead seen in surface mount cross sections. Through-Hole Technology: Mixed results with fatigue life for CPGA-84 better than eutectic tin-lead; for CDIP-20 worse than eutectic tin-lead.
Sn-3.5Ag-4.8Bi	210 °C to 205 °C	Consumer Electronics Telecommunications Aerospace Automotive	Surface Mount Technology: Longer fatigue life than eutectic tin-lead at 0 °C to 100 °C; no failures in 1206 resistors up to 6,673 cycles; fatigue life equivalent to eutectic tin-lead at -55 °C to +125 °C; less fatigue damage than eutectic tin-lead seen in surface mount cross sections. Through-Hole Technology: Most joints show failure by fillet lifting.
Sn-3.5Ag	221 °C (eutectic)	Consumer Electronics Telecommunications Aerospace Automotive	Simple two-component eutectic alloy. Surface Mount Technology: Fatigue life equivalent to eutectic tin-lead at 0 °C to 100 °C; worse than eutectic tin-lead at -55 °C to +125 °C. Through-Hole Technology: Less susceptible than other high-tin solders to fillet lifting but results with Sn-2.6Ag-0.8Cu-0.5Sb indicate through-hole reliability still may be compromised.

The NCMS conclusions state that a ‘drop-in’ replacement for eutectic tin-lead solder was not identified. Investigators involved in soldering and lead-free work always expected this conclusion. The limitation of elements available for alternatives almost automatically leads to this conclusion; however, much work was carried out in the early 1990’s by companies hoping to achieve a commercial gain by patenting one particular composition. This increased the confusion of potential users over which alloy should be chosen when most offer no particular benefit over the previously known, simpler, alloys such as the SnAg eutectic.

Research work on lead-free soldering is now much more focused on the more limited alloy choice and this will increase the knowledge base and understanding of the systems significantly over the next few years.

In summary, much flux development work, improvement of coatings etc has been carried out since the project was initiated which, together with more experience of the topic, would have improved the general joint quality and reliability of the lead-free alloys under test.

JIEP Project (Japan Institute of Electronics Packaging) and NEDO (New Energy and Industrial Technology Development Organisation)

The JIEP project finished two years ago and focused on the Sn-Ag-Bi (Bi 7-25%) alloys, the report was completed last year (in Japanese). A new project was also started last year.

Many of the companies involved in the JIEP projects are also involved with the NEDO research programme. The aim of this work is the same as the previous Japanese research work and that is to find a 'standard lead-free solder and standard soldering conditions'. Another aim is to compile a database of solders that can be considered for industrial use (similar to that of the Open University aim).

Many tests are to be performed on the solder alloys such as mechanical, electrical and microstructural analysis. Tests include, solderability using model boards, thermal exposure and thermal fatigue.

The conclusions made from the JIEP work were that any solder alloys containing more than 7% bismuth were very brittle and fillet lifting became a serious concern even though the melting temperature of the solder alloy is relatively low. The tin-silver-copper alloys with or without a few % of bismuth proved to be useful. It was also discovered that tin-zinc and tin-copper alloys have a great potential as use as solder alloys. Research work concerning these alloys began last year.

It is hoped that a preliminary report for the Japanese NEDO programme will be released in April 1999.

TWI Research Project, Wettability of surfaces with new solder/flux compositions

The objective of this research programme is to characterise the surface wetting of electronic packaging materials when using new, environmentally friendly solders and fluxes. A survey of solder/flux manufacturers and end users will be conducted in order to identify materials that are most likely to be accepted within the soldering industry. A study of the wetting characteristics of selected materials in conjunction with a range of plated finishes will be undertaken. This will include an examination of surface chemistry, dissolution of material into the solder and the mechanical/environmental properties of the joints. The benefits arising for this type of research work are, reduced manufacturing costs arising from improved productivity, reliability and reduced rework, more environmentally friendly assembly and reduced cleaning.

IVF, Integrity of Lead-free Solders – industry funded

The objectives of this two-year programme are

1. To assess and characterise currently available lead-free systems in terms of manufacturability and reliability by environmental testing in various electronics applications. The manufacturability will be assessed in terms of solderability, printability, reflow and wave soldering processes and conditions.

2. To generate an understanding of the failure mechanisms, design rules and process specifications in terms of reflow and wave soldering of lead-free soldering systems.
- 3 To generate long-term reliability data for lead-free solder alloys by generating low cycle mechanical fatigue life data in a humid atmosphere. The data will be, if possible, used for prediction of the real service life at various application conditions.

Critical issues present during reflow and wave soldering may have a profound effect on the joint quality, therefore various conditions need to be examined. The alloy systems to be used in this programme are Sn-Ag, Sn-Ag-Cu and Sn-Ag-Bi with no-clean flux package.

Experimental evaluation includes wettability tests using wetting balance method, suitability for reflow and wave soldering, fine-pitch capability down to 0.65 mm pitch quad flat packs and BGAs. Flip chip will also be considered. Reliability testing mainly involves temperature cycling and damp heat. A failure mechanism study will be carried out, and a preliminary suggestion is to study ageing and failure mode during wave and reflow soldering.

Determination of long-term reliability data will be undertaken to characterise the mechanical low cycle fatigue properties under different environmental conditions of lead-free solders. The microstructural change during the fatigue test will be analysed using SEM and TEM. The “electrical signal change” will be monitored to find out the relationship between microstructure degradation/evolution and electrical performance of the joint.

NPL Research in Lead-free solders

NPL has been actively involved in research in lead-free soldering for many years. Recent projects include an investigation of assembly yields from Pd/Ni terminated components involving 6 companies, and on-going work in the solderability testing of Pb-free alloys in air and low oxygen environments. Relevant reports are available on request.

In addition, in collaboration with suppliers and users, NPL will commence a new 3 year research project in lead-free solders in April 1999. This project aims to address many of the lead-free soldering issues faced by UK industry by providing;

- widely available up to date information on the state-of-the-art.
- new test methods to aid development of lead-free microelectronics products.
- best practice guides for the assembly of lead-free microelectronics products.

Specific areas of technology to be addressed will include visual inspection, rework and repair, solderability and reliability.

Lead-free Research at ITRI

ITRI has been involved with lead-free research for over a decade. Investigations have been completed in many areas in order to obtain an understanding of the basic properties of the

alternative alloys and research is currently on-going into reliability and process issues. Information is available for the most common lead-free solders on:

- strength and reliability
- wettability
- performance of pastes
- compatibility with a range of substrates
- intermetallic growth
- drossing
- low temperature properties, etc

Legislative updates and information on new lead-free products can also be found on the ITRI website www.itri.co.uk.

8.3 CONCLUSIONS OF WORK SO FAR

Although many research projects are still underway and will provide valuable data in the future, some conclusions can be made with reference to the work that has already been completed:

- The wetting achieved when using lead-free solder alloys with ‘modified’ reflow cycles is acceptable.
- Most lead-free alloys are compatible with existing paste and foam/spray flux systems
- Lead-free alloys are compatible with many lead-free board finishes
- The reliability of the joints produced using lead-free soldering technology proved to be good
- Many of the research programmes have determined that tin-silver-copper alloys proved to be the most promising solder for general use

9 FLAME RETARDANTS

The current EC draft proposes to phase out halogenated flame retardants by 1 January 2004, provided that alternative flame retardants can meet the minimum fire safety standards.

At present, halogenated flame retardants, particularly those which can be classified as aromatic bromine compounds, are widely used in the electronics industry. This group of compounds can further be divided as follows:

- (1) Polybromodiphenyl oxides (PBDPO's), including decabromodiphenyl oxide (DBDPO), octabromodiphenyl oxide (OBDPO) and pentabromodiphenyl (PeBDPO), which are extensively used (often in conjunction with antimony trioxide synergist) in

plastics for television sets, computers, telephones and other electrical and electronic equipment housings. The main polymers involved are ABS (acrylonitrile-butadiene-styrene copolymer), HIPS (high impact polystyrene) and polycarbonate/ABS blends.

- (2) Tetrabromobisphenol A (TBBPA), which is the main flame retardant used in epoxy resin printed circuit boards.

Moves by environmental groups to ban the use of these brominated flame retardants have arisen since the mid-1980's when laboratory studies suggested that, under certain combustion conditions, these compounds could generate brominated dioxins and furans, which are known to be highly toxic. Concerns over the use of halogenated compounds are concentrated around central Europe and Japan, with less activity seen in the USA.

The industry response has been spear-headed by the relevant trade associations (BSEF, PCIF, EBFRIP) and the approach has been to lobby the EC on technical grounds. They claim

no attempt has been made to assess the relative environmental impact of halogenated and non-halogenated flame retardants

- the presence of halogenated flame retardants does not affect recyclability any differently than other additives

the halogens themselves can be recycled from plastics used in EEE

- the proposed phase-out of halogenated flame retardants would unjustifiably prevent the recycling of materials from equipment currently in use, and would preclude development of products and processes that may provide the best solutions for future recycling goals.

A statement from the European Brominated Flame Retardant Industry Panel (EBFRIP) shown in Appendix 4 reports that:

- (a) the commercially used brominated flame retardants do not pose an environmental threat or health hazard, and
- (b) a phase-out of these flame retardants will result in diminished fire safety,

However, it is generally perceived that these brominated flame retardants will eventually be banned and many companies are already looking at alternatives. Other methods are being used to encourage a reduction in their use such as in specification for eco-labels.

It should be noted that the Scandinavian countries are the most active in Europe in working towards banning all bromine-containing materials.

(1) Replacements for PBDPO's in ABS, PC/ABS and HIPS (eg equipment housings)

Since it is generally recognised that brominated flame retardants are the most effective types in terms of cost/performance, alternatives to PBDPO types have been developed and commercialised by the major bromine FR producers. These include proprietary aromatic

bromine compounds which, by virtue of their chemical structure, cannot generate dioxins or furans during combustion, and tetrabromobisphenol A - epoxy oligomers.

Certain halogen-free alternatives have also been suggested, including phosphate esters, melamine and inorganic fillers such as alumina trihydrate (ATH), magnesium hydroxide and magnesium carbonate. However, relatively high loadings of these additives are usually required to achieve an adequate level of flame retardancy and this makes processing more difficult, and degrades the physical properties of the polymer.

Finally, some companies are looking seriously at inherently flame-retardant polymers such as modified polyphenylene oxide (PPO), which is very costly compared with the existing materials, and blends of polymers such as ABS/PVC. In the latter case, flame retardancy is imparted by the chlorine content of the PVC. Although antimony trioxide is the established synergist for improving flame retardancy of PVC-containing systems, alternative inorganic synergists, such as zinc hydroxystannate (ZHS) and zinc stannate (ZS), are beginning to replace Sb_2O_3 of their non-toxicity and their combined flame-retardant and smoke-suppressant properties.

(2) *Replacements for TBBPA in epoxy resins (e.g. as boards)*

Alternative flame retardants to the established brominated system are limited to red phosphorus (which itself has problems associated with its thermal instability and its toxicity) and high levels of inorganic fillers. In the latter case, typical loadings of up to 50% by weight of either alumina trihydrate (ATH) or magnesium hydroxide are needed for the required flame retardancy. These high loadings adversely affect physical properties of the board. In particular, there is enhanced rigidity and stiffness, with increased brittleness, reduced impact strength and tensile strength. In addition, hydrated fillers such as ATH and $\text{Mg}(\text{OH})_2$ tend to be somewhat hygroscopic, which increases water absorption in the board. Longer drying times may be required for boards incorporating these alternative flame retardants.

The use of zinc hydroxystannate (ZHS) or zinc stannate (ZS) in conjunction with inorganic fillers to achieve adequate flame retardancy in laminated circuit boards, has recently been patented by the Japanese company, Sumitomo Bakelite (Japan Patent 98 146,917). The resulting epoxy composition is claimed to have good fire resistance, good solder heat resistance and reduced release of smoke and harmful gases.

In conclusion, although bromine compounds are almost certainly the most effective flame retardants for electrical and electronic equipment, replacement is possible. However, there is generally a compromise in terms of other properties, particularly mechanical ones, due to the higher loadings required. The higher flame retardant content required to achieve adequate safety standards with the non-bromine systems generally makes the product more costly although it is not possible to estimate the extent of this increase without further work. Some parts of the industry have quoted that the cost of the alternative flame retardants will be up to ten times that of the conventional brominated counterparts, although this is thought to be excessive.

10 LEGISLATION

UK - EUROPE

Second Draft Proposal for an EC Directive on Waste from Electrical and Electronic Equipment.

The publication of this WEEE document has focused a much greater interest onto many aspects of Pb-free soldering, and many professional and trade organisations have been lobbying national and European Government Departments on particular issues raised in this second draft.

The timescales are short. The full proposal for the EC Directive is likely to be published around April 1999, and may include modifications based on submissions and comments occasioned by the second draft. The EC Directive itself is expected to follow later in the year. National Governments will then have eighteen months to enact national legislation to comply with the Directive i.e. the legislation could be in place by the beginning of 2001. The key date given in the second draft for the implementation of its provisions is 1st January 2004, leaving little time for technical compliance.

This draft Directive sets out measures that aim at

- the prevention of waste from electrical and electronic equipment (EEE)
- the re-use, recycling and other forms of recovery of such wastes
- minimising the risks and impacts to the environment associated with the treatment and disposal of EOL (end-of-life) EEE
- harmonising national EOL measures

Although principally about recycling, clauses in the second draft seriously affect aspects of electronics manufacturing. The salient clauses are:

Article 2 No. 1. *“EEE shall mean equipment which is dependent on electric currents or electromagnetic fields in order to work properly falling under the categories set out in Annex 1A, and designed for use with a voltage rating not exceeding 1000 Volts for alternating current and 1500 Volts for direct current.”*

The Annex 1A lists the eleven categories of EEE covered by the Directive with illustrative examples. Whilst not exclusive the list does cover the vast majority of electronics applications, and certainly all the high volume sectors of the market. The eleven categories are:

Large Household Appliances	Small Household Appliances
IT Equipment	Telecommunications
Radio, TV, Electroacoustic, Musical Instruments	
Lighting Equipment	Medical Equipment Systems
Monitoring & Control Instruments	Toys
Electrical & Electronic Tools	Automatic Dispensers

It should be noted that there are significant omissions from this list including EEE for the defence, aerospace and space sectors. The automotive sector is expected to be covered by other legislation specific to that industry.

- Article 2 No. 1 *“EEE includes all components and sub-assemblies which are part of the product as well as consumables referred to in Annex II”*

For the first time consumables are listed in the definition of EEE. The consumables mentioned in the Annex include records, tapes and other media for sound or other phenomena, all ink and toner cartridges, and fluorescent lamps.

- Article 4. No. 4 *“Members states shall ensure that the use of lead, cadmium, hexavalent chromium and halogenated flame retardants is phased out by 1st January 2004”.*

This measure is aimed to improve recycling, and a list of proposed exemptions from this provision is provided. In particular, there are two exemptions to the ban on the use of lead (in radiation protection; in CRTs, light bulbs and fluorescent tubes). Clearly soldering is not exempt, although some lobbying for exemption has been undertaken by trade organisations. It is this clause that has accelerated the lead-free soldering debate.

Lobbying has also occurred regarding the ban on the use of halogenated flame retardants. The central argument is that possible replacements cannot satisfy the technical requirements of the relevant fire safety standards (BS EN 60065 “Safety Requirements for mains Operated Electronic and Related Apparatus for Household and Similar General Use”; and UL94 “Test for Flammability of Plastic Materials for Parts in Devices and Appliances”). Since this point on safety is quoted as a grounds for exemption, the lobbyists are optimistic on this point.

- Article 6. No. 3 *“Member states shall ensure that producers set up systems to provide the for pre-treatment of EOL EEE that is separately collected and destined for landfilling . . .”*

This means that components containing lead, cadmium, hexavalent chromium, halogenated flame retardants etc, will have to be removed from any end-of-life EEE which is destined for landfilling, incineration, or recovery. This would entail prohibitive costs, and hence underlines the need to eliminate their use.

- Article 7. No. 5 *“Member states shall ensure that the share of recycled plastic in new EEE amounts at least to 5% of the total plastic content by 1st January 1999”*

The problem here is how to ensure that the 5% recycle complies with any ban on halogenated flame retardants. The vast majority of existing parts, from which recycle would presumably be collected, all currently contain halogenated flame retardants.

AMERICA

There is currently no legislation relating to the lead-free issue in America. The previously proposed legislation (see section 4) has not been enacted, although great interest is being shown on the progress of legislation in other countries, particularly in Europe.

JAPAN

In May 1998 the Japanese Government introduced legislation relating to recycling. Although lead was not specifically mentioned the implication was there. The industry has taken heed of “guidelines” from the Japanese EPA and the government suggesting reduced use of lead as part of the increased recycling, and many major companies have taken up the challenge and have announced measures and timescales to reduce and eliminate lead in the solder (see section 10). It is this move by the Japanese industry in the absence of an overt legislative driver, that is the cause of interest and concern in North America.

11 INTERNATIONAL PERSPECTIVE

The growing trend for manufacturer responsibility makes companies aware of the environmental effects of their products from design to disposal, including any recycling that may be required. The use of hazardous materials in products that may be covered by these regulations raises concerns over public and worker safety, and waste disposal. The following sections outline which companies are taking the threat to lead use most seriously.

11.1 NORTH AMERICA

Although the first moves against the use of lead in electronics solders were made in the USA around ten years ago less attention has been paid to the topic in more recent times. The Republican majority returned to the US government in 1994 meant that interventionist policies were no longer favoured from this time. No voluntary or legislative proposals affecting lead solders in the US have been seen since that time and are still unlikely because large Democrat gains were not obtained in the last congressional elections of November 1998.

Although in 1990 the US electronics industry believed that lead would remain in electronic solder for a significant time, many collaborative programmes were initiated, and millions of dollars spent, developing new lead-free solders alloys and investigating the properties of the best available. Eight years on from when the Reid Bill was first proposed (see section 4) it has been demonstrated that leaded solders can be replaced with little or no affect on product cost, and maintain reliability. *The argument used to defend the electronics industry from change, that it is not possible to use lead-free solders, will be difficult to use again.*

Many programmes were carried out early in the 1990’s on a wide range of consumer and industrial electronic products but the work was gradually abandoned in many areas. Serious evaluation of lead-free alloys has continued in the USA in one particular area, for automotive applications, where the higher melting temperatures of the lead-free alloys can provide higher

strength and fatigue life at higher service temperatures. Companies such as Delco, Ford and Motorola have continued studies and qualification of lead-free products for this purpose despite the lack of legislative pressure in the USA. *It should be noted that the key driver for Pb-free soldering in the USA is seen as competition from Japan.*

Nortel remain as one of the few North American companies to consider the use of lead-free solders in consumer electronics. In this case the incentive was seen as potential advantage over other suppliers in contract negotiations.

Examples of work carried out by relevant North American companies is summarised below:

Nortel Networks

Nortel Networks (formerly Nortel Technology) has produced approximately 500 lead-free Meridian phones at four different sites across North America and Europe. They chose the eutectic Sn-0.7%Cu to replace Sn-Pb solder for both surface mount and through-hole component connections.

The study is relevant to the consumer product market. Nortel used a large number of component finishes including SnPb and lead-free coatings in order to gauge the effect of different coatings on the solder joints. The coatings used were Ni/Pd, Ni/Au, silver, tin-copper, tin and tin/lead (tinned). They found all the specified component finishes gave satisfactory wetting and component reliability, even the tin-lead, but recommend tin or tin-copper as the solderable finish for this alloy. No fillet lifting was seen with the tin-lead coated leads.

Type FR-4 boards were used for the entire run of test assemblies. OSP (Entek) solderable coating was used on the lead-free test assemblies and HASL solderable coating was used on the tin-lead containing assemblies. No problems were experienced with the board.

The tin-lead Pcb's were used as controls for the thermal cycling trials performed on the completed phone assemblies.

In summary the conclusions were that:

- Eutectic tin-copper is a viable alternative to eutectic tin-lead solder.
- Standard surface mount components can withstand the harsher process conditions.
- Thermal fatigue resistance of eutectic tin-copper is superior to that of eutectic tin-lead (no matter what component coatings were used).
- Other than the use of a nitrogen environment no other machine alterations were necessary to complete the builds.

Motorola

Motorola are trialing lead-free alloys for use in under bonnet applications (e.g. engine management systems). Lead-free alloys are being used to increase the working temperature of the electronics, without reducing the overall life expectancy of the assemblies.

The increase in working temperature would allow the use of more electronics under the bonnet, so relocating the electronics from within the passenger compartment to the engine bay. This in turn reduces the length of cabling that is required within the car so reducing the weight and cost of the vehicle.

Ford Motor Company

The Ford Motor Company has also concentrated its research on under bonnet applications. Ford chose Sn-3.5% Ag for their trials and the main effort of their work was on no-clean fluxes. The conclusions were as follows:

- Sn-Ag solder can be used in no-clean applications.
- The lead-free eutectic Sn-Ag solder has been found to enhance reliability over Sn-Pb solders.
- Overall the Sn-Ag (96.5/3.5) solder has been found to be a suitable replacement for Sn-Pb solder.

The functionality of aluminium electrolytic capacitors was observed to fail at around 225°C and as such were seen to need replacement. Replacement components are being evaluated for their suitability. No other problems were reported.

Texas Instruments

Texas Instruments have undertaken a complete study on the use of lead-free solder for the replacement of Sn-Pb lead solder joints. The study was carried out using ENTEK PLUS (OSP) coated FR-4 boards and Ni/Pd and Ni/Pd/Au component lead finishes. The alloy used was SnAgCuSb no-clean solder paste. The conclusion of the study was:

...it is now possible to achieve a totally Pb-free solder joint.

Other conclusions made from the study were:

- The increased contact angle for the lead-free alloys was cosmetic and had no affect on joint properties.
- Sn-Pb gave a lower lead pull strength than that of all the lead-free alloys evaluated.

- Thermal cycling gave no failures after 3000 cycles for all alloys evaluated. The cycle range was - 65 to + 150 °C.
- Cross section of cycled units showed no cracks up to 250 cycles

After the completion of over 5 years of studies on the use of Ni/Pd coatings as replacements for tin-lead, Texas Instruments are so confident that Ni/Pd is a viable replacement for component solderable coatings, that some product lines are now only available in Ni/Pd format. Also the use of high lead solder for die-attach has been replaced completely throughout Texas Instruments' component ranges. Die-attach is carried out using silver-loaded epoxies. This method is seen to be cleaner and more efficient than the use of soldered joints although not suitable for high power applications.

11.2 JAPAN

Following the 'guidelines' from the Japanese EPA and the government suggesting reduced use of lead and increased recycling, a number of major Japanese electronic equipment manufacturers have announced voluntary plans to reduce their use of lead in solder;

- Hitachi aim to reduce their use of lead by half during 1999 (compared to 1997 levels) and to stop using lead solder by 2001
- NEC intend to reduce lead use by 50% by 2002 compared to 1997
- Matsushita (Panasonic) aim to stop using lead solder by 2001
- NTT are intending to only purchase equipment safe for the environment (i.e. no lead or cadmium) by 2001.

Many other announcements are expected during the first half of 1999 from other OEMs who are working on lead-free products at the moment.

JEIDA (Japan Electric Industries Development Association) feels that "It is none other than [the] ability to be environmentally friendly that will lead to new added value," and, while it is possible that things may change "on their own," the "added value of environmental technologies will not manifest itself if we sit and wait." JEIDA is therefore encouraging industry to act on the lead issue now. As the US IPC committee says 'In this era of bottom lines, one would think it unlikely that good intentions are enough to satisfy the [possible] higher cost to consumers. Yet in Japan, Hitachi, Matsushita, and Toshiba have already begun the conversion.'

JEIDA has recognised the deadlock between component suppliers and OEMs and is planning to progress the use of lead-free solders in Japan. It recommends using the SnAgCu alloys while supply of lead-free components is limited, and then to move in some cases to the SnBiAg when more lead-free coated components are available.

Matsushita

At the forefront of these moves is the Matsushita group of companies with lead-free working groups organised throughout the company to meet their environmental target.

Panasonic have done extensive trials using lead-free solders and have picked the Sn-Ag-Bi-x alloy series for their first lead-free product line. The portable MiniDisc player is now on sale in Japan and over 40,000 units are being manufactured per month. It is expected that this product will be introduced onto the European market in March 1999.

Another MiniDisc will be produced using lead-free solder very shortly and other products known to be on the way are televisions, refrigerators, washing machines and air conditioning units. All these products are due to be lead-free by 2000 with all use of lead solder to be ended during 2001. Matsushita continues to promote and develop practical application of lead-free solders within environmentally friendly products. Lead-free soldering technology will be transferred to overseas production plants in the near future.

The conclusion from technical trials is that 'installation of lead-free solder can be achieved such that no problems regarding material properties, installation quality, reliability etc, arise in actual production, and, implementation is being proceeded with.'

A lead-free label used on the MiniDisc launched in October 98 is expected to be adopted by the Japan Electric Industries Development Association as a standard indicator. Discussions are also underway to allow other lead-free manufacturers to adopt the same label and increase global awareness of the lead issue with the public.

Hitachi Ltd

Hitachi have an environmental policy similar to that of Matsushita but have not yet released any units. Certain products are expected to be launched shortly. The SnBiAg type alloys are also favoured by Hitachi.

NEC Corporation

NEC are aiming for a lead reduction but not as aggressively as Matsushita or Hitachi. NEC appear to favour the higher temperature SnAg and SnAgCu alloys for their products.

Toshiba Corporation

Toshiba have not made an announcement regarding their reduction of lead but are known to have developed lead-free solders suitable for high density cellular phones. A significant amount of work is being carried out at Toshiba.

Sony Corporation

Sony have developed a Sn-2Ag-4Bi-0.5Cu-0.1Ge for their own use said to have five times the reliability of SnPb. Sony previously announced a lead reduction policy but have not yet set a target date for lead solder reduction in their products.

11.3 EUROPE (NON-UK)

In Europe the greatest concerns over the continued use of lead come from Scandinavia, in particular Denmark and Sweden. A meeting of the Nordic Ministers of Environment in 1994 produced a statement that 'in the long run the phasing out of lead is necessary to reduce risk from lead exposure on human health and the environment'. This statement was signed by Denmark, Sweden, Norway, Finland and Iceland and led to the outline of draft legislation on lead by Denmark. Once accepted by the EC, it is likely that other Nordic countries will introduce similar legislation that may also extend to other solder products.

Sweden has recently updated its Environmental Quality Objectives in which it is stated that all use of lead should eventually be phased out. By 2020 any new products introduced in Sweden should be largely free from lead. This objective also applies to lead in batteries, despite their well established recycling network, and an acknowledgement that at present there are no alternatives superior from an environmental point of view.

Siemens and Philips

Siemens and Philips have both done a great deal of work on lead-free in the laboratory as part of the Brite-Euram project and also for their own purposes. However, it is thought that neither have progressed to production trials of significant quantities of product. Although specific information is not available it is thought that lead-free product will be available this year (1999).

Ericsson and Nokia

Both these companies have completed trials into lead-free alternatives but are not willing to talk about their findings in any detail. It is thought that they have had complete success with the Sn_{3.8}Ag_{0.7}Cu alloy, and although they initially used SnPb coated components successfully, have now been able to switch to Ni/Pd.

Motorola

Development of non-automotive lead-free products is also underway at Motorola. Certain products should be available by the end of the year, with a more complete switch planned in time for 2004.

Far East owned UK sites

In general, Japanese affiliated sites in the UK will take part in group wide change over of solder alloy at a date earlier than that expected by the EC draft. Alloy type will be defined through completion of development/production trials in both Japan and Europe. Components for worldwide supply are mainly sourced through a central agent and it is for this reason that the switch to lead-free soldering will be co-ordinated worldwide.

12 PRELIMINARY DISSEMINATION

One of the objectives of this study was to undertake the first steps in disseminating the gathered information and data. This was seen as being central to help raise awareness within the industry, and to provide a platform on which to decide what further activities need to be undertaken to enable the industry comply with any legislation. It is anticipated that there will be several dissemination activities, some of which have already been discharged:

- (i) distribution of the full report to relevant key individuals, trade organisations and companies with some restriction on confidentiality. This will be accompanied by a much wider distribution of a summary report.

a presentation of the study and its findings at a meeting of the *DTI Pb-free Working Group* (February 3rd 1999) at the DTI.

a presentation of the study and its major findings at a *Pb-free Seminar* arranged by the SMART organisation (February 10th 1999) at High Wycombe to an expected audience in excess of 120.

full presentation of the study and its detailed findings to an open meeting dedicated to the study; this will be arranged following the publication of the EC Proposal (expected March/April 1999).

13 CONCLUSIONS

The main conclusions of this study are summarised below:

Lead-free soldering is technologically possible, but key implementation issues need to be addressed:

- in most cases, higher process temperatures are required than for SnPb solders, and this may be incompatible with *some* materials, components and equipment.
- processes will have to be modified in many cases to accommodate the higher soldering temperatures. More flexible reflow ovens provide a relatively easy way to switch to lead-free solder use. More difficulties may be experienced with IR ovens.

- equipment may have to be modified to accommodate the higher soldering temperatures (including modifications for safety reasons).
- the process windows for Pb-free soldering are narrower than for SnPb,
- careful optimisation of the soldering process is required with wave soldering to eliminate fillet lifting defects, especially with Bi-containing alloys and components with Pb-containing terminations. A simple diagram illustrating fillet lifting is shown in Appendix 5.
- the changeover to lead-free technology is more straightforward for reflow than for wave soldering due to a reduced probability of fillet lifting.
- in the case of wave soldering the preferred changeover sequence is to Pb-free boards and components BEFORE Pb-free solders, due to the problems associated with fillet lifting. The changeover sequence for reflow soldering is not as critical because of the much lower risk of fillet lifting.
- criteria for visual and X-ray inspection methods may need to be modified.
- problems of fillet lifting and poor reliability may occur with boards which have been initially soldered using lead-free technology, but which are subsequently repaired/reworks using lead-containing solders. Appropriate labelling should reduce the problem.
- in some cases, cleaning processes may have to be modified.

Many lead-free alloys are readily available, however there has been no universal drop-in replacement identified so far.

- Some specific alloys may be dropped into specific processes without significant problems.
- At the moment one of the most promising alloys for general purpose soldering appears to be that based on Sn-Ag-Cu. Other alloys with potential are Sn-0.7Cu, Sn-3.5Ag and Sn-Ag-Bi.
- No viable alternatives for the high lead, high temperature alloys have yet been identified.
- The availability of Pb-free solders and board finishes is not an issue, and can be sourced within Europe. Solders are available in all forms required, and whilst certain alloys are patented, other attractive alloys are available for free use. Many lead-free boards are in widespread use, and there are not expected to be any compatibility problems between these coatings and lead-free alloys.

- The availability of components with Pb-free finishes, generally supplied by the multi-nationals into a global market, may pose a problem, particularly in the short term. Some components are already available with lead-free coatings but supply is currently limited. Some sectors of industry are already moving towards the use of Pd-Ni terminations for reasons other than lead-free compatibility.
- All necessary fluxes are available, although it appears that little or no change in flux chemistry will be required.
- Indications on reliability so far are that joints made with the proposed replacement Pb-free alloys are at least as good as those made with SnPb.

The main barriers to implementation of lead-free soldering are;

- lack of information on any necessary equipment and process modifications.
- poor understanding within the SMEs of the issues and implications of changing to Pb-free technologies
- the availability of components with Pb-free finishes,
- absence of sufficient in-depth R&D results in the public domain.
- lack of information on the reliability of complex devices such as BGAs, μ BGAs, flip-chip attachments, etc.

There is a huge variation in awareness between OEMs and SMEs.

- the apparent awareness of the SMEs is only superficial and not supported by detailed understanding of the issues, timescales and implications involved. Even with OEMs, whilst the awareness may be high at the technical level, senior management understanding, commitment and activity, are often surprisingly low.

trade organisations, the trade press and scientific meetings appear to offer the most efficient channels for dissemination.

The two main drivers for a change to lead-free technology remain the “green” activities in Japan and the proposed EC legislation.

- many multi-national companies intend to change to lead-free technologies earlier than the WEEE Directive proposes. This change is not dependant on the EC legislation being enacted and will impact on sub-contractors and suppliers.

Alternatives to halogenated flame retardants are available.

- higher loadings of some of these compounds are required to achieve the required safety standards.

these alternatives are expected to increase cost and may degrade other properties.

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The following is a non-exhaustive list of some of the source material used in this work (publications, meeting/Conference documents, seminars etc), and which provide excellent background reading. The numerous articles which have appeared in the trade press (Circuits Assembly, Surface Mount Technology, Circuit World, Electronics Production, EP&P, SSMT etc) are not recorded.

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APPENDIX 1

LEVEL OF AWARENESS QUESTIONNAIRE CONTENT

The following questions were asked, in this order of appearance in both the printed and e-mail versions of the questionnaire survey.

1. Are you aware of lead-free soldering as an issue in the industry?

1a) If yes, how did you become aware? (please tick)

Trade Associations☐

Scientific Meetings☐

Suppliers☐

Others ...☐

Via Customers☐

Trade Press☐

2. Are you aware of the impact that lead-free soldering might have on the assembly of Pcb's? Y/N

2a) If yes, how did you become aware? (please tick)

Trade Associations☐

Scientific Meetings☐

Suppliers☐

Others ...☐

Via Customers☐

Trade Press☐

2b) If yes, do you know what the impact might be on:-

Equip purchase/modifications☐

Any materials compatibility☐

PCB assembly/processing☐

Reliability of the assembly☐

3. Do you know where you can obtain lead-free materials?

Components with lead-free terminations☐

Solders☐

Pb-free finished boards☐

4. If you were to require help/advice on any lead-free soldering issues, where would you go?

Customers☐

Universities☐

Trade Associations☐

Gov. Dept (e.g. DTI)☐

RTOs (e.g. NPL, ITRI)☐

Others.....☐

5. Are you currently undertaking any activities relating to lead-free soldering?

5a) If yes, are you:

Gathering information☐

Undertaking pilot processing☐

Undertaking test/trials☐

Making saleable product☐

6. Do you know of any existing, or impending legislation relating to lead-free soldering? Y/N

6a) If yes, how did you become aware?

Trade Associations☐

Component /equip suppliers☐

Via Customers☐

Trade Press☐

Scientific Meetings☐

7. Which of the following applies to your business (tick as appropriate)?

Employees?<50☐

50-250☐

>250☐

Industry served?

Space/aerospace☐

Telecommunications☐

IT/Computers☐

Household Goods☐

Consumer☐

Other☐

8. Which of the following best describes your business?

Bare Board Manufacturer☐

Component Supplier☐

PCB Assembler☐

Equip Supplier☐

Solder Supplier☐

Recycler☐

Other☐

9. Are you interested in further information on the lead-free soldering issue? Y/N

10. Would you be willing to discuss the above information in more detail? Y/N

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ANALYSIS OF THE GENERAL AWARENESS QUESTIONNAIRE

(i) Introduction

Over 4000 copies of the questionnaire were distributed through the mailing lists of NPL, ITRI, PCIF, and FEI. In addition, the questionnaire was also distributed electronically via SMART-e-link and IPC Technet with the assistance of SMART.

The total number of responses received originating from within the UK and Eire was 112, representing a response rate of approximately 3%.

The following figures summarise the response to each question. It should be noted that in all the figures, the response is expressed as the *percentage of respondents indicating a YES to that particular question*. Since many of the questions allow for each respondent to indicate more than one YES answer the displayed percentages will, in many cases, add up to more than 100%.

(ii) Respondent Profile

Questions 7 and 8 provide information about the business profile of each of the respondents. The responses to question 7 are summarised in fig. 1.

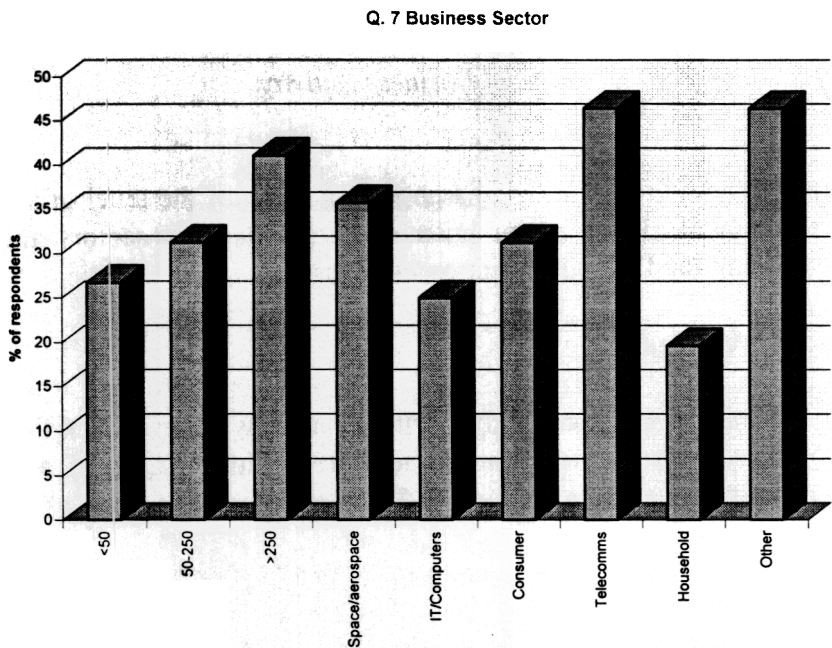


Fig. 1. Profile of Business Size and Sector.

The data demonstrate that the survey generated responses from a wide spread of both company sizes and industry sectors. Approximately 55% of all the respondents were from SMEs (250 employees or less) with a significant proportion of these having less than 50 employees. All major business sectors are represented with telecommunications related businesses providing nearly half of all responses.

The responses to question 8 are summarised in fig. 2. These data demonstrate that a significant proportion of respondents are involved in either PCB assembly, or equipment manufacture, two activities which will be significantly affected by a change over from SnPb to lead-free soldering technology. All the major activities upon which lead-free soldering is expected to have an impact are represented, including the recycling of electronics.

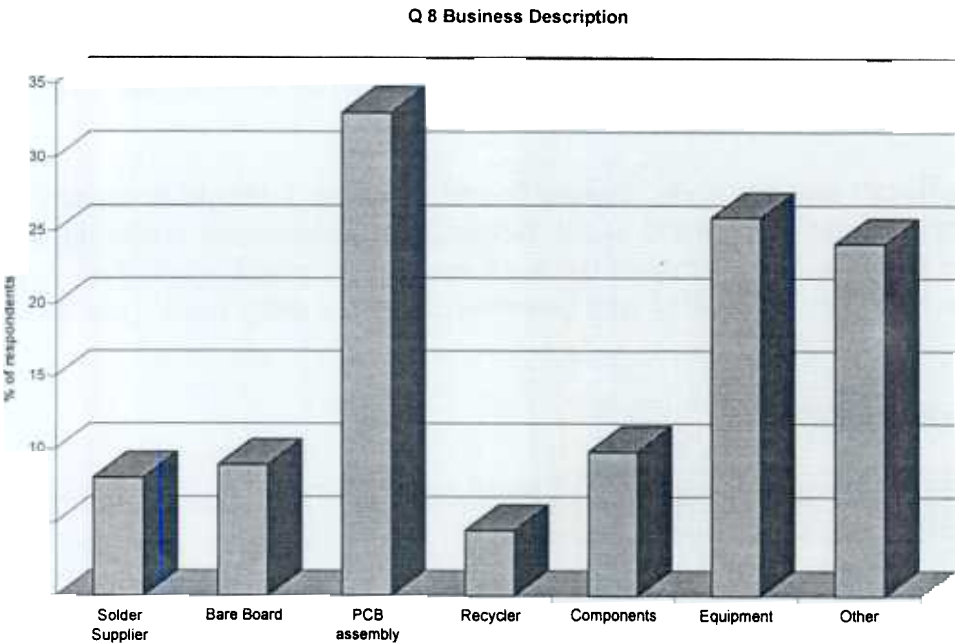


Fig. 2. Profile of Business Activity.

The results of the survey should therefore give a good indication of the level of awareness of lead-free soldering throughout all the major business sizes, business sectors and business activities encountered within the UK microelectronics industry.

(iii) General Level of Awareness

The responses to the four major questions dealing with general awareness (Q1), the impact on PCB assembly (Q2), current activity relating to lead-free solders (Q3) and awareness of legislation (Q4), are respectively summarised in fig. 3.

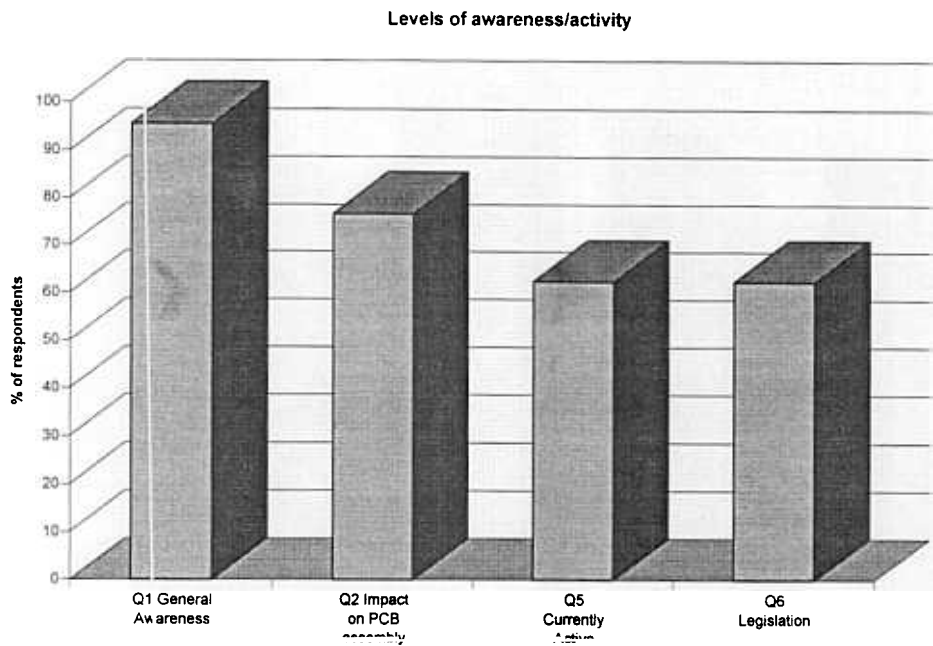


Fig. 3. General Level of Awareness/Activity

The data would seem to indicate that the general level of awareness is high with nearly all (~95%) respondents claiming to be aware of lead-free soldering as an issue within the industry. Similarly ~75% of those responding stated that they were aware of the impact that lead-free soldering might have on the assembly of Pcb's. Approximately 60% of respondents were also aware of legislation relating to lead-free soldering, and a similar proportion were engaged in lead-free soldering activities.

(iv) Awareness of Impact.

Figure 4 summarises the areas where respondents were aware that lead-free soldering technology may have an impact.

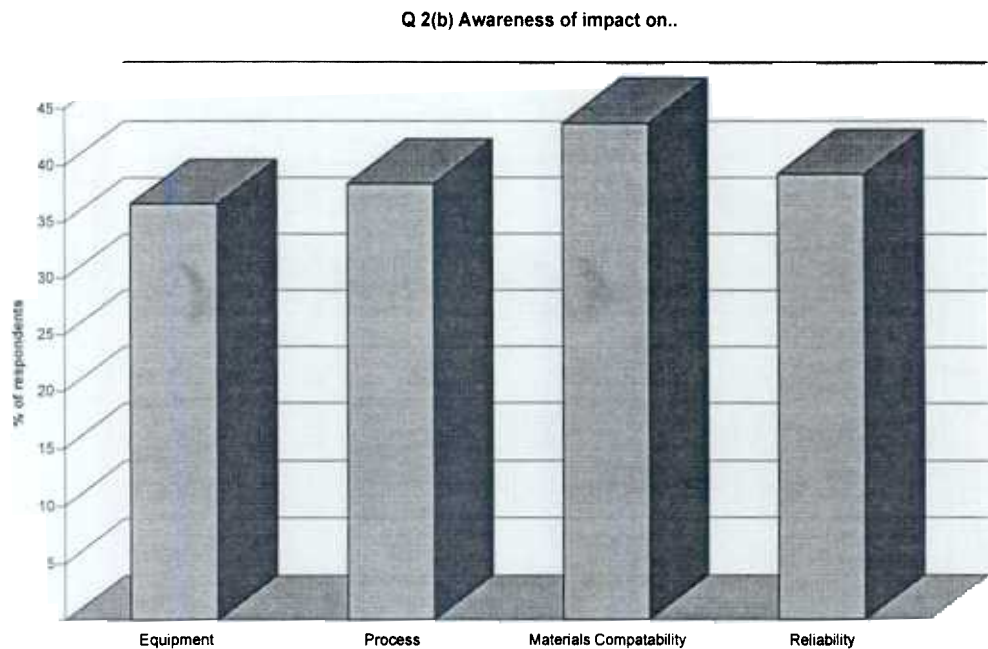


Fig. 4. Awareness of impact on areas of PCB assembly.

It is clear from the data that a similar level of awareness (between 35% and 45%) is evident across all four aspects of the soldering process. However, given that the stated awareness of the overall impact on PCB assembly was ~75%, the level of awareness of these four areas within individual companies must be unevenly spread.

(v) Current Activities.

Current activities relating to lead-free soldering are summarised in fig. 5. Just over 50% of respondents were involved in information gathering activities, identified as the major activity. Approximately 22% of respondents were engaged in tests or trials of lead-free soldering technology, the majority being large multinational companies. Relatively low proportions (<10%) were involved in pilot production or actually selling products. It should be noted that 6% of all respondents were solder suppliers and that lead-free solder products are already available from most major suppliers at this time.

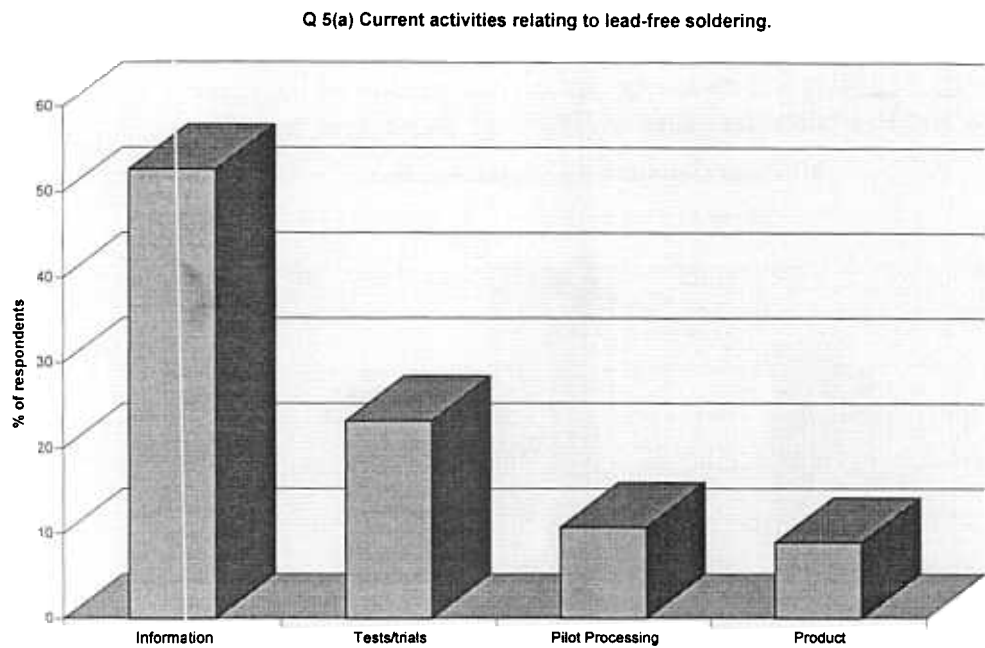


Fig. 5. Current activity in lead-free soldering.

(vi) Availability of materials.

Fig. 6 shows the awareness of availability of lead-free materials.

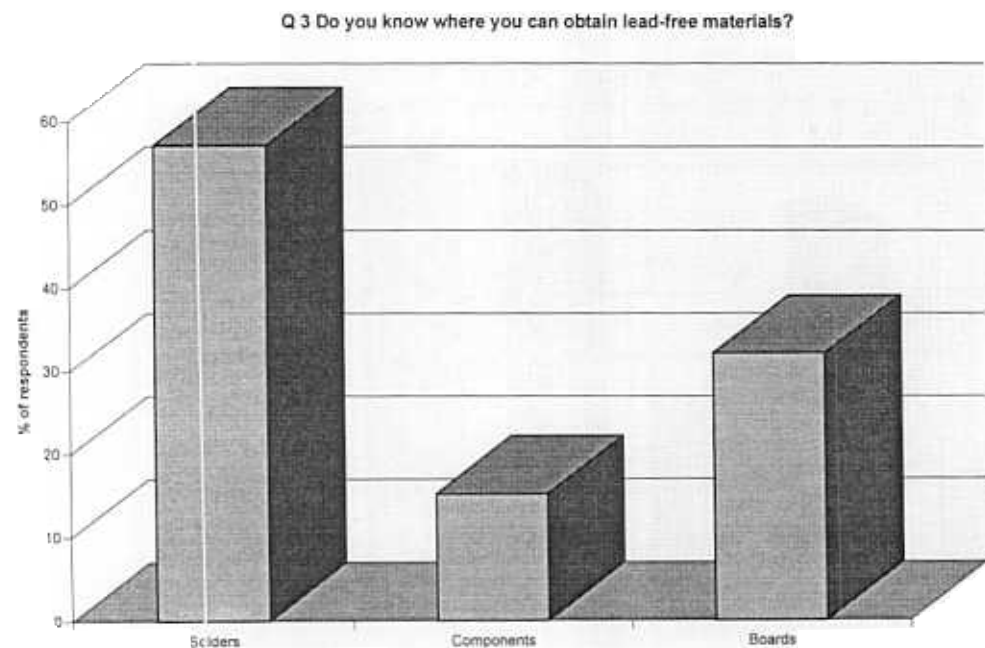


Fig. 6. Availability of materials

The data show that lead-free solders and boards are relatively easy to source, whereas the awareness of availability lead-free components is comparatively low.

(vii) Mechanisms of Generating Awareness

The mechanisms of generating awareness within the industry of the general issue, impact on PCB assembly and legislation are summarised in figs 7 - 9 respectively.

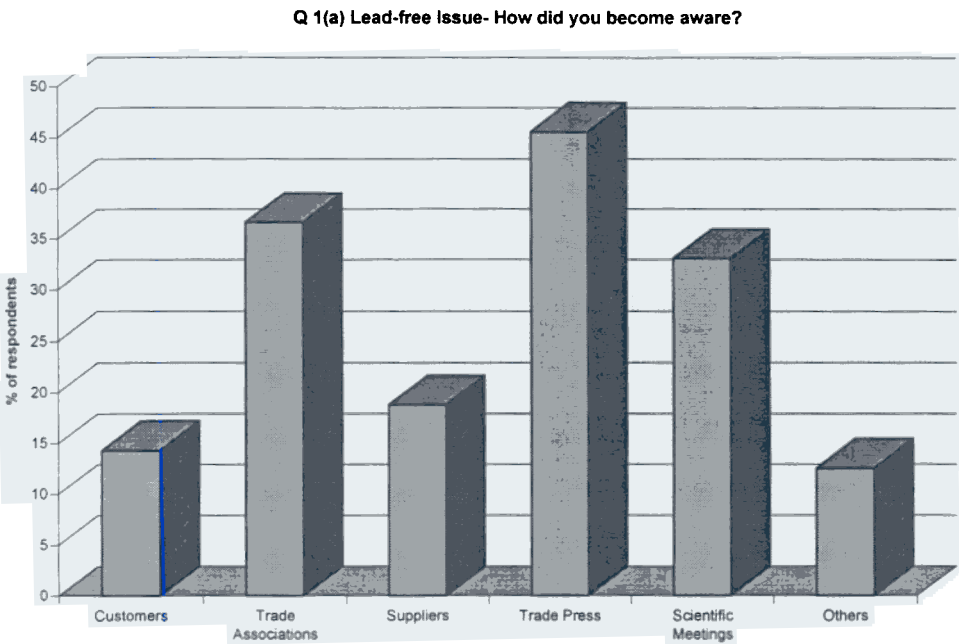


Fig. 7. Awareness generating mechanisms - general awareness

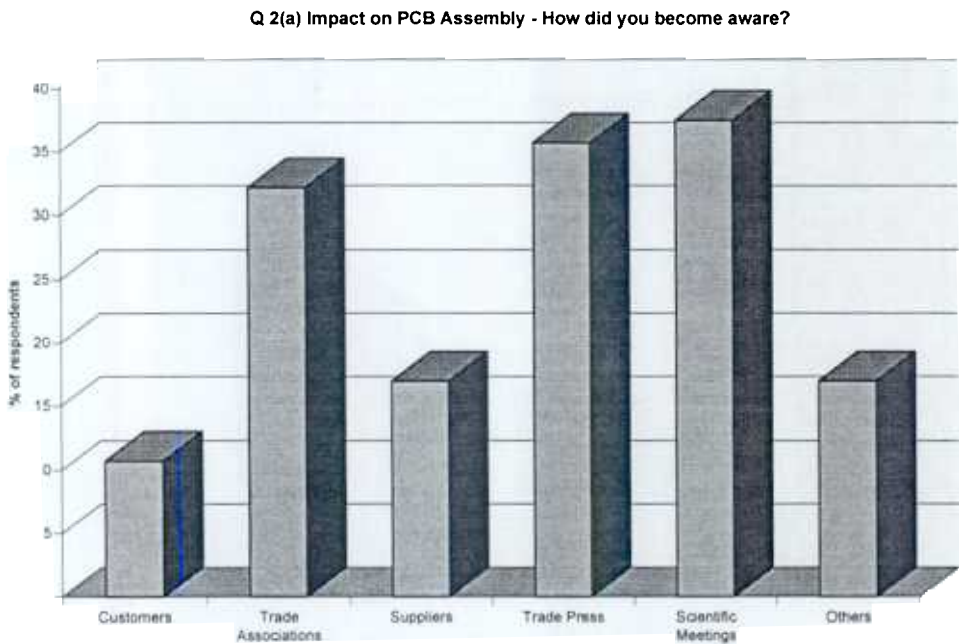


Fig. 8. Awareness generating mechanisms - impact on PCB assembly

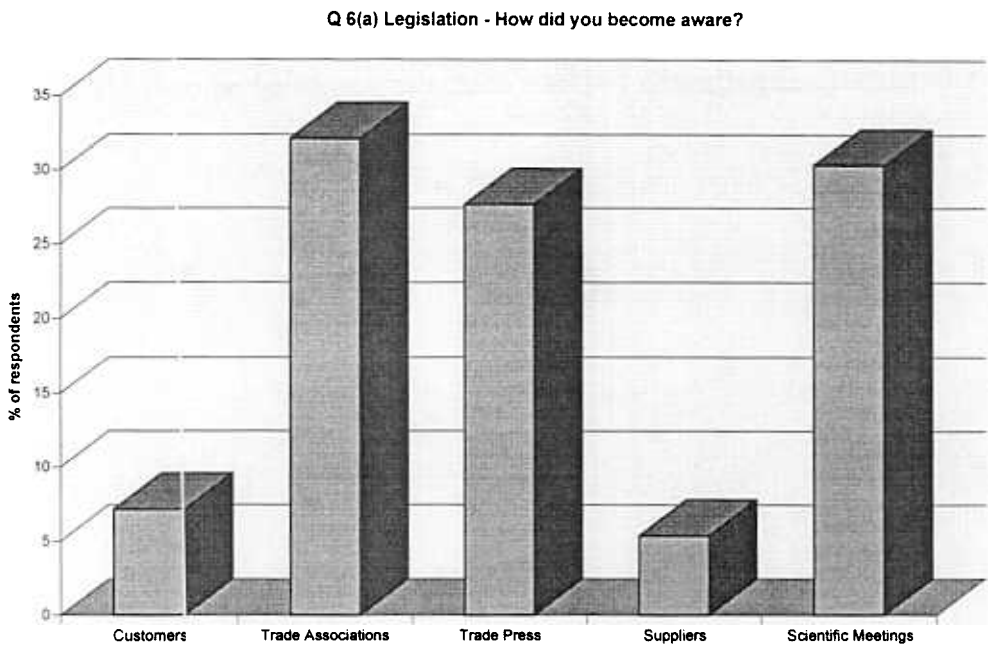


Fig. 9. Awareness generating mechanisms - legislation

The first point to note is that the level of responses are broadly consistent between all three questions; this is a good indication of the overall high quality of the responses to the questionnaire. The second point to note is that the major mechanisms for generating awareness appear to be; trade press, trade associations and scientific meetings. These channels should be noted for future awareness generating exercises.

(viii) Advice on Lead-free Soldering

The responses to where people would go for advice on lead-free soldering are summarised in fig. 10.

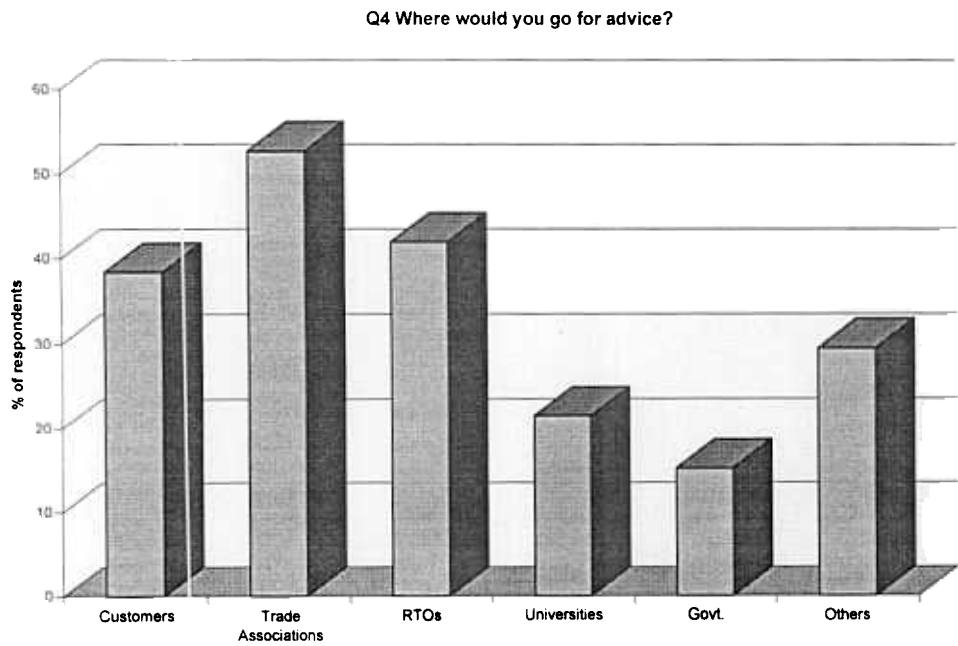


Fig. 10. Where to go for advice on lead-free soldering.

A majority of respondents identified trade associations (~55%) as being somewhere to go for advice on lead-free soldering, with RTOs and customers being a close second. Universities (~20%) and Government Departments (~15%) were also identified as possible sources of advice.

APPENDIX 2: SUPPLIERS OF LEAD-FREE SOLDERS WITHIN THE UK

Due to the fact that many alloys have a melting range rather than an absolute melting point the indication of melting temperatures in the listings below are approximate.

NB1. DKL supply a patented alloy SnAgCuSb (ie the Castin alloy which is available in all forms).

NB2. The above table indicates those suppliers who currently market these alloys. It should be noted that all the suppliers are capable of making the alloys if requested (subject to patent restrictions).

Table 7: Paste Suppliers

PASTE	Sn-Ag	Sn-Cu	Sn-Ag-Cu	Sn-Ag-Bi
Alpha Metals	•	•	•	•
DKL Metals Ltd	•	•		
ESL Europe	•			
E.S.P	•			
Eutectic Co Ltd	•	•		
Fusion Automation Inc	•	•		
Heraeus Silica & Metals	•	•	•	•
Indium Corporation	•	•		
Litton Kester	•	•	•	•
Multicore Solders Ltd	•	•	•	
Mounstar Metal Corp		•		
OMG U.K	•			
Turbo Braze (Europe) Ltd	•	•		
Warton Metals	•		•	

Other alloys available as paste around the world:

Melting below 180 °C

Sn-58Bi

Sn-42In

Sn-50In

Sn-52In

Melting between 180 and 200 °C

Sn-8Zn-3Bi
Sn-Zn-Bi
Sn-Zn-Bi-In
Sn-8.8In-27.6Zn
Sn-20In-2.8Ag
Sn-10.5In-2Ag-0.5Sb
Sn-9.5Bi-0.5Cu

Melting between 200 and 230 °C

Sn
Sn-0.7Cu
Sn-1Cu
Sn-2.5Ag
Sn-3.5Ag
Sn-4Ag
Sn-5Ag
Sn-3.4Ag-1.2Cu
Sn-3.4Ag-1.2Cu-3.3Bi
Sn-3.5Ag-0.7Cu
Sn-4Ag-0.5Cu
Sn-4.7Ag-1.7Cu
Sn-Ag-Cu-Ge
Sn-2.5Ag-0.8Cu-0.5Sb
Sn-Ag-Bi
Sn-1.5Ag-2Bi-0.5Cu

Melting above 230 °C

Sn-1Sb
Sn-3Sb
Sn-5Sb
80Au-20Sn
Sn-3Cu
Sn-25Ag-10Sb

Table 8: Bar Suppliers

BAR	Sn-Ag	Sn-Cu	Sn-Ag-Cu	Sn-Ag-Bi
Alpha Metals	•	•	•	•
DKL Metals Ltd	•	•		
Frys Metals	•	•		
Geo W Neale Ltd	•	•	•	•
Heraeus Silica & Metals	•	•	•	
Hoyt Alloys Ltd	•	•		
Indium Corporation	•	•	•	
Litton Kester	•	•		
M.C.P	•			
Mountstar Metal Corp Ltd	•	•		
Multicore Solders Ltd	•	•	•	
Warton Metals	•	•	•	
William Rowland Ltd		•		

Other alloys available as bar around the world:

Melting below 180 °C

Sn-30Bi
Sn-40Bi
Sn-58Bi
Sn-52 Bi
Sn-50 In
Sn-52In
Sn-57Bi-2In

Melting between 180 and 200 °C

Sn-9Zn
Sn-10Zn

Melting between 200 and 230 °C

Sn
Low Alpha Sn
Sn-2Ag
Sn-2.5Ag
Sn-3Ag
Sn-3.5Ag
Sn-3.6Ag
Sn-3.65Ag
Sn-4Ag
Sn-4.6Ag
Sn-5Ag

Sn-3.5Ag-0.5Cu
Sn-12Zn
Sn-0.7Cu
Sn-1Cu
Sn-1.7Cu-4.7Ag
Sn-3.4Ag-1.2Cu
Sn-2.5Ag-0.8Cu-0.5Sb
Sn-Ag-Cu-Ge
Sn-0.7Cu-1.5Sb
Sn-3Bi-5Sb

Melting above 230 °C

Sn-2Sb
Sn-2.5Sb
Sn-3Sb
Sn-5Sb
Sn-3Sb-1Cu
Sn-2Sb-1Cu-2Ag-2Zn
Sn-4Sb-2Cu
Sn-7.5Sb-0.5Cu
Sn-1Sb-3Cu-0.5Ag
Sn-5Sb-3.5Cu-1Ni-0.25Ag
Sn-20Zn
Sn-25Zn
Sn-30Zn
Sn-40Zn
Sn-9.5Bi-0.5Cu
Sn-2Cu
Sn-3Cu
Sn-4.5Cu
Sn-3Cu-0.5In
Sn-3.9Cu-0.1Ag
Sn-4Cu-0.5Ag
Sn-4Cu-0.8Ag
Sn-2Cu-0.8Sb-0.2Ag
Sn-4.7Cu-0.3Se
Sn-6.8Cu-0.1Si-0.1Ag
80Au-20Sn
Sn-5.6Ag
Sn-10Ag
Sn-10Ag-3Cu
Sn-95Ag
Sn-56Ag-22Cu-17Zn
Sn-25Ag-10Sb

Table 9: Wire and Cored Wire Suppliers

WIRE	Sn-Ag	Sn-Cu	Sn-Ag-Cu	Sn-Ag-Bi
Alpha Metals	•	•	•	•
DKL Metals Ltd	•	•		
Engelhard-CLAL UK Ltd			•	
Eutectic Co Ltd	•		•	
Fry Metals	•	•		
Heraeus Silica & Metals	•	•	•	
Indium Corporation	•	•		
Litton Kester	•	•		
Multicore Solders Ltd	•	•		
Warton Metals		•	•	

Other alloys available as wire around the world:

Melting below 180 °C

Sn-40Bi
Sn-58Bi
Sn-52 Bi
Sn-50In
Sn-52In
Sn-57Bi-2In

Melting between 180 and 200 °C

Sn-9Zn

Melting between 200 and 230 °C

Sn
Sn-2.5Ag
Sn-3Ag
Sn-3.5Ag
Sn-3.65Ag
Sn-4Ag
Sn-5Ag
Sn-0.7Cu-1.5Sb
Sn-3.5Ag-0.5Cu
Sn-4.7Ag-1.7Cu
Sn-2.5Ag-0.8Cu-0.5Sb
Sn-1Sb
Sn-0.7Cu
Sn-12Zn

Melting above 230 °C

Sn-5.5Ag
Sn-6Ag
Sn-10Ag
Sn-8 Ag-0.1 In
Sn-10Ag-3Cu
Sn-25Ag-10Sb
Sn-0.5Ag-4Cu
Sn-0.1Ag-0.2Ni-4Cu
Sn-0.01Ag-0.2Ni-3Cu-5Sb
Sn-56Ag-22Cu-17Zn
Sn-95Ag
Sn-2Sb
Sn-2.5Sb
Sn-3Sb
Sn-5Sb
Sn-6Sb
Sn-7.5Sb-3.5Cu
Sn-2Cu
Sn-3Cu
Sn-1Cu-3Sb
Sn-2Cu-0.8Sb-0.2Ag
Sn-3Cu-0.5Ag-1Sb
Sn-3.9Cu-0.1Ag
Sn-6.8Cu-0.1Si-0.1Ag
Sn-0.5Cu-0.5Ag-3Sb-1.5Zn
Sn-4.7Cu-0.3Se
Sn-15Zn
Sn-20Zn
Sn-25Zn
Sn-30Zn
Sn-40Zn
Sn-20Zn-5Al
80Au-20Sn

APPENDIX 3

SUPPLIERS OF LEAD-FREE BOARD AND COMPONENT COATINGS WITHIN THE UK

Table 10: Suppliers of Boards With Lead-free Coatings

BOARD FINISHES	Sn, Ni-Au, Ni-Pd, Pd, O.S.P., Ag
SUPPLIERS:	Alpha Metals, Artech Circuits Ltd, Atotech, Enthone-OMI (U.K.) Ltd. Eurotech Ltd, Mitel (formerly G.E.C. Plessey Semiconductors), Lea Ronal, Manchester Circuits Ltd. Schloetter Co. Ltd., Shipley Europe Ltd. Tamura Kaken (U.K.) Ltd, VIA Systems

Other board coating types available around the world:

Sn-Bi
 Sn-Ni-Au
 Sn-2.5Ag-0.8Cu-0.5Sb
 Cu
 Ag with chromium passivation layer
 Ag with organic passivation layer

Table 11: Suppliers of Components with Lead-free Coatings

COMPONENT FINISHES	Sn, Ni-Pd, Ni-Sn, Ag-Pd, Ag-Pd-Pt, Ni-Au
SUPPLIERS:	AVX Limited, Mitel (formerly G.E.C. Plessey Semiconductors), Texas Instruments, Philips Components Ltd, Vitramon Ltd, Vishay Ltd

Other companies (such as Motorola, Murata, Rubicon, TDK, Toshiba) have programmes aimed at producing lead-free compatible components, and the introduction of products is expected shortly.

Other lead-free component coatings available around the world:

Sn coated wire for lead frames
 Stripped /Redipped Sn
 Stripped /Redipped Sn-3.5 Ag
 Pd

APPENDIX 4

EBFRIP STATEMENT (<http://www.ebfrip.org/weee.html>)

15 September 1998

EBFRIP statement regarding recent studies on flameretardants

Recent studies concerning brominated compounds have been reported with varying degree of accuracy in the press. Mainstream press reports have ranged from the serious to the ridiculous, including attributing the use of brominated flame retardants in cars to the occurrence of car sickness and also the supposed "scrambling" of the brain to the non-existent use of brominated flame retardants in telephones.

Some of the recent studies, which have reported findings of certain polybrominated diphenyl ethers (PBDEs) in mammals and humans, raise important but as yet unanswered questions. Serious and swift follow-up research is required in order to trace the sources of the substances found. The bromine chemical industry's global organisation, the Bromine Science and Environment Forum (BSEF) has been in contact with study authors and is in the process of commissioning independent scientific institutes to take this work forward. However, it is premature to conclude that the only possible origin of these compounds is from their use as flame retardants, in plastics. For example, it is known that many organo-bromine compounds, including chemical precursors of brominated flame retardants, are naturally present in the marine environment.

These mainstream press reports have also failed to make it clear that in none of the studies was the major PBDE flame retardant, decabromodiphenyl ether, detected at all. This fact alone demands that there be no rush to judgment on the future use of PBDEs as flame retardants.

What is needed is a clear understanding of the sources and significance of the substances found. At the same time, it is essential to remember that flame-retarded products play an important role in today's society. Brominated flame retardants have clear demonstrable benefits in terms of saving lives and protecting property from the effects of fire.

EBFRIP STATEMENT **(<http://www.ebfrip.org/weee.html>)**

Waste Electrical and Electronic Equipment Directive

You may be aware that the European Commission's DG XI has recently distributed the 2nd draft of the "Proposal for a Directive on Waste from Electrical and Electronic Equipment" (WEEE). In this draft, a proposal is made to phase out Halogenated Flame Retardants (HFRs) by 1 January 2004 if alternative flame retardants can meet minimum fire safety standards. EBFRIP would wish to highlight the following concerns with this element of the draft proposal:

1. A phase-out of HFRs will result in diminished fire safety. Most original equipment manufacturers (OEMs) have traditionally exceeded the minimum levels of fire safety required by European standards. Enactment of the draft WEEE Directive will seriously diminish, if not eliminate, the ability of OEMs to continue to provide the level of protection which European consumers have come to expect.
2. No attempt has apparently been made to assess the relative environmental impact of halogenated and non-halogenated flame retardants. It is imperative that DG XI establishes a transparent, and scientifically-based, set of human health and environmental objectives upon which to base the draft WEEE Directive. Only then can objective comparisons be made and meaningful conclusions be reached regarding the selection of flame retardants for use in E&E products.
3. If the concern is that HFRs in some way adversely affect the recyclability of plastics, then this is not reflected by the "on-the-ground" reality of E&E recycling. In fact, the copiers industry convinced the German Environment Agency to delay eco-label criteria discriminating against brominated flame retardants precisely because HFR plastics were preferable from the point of view of recyclability.
4. Furthermore, the presence of HFRs does not affect recyclability any differently than other additives. E&E recyclers agree the presence of any additives (and not just HFRs) makes plastics less pure and hence more complicated to market.
5. It is important to recognise that halogens in themselves can be recycled from E & E plastics. Brominated flame retardant producers, with the support of E & E recyclers, are studying processes to accomplish this on a commercial scale.
6. Finally, the proposed phase-out of HFRs would unjustifiably prevent the recycling of materials from equipment currently in use, and would preclude the development of products and processes that may provide the best solutions for future recycling goals.

EBFRIP also supports calls for energy recovery to be included in the draft proposal's recovery targets. Such targets need to be realistic in terms of market demand for secondary raw materials while ambitious in terms of optimising levels of recycling. Only by including energy recovery within the recovery targets can this balance hope to be achieved.

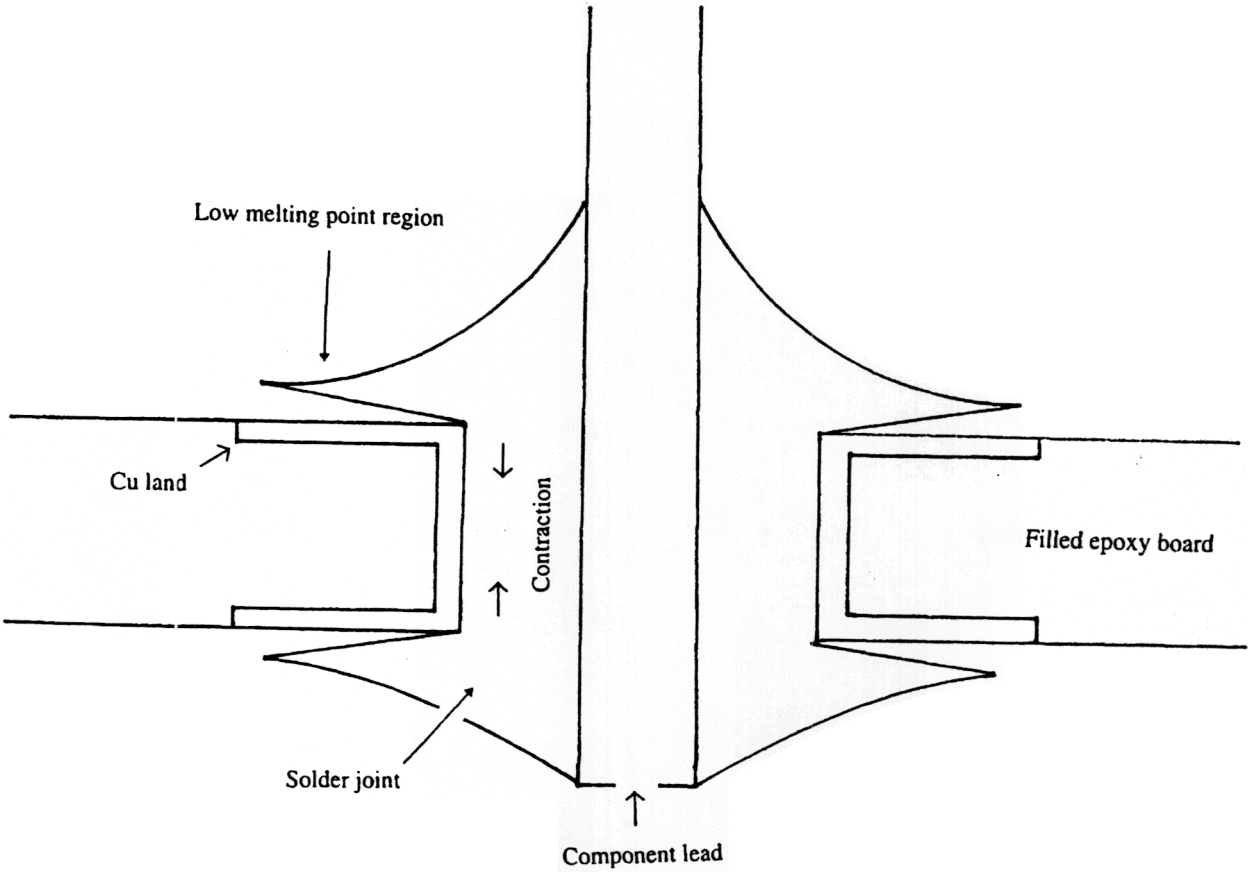
In short, the DG XI should clarify the following points:

- What are the concerns with regard to halogenated flame retardants;
- What is the basis for these concerns;
- What is the relative environmental impact of alternative flame retardants; and
- What effect will a move away from HFRs in the EU have on E&E equipment fire safety.

Bent Jensen
EBFRIP Secretariat
3 September 1998

APPENDIX 5

DIAGRAM ILLUSTRATING FILLET LIFTING



The phenomenon of fillet lifting associated with wave soldering, is essentially the parting of the solder fillet from the land surrounding the hole in through-hole joints. The precise mechanism of its formation is not fully understood.