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Lead-free soldering:
Materials, Components, Processes

Technological Assessment
of the Change-Over Scenario

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Lead free soldering: Materials, Components, Processes
Technological Assessment of the Change-Over Scenario

Department Research, Human Resources Development, Production Engineering

Contact: Dr. Bernhard Diegner
Stresemannallee 19, D-60596 Frankfurt, Germany
Phone: +49/69/6302-277, Fax: +49/69/6302-286
email: forschung@zvei.de

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Executive Summary

For some time now the market pressures and current legislative projects have confronted the electrical industry with the demand for lead-free alternatives for its most important connection technology, soldering.

If one looks at the present status of work on lead-free connection technologies, one arrives at the following situation.

1. **There is no „drop-in-solution" as substitute for soft solders containing lead**. No known alternative alloy fulfills all requirements regarding melting point, costs, processibility and reliability. There are no lead-free alternatives to the non-conformable solders, used, for example, in components for chip assembly.

2. There is little data on the reliability of electronic assemblies soldered lead-free and what is available is incomplete.

3. All standards and regulations concerning quality and reliability are based on soft solders containing lead. Transferability to lead-free alternatives is not guaranteed.

4. In most cases the use of lead-free alternative solders requires raising soldering temperatures by 20-30 K and consequently a higher heat resistance of processed components. Manufacturers of components have not yet sufficiently mastered this problem.

5. Connection surfaces of electronic components mostly contain lead. Lead-free alternatives are partly available, however their interaction with new lead-free solder alloys is known only for single systems.

6. Printed circuit board materials with higher heat resistance and with lead-free surfaces are available. Metallurgic interactions with new solders at higher temperatures and interaction with the supporting plate (blow, heat expansion) have yet to be assessed.

7. A great number of reflow soldering systems used, at present, have not been adapted to the new processing temperatures. Specific technical problems arise when lead-free wave soldering processes are introduced. In any case, the process window is significantly narrowed.

8. There is no method of inspecting soldered junctions (optical or X-ray) and no assessment catalogue for soldering joints.

9. New guidelines must be established for development and design of components.

10. The combination of different solder alloys critically affects reliability. All products and parts must be identified in order to enable repairs and rework to be carried out.

11. At present electrical conductive adhesion is only a solution for special applications and not a general alternative to soldering.

12. The change-over to lead-free soft solders is not proved to benefit ecology. An assessment of the effects on the environment still needs to take place.

This leads to the conclusion that there can be no question of banning lead-free solders until the problems outlined above have been solved and there are industrialized lead-free alternatives.

However there is a trend towards lead-free solder connection technologies: on the one hand, there is the increased demand of the market for lead-free soldered equipment, on the other electronic assemblies are increasingly being designed to withstand higher working temperatures, promoting the use of lead-free solders with higher melting points.

According to the level of product specific requirements for reliability, a **gradual increase in the application of lead-free connection technologies** is expected, starting from products without safety functions and ending at electronics with safety relevant functions.

Because of the electrical industry's worldwide links – a large part of components processed in the EU comes from the USA or Japan - **only a globally structured procedure can be successful**.

Our recommendations to the electrical industry are:

- to closely follow the trend towards lead-free soldering technologies, actively adopt it and take part in its shaping,
- to start basic investigations and application specific compatibility tests focusing on reliability,
- to contact components manufacturers and confront them with the demand for more temperature resistant components with lead-free finishes,
- to assess, together with suppliers, equipment manufacturers and customers the suitability of new lead-free solders, as a substitute for *specific applications* and to introduce them where possible.

Our recommendations to the legislator are:

- to evaluate and demonstrate the ecological advantage of a change-over to lead-free solders,
- not to pursue a ban of use of lead containing soft solders as a regional initiative,
- to follow market laws and to enable the electrical industry to gradually introduce lead-free soldering in an economically feasible way,
- to support research and development of lead substitutes by furthering R&D projects,
- not to ban lead in electrical equipment.

1. Motivation and aims

The basic connecting technology for global electro-technics and electronics is soldering with solder alloys containing lead (SnPb). Soldering processes have been developed and perfected for centuries, practically all components, printed circuit board materials and process materials are adapted to technologies based on solders containing lead and their parameters. The solders can be universally used, different alloys are compatible with each other. Lead from soldering joints can be reclaimed in well functioning recycling procedures and reintroduced to the material cycle.

Lead is a potentially dangerous heavy metal. In efforts to reduce the amount of lead brought into the environment, current development in legislation is also confronting the electrical industry with the demand for lead-free alternatives for its soldering technologies (see section 2).

Besides legislation initiatives the commercial market is also increasingly demanding lead-free soldered electrical equipment. Apart from this there is a technological trend to adapt electronic components to higher application temperatures.

The issue of substition of lead in solders is of vital significance for the whole electric branch. Therefore the ZVEI production committee has commissioned the present manual.

The manual

- aims to attract attention in the branch. The trend towards substitution of solder alloys containing lead is still not noticed widespread.
- concentrates on soft soldering of electronic assemblies and electro-technical and electronic equipment as this concerns the whole branch.
- uses the term „lead-free“ in the sense of „free from lead as a technical package part of solder alloys“ and does not mean concentrations of trace amounts or impurities.
- assesses and summarizes data on lead-free soldering.
- shows the complexity of the subject in all its breadth – from standardization via materials and processes to inspection and reliability.
- evaluates the stages of a possible substitution of lead with regard to technical issues, costs and time frame, and identifies special problem fields.
- establishes priorities for a substitution of solder alloys containing lead.

2. State of environmental legislation, current activities of the electrical industry

The heavy metal lead is among the materials included in environmental legislation. The environmental pollution by lead is the result of a multitude of different technical applications. The legislator is aware that contributions from individual sources are often very small. But all these sources contribute to total contamination. Untreated or inadequately treated waste containing lead can in particular harm the environment.

Solder alloys containing lead as they have been used for centuries are among the sources which may, to a small extent, contribute to the existing general lead pollution. Soldering has been the basic connection technology for decades for the global electrical industry.

The electrical industry is the most important branch of the processing business in Germany: in 1998 the annual turnover of the German electric industry amounted to nearly DM 250 thousand millions. The German electrical industry employs about 850,000 people. It contributes about 5% (after net product) of the gross national product, to say nothing of its strong influence on all sectors of the modern national economy. An immediate ban on lead only in the EU would have unforseeable consequences for this industry.

The electrical industry's lead consumption for solders containing lead is very small in comparison with other applications: at maximum an estimated 2 % of the total consumption of lead in Germany amounting to 322.000 t (1997), i.e. maximum 6500 t, is attributed to solders containing lead in electrical equipment. ITRI estimates Great Britain's share to be only 0,6% [ITR99].

International environmental legislation is increasingly focusing on the use of lead as a constituent of solders in the electrical industry despite its small share in total lead consumption:

The first actions began in the **USA** at the beginning of the 90s. The drafts of the „Lead Exposure Reduction Acts" of 1991 and 1993 met with the violent protest of the branches concerned and have since been shelved. The protest of the industry was justified. As there was no technological necessity for a substitution of solder alloys containing lead hardly any work on this sector had been done and no known alternatives existed at that date.

The Recycling-Law of 1998 in **Japan** does not apply to lead. The guidelines of the Japanese Environmental Protection Agency and government, however, do recommend a reduction of lead consumption and an intensified recycling programme.

In 1994 the Scandinavian Ministers of the Environment signed a declaration of intent with the aim of eliminating the use of lead in the long term. In **Sweden** the Environmental Quality Objectives intends to ban it completely by 2020. The draft of a regulation to ban lead in **Denmark** prohibits lead in many applications, but expressly excludes lead in solder alloys for the electrical industry from the ban.

In 1998 the **EU**-commission presented the draft on a Directive on Waste Electrical and Electronic Equipment. The ban of lead in electrotechnical products planned in this draft would apply among others to solder alloys containing lead. According to this draft the use of solder alloys containing lead in electrical equipment will be banned from 1st January 2004. The regulation concerning old vehicles also provides for a ban of lead in motor vehicles.

The extremely short and unrealistic deadline not only presents the European electrical industry with massive problems. The commission's draft also ignores the close global links within this branch. Finally alternative technologies must be adapted for package suppliers situated largely in non-European countries. In addition, such a regulation would cause non-tarif-related trade obstacles leading to protests from the USA [NEM98] and Japan [JBC99].

Bans of materials must be justified by prior scientific tests. At the same time ecological, technical and economic feasibility must be secured and substitute technologies and substitute materials made available. These prerequisites have not yet been fulfilled.

An additional problem is that in more recent drafts concerning European environmental legislation bans of material are not horizontally grouped in a legal regulation for chemicals as would be logical but are included in individual regulations on waste products. Different regulations for identical electronic assemblies built-in in different end products cause additional confusion for the manufacturing branches concerned. Orgalime, the umbrella organization of the European metal and electrical industry, also points this out in a recent comment [ORG99].

How is the industry reacting to the new challenges?

The substitution of lead is part of electrical industry's overall strategy for the realization of products and processes with a minimal effect on environment. In this context they also regard the development and introduction of „lead-free" soldered equipment as a chance to create a distinct image and persuasive marketing strategy. Naturally first pronouncements and commercial offers of this kind will be found in the product areas characterized by short innovation cycles and relatively uncritical operation conditions (e.g. telecommunication, consumer electronics).

Within the **EU**, besides national initiatives – in Germany, for example, within the framework of the BMBF-programme 'Neue Materialien' [new materials] (MaTech) - and initiatives within enterprises, leading European manufacturers (GEC Marconi, Philips, Siemens, Multicore and Witmetaal in cooperation with NMRC) have investigated possible substitutes for lead in solder alloys within the IDEALS-project (1996-1999, under the cover of the EU 4th FTE-framework programme).

In **Japan** the Guidelines of the Japanese EPA and the government on reducing lead were taken up by several enterprises who saw it as a chance to participate successfully in the course of the environmental discussion. Individual companies have published their own reduction aims for specific production sectors. Examples are Matsushita, NEC, Hitachi.

In the **USA** a NCMS-project in 1992-1996 marked the start of the systematic search for alternatives. The „NEMI Lead-free-Readiness Task Force" was founded at the beginning of May 1999 [NEM99]. NEMI is a consortium managed by the industry consisting of more than 50 electronics manufacturers, suppliers, associations, government agencies and universities. This Task Force also intends to investigate processes and materials for the production of lead-free electronics assemblies.

The results of the above mentioned investigations are the main basis for the following statements.

There is good reason for the projects to focus on new alloys for soldering as connecting technology: as things stand electrical conductive adhesives are admittedly not a general alternative to soldering but only in special cases.

The present leading electrical conductive adhesives with silver particles as electrical function carriers and a filling share of about seventy to eighty percent of weight definitely do not constitute a global substitute for lead solders due, amongst other reasons, to the limited resources of silver.

In addition, a series of technological deficiencies limits the use of electrical conductive adhesives in Surface Mount Technology. In this context we want to point not only to the lower mechanical stability compared to soldering but also in particular to the fact that bonding agents absorb humidity. The latter leads to a distinct deterioration of the electrical and mechanical properties of the bonding agents in contact with the surfaces of the interconnection partners containing tin. The demand for tin free surfaces cannot be fulfilled in all areas of the SMT at the present time, however, so that this is a further reason to regard electrical conductive adhesives only as a solution in special cases.

3. Requirements for soldering joints in electronical equipment

In evaluating the problems and consequences of a substitute for solder alloys containing lead the following criteria have been established and applied in the following sections:

A: Technical problems:

1 no technical changes necessary
2 well tested change-over technology exists
3 material changes necessary
4 moderate technical problems expected
5 considerable technical problems expected
6 strategy undetermined

B: Costs (these are permanent costs *following* change-over, i.e. running costs):

1 cost reduction
2 no change of running costs expected
3 price rise in individual processes
4 considerable increase in costs
5 costs implications not estimable – financial risk

C: Change-over costs (these are costs which occur only during and at change-over, i.e. one-time costs):

1 no change-over costs expected
2 moderate change-over costs expected
3 considerable change-over costs expected
4 materials and technologies for change-over non-existent, significant development needed

The evaluation attempts where possible to categorize the above criteria by letter and number:

For example a change-over with estimated moderate technical problems, an increase of costs in individual processes and moderate change-over costs would be categorized as follows:

A	4	moderate technical problems expected
B	3	price rise in individual processes
C	2	moderate change-over costs expected

3.1 Requirements of the different applications of electronic assemblies

Depending on field of application and operative range of the electronic package there are different requirements for the respective junction point between component and printed circuit board. The following (Table 1) lists important application groups with their characteristic operation temperatures (Worst Case Environment) according to DIN IEC 52/572/CD (construction and use of printed-board assemblies):

Use Category	T_{min} in °C	T_{max} in °C	average operational time in years
Consumer	0	+60	1-3
Computers	+15	+60	5
Telecom	-40	+85	7-20
Commercial Aircraft	-55	+95	20
Industrial & Automotive Passenger Area	-55	+95	10
Military Ground & Ship	-55	+95	10
Space	-55	+95	5-30
Military Avionics	-55	+95	10
Automotive Under Hood	-55	+125	5

Table 1*: operative ranges of electronic assemblies*

Latest developments in different sectors show a trend to significantly higher operating temperatures sometimes above the maximum load limit of tin-lead-solders (see table 2 below).

Temperature classes	Status	Average temp.	Peak temperature
Car interior	state of art	-40°C/+90°C	105°C
Engine area	state of art	-40°C/+120°C	120°C
Motor mounting	under development	-40°C/+140°C	150°C
Within gearbox	system development	-40°C/+140°C	160°C

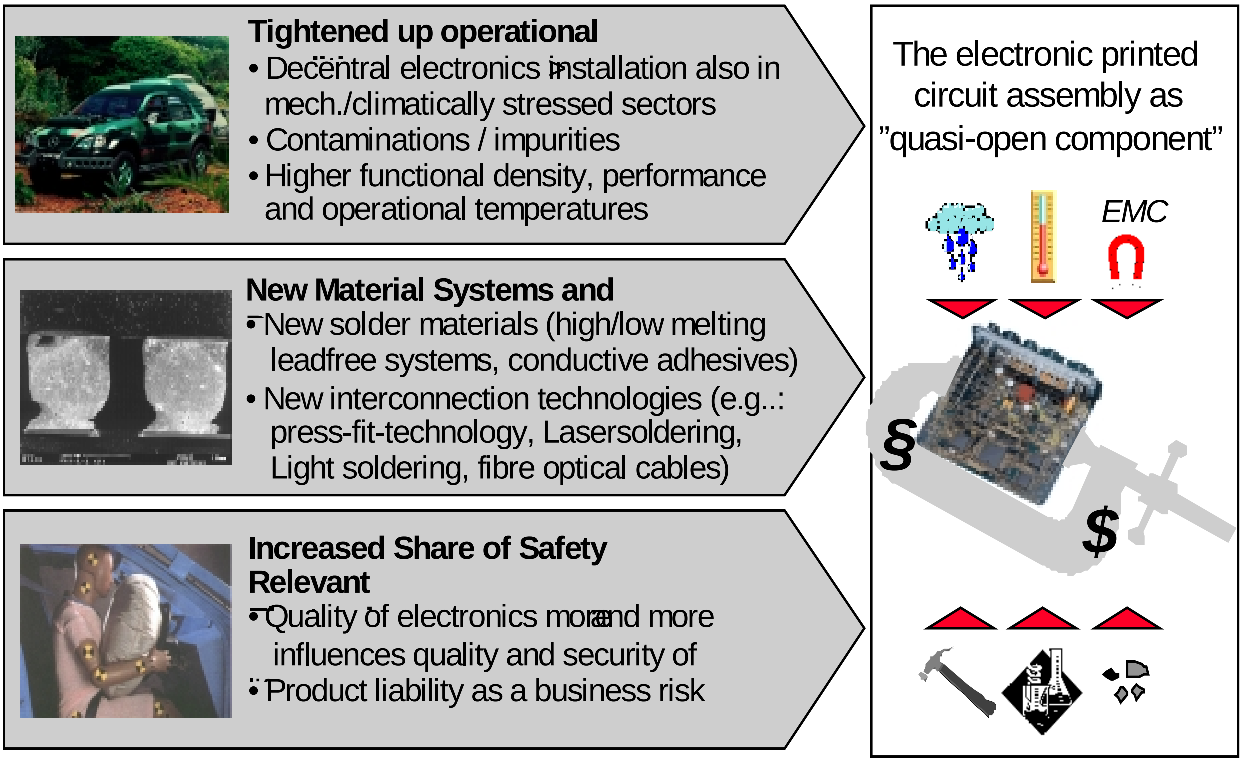
Table 2*: Examples of requirements for electronics in automobiles [BER98]*

Three important trends regarding the requirements for electronical products are envisaged for the future [DEN99] (see picture 1):

- Tightening-up of operation conditions: the requirements for resistibility of electronic assemblies are perceptibly increasing. This is due to a growing tightening-up of environmental conditions as well as increasing density of assembly.

- New material systems and processes: There is an increasing variety of materials and processes available requiring an expansion of basic knowledge to include solder alloys and soldering technologies.

- Increased safety relevance: the overproportional increase of safety relevant electronics, for example, in passenger transport sectors or medical-technical procedures makes the aspect of product reliability increasingly important.



***Picture 1**: Trends as to requirements for products [DEN99]*

The assembly with its filigrane and complex structure finally appears as „quasi-open component“ directly exposed to environmental influences and is additionally subject to the basic rules of economics and law.

3.2 Requirements for the interconnection between component and printed circuit board

Function of the soldering connection [KLE91]:

- sufficient electrical conducting capacity (as SnPb-solder or better: spec. el. resistance $\rho_{60Sn40Pb}$= 1,7x10^{-5}Ωcm),
- sufficient mech. stability (as SnPb-solder or better: shear resistance in ring-extraction-test at T=20°C, deformation speed 0,05mm/min: $\tau_{60Sn40Pb}$= 20N/mm^2),
- sufficient shear resistance or tensile strength of the bonded components (at least on a level with SnPb-solders),
- balance of different thermal expansion coefficients of the joining partners (e.g.: SMD-resistance (1206): approx. 6ppm/K; SMD-IC (SO8): ca.21ppm/K, SnPb-solder: 24,5 ppm/K, FR4: 10-15ppm/K),
- sufficient thermal conductivity (at least on a level with SnPb-solders: $\lambda_{60Sn40Pb}$=51W/mK at 25°C).

Reliability:

- of the function under operation conditions during lifetime (temperature resistance and fatigue strength),

- „absolute reliability“,
- ionical impurities must not impair function or cause corrosion.
- morphology (structure with low degradation)

Total functionality:
- no migrations,
- insulation properties of the total system.

Test/Repair capacity:
- sufficient testability of the joint,
- reversible separability of the joint (for repair or recycling),
- repairability.

Working / process:
- safety during process,
- no thermal deterioration of joining partners in process,
- short duration,
- allows sufficient storage/working time at room temperature (handling) during and after application of connecting medium, before packaging/soldering process,
- sufficient wet adhesion,
- compatibility with type of joining partner (THD/SMD; Chips, SOICs, PLCCs, QFP, BGA, FlipChip etc) and surfaces (also SnPb!),
- availability of joining material.

Competitiveness:
- cost efficient

3.3 International Specifications, Standards, Test Regulations

A great number of national and international specifications list requirements for the quality of soldering joints. The most relevant specifications are:

- ANSI/J-STD-001 Requirements for Soldered Electrical and Electronic Assemblies (Geometrical requirements for SMD-soft soldering joints, test methods, test frequencies etc)
- ANSI/J-STD-004 Requirements for Soldering Fluxes
- ANSI/J-STD-005 Requirements for Soldering Pastes
- ANSI/J-STD-006 Requirements for Alloys and Solder Products
- ANSI/J-STD-012 Implementation of FlipChip and ChipScale Technology

- IPC-A-610 Acceptability of Electronic Assemblies (mainly illustrated presentation of geometric requirements (THT and SMT))
- IPC-TM-650 Test Methods Manual (Visional, Dimensional, Chemical, Mechanical, Electrical, Environmental)
- IPC-SM 785 Guidelines for Accelerated Reliability Testing of Surface Mount Solder Attachments

- MIL STD 883E Test Methods and Procedures for Microelectronics

- DIN EN 60068-2 Environmental tests, part 2: tests including: DIN EN 60068-2-20 Electrical engineering; basic environmental test procedures; test group T: soldering or DIN EN 60068-2-44 Environmental tests part 2: tests, manual for test group T, soldering

- DIN EN 60721-3-5 classification of environmental conditions; part 3: grades of extent of environmental influence and their limits; application on and in road vehicles (as well as also the parts 3-1 to 3-7)

- DIN IEC 50/395/CD-1 Manual for classifying environmental conditions under DIN IEC 60721-3 for tests according to DIN EN 60068-2

- DIN EN 61189-1 to 3 (=DIN IEC 61189-1 to 3): Test procedures for electrical materials, printed circuit boards and other connections and assemblies

- DIN IEC 61191-1 Requirements for soldered electrical and electronical assemblies using surface mount and related assembly technologies
- DIN IEC 61191-2 Requirements for surface mount soldered assemblies
- DIN IEC 61191-3 Requirements for through hole mount soldered assemblies

- DIN IEC 91/96/CDV Requirements for soldered electrical and electronical assemblies using surface mount and related assembly technologies (draft)
- DIN IEC 91/97/CDV Requirements for surface mountable soldered assemblies (draft)
- DIN IEC 91/98/CDV Requirements for through hole mount soldered assemblies (draft) corresponding to IEC 61191-specifications

- DIN 8526 Testing of soft solder attachments, shearing stress (ring and plug; gap soldering attachment: shear resistance, long-term rupture strength)
- Shearing test [SCH97]

- DVS 2610 Visual assessment of soft soldering joints; SMD on printed circuit board; technical documents – a survey (including some of the norms listed particularly those of interest for military technics),
- DVS 2611 Visual assessment of soft soldering joints; SMD on printed circuit board; technical documents – criteria in synoptic comparison (summary of specifications listed in DVS 2610!)

for the telecommunications sector:

- Bellcore GR-63-CORE Network Equipment – Building System (NEBS) Requirements (Physical Protection),
- Bellcore GR-78-CORE Generic Requirements for the Physical Design and Manufacture of Telecommunications Products and Equipment.

Certain product areas / products have a great number of specifications apart from those listed. The following tables show high specification standards for reliability of electronical assemblies set by the important and demanding automobile sector (see tables 3 and table 4):

Specifications for:

- BMW S 600 13.0 Part 1 (June 1998) – BMW,
- GM I 12558 (August 1996) – General Motors, Opel,
- VW 801 01 (January1998) – VW, Seat, Skoda, Audi.

		T_{max} (in operation)			T_{maxk}	T_{min} (operation)
		GM	**VW**	**BMW**	**GM**	
Engine compartment						
in motor, cylinder head		140°C	140°C	140°C-150°C(*)	155°C± 3K	-40°C for all
motor extension		125°C	140°C		140°C± 3K	sectors
drive/brake				140°C		
near motor		120°C	120°C	120°C (**)	140°C± 3K	
away from motor		105°C	120°C	105°C (***)	125°C± 3K	
Passenger area						
in sun		80°C	90°C (****)	105°C	105°C± 3K	
without sun		70°C	70°C	80°C	90°C± 3K	
Doors and hinged flaps						
	inside	70°C	70°C	80°C	90°C± 3K	
	outside	70°C	70°C	80°C	90°C± 3K	
Boot area		70°C	70°C	80°C-90°C (*)	90°C± 3K	
*= Hot Engine "Off"-Temperature **= for example "in/at ventilator" ***= at chassis ****= passenger area roof T_{maxk} maximum temporary operating temperature						

***Table 3**: Temperature range in automobiles*

	T-Alternating tests (slow change-overs) **(‚m.B.' = with functional strain, ‚o.B.' = without functional strain)**	
GM	3h m.B. $T_{min,}$ transposition m.B.f rom T_{min} to T_{max} (3K/min), 1h m.B. $T_{max,}$ transposition m.B. from T_{max} to T_{min} (1K/min)	20 cycles
VW	1h o.B. $T_{min,}$ 2h transposition m.B. from T_{min} to $T_{max,}$ 1h m.B. $T_{max,}$ 2h transposition m.B. from T_{max} to T_{min}	40 cycles
BMW	1,5h m.B. $T_{min,}$ transposition m.B. from T_{min} to $T_{max,}$ 1,5h m.B. $T_{max,}$ transposition m.B. from T_{max} to T_{min}, cycle duration: 8h	35 cycles
	T-Alternating tests (thermal shock)	
GM	2h o.B. $T_{min,}$ transposition o.B. from T_{min} to T_{max}: <20s, 2h o.B. $T_{max,}$ transposition o.B. from T_{max} to T_{min}:<20s	60 cycles
VW	20min o.B. $T_{min,}$ transposition o.B. from T_{min} to T_{max}: <10s, 40min o.B. $T_{max,}$ transposition o.B. from T_{max} to T_{min}:<10s	100 cycles (*)
BMW	30min o.B. $T_{min,}$ transposition m.B. from T_{min} to T_{max}: <30s, 30min m.B. $T_{max,}$ transposition m.B. from T_{max} to T_{min}:<30s	100 cycles

*) at increased requirement: 288 cycles

***Table 4**: Temperature alternating tests on electronical assemblies in automobile sector*

3.3.1 **Moisture resistance** (usually under stress), example: General Motors

Combined moisture-heat-alternate stress
Test according to IEC 68-2-38-Z/A, highest temperature: 65°C, lowest temperature: 10°C, during operation distribution voltage is repeatedly switched on resp. off every 1 h

Humidity (particularly in the passenger area / boot)
Test according to IEC 68-2-56-Cb, temperature: 40°C+-3K, rel. humidity: 93%, duration 21 days

Dew (assembly without casing!) – particularly for assembly in doors/flaps
2h at 0°C+-2K then 22h: 40°C+-3K, rel. humidity 98+-2% (transport into moisture chamber within max 3 min); total 10 cycles during test duration function cycles according to component regulations

3.3.2 Protection against dust and water

Test according to DIN 40050 part 9

3.3.3 **Mechanical stability** (partly with superimposed T-strain)

Oscillation stimulation, sinusoidal (according to DIN EN 60068 part 2-6) for components in the motor
Oscillation duration per space axis: 22-24h, frequency change: 1 octave/min

Oscillation stimulation, wide band random vibration (according to DIN EN 60068 part 2-64) not for motor extensions
Oscillation duration per space axis: 8h (VW, BMW), 22h (GM)

Shock resistance (according to DIN EN 60068 part 2-27), half sinusoidal shock form (g = acceleration due to gravity)

	VW	**GM *)**		GM – door mounting	**BMW **)**	
peak acceleration:	40 g	100 g	25 g	40 g	30 g	50 g
shock duration:	11 ms	11 ms	6 ms	6 ms	6 ms	11 ms
number of shocks	1	6	330	50000***)	dep. on position	

per direction:
*) both tests must be carried out
**) 50 g-test at increased requirements
***) in main direction

Free fall according to DIN EN 60068 part 2-32 (all components)
Height of fall: 1±0,05m, number of tests: 3 (fall twice in each case so that all 6 fall directions are tested)

3.3.4 **Resistance to chemical reagents** (example VW)

Dampening of assembly with cotton cloth (30cm x 30cm), impregnated with 50 ml of respective reagent, blow dry approx. 15s, storage time 48h at room temperature.

Reagents according to assembly: diesel fuel, FAM-test fuel, battery acid, brakefluid, cooland agent additive, preservative compound, de-preservative agent, engine oil, cold cleaner, spirit, gear oil, ATF, inside cleaner, M15 (test fuel with 15% methanol), diesel fuel, central hydraulic transmission fluid, window cleaner

3.4 Conclusions

All specifications and directions concerning the quality and reliability of soldering joints reflect decades of experience with conventional SnPb solder materials. There is no automatic guarantee that this will apply to alternative materials and each case must be individually assessed. The great number of the relevant specifications gives an idea of the amount of work involved.

Evaluation:

A	1	no technical changes necessary
B	2	no change of running costs expected
C	3	considerable change-over costs expected

4. Application areas and processes for soldering technologies: comparison between SnPb based solders and lead-free alternatives

4.1 Metals and alloys: availability, physical properties

Several procedures of soldering technology have been developed for the production of soldering joints on electrical assemblies. There are well known fundamental differences between manual soldering and machine soldering as well as between partial and simultaneous soldering processes. New and improved developments of the processes aim to produce a great number of high quality cost efficient soldering joints while process technology keeps pace with development of new connection geometries of components.

Solder material has remained an almost constant system parameter despite electronic innovations. The wide variety of electronical products is mostly manufactured with near-eutectic tin/lead based solders.

Widely used soft solders must fulfill different requirements:

- Melting point
  The thermal stability of components and printed circuit material, which are currently inexpensive, limits maximum temperature of the soldering process to 255°C over a period of 8 seconds. Experts (e.g. Shangguan) [BER98] fix the upper limit for the melting temperature of the solder at 225°C and prefer alloys with a limited melting sector or near-eutectic composition.

- Process compatibility
  Alternative alloys must be compatible with No-clean-fluxes and suitable for the production of bar solder, solder paste and solder wire. The temperature resistance of printed circuit boards must be tested.

- Toxicity
  The alloys should contain neither cadmium, antimony nor any other elements classified as hazardous materials.

- Physical, mechanical and electrochemical properties
  The main physical properties are determined by electrical and thermal conducting capacity, density, surface tension and wetting reaction. The mechanical quality refers to flow properties and fatigue reaction. Corrosion, oxidation and migration tendency determine electrochemical quality.

- Costs and availability
  Metals make about 60% of the costs for bar solder in the case of a 63Sn37Pb-alloy, but in the case of solder pastes, only 5-8%. Production steps such as mixing and filling create the main costs for solder pastes.

It is very difficult to evaluate toxity of metals. The estimate in table 5 shows the present state of knowledge and serves as an indication for future developments.

Element	price* [US$/kg]	Toxicity	Capacity worldwide [p.a.,1000t]	Production worldwide [p.a.,1000t]	Share in alternative solders realizable at maximum due to availabity **
Sn	5,50	no	281	160	100%
Pb	0,70	yes	very high	unknown	unknown
Ag	193,80	no	15	13	approx. 2-3%
In	195,00	yes	0,2	0,1	approx. 0,15%
Zn	1,20	no	7.600	6.900	100%
Sb	4,00	yes	122.000	78.000	100%
Cu	1,60	no	10.200	8.000	100%
Bi	10,10	no	8	4	approx. 5-7%
Au	10311,00	no	small	unknown	unknown
Cd	3,70	yes	small	unknown	unknown

* prices for orientation as per March 1999

** at an estimated yearly consumption of solders by the electrical industry world-wide of 60.000 t. Example reads: At this rate of consumption a SnAg-alloy used world-wide might contain a maximum of 3% Ag as theoretically only 2000t are additionally available (capacity – production = capacity reserve).

Table 5*: alloy elements for solders [MIR97, MIR99]*

4.1.1 SnPb-solders

In electronics, lead is used as a constituent of the common SnPb-solder materials. Soldering with such solder materials is the basic connection technology for global electrical engineering and electronics industries. The soldering processes have been developed and perfected for decades. Practically all components, printed circuit board materials and process materials are adapted to technologies based on solders containing lead and their parameters. The solders can be used universally, different alloys are compatible with each other.

The use of lead compounds is associated with certain health risks. Constant exposure to lead can cause changes in the blood and damages nerves. Lead poisoning can be easily recognized in a human being by blood tests.

In the production of electronic assemblies, lead causes little harm as it is dangerous when inhaled as dry airborne powder particles. Years ago, electronic manufacturers realized already that the main risk was during eating and drinking during work and prohibited this.

The risk remains when old equipment is scrapped or incorrectly recycled that washing processes introduce lead into ground water consequently harming the environment.

In the USA, after 1990, the search for alternative solders for industrial applications was intensified for various reasons. For example, in the automobile industry, more and more electronic assemblies are mounted directly at the engine block for the optimization and monitoring of motor processes, therefore fewer cables are necessary. For these extreme requirements, solders with higher melting point are required.

There are more than 200 solder materials known to have a melting point under 300°C for joint production in electrical structures; these can be subdivided according to different criteria.

There are three different alloy modifications:

- variation of the tin-lead-ratio with a melting range (not eutectic),
- adding further elements to tin-lead-basis alloys,
- alloy systems not based on tin-lead.

4.1.2 Lead-free alternatives

Tin is also the basic material for the introduction of lead-free alloys. The reasons for the use of tin are the low costs, world-wide availability, and excellent physical, electrical, and thermal properties. Tin is the basis for the group of the SnPb-solders currently used.

Elements which may be combined with tin are:

- silver (Ag)
- indium (In)
- zinc (Zn)
- antimony (Sb)
- copper (Cu)
- bismuth (Bi)
- gold (Au)
- cadmium (Cd)

These elements mainly serve to lower the melting point.

Table 6 shows the basis data of the elements and alloys with prices, melting points and melting ranges.

elements	**melting point [°C]**	**possible alloys**	**alloy price * [US$/Kg]**	**melting range of alloy [°C]**
Sn	232			
Pb	327	**63Sn37Pb** **62Sn36Pb2Ag (standard)**	3,70 7,50	183 179
Ag	960	96,5Sn3,5Ag	12,10	221
In	157	52In48Sn 97In3Ag 77,2Sn20In2,8Ag	104,00 195,00 48,70	118 143 179-189
Zn	419	91Sn9Zn	5,10	199
Sb	630	95Sn5Sb 65Sn25Ag10Sb 96,7Sn2Ag0,8Cu0,5Sb	5,40 52,40 9,20	232-240 230-235 217-220
Cu	1083	95,5Sn4Ag0,5Cu 95,5Sn3,8Ag0,7Cu 95Sn4Ag1Cu 99,3Sn0,7Cu	13,00 12,60 14,60 5,50	216-219 217-219 216-219 227
Bi	271	58Bi42Sn	8,20	138

		90Sn2Ag7,5Bi0,5Cu 91,8Sn3,4Ag4,8Bi	9,60 12,10	198-212 200-216
Au	1063	80Au20Sn	8249,90	280
Cd	320	67Sn33Cd	4,91	170

* prices for orientation as per March 1999

***Table 6**: comparison between different metals as alternatives to lead [MIR99]*

Table 7 shows a choice of possible alloys which have a melting range near the eutectic 63Sn37Pb.

alloy	**suitability ***	**melting ranges [°C]**	**patent applied for**	**remarks**
63Sn37Pb (basis of comparison)	standard	183	no	lead in alloy
96,5Sn3,5Ag	yes	221	no	etches copper
96,3Sn3,2Ag0,5Cu	yes	217-218	no	-
99,3Sn0,7Cu	yes	227	no	-
95Sn5Sb	yes	232-240	no	high melting point, bad wetting
77.2Sn20In2.8Ag	no	179-189	yes	susceptible to corrosion at high air humidity, expensive, scarcity of indium
85Sn10Bi5Zn	no	168-190	no	constituents: zinc and bismuth (bad wetting)
91Sn9Zn	no	199	no	rapid oxidation, extreme amount of dross, corrosion problems
97Sn2Cu0.8Sb0.2Ag	no	226-228	yes	4 different metals in the alloy: very difficult to produce

* – refer to the present reliability tests

***Table 7**: alloys without lead [MIR97, BAS97]*

4.1.3 Conclusions

There is currently no known alloy providing a "drop-in-solution" as regards melting point. Those alloys which have no melting range but a near-eutectic composition are preferable, for example 96,5Sn3,5Ag, 99,3Sn0,7Cu, 91Sn9Zn or 97Sn2Cu0,8Sb0,2Ag. Alloys with solidification ranges have the ability to develop intermetallic phases and crystals in the solder. Their size depends on the cooling range and reduces the reliability of the soldering joint.

Reliability tests have not been concluded for most of the alloys mentioned. None of the alloys fulfills the requirements of electronics with regard to a melting point of approx. 180°C, low cost of materials, sufficient quality and reliability.

Evaluation:

A	3	material changes necessary
B	3	price rise in individual processes
C	4	materials and technologies for change-over non-existent, further development necessary

4.2 Components

The demand for „lead-free electrical equipment“ is significantly influenced by the availability of completely lead-free components which fulfill product engineering requirements (especially soldering heat resistance). The following description – based on a recent survey[1] in spring 1999 of a typical selection of components manufacturers – is the actual situation today with regard to the availability of lead-free components. It is evident that the manufacturers are not fully aware of the problem.

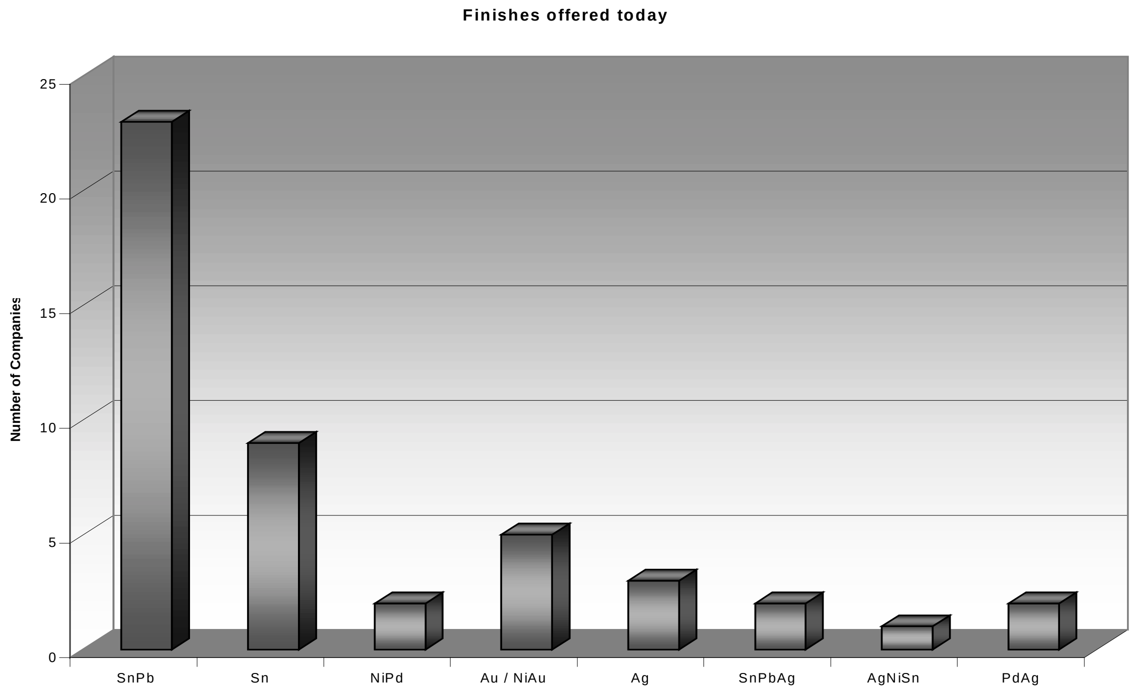
4.2.1 Lead in components: current situation

Currently the components market is completely directed to a soldering process based on eutectic tin/lead solder. Consequently metallizations of the contact pads are mostly also tin/lead. At the same time the structure of the component is designed in such a way that the necessary process temperature of this solder material of 230°C is just still possible.

4.2.1.1 Metallization film on contact areas

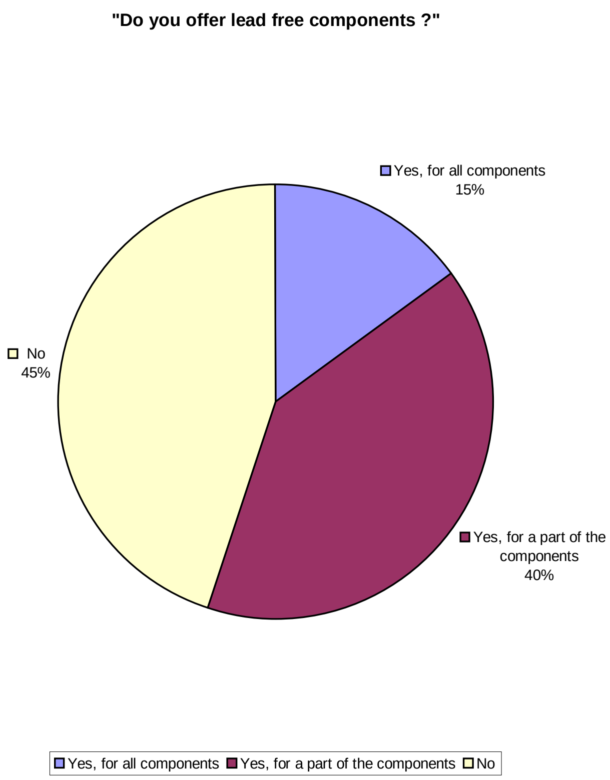
Picture 2 shows finish modifications available today for the total component spectrum. Besides the wide spread tin/lead final surface, some constituents (especially passive components) are additionally available in pure tin. In special cases there are finishes in NiPd (in some ICs) as well as in gold or NiAu (especially in electro-mechanical components).

[1] The wording of the separate questions can be found in the annex to this manual.



Picture 2: *Finish modifications currently available (for the whole components-spectrum)*

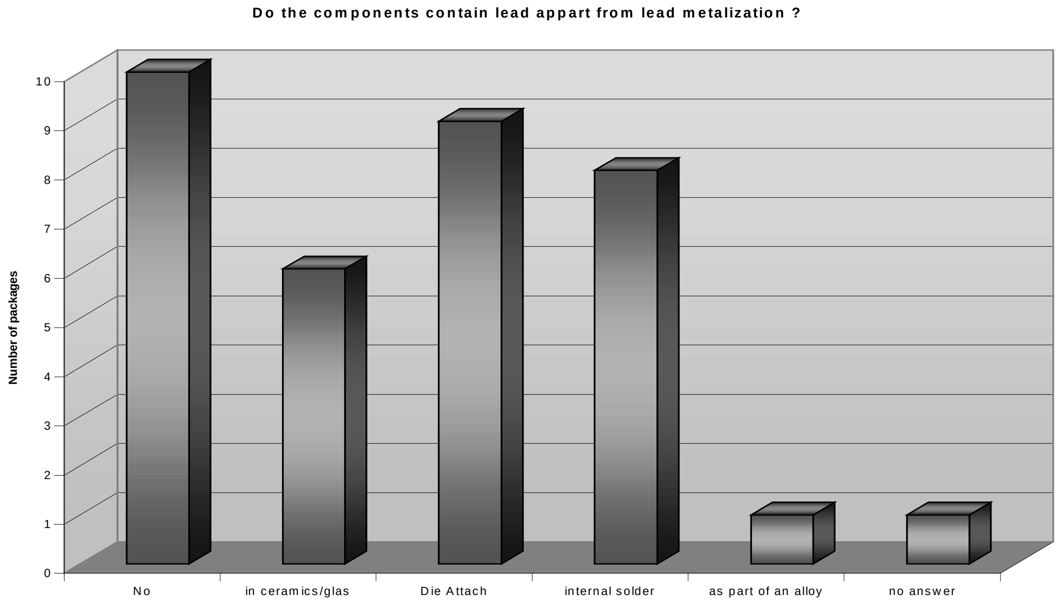
Lead-free alternatives, however, are available only for a fraction of the product spectrum. According to their own statement more than half of the manufacturers offer lead-free finish modifications but only 15% cover the total product spectrum. The total market share of the components with tin/lead surface currently amounts to > 95%.



Picture 3: *General availability of lead-free finish metallizations*

4.2.1.2 Lead in components

Beside finish metallization lead is also present in a great number of components. This applies in particular to ceramics as well as internal joint solders. Picture 4 shows a market-based analysis of materials containing lead:



Picture 4: *lead in the components*

4.2.2 Lead-free alternatives: requirements for components

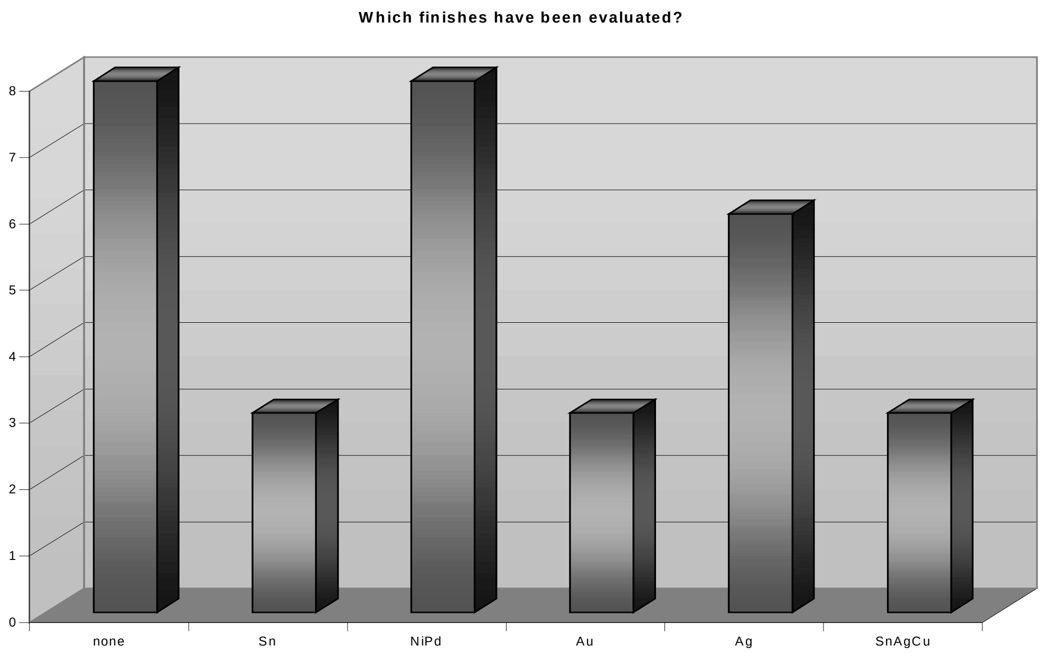
4.2.2.1 Finish metallization

The tin/lead surface is currently the most widespread for the finish metallization due to its compatibility with solders used (cf. picture 2). A substitute material must guarantee the same properties with regard to solderability and reliabilty of the soldering joints (for example no low-melting phases may occur reducing the strength).

The most promising product-tested candidates in this respect are surfaces of block tin or palladium. Gilded connections are offered in particular to the plug-and-socket connector sector while excess of gold in the soldering joint has to be avoided because of the reduction of strength.

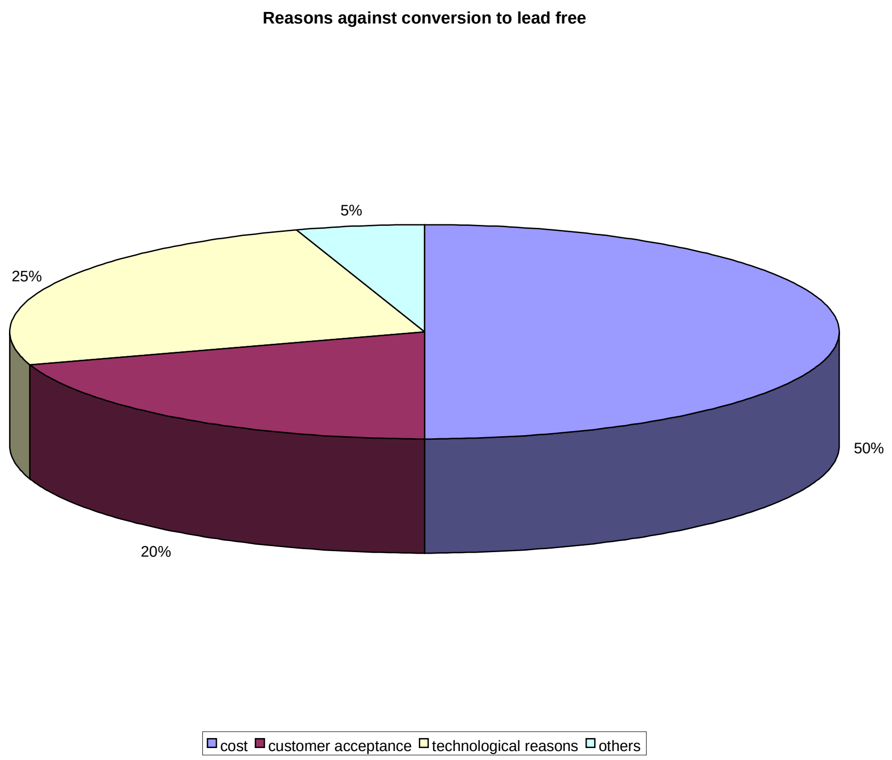
The main obstacle in change-over to lead-free finish metallizations are costs incurred by process changes, for example, by altered galvanic processes. Therefore only an increased demand from the processing industry will trigger such activities.

Manufacturers still do not at all agree as to which alloy can be considered as a lead-free alternative to tin/lead metallization. Currently individual producers evaluate the following modifications beside available finishes:



Picture 5: *possible finish modifications*

Price in particular is an argument given against change-over to lead-free components (and this is unpopular with customers). Only 25% of those who replied gave technological reasons.



Picture 6: *manufacturers' arguments against a change-over to lead-free components*

4.2.2.2 Lead in components

Comparable requirements are valid for application of lead-free alloys in soldering joints within the component which are partly additionally increased, for example, when bare dies are soldered (die attach). For example, the thermal stress of the soldering joint directly at the chip is usually higher than at connection to printed circuit board.

At present components manufacturers see no substitute as a short or medium term solution for *any* of the applications stated in picture 4.

4.2.2.3 Temperature resistance of components

The additional requirements for components from the point of view of product engineering mainly result from the higher melting temperature of lead-free solders: the melting range of present alloy ranges from 217°C (SnAgCu) to 227°C (SnCu). During the soldering process the temperature must be 30 K above this temperature in order to guarantee sufficient wetting of soldering areas and complete reflow of solder. In addition a safe soldering process requires a minimum process window of 10K so that the maximum process temperature is between 250°C and 260°C. The typical process time above melting temperature of solder amounts to 60–90 seconds.

This explains the demand for components to withstand 260°C for at least 10 seconds. For a number of components (e.g. BGAs, relays, crystals) this demand is currently not fulfilled and probably cannot be fulfilled for reasons of physics. Thus we have a great number of components which can no longer be processed with production processes available.

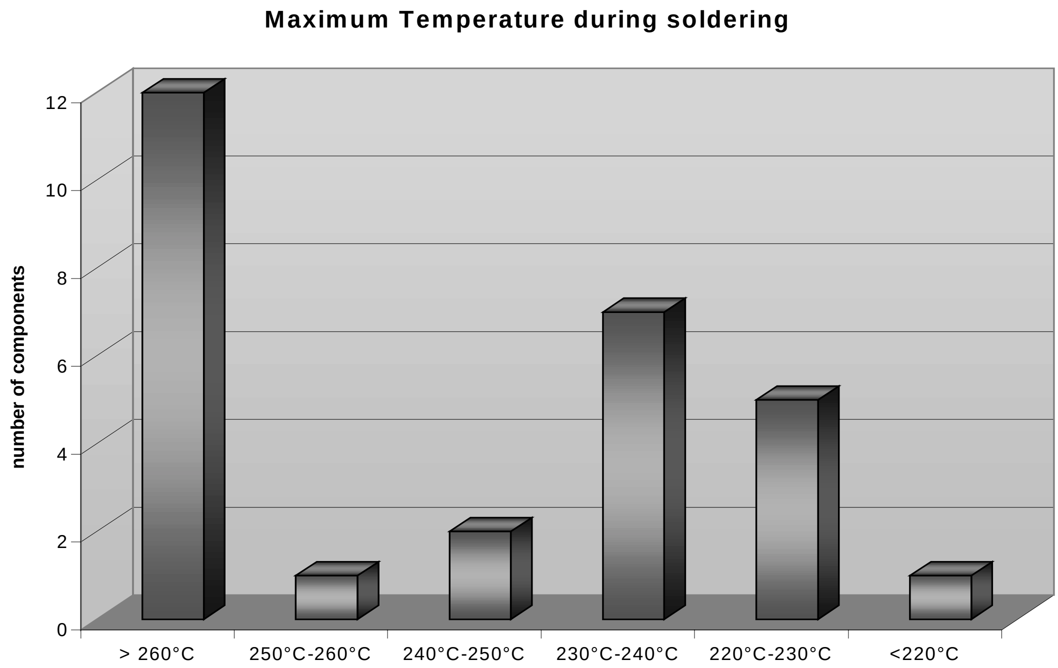
The permissible maximum temperatures are below these levels for a number of components currently soldered in the standard reflow procedure. The following components / structures are important examples:

ceramic capacitors / Alu–Elko's:	220°C – 240°C
Ball Grid Arrays:	220°C
SMD-Relays:	245°C
SMD-connectors:	245°C
Finepitch-connectors:	230°C
Test socket:	220°C
Crystal oscillators:	235°C

The upper limits are mainly based on the fact that above this temperature the essential physical parameters change to such a degree that the component no longer fulfills its function (e.g. spring rate at relays, frequency of oscillators).

In the case of connectors, sockets etc. plastic materials are additionally damaged. Furthermore in the case of large area components with high connection numbers excessive heat can cause the component to warp preventing a reliable soldering process.

An assessment of all components types shows that most of the temperature-sensitive components have a temperature upper limit of approx. 230°C:



Picture 7: *temperature upper limit of components*

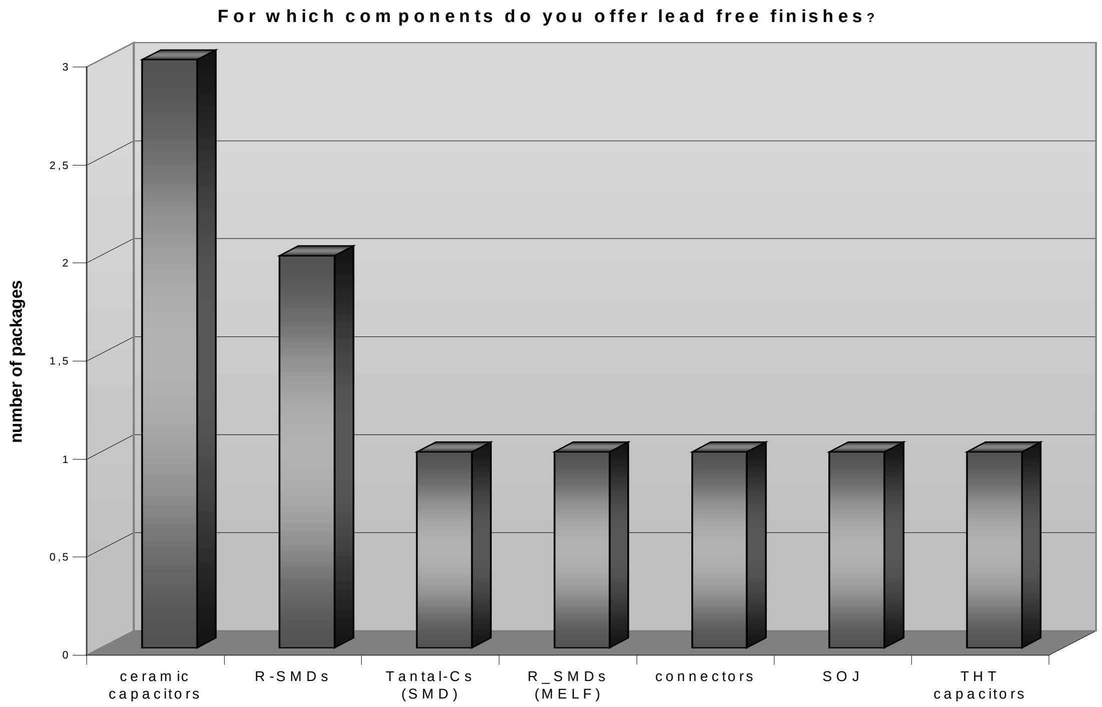
Adapting temperature resistance requires considerable development with regard to the structure of components as well as to the supporting plates used (potting compounds, substrates, plastic materials etc.).

4.2.2.4 Manufacturers' roadmaps

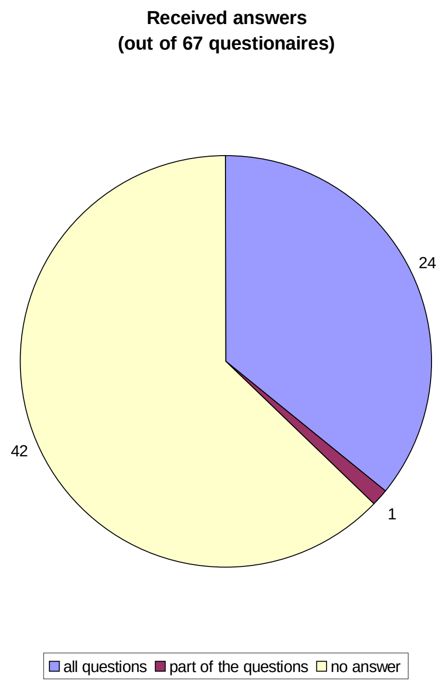
The components manufacturers' reactions show that the majority do not fully recognize the problem of avoiding lead. Only one third of the manufacturers questioned could reply within 6 weeks.

Evaluation of individual replies which most probably come from those manufacturers who have already examined closest the issue of lead-free components shows that the supply situation will remain critical at least for some years. At present only 10 % of the firms questioned are able to estimate at all when lead-free components will be available (picture 10).

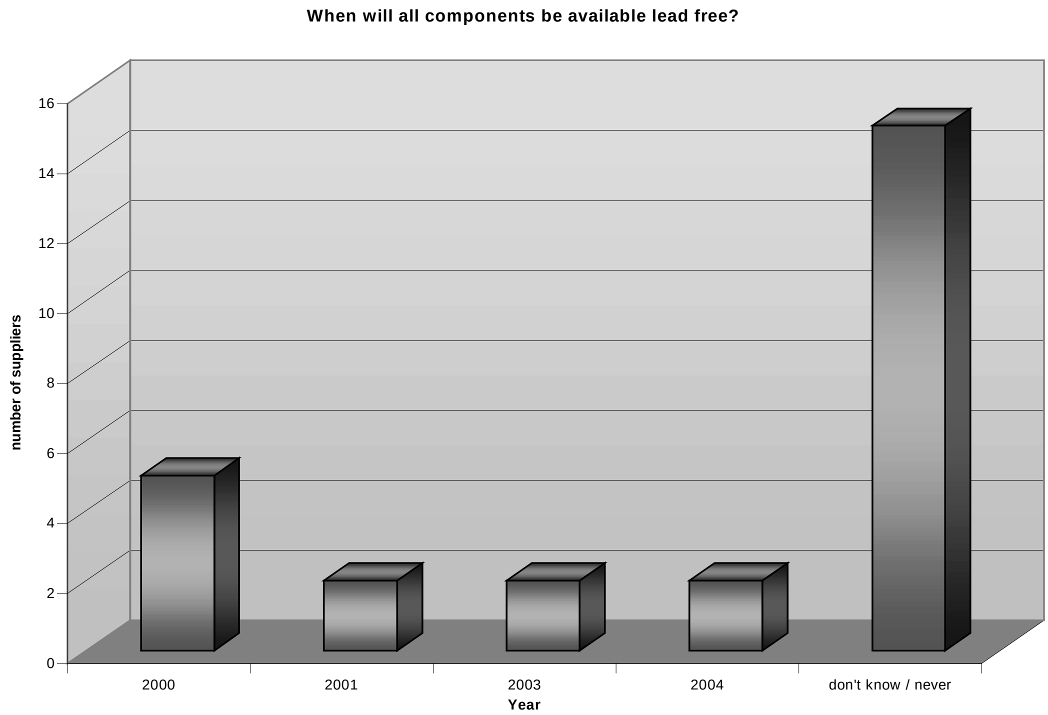
Picture 8 shows in addition that the few lead-free components offered come from a very limited part of the components spectrum so that it will be some time before a larger area is covered:



Picture 8: *(partly) lead-free components currently available.*



Picture 9: *response to BE-manufacturers' inquiry*



Picture 10: *manufacturers estimate when lead-free components will be available*

4.2.3 Conclusions

Only a minority of the components manufacturers regards the present discussion as grounds to make concrete plans for change-over to completely lead-free components. Even fewer are interested in improving heat resistance. At present the unanimous opinion is that there will be no significant progress for some years (if at all). One reason is that manufacturers do not yet have the processing paramenters for lead-free soldering.

The consumer has the general impression that it will be some time before commercial components manufacturers are able to supply the whole components spectrum according to the demand. The majority of the manufacturers are waiting for the processors to approach the problem.

The manufacturers' main objections to a change-over are increased costs and customer acceptance; lead-free components will only become available if there is a substantial demand by the processing industry. However, here the consumers must clearly define their requirements regarding processing technology (for example temperature resistance during soldering) and present them to the appropriate international committees (IEC, JEDEC....). This will take considerable time.

The amended production paramenters for the processing of lead-free solders have also caused problems. From today's standpoint the fact that the soldering temperature is up to 40 K higher means that numerous components cannot be processed any longer in existing production procedures. Further development is necessary to adapt components to the new requirements.

Overall evaluation of the components:

A	6	strategy undetermined
B	5	costs implications not estimable – financial risk
C	4	change-over materials and technologies non existant, significant development needed

4.3 Printed circuit boards

4.3.1 Printed circuit boards for soldering technologies on SnPb-basis

4.3.1.1 Base materials

FR4 is most frequently used as base material It shows a glass transition temperature Tg of approx. 130°C. Alternative base materials are already used where required, for example in the high frequency range > 1GHz or interposers. Table 8 shows the typical examples and their characteristics [DEM98]:

Producer	Product	Stiffening	Resin	Thickness [µm]	Tg [°C]	εr [1MHz]	tanδ [1MHz]	Water absorption [%]	Remarks	Price **
Gore	Speedboard N	Expanded Teflon	Epoxy	50	130	3,2	0,02	0,2	low εr	6x
Gore	Speedboard N10	Expanded Teflon	Epoxy	50	130	10	0,02	0,2	very high εr, commercially not yet available	10x
Isola	Duramid	Aramid	Epoxy	60	160	3,9	0,025	0,7	low expansion coefficient	2x
Isola	Duraver BT	Glass fabric	BT*	60	210	3,9	0,011	0,3	low εr, high Tg	4x
Isola	Duraver CE	Glass fabric	Cyanatester	60	230	3,8	0,004	0,3	very high Tg, low εr	4x
Isola	FRN	Glass fabric	Epoxy/-PAIC***	60	160	4,7	0.02	0,4	halogen-free	2x
Mitsubishi	Foldmax	Aramid	BT*	60	180	3,3	0,015	0,2	low εr, high Tg	2x
Isola	FR3	Hartpapier	Epoxy	≥50	130	4,9	0,04	0,3		<1x
Isola	**FR4**	**Glass fabric**	**Epoxy**	**≥50**	**130**	**4,7**	**0,02**	**0,2**	**Standard**	**1**
Isola	FR5	Glass fabric	Epoxy	≥50	160	4,6	0,016	0,25	higher Tg	1,2x

* BT: Bismaleimid-Triazin ** Prices xFR4 ***PAIC: Polyarylaminoisocyanurat

Table 8: *Base materials*

4.3.1.2 Surface finishes

Open melt SnPb-layers (HASL: **H**ot **A**ir **S**older **L**evelling) are the most widely used finishes. The finish has been used for decades because of its excellent soldering properties. As detailed tests [STR98] show these properties are not affected by temperature and climate storage. The weak point is the uneven deposit and its inhomogenous thickness.

Recent years have seen the development of „electroless Sn“ as an alternative. It shows good soldering properties at up to 3 reflow passes. The layer is susceptible to increased storage temperatures (Cu-diffusion).

The Cu-antitarnish is particularly suitable for simple soldering processes. The finish shows weaknesses when subject to repeated reflow passes or variable temperature storages.

Electroless Ag is used especially in Asia. The maximum thickness of the deposit is 0,2µm and an organic antitarnish is deposed together with the Ag. As opposed to electroless Sn electroless Ag additionally offers the possibility of wire bonding. The thinness of the deposit makes it more susceptible to thermal stress than electroless Sn. Solderability clearly decreases after 8h at 155°C. Soldering properties are largely unaffected when it is exposed to climate for several days (40°C and 93% relative humidity).

Electroless Ni/Au or Ni/Pd with Au-Flash (product name „Universal Finish“) are available if good wire bonding properties are additionally required. At temperature and climatic storage both surface finishes show soldering properties similar to HASL. They are, however, affected by steam.

Table 9 shows the solderability and suitability for fine line. They are graded from 1 (very good) to 6 (bad). The prices stated are based on HASL.

finish	state at delivery	thermal stress	climatic storage	minimum conducting path distance [µm]	price
HASL	1	1	2	130µm	1
chemical Ni/Au	1	2	2	80µm	4
chemical Pd	1	1	1	80µm	5
chemical Ag	1	4	2	50µm	3
chemical Sn	1	3	3	50µm	2
Cu with organic passivation (OSP)	1	5	3	50µm	1

***Table 9**: finish properties (1 =very good, 6 = bad)*

4.3.2 Printed circuit boards for lead-free alternatives

4.3.2.1 Base materials

The soldering temperature for lead free solders must probably be increased by about 20–30°C. As current temperatures are already well above the glass transition point this puts base materials under considerable stress.

If FR4 is still used, increased twisting and warping is to be expected. Furthermore, outgassings and delaminations can occur.

If alternative base materials are necessary, a considerable rise in the price of semi-finished products is to be expected – as the table in 4.3.1.1 shows. An average increase in costs for semi-finished products of 30% is assumed.

Evaluation:

A	5	considerable technical problems expected
B	4	considerable price increase
C	3	considerable change-over costs expected

4.3.2.2 Surface finishes

The properties of the finishes of printed circuit boards with regard to soldering with solders containing lead are well known [STR98]. As Wege and Bergmann tests show, however, these need not necessarily apply to lead-free solders [WEG99]. Finishes as alternatives to HASL must be re-tested for their soldering properties in combination with the particular lead-free solder.

Electroless Ni/Au and Ni/Pd with Au-Flash demonstrate excellent soldering properties. Costs rise considerably here due to the use of precious metals. The diffusion of Ni caused by increased soldering temperatures should be separately assessed. Ni will eventually oxidize and decrease solderability. Diffusion by reductively strengthened Au layers is one example: There is no negative effect on Ni-diffusion at a storage of 6 min at 240°C but probably after 9 min at 275°C.

At present electroless Sn-finishes can only be stored for a limited period because of natural Cu-diffusion. After a 4 h storage at 155°C a Cu-diffusion of approx. 0,5 µm is evident. Therefore actual thickness of the Sn deposit is about 0,3 µm. Afterwards any further thermal stress may result in only being able to solder with higher activated flux because Cu diffuses to the surface.

Electroless Ag's soldering properties weaken as thermal stress increases. Because of the thinness of the Ag deposit Cu can already be expected at the surface after the first reflow pass (profile for Pb-free solders). It remains to be seen how soldering can be carried out under these circumstances.

With Cu antitarnish (Cu with organic passivation) increased thermal stress eliminates or limits multiple solderability. Usage would then be limited to applications with a simple soldering pass.

Evaluation:

A	5	considerable technical problems expected
B	4	considerable cost increase
C	3	considerable change-over costs expected

4.3.3 Conclusions

The printed circuits' problems of twist and warp will be aggravated. Additionally delaminations are to be expected in combination of electroless components with very high heat capacity and large surface area. Corresponding design rules must be worked out. Furthermore it must be examined to what extent organic outgassing products impair the properties of the metallic surfaces. The base materials and the printed circuit boards produced here must be adapted to withstand increased thermal stress.

As the electroless finishes have a relatively thin deposit diffusion processes occurring with increased thermal stress have to examined in detail. The surface finishes also have to be adapted to the increased thermal stress.

4.4 Processes

4.4.1 SnPb based processes

This section presents and describes the current processes employing SnPb solders. To this end significant parameters are given for the processing of these solders. Finally, section 4.4.2 concludes by analysing the changes necessary if lead is to be eliminated from solder.

In electronics soldering technique is concentrated in the following sectors:
- stencil printing of solder paste,
- component placing,
- soldering,
- wave soldering for reverse side of printed circuit boards and through hole technology,
- inspection of solder joints,
- rework/repair,
- soldering processes using solder wires or core solder: iron soldering, laser soldering, repair soldering,
- boundary conditions for design and development of an assembly.

4.4.1.1 Solder paste printing

Standard stencil printers are used in electronics production for solder paste printing. Following parameters apply to paste processing:
- Durability: the extent of surface oxidation of solder balls present in the solder paste must be limited. Therefore the solder paste must be processed immediately on removing wrapping.
- Processability: to ensure safe processing of solder paste various additional agents are added to the activators necessary for the actual soldering: resins, solvents, thixotropy agents, adhesives (adherence of paste in stencil openings after direction of squeegee, dimensional stability of printed paste).

- Tool life: In some applications (e.g. in sample construction) the printed circuit board cannot be assembled directly after stencil printing so that the solder paste must maintain its wet adhesion for a certain period.

4.4.1.2 Component placing

In electronic assembly procedure components are put onto the printed circuit board by an automatic placing machine. The fully assembled board then goes to a furnace for soldering. Individual components must remain fixed during assembly and transport, i.e. the solder paste must be strong enough to keep the components in position.

4.4.1.3 Soldering

Current methods of heating SMT printed circuit boards are: full convection, i.e. heating by hot gas, infrared heating or a combination of both. The latest vapour phase soldering systems which use condensed saturated vapour to heat and are suitable for inline have not yet been fully tested. Nitrogen is often used as inert gas to prevent oxidation particularly in the melting range of the soldering area.

The main parameters for simultaneous soldering in the soldering furnace are:
- Minimum temperature: a minimum temperature must be reached over the whole printed circuit board in order to ensure reflow soldering and wetting (according to processing 190-220°C at a solder melting temperature of 183°C), i.e. the coldest soldering joint of the printed circuit assembly has this minimum temperature.
- Temperature splitting: small components heat faster than components with greater heat capacity, i.e. they become significantly hotter than the melting temperature of the solder as the solder has to melt and wet well even at the coldest point. This means the components must also be able to withstand a higher temperature.
- Maximum temperature: it adjusts itself according to the minimum temperature requirement at the coldest point depending on the components of the printed circuit board. It should be noted that FR4-standard-printed circuit boards may not be hotter than 260°C and certain components (e.g. BGA-cases) not hotter than 220°C [specification components manufacturer].
- Temperature profile: a definite temperature profile has to be set for soldering: the printed circuit assembly must reach a preheat temperature (observing a maximum temperature increase gradient); the flux has a limited range of action which must be maintained and finally the soldering temperature must be reached within a short time in order to protect components and printed circuit board from excessive heat stress. The furnaces also often consist of several zones. Conveyer belt speed must be adjusted to furnace parameters according to the complexity of the printed circuit assembly (length of furnace, number of heating zones, width of heating zones, adjustable gas or radiator temperatures).

4.4.1.4 Wave soldering for the reverse side of the printed circuit board and through hole technology

For soldering with solder wave the components to be soldered are glued to the printed circuit board and afterwards driven over a wave of fluid solder produced by special nozzles. The necessary stages in detail:

- Application of SMT-glue: the adhesive must keep the components in place during transport of printed circuit, during heat shock on introduction into the wave and during thermal stress from fluid solder. The glue is applied by stencil printing or dispensing and the quantity and position must be carefully adjusted in order to guarantee good adhesion and not to contaminate surfaces to be soldered. Afterwards the adhesive is thermally hardened.
- A placement machine carries out SMD and wire components insertion.
- Foam, spray or dip fluxers apply the fluid flux.
- In the preheating zone (IR or convection) the printed circuit assembly is heated to a temperature of 80-120°C using alcohol based fluxes whereby the solvent evaporates.
- A solder wave is produced by special nozzles over which the printed circuit assembly is driven during soldering (dual wave: turbulent and laminar wave in series). Nitrogen can be used to prevent oxidation of the wave surface. The pull-off zone of the wave is decisive for successful soldering (no bridge, stud or shadow development, sufficient hole filling) this is determined by surface tension and depends on the composition of solder, impurities (e.g. dissolving of pad surfaces), wave flow and printed circuit assembly design.

4.4.1.5 Inspection of solder joints

The following techniques can be considered for inspecting soldering joints:

- Visual inspection by staff.
- Automatic optical inspection by an inspection system which takes pictures of the printed circuit assembly and evaluates them.
- X-ray inspection

In the case of optical procedures good/defective evaluation can be effected only by means of the shape of the soldering joint (meniscus, reflection); in the case of X-ray inspection by means of the geometric distribution of the solder (the difference of the radio absorption coefficients of solder and printed circuit board/component is the determining factor). The shape of a soldering joint and subsequent evaluation largely depends on the properties of the solder on the respective surfaces (solder spreading, wetting, surface oxidation).

4.4.1.6 Rework/Repair

Rework is necessary if the printed circuit board or components are damaged or in case of faulty procedure. The defective components are desoldered with hot air nozzles and vacuum pipettes or with soldering iron. Soldering of the new component is effected by means of the frame soldering process, with the soldering iron (see point 4.4.1.7) or by partial hot gas soldering.

4.4.1.7 Soldering processes using solder wires or core solder: iron soldering, laser soldering, repair soldering

These processes are among standard applications of soldering technique for eutectic SnPb solder. Here soldering joint and core solder are heated by the hot soldering iron or laser radiation enabling the soldering joint to be wetted.

4.4.1.8 Boundary conditions for design and development of a printed circuit assembly

The design of a printed circuit assembly must be adapted to soldering processes used and boundary conditions:

- solder paste printing: structures of the printed circuit board must be cleanly printable.
- reflow soldering: careful grouping of components, observance of heat capacities of components types on front and rear side of the printed circuit assembly.
- wave soldering: application of not too fine a geometry to prevent short circuits, positioning components at a certain angle to wave front, guarantee of a complete hole filling at through-hole platings.
- inspection: too tight packaging prevents lateral illumination; X-rays cannot distinguish front and back, i.e. components must be evenly grouped on both sides.
- rework: there must be space round components for e.g. gas nozzles; sensitive components must be prevented from overheating.
- soldering joints not on a surface mounted printed circuit assembly, e.g. cable pad connections: the soldering joint must be designed in such a way that no overheating or damage to surroundings may occur, e.g. plastics directly adjacent.

4.4.1.9 Conclusions

The total operation, i.e. every single process including all materials and constituents (printed circuit board, components), is adapted to SMD production and its current requirements. This applies in particular to the actual soldering process with the requirement of a solder melding temperature of 183°C.

4.4.2 Processes based on lead-free solders

The various SMT processes were dealt with in section 4.4.1. Modifications necessary for a change-over to lead-free solders, the amount of work involved and the estimated expenses are discussed here.

4.4.2.1 Solder paste printing

- Change of metal alloy: the cost of metals in lead-free alloys are two to four times higher than for eutectic SnPb. The production of metal powder with uniform granules is not a great technical problem.
- Changes of solder paste fluxes : in view of tendency to oxidation and higher process temperatures the flux system has to be modified without impairing printing properties of the solder paste.

Evaluation:

A	3	material changes necessary
B	3	increase in price in individual processes
C	2	moderate change-over costs expected

4.4.2.2 Component placing

Changes in the procedure rules can be expected in view of permissible offset as the set components can blur under certain circumstances or the self-centering effect is less effective due to altered wetting conditions. Design specifications would be affected or process window would be narrowed.

Evaluation:

A	4	moderate technical problems expected
B	2	no change of cost expected
C	1	no change-over costs expected

4.4.2.3 Soldering

A *reduction* of the soldering temperature in change-over to low-melting solder (melting temperature ~140°C) is unproblematic as regards machine and processing techniques.

The high requirements regarding vibration stability, temperature resistance and temperature cycling resistance of assemblies will make solders with a *higher* melting point and an accompanying increase of soldering temperature essential for most applications. For physical reasons solders with melting temperature of about 220°C must be used resulting in an increase by 40K.

The following discusses the necessary process changes according to 4.4.1. It has to be particularly emphasized here that only the parameters required by the process are considered and that in this respect combined effects with printed circuit board and components is particularly critical.

- Minimum temperature: the melting temperature of lead-free solders will be higher by approximately 40 K. It is unclear whether the minimum temperature must also be increased accordingly or whether for example 20 or 30 K will be sufficient. This lastly depends on the wetting behaviour of the solder and therefore on surfaces and flux system.
- Temperature splitting: when the soldering temperature is raised temperature splitting increases considerably in convection furnaces as well as IR furnaces (with constant conveyor belt speed and same profile). Such a problem would warrant a total change-over from soldering process to vapour phase soldering.
- Maximum temperature: increasing minimum temperature simultaneously increases effective maximum temperature. With current furnaces this rise can be significantly higher than the increase of minimum temperature if there is to be no reduction of clock-time. Total energy input and thermal stress of components significantly increases when conveyor belt speed is reduced. This critically affects the heat load of printed circuit board and components.
- Temperature profile: higher temperatures must be set for temperature profile as a whole. The temperature profile must be adapted to scope of flux and to duration of separate phases; further tests must be carried out here (adjustment of soldering zones, reduction of conveyor belt speed and consequently clock-time). The critical question is whether electric furnaces used currently are able to produce these higher temperatures. What additional energy costs are involved? How does this affect typical soldering defects (blobs, tombstone effect, ...)?

Evaluation:

A	6	strategy undetermined
B	5	costs implications not estimable – financial risk
C	4	change-over materials and technologies non-existent, significant development needed

4.4.2.4 Wave soldering for reverse side of the printed circuit board and through hole technology

- Glue application: no change necessary; the adhesive must withstand higher temperature of solder wave without damage.
- Placing: no change.
- Flux application: no change in application process but in the choice of flux, i.e. more work necessary on releasing the process.
- Preheating must be raised – this should be no problem.
- Solder wave: the form of the solder wave depends on the transfer of metal by pumping. A higher oxidation tendency must be prevented by a protective inert gas rinse or increased amount of dross is to be expected. Sn enriched solders can affect soldering tools and metallizations of components. The dissolution of non-solder elements in the solder bath can have unknown effects on processibility and reliability of finished assemblies. Increased stud development and consequently higher tendency for solder bridges to develop are to be expected during the soldering process itself. This can only be prevented by amending layout specifications to extend the area required; this is in direct contrast to increasing miniaturization. The raised bath temperature subjects printed circuit board and components to greater thermal stress than in solders with SnPb so that maximum temperatures must not be exceeded.
- Modified solder alloy may require new materials for the solder pot in order to avoid increased corrosion and consequent deterioration of the system.
- The effects of a change-over on error rates and mechanism are unknown.

Evaluation:

A	5	considerable technical problems expected
B	3	price rise in individual processes
C	4	change-over materials and technologies non-existent, significant devolopment necessary

4.4.2.5 Inspection of solder joints

Solder joint inspections are essential: a high pseudo error rate increases processing costs; slippage rate should not increase accordingly.

- Visual inspection: visual inspection of the soldering joint depends on solder spreading, i.e. the interaction of solder with pad surface and the reaction properties of the solder. Drawing up a new catalogue of criteria for evaluating solder joints and modifying machine parameter of AOI systems involves a lot of work.
- X-ray test: all metals used as lead substitutes have reduced absorption coefficient (reduced by 5-10 times). Considerable problems are expected with automatic X-ray tests due to

lower contrast soldering joint/background (reverse side, interlayer metallizations): it is unclear whether existing image processing strategies can be used.

Evaluation:

A	5-6	considerable technical problems expeted, strategy undetermined
B	5	costs implications not estimable – financial risk
C	4	change-over materials and technologies non-existent, significant development needed

4.4.2.6 Rework/Repair

See also 4.4.2.7. Employees could be exposed to flux vapours occurring in a flux system adapted to lead-free solder. The repair of packages with hidden connections (BGA) poses additional problems similar to heat stress in reflow soldering.

In order to carry out repairs conduct path surfaces, solders and surface metallizations of individual components must be clearly labelled. Using wrong alloys for repairs can cause brittle phases in solder structure. Only tested and approved material compositions should be used in production.

Evaluation:

A	4	moderate technical problems expected
B	3	price rise in individual processes
C	3	considerable change-over costs expected

4.4.2.7 Soldering processes using solder wires or core solder: iron soldering, laser soldering, repair soldering

Problems arising are:

- It is not possible to produce lead-free solders as core solder or solder wire for all lead-free substitute alloys as these are sometimes too brittle for processing. When using such alloys as solder paste a different alloy has to be used for repairs; undefined phases formed may have a negative effect on the durability of the connection.
- Greater care must be taken when using plastic near joints because of rise in temperature respectively longer process time caused by higher melting temperatures of the lead-free solders.
- Clock-time is increased when adapting soldering irons to higher temperatures or using laser soldering with longer radiation periods and costs rise accordingly.

Evaluation:

A	4	moderate technical problems expected
B	3	price rise in individual processes
C	2	moderate change-over costs expected

4.4.2.8 Boundary conditions for design and development of a printed circuit assembly

- As described in 4.4.2.3 and 4.4.2.4 assembly design depends to a large extent on the different processes: design specifications have to be modified accordingly.
- Greater priority must be given to inspection of soldering joints (4.4.2.5).
- Other materials and geometries may prove suitable for printed circuit board pads and coatings.

Evaluation:

A	3	material changes necessary
B	3	price rise in individual processes
C	3	considerable change-over costs expected

4.4.2.9 Conclusions

All materials and processes used in soldering techniques are compatible to solder with melting temperature of 183°C. For metallurgical reasons no alternative is available in this temperature range. The phases of a change-over to lead-free solders with higher melting temperatures have not been established.

Decades of continuous improvement of process have made it possible to bring soldering error rates down to the dpm range. These present error rates, however, are now the *minimum* requirement for introducing new techniques. A great amount of work still has to be done to fulfill the new technological requirements.

4.5 Reliability

4.5.1 Definition of reliability

Reliability is the „probability that the required function of a product will be carried out without failure under the given working conditions during a fixed period.“ [BIR97]

4.5.2 Reliability of a printed board assembly

The reliability of a printed board assembly is the immanent ability to guarantee specified function at any required time. Basically the *overall reliability* of a printed board assembly is the integral of all parameters and effects which can affect the reliability of the printed board assembly.

If all criteria and phenomena that affect and determine the function of the printed board assembly are considered the resultant evident reliability can be divided into two categories: reliability of dielectrics and reliability of current-carrying systems.

4.5.2.1 Reliability of the dielectrics

A prerequisite for reliability of dielectrics is that ionic contamination from the environment and of conductive particles caused by corrosion or electromigration which in combination with humidity will not form conductive paths, e.g. *between* conducting paths, pads, etc. on *one* circuit layer or between circuit systems on different circuit layers.

Measuring criterion: R_{is} (insulation resistance of the dielectric)
Requirement $R_{is} > R_{is, min}$

Apart from design parameters, such as spaces between conducting paths , layer thicknesses of dielectrics or geometrically adverse layouts of current conducting systems (sharp angles, contractions, distentions in the conducting paths) which may cause peaks of electric field strength, both the basic material compositions and corresponding areas where materials come into contact and overlap may significantly affect insulation resistance.

The printed board assembly is also affected by pollutants present in the environment such as pollutant gases and hygroscopic dusts or stressed by thermal cycles.

4.5.2.2 Reliability of current-conducting systems

The reliability of current-conducting systems is impaired if electric current cannot be supplied as specified without interruption.

Measuring criterion: R_V, R_C (volume resistance, contact resistance)
Requirement: $R_V < R_{V, max}$
$R_C < R_{C, max}$

Basically some phenomena (e.g. corrosion) can cause reduction of surface resistance as well as increase of contact or volume resistance.

Corrosion caused by environment, mutual material effects, critical design parameters or mechanical influences such as vibration or mechanical shocks can jeopardize the required performance or even the general function of a printed board assembly by causing material abrasion, alteration or interruption of current-conducting systems.

These reliability criteria can be assessed in several ways: electrically (dielectric resistance, contact and volume resistance); visually by examining the surface of the printed board assembly (corrosion, electro-migration products, defects and interruptions in the conducting systems as well as impurities caused by processing or environmental conditions); or by physical-chemical analysis (FT infrared spectroscopy, ionography, ion contamination test, TGA, DSC etc.).

Phenomena which affect reliability and cannot be assessed by the above methods or only with great difficulty are a special problem. This applies, for example, to latent chemical processes which can occur in interior layers of the printed circuits (caused by residues from processing).

Data on reliability of components used can be obtained by assessing so-called *failure rates*.

Special attention must be paid to changing properties of joint and connection areas (particularly the solder joints) which are affected in function or in the field. General mechanical or electro-mechanical influences resulting in creep or fatigue or aging of the joint material can eventually cause permanent damage where materials adjoin. [KLE91].

4.5.3 Status of reliability of printed board assemblies focusing on current SnPb based solder materials

As can be seen above the properties of solder and consequently of reliability of solder joints significantly affect the expected functional life of the printed board assembly in the field.

The vast majority of current processes and procedures for assembling printed board assembly are compatible with eutectic 63Sn37Pb solder. The 183°C melting point of the solder defines and determines the thermal conditions of so-called „soldering profiles“ of reflow and/or of wave soldering processes and also in part of repair and other soldering processes; the relevant thermal stress parameters accordingly affect total assembly and in particular sensitive components during soldering processes (see also section 4.4 „Processes“).

These parameters therefore affect functional reliability of assembly and components predetermined during assembly and mounting processes and furthermore determine the long-term reliability within the predicted field life.

Any insufficient single process of the total process chainaffects the resulting final overall reliability of the produced assembly. Likewise any modification of standard processes affects reliability of the total system. Predetermined failure rates in particular with regard to the components, the weakest point of the assembly, can no longer be maintained.

In the framework of so-called process qualification all materials from printed circuit via components to peripheral connections as well as all attachment and joining areas involved in the mounting process of the assembly were tested under specific conditions. Maximum reliability is achieved with SnPb technology when specific requirements and corresponding marginal conditions are maintained.

The same applies to controllability and loading capacity of solder equipment. Both adjustment range and maximum thermal stress of existing equipment are adapted to the melting point of SnPb solders respectively the processing parameters of corresponding solder pastes.

If the set soldering profile shows a clear tendency to higher thermal stress, the possible effects on the reproducibility of process conditions must be assessed as this in turn influences the final reliability of the assembly.

However the relatively low melting point of SnPb solder of 183°C also determines the optimum operation temperature with respect to reliability of the manufactured assembly. With thermally sensitive components on the assembly the soldering process cannot always be run with the normal SnPb solder profile without consequently jeopardizing reliability of components. On the other hand drastic reduction of soldering temperature can significantly affect reflow characteristics of solder and in turn impair reliability of the solder joint.

Assemblies designed for high-temperature use need special high melting solders. The mechanical properties of solder joints of conventional SnPb alloys distinctly deteriorate when temperature ranges approach solder melting point in function.Temperature cycle tests show that with higher temperatures there is increasing plastic deformation of solder and numerous recrystallization and grain growth processes also occur in the solder. Therefore microstructural stability and strength of the solder joint alter, in turn affecting reliability.

As seen above conventional SnPb solders have a narrow process window if reliability is not to be jeopardized.

However, SnPb solders have been tried and thoroughly tested for a relatively long time so that this narrow window and related reliability risks are sufficiently familiar.

4.5.4 Lead-free alternatives

A transition to new solders appropriate for high temperature applications, in particular if these solders claim to be universally applicable, will necessitate new comprehensive and extensive investigations in order to ensure guaranteed product reliability.

The following section attempts to clarify reliability problems and compare advantages and disadvantages of alternative lead free soldering joints with SnPb solders.

4.5.4.1 General effects of using lead free alternatives on reliablity

- tendency to oxidation

Every alloy shows a stronger or lesser tendency to oxidation. Most oxides are soluble in fluid solder whereby solubility increases with rising temperature.

- copper dissolution

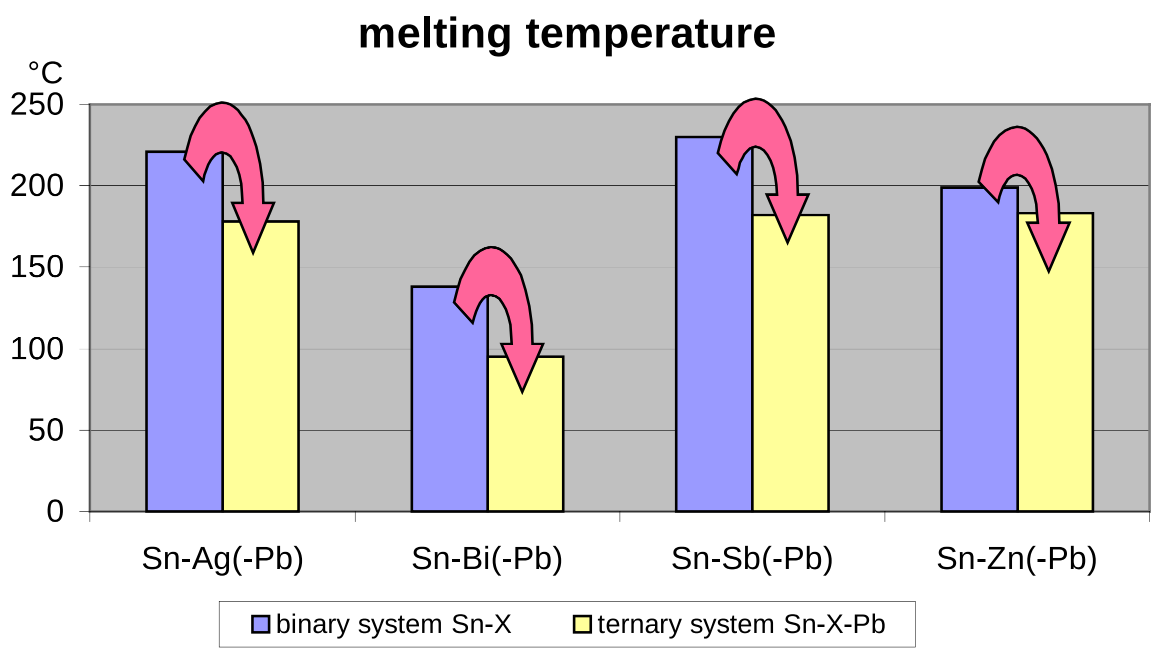
Some alloys show tendency to copper dissolution at respective material overlap points. Critical alloys are those with high tin content and higher melting point, which applies to some of the alternative alloys currently examined.

If a significant amount of copper dissolves in the solder, many intermetallic phases (Cu_6Sn_5) develop. These very brittle phases impair the mechanical properties of the soldering joint. By adding only small amounts of Cu to the solder alloy the tendency of the solder to dissolve copper from the metallization decreases.

- low melting binary and ternary phases

Some lead-free solders develop low-melting binary or ternary phases (see picture 11) in combination with lead. Corresponding mixed phases may also occur in combination with In or Bi.

Such low-melting phases have negative effects upon the reliability of the soldering joint. This is evident in a reduced temperature cycling resistance at higher temperatures. Therefore combinations of solders containing lead and lead-free solders and component finishes should be avoided.



***Picture 11**: reduction of the melting temperature of lead-free solders by addition of lead [HAM93]*

- Intermetallic connections

Longterm reliability of a soldering joint greatly depends on type and number of intermetallic connections which develop during the soldering process.

When soldering is carried out on copper or nickel the development of intermetallic phases in the boundary area is necessary in order to achieve good wetting and consequently a good joint.

If layers are too thick or very brittle intermetallic zones develop, temperature cycling resistance is impaired. Intermetallic layers can slowly increase even at ambient temperature. However intermetallic layers only grow excessively at increased temperatures, in particular with a longer dwell time in the reflow oven above melting point, resulting in a very negative effect on reliability of the soldering connection.

The lower the melting point of the intermetallic connection, the higher the growth potential and consequent impairment of ductility and stability of the soldering joint. (N.B.: intermetallic inclusion compounds disturb the microcrystalline structure of the soldering connection and cause embrittlement.)

- Alternative surface metallization

Combining lead-free alloys with alloys containing lead can seriously affect mechanical properties of the soldering joint (see also picture 11). Therefore it is not advisable to introduce lead-free solders as long as lead is present in metallization of printed board or metallization of components joint. The solder material itself as well as the metallization strongly affect temperature cycling resistance of a solder joint.

Electronic manufacturers already partly use the following available established alternatives (see also section 4.3.1.2):

***Ni-Au*:**
Au gives good protection against oxidation provided the application is not too thin or too porous. In too thick a layer intermetallic phases develop such as $AuSn_4$ causing embrittlement of solder joint. An optimum Au application ensures even and coplanar surface with suitable properties for joints with SnPb solders. Rise in soldering temperature for Pb free solders increases the risk of Ni diffusion. It must, therefore, be ascertained whether the solderability of the 2nd side of the assembly is still sufficient.

***Cu with organic passivation*:**
Good oxidation protection is achieved at normal soldering temperatures and during soldering under nitrogen. Soldering in normal atmosphere increases the risk of oxidation. When the soldering temperature is raised for lead-free solders this can significantly impair solder properties on the 2nd side as organic passivation is thermically not sufficiently stable.

Chemical Sn:
Chemical Sn is deposited in layers of about 1µm. At increased temperatures an intermetallic phase develops between Cu and Sn. When solders containing Pb are used there is good solderability for up to 3 reflow passes. As the temperature must be increased for Pb free solders there is the danger of Cu diffusion to the surface already during the first pass.

Thin silver coatings:
Chemical Ag is deposited in a layer up to 0,2µm with an organic protection. At increased soldering temperatures there is a risk of destroying the protective organic coating. In addition Cu can diffuse through the thin Ag layer and consequently impair solderability.

Thin palladium coatings:
Solder material and also metallization significantly affect the temperature cycling resistance of a solder joint. Cu and Ni diffusion resulting from thermal stress with the use of Pb free solders must be assessed.

- Alternative circuit board materials

The temperature cycling resistance of FR4 materials is sufficient for most lead-free alloys. Reflow temperatures of 260° up to 280°C could be exceeded with certain alloys with higher melting point. In this case there are alternative board materials such as FR5, glass/BT-epoxy, glass/polyimide (see 4.3.1.1, table 8).

4.5.4.2 Reliability aspects of the most important lead-free alternative materials and alloys
[BER98, LEE97, MIR97, NCM97, RAH95, WEG98]

- **SnAg**

The high stability of alloy Sn3,5Ag is supplemented by a relatively good temperature cycling and creep resistance. At higher temperatures there will be increasing damage due to thermal stress. Whereas high solubility of lead in tin and vice versa in SnPb alloy means that micro-structure instability and aging cracks will occur at higher temperature, the solubility of silver in tin is limited and coarser structures are less likely to develop. The Sn3,5Ag alloy therefore distinguishes itself from SnPb by a stabler and more uniform microstructure.

On the other hand diffusion rate of copper (in the case of copper soldering contact pads) in pure tin is greater than in SnPb alloy. Given the high amount of tin in SnAg solder and the necessarily higher reflow temperature, copper dissolution in SnAg solder is also more rapid than in SnPb alloy. Consequently intermetallic brittle phase of Cu_6Sn_5 is constantly increasing, in turn affecting reliability of the solder joint.

Evaluation: reliability undetermined, moderate risk

- **SnAgCu**

The most important alternative solders of such metal alloys contain between 0.5 to 2 % Cu and 3.8 to 4.7 % Ag. With this combination the melting point is between 216° and 219°C.

The higher melting point of SnAgCu solders distinguishes them from the SnPb solders by improved mechanic stability at increased temperature cycling stress and they are therefore suitable for high temperature applications up to 175°C. With conventional fluxes the wetting of Cu with SnAgCu solders is not as good as with SnPb solder. Therefore special fluxes adapted to high temperature application are required here to improve wetting. Thermal resistance requirements of components to be processed also increase.

When taking the Sn content, which is between that of SnAg alloys and SnPb alloys, it is clear that the tendency to dissolve copper and consequently to develop intermetallic Cu_6Sn_5–phases for SnAgCu alloys, in comparison with above alloys, must also be approximately in the middle. Reliability is affected accordingly.

Evaluation: good reliability prognosis

- **SnCu**

The alloy Sn0,7Cu with a melting point of 227°C is also suitable for high temperature applications and shows good temperature cycling resistance as expected.

Evaluation: reliability undetermined but good prognosis

- **SnAgBi**

With a proportion of bismuth Sn3,4Ag4,8Bi melting temperature range is reduced to between 200 and 216°C. These solders distinguish themselves by increased stability and good temperature cycling resistance at temperatures of up to 175°C. „Fillet lifting“ can be a problem when soldering THDs; the solder comes away from the circular contact surface of the circuit board along the boundary area between solder and intermetallic SnCu phase directly after the soldering process [NCM97].

Evaluation: reliability undetermined but good prognosis

- **SnAgBiCu**

Although Sn2,0Ag7,5Bi0,5Cu (138° respectively 198° up to 212°C) has a better wetting and stability than the bismuth-free alloy, with the small proportion of about 1% of an eutectic phase of SnBi with a melting point of 138°C there is an as yet unassessed reliability risk when the operating temperature of 138°C is approached.

Evaluation: reliability undetermined, moderate risk

- **SnBi**

With a melting point of 138°C 58Bi42Sn is suitable as solder for temperature sensitive components and substrates. During temperature cycling tests in the range of –55°C up to +125°C despite approaching its melting point of 138°C SnBi alloy proved better than SnPb alloy also tested. The raw material bismuth occurs as a by-product of lead production. Therefore contamination of SnBi alloy with lead and development of a destabilizing BiPb phase at 97°C cannot be excluded.

A further reliability risk is the alloy’s distinct tendency to oxidization in air and the consequent need for a stronger solder flux. The soldering joint is more brittle due to the high Bi content.

Evaluation: reliability undetermined, moderate to high risk

- **SnSb**

Despite extreme hardness and stability of alloy Sn5Sb and its suitability for high temperature applications (melting range 232° to 240°C) the question of toxity arises when using Sb alloys. In addition there is the bad wetting property of Sb, the possible development of intermetallic SbSn phases as well as the lower tensile strength of solder joints.

Evaluation: reliability undetermined, moderate to high risk

- **SnAgSb**

The alloy Sn25Ag10Sb (melting range 230° to 235°C) has a high melting point and shows good creep resistance. The high Sb content leads to development of hard SbSn phases causing cracks in microstructure of solder joint and may consequently cause faults. In addition this solder has bad wettability and oxidizes rapidly. Needle shaped Ag_3Sn phases occur with an ensuing tendency for cracks to develop so that temperature cycling resistance is expected to be low. The alleged toxicity of Sb is a further argument against the use of this solder.

Evaluation: reliability undetermined, moderate to high risk

- **InSn**

52In48Sn (melting point 118°C) is suitable for use at low temperatures. In is sufficiently resistant to oxidation but rapidly corrodes in humidity. Being a soft material it tends to cold welding. Due to the low melting point this alloy has a relatively low temperature cycling resistance at higher temperatures.

Evaluation: reliability undetermined, moderate to high risk

- **SnZn**

The alloy Sn9Zn (melting point 199°C) is susceptible to oxidation and corrosion. Zn reacts with acids and lyes and therefore affects stability in storage. During wave soldering solder tends to produce heavy slag.

Evaluation: high reliability risk

- Summary

In table 10 lead-free solder alloys based on binary systems with characteristic properties are once again listed in summary.

System	Typical alloy (E)=eutectic	Melting Point	Characteristics
Tin/ Indium	52In48Sn (E), 58Sn42In	118°C	Oxidation resistant, susceptible to corrosion, low mechanical stability and thermal stress resistance, bad wetting, high tendency to creep, low availabilitity / high price of In
Tin/ Bismuth	58Bi42Sn (E), 60Sn40Bi	138°C	Low thermal stress resistance, low creep resistance at room temperature, low resistance to oxidation, low elasticity
Tin/ Zinc	91Sn9Zn	199°C	Zinc tends to oxidize at high air humidity, high slag-formation
Tin/ Silver	98Sn2Ag, 96,5Sn3,5Ag (E), 96Sn4Ag, 95Sn5Ag	221-240°C	High resistance to temperature cycling stress, rapid Cu dissolution
Tin/ Copper	99,3Sn0,7Cu (E), 99Sn1Cu, 97Sn3Cu	227-250°C	Good temperature cycling resistance, bad wetting compared to conventional solders
Tin/Antimony	99Sn1Sb, 95Sn5Sb	235-240°C	Good mechanical properties, bad wetting, toxic

Table 10: *Comparison of various lead-free binary solder materials characteristic properties*

4.5.5 Conclusions

None of the alternative alloys can replace the eutectic or nearly eutectic SnPb alloys in every respect.

Compromise could be reached on luster of the solder joint, lesser wetting or slightly higher melting-point of alternative solder. However the electronic industry will not be able to change to lead-free solders until there is an alternative alloy in every respect as reliable as the SnPb eutectic.

More recent work with SnAg or SnAgCu, for example, show that good beginnings are being made. But considerable action is still needed and a great amount of time and money will have to be spent on solving this problem.

Evaluation of system reliability as a whole:

A	6	strategy undetermined
B	4	considerable increase in costs
C	3	considerable amount of work and costs expected

Remark:

Section 4.5 gives reliability prognoses for alternative lead-free solder materials respectively supporting base materials and metallizations of printed circuit boards. These evaluations of „lower levels“ must be taken into consideration when designing an assembly as a basis for evaluation of overall reliability of soldering joints and must be supplemented with reliability estimates for components used. In this context final total reliability cannot exceed the most critical assessment of a “lower level”.

In addition characteristic properties of connecting partners involved in the interconnection system may cause incompatibilities all of which may lead to further deterioration of the required integral reliability. Any doubt about components, soldering processes and inspection („strategy unclear“) therefore inevitably also applies to reliability of solder joint as a whole.

4.6 Summary of sections 3 and 4

Sections 3 and 4 discuss in detail problems arising when converting soldering technologies to lead-free solders, costs (i.e. regular costs after change-over) and actual cost of change-over (i.e. one-time change-over costs).

The criteria previously listed were applied in evaluating materials, components and processes as well as reliability. The evaluations reflect the opinion of the authors and are based on estimated trends.

The result is summarized here in order to clearly emphasize the critical sectors. Individual evaluations expressed in figures are shaded as follows:

- White is for sectors where change-over is not expected to cause technical problems or additional costs. Only modifications relevant to change-over will be effected.
- The light grey area shows cases where additional costs are expected. Minor technical problems are expected, costs of individual processes will rise.
- Middle grey shows where already considerable technical problems and cost increase are expected.
- Dark grey shows undetermined strategy respectively financial risk. Change-over would involve considerable cost. Costs can only be estimated.

Table 11 gives an overall view of evaluation scale in this form:

A: technical problems:	
1	**no technical changes necessary**
2	**change-over technology available and well tested**
3	**material changes necessary**
4	**moderate technical problems expected**
5	**considerable technical problems expected**
6	**strategy undetermined**

B: Costs:	
1	**cost reduction**
2	**no change in regular costs expected**
3	**price increase in individual processes**
4	**considerable increase in costs**
5	**costs implications not estimable – financial risk**
C: Change-over costs:	
1	**no change-over costs expected**
2	**moderate change-over costs expected**
3	**considerable change-over costs expected**
4	**change-over materials and technologies not available, further development necessary**

Table 11: *Evaluation criteria*

The results of sections 3 and 4 are summarized on this basis in table 12. Here, the categories A „Technical problems“, B „Costs“ and C „Change-over costs “ are applied to the most important process steps, components and process materials, and to standardization and reliability. (To understand categories A, B and C see introduction to section 3). By evaluating the single columns A, B and C an overall evaluation of each individual topic was achieved. If the result was undetermined, technical problems were given more weight.

	A	**B**	**C**
Overall evaluation	***Evaluation of individual aspects***		
	Technical Problems	***Costs***	***Change-over costs***
Standardization	**1**	**2**	**3**
Solder alloys	**3**	**3**	**4**
Components	**6**	**5**	**4**
Supporting plates	**5**	**4**	**3**
Circuit board surfaces	**5**	**4**	**3**
Solder paste printing	**3**	**3**	**2**
Component insertion	**4**	**2**	**1**
Soldering reflow	**6**	**5**	**4**
Soldering wave	**5**	**3**	**4**
Soldering joint inspection	**5-6**	**5**	**4**
Rework/repair	**4**	**3**	**3**
Soldering wire processes	**4**	**3**	**2**
Design of assembly	**3**	**3**	**3**
Reliability	**6**	**4**	**3**

Table 12: *Summary evaluation of problem areas*

Result:

The greatest difficulties in changing to lead-free soldering procedures will probably occur in the following sectors:

1. Components are expected to present the greatest problems as there is no strategy for coping with an universal change-over to lead-free products or for the higher thermal stress during the soldering process.

2. In the case of a change the greatest attention has to be paid to reflow soldering. It is not clear whether existing devices are compatible with higher melting solders.

3. There is no appropriate procedure for inspecting joints with lead-free solders.

4. Reliability has not been tried and tested.

5. Conclusions

5.1 Need for action

A great deal of work must still be done in order to solve the problems identified in section 4.6 (table 12). Everyone will have to contribute his part.

Table 13 shows the need for action by manufacturers of materials and components, by equipment suppliers and assemblies manufacturers as seen by the authors of this manual. It shows that in spite of the progress that has already been made there are still several obstacles to be surmounted before there is comprehensive use of lead-free soldering technologies in the industry.

Need for action by in the	**Manufacturers of materials and components**	**Manufacturers of equipment**	**Manufacturers of assemblies**
Step/Topic			
Assembly design	+	0	+++
Standardization	+++	0	+++
Solder alloys/pastes/ fluxes	+++	++	+++
Components	+++	0	0
Supporting plates	++	+	+
Circuit board surfaces	+	0	+
Solder paste printing	+	+	+
Component insertion	0	+	+
Soldering reflow	0	++	+++
Soldering wave	0	+++	+++
Soldering joint inspection	0	++	+++
Rework/repair	++	+	+++
Soldering wire processes	++	+	+++
Reliability	+++	+	+++

Explanation: 0 – no need for action, + - observation, ++ - research and development necessary, +++ - considerable research and development necessary

***Table 13**: Need for action*

5.1.1 Need for action by manufacturers of materials and components

Here the most action will be required from suppliers of components and solder materials:

Neither the roadmaps available nor our current survey of component manufacturers show an awareness of the consequences of a potential use of high melting solder alloys.

Solutions will have to be found in order to secure higher thermal resistance, for example, in plastics and electrolytes used so that these components do not have to be manually applied. In particuar the problems arising with increasing use of Area Array Packages such as BGA have not yet been seriously approached. Component manufacturers must also optimize processes in order to enable lead-free joints to be adopted on a large scale at reasonable costs for example in fine pitch components. More time must be spent on assessing reliability of components in use at high temperatures.

There must be basically closer cooperation between manufacturers of components and assemblies in order to solve, for example, the problem of „fillet lifting".

Substitute alloys have still not been determined for different application ranges. Manufacturers of solders, solder pastes and fluxes have to modify their products to future requirements. In particular solder pastes must be able to withstand new soldering temperatures. Further tasks are to prove reliability of assemblies soldered with new materials and to modify current soldering norms for lead-free solders.

5.1.2. Need for action by equipment suppliers

There is particular need for action in wave soldering. In recent years equipment designed for wave soldering has moved from nitrogen tunnel systems to so-called open systems where only the surface of the solder pumped up is treated with nitrogen. Because of expected increased dross development in lead-free solders this trend will be reversed again.

Current preheating systems will have to be expanded to provide increased heat. Also new crucible materials which are compatible with tin enriched alternative solders will also have to be employed.

Comprehensive modifications will be necessary in the infrared and convection reflow soldering systems sector in order to maintain the smaller process windows available when lead-free solder alloys are used. These systems partly produce far more extreme fluctuations respectively temperature differences on an assembly than convection furnaces do. Vapour phase soldering as a process technology would lower thermal stress for assembly and individual components and therefore facilitate the introduction of high melting solders.

Manufacturers of soldering joint inspection systems (visual or X-ray) must also modify their equipment to evaluation guidelines which must be drawn up to assess good/bad soldering joints. In addition it must be shown that automatic inspection of soldering joints with lead-free solders achieves the same low pseudo defect rates as current standard machines, with exception of slippage.

The final question is whether all equipment suppliers have already taken the requisite higher temperatures into consideration in their safety systems. Manufacturers of reflow and wave soldering equipments must find ways to reduce the increased energy demanded by requirements of higher process temperatures if change-over to lead-free solder alloys is not inevitably to be paid for with increased CO_2 pollution .

5.1.3. Need for action by assemblies manufacturers

It is in the sector of the assembly manufacturers where all the identified problems are concentrated and it is they who will have to introduce any change-over of their systems and processes applicable for all products. This means collectively resolving all problem areas discussed in the manual – in particular with regard to soldering processes and inspection – with the goal to continue to supply high quality products at a reasonable cost.

There will be additional problems in the wavesoldering sector: here change of solder bath is accompanied by high costs for both solder bars and stoppage while the bath is changed. The permissible pollution level of metals in the solder bath in wave and immersion baths will have to be re-assessed in order to guarantee reliability of soldering connections.

As there is no universally applicable drop-in-solution for lead-free solders assembly manufacturers will have to accept regulation exceptions and specific product regulations. This could mean that different production lines use different alloys in order to fulfil the respective product requirements. The increasing range of modifications will result in considerable costs in logistics and subsequent identification of product.

A clear stragegy must be developed to implement new design aspects in order not to fall short of established global quality requirements in the dpm range. The IPC A-610, the standard for visual assembly inspection, will have to be assessed with regard to compatibility with lead-free solders and modified if necessary.

At the same time present knowledge shows that the industry must direct more attention to process control data in order to maintain smooth production despite the narrow process window.

Dependence of reliability on mechanical and electrical properties is a particularly complex area. Microstructure plays a vital role here. Microstructure alters with each production parameter, storage temperature and time. A considerable amount of research is necessary in this respect.

5.2 Recommended action

Conclusions are drawn from section 4.6 (table 12) and section 5.1 which determine the need for action (table 13) from which final recommendations for further procedure can be made.

The technical point of view is clear: a general introduction of lead-free soldering and „lead-free“ electrical equipment at a fixed date is not feasible.

Within several decades SnPb technology has achieved a level that meets very high reliability requirements. Assemblies manufacturers must guarantee to maintain quality and long-term reliability as required by the customer. Any substitute must fulfil these established standards.

As it is obvious that no alternative lead-free solder can cover the total current application range achieved by SnPb solders their suitablity as a substitute for specific applications must be assessed.

Components are a problem area: component manufacturers in particular still need to invest a great deal of time and effort in developing more thermal resistant lead-free components. Increased demand from customers will accelerate this process. However the power of demand from European components and equipment manufacturers is limited as Japan or the USA supply a large part of components used. It is consequently obvious that only a global course of action will succeed.

In order to be able to raise reliability level of lead-free soldered assemblies to current high standards, much basic research and many application specific compatibility tests will have to be carried out: printed circuits require modified surface structure and lead-free finishes. Compatibility risks of components in connection with specific printed circuit boards must be ascertained, evaluated and clarified. This is more time consuming than the solder materials tests themselves.

There are already certain applications where, although printed circuit assembly is not completely „lead-free“, nevertheless lead-free solders are used in assembly. This trend answers market demand for products which do not affect the environment on the one hand. On the other hand the trend to adapt assemblies to higher application temperatures encourages use of lead-free solders with a significantly higher melting point than standard SnPb solders.

This proves that the trend to lead-free solders exists independently from legislative initiatives. The use of lead-free solders in our self-regulating market will increase.

A *step by step* extended application of lead-free technologies adapted to specific product reliability requirements can be foreseen, starting with products with no safety relevant functions and on to electronics with safety relevant functions (for example airbag).

There is, therefore, no need for restrictive legislative intervention on market determined substitution processes which are already dynamically expanding to gradually replace lead soldering technology. Rather than prohibit SnPb solders research and development should be supported so that electrotechnics and electronics are still able to offer competitive products in the future.

Economic effects of legislative projects must be examined *before* they are drawn up. Neither ecological consequences of a change, e.g. the effects of possible substitutes and their production processes on environment nor energy consumption have yet been fully investigated.

On principle bans on materials should not come under legislation on waste products but under legislation on use of chemicals. Technical, economical and political feasibility must be secured before regulations are drafted and enforced. The economic existence and competitiveness of the branches concerned must not be jeopardized.

In today's globally linked market economy there is no room for individual national and regional actions which ignore, on the one hand, the world-wide interdependence of suppliers, and, on the other, lead to the establishment of non-tarif trade obstacles and jeopardize global free trade.

It is a fact that the target date, January 1, 2004, for the required total change-over of solder materials and connected components, printed circuit boards, equipment, production technologies and standards cannot be met and from an economic and a technical point of view is not advisable. A gradual conversion to substitute solutions following a pragmatic approach, however, will achieve the aim.

Our recommendations to the enterprises of electric industry are in short:

- to follow closely the trend to lead-free soldering technologies, actively adopt it and take part in its shaping,
- to start basic investigations and application specific compatibility tests focusing on reliability,
- to contact the components manufacturers and confront them with the demand for more temperature resistant components with lead-free finishes,
- to assess, together with suppliers, equipment manufacturers and customers the suitability of new lead-free solders as a substitute for *specific applications* and to introduce them where possible.

Our recommendations to the legislator are:

- to evaluate and demonstrate the ecological advantage of a change-over to lead-free solders,
- not to pursue a ban of use of lead containing soft solders as a regional initiative,
- to follow market laws and to enable the electrical industry to gradually introduce lead-free soldering in an economically feasible way,
- to support research and development of lead substitutes by furthering R&D projects,
- not to ban lead in electrical equipment.

Annex: questions to the components manufacturers

‚Lead-free Soldering‘: Questionnaire to the Components situation

1. What kind of different finishes do you offer for your components? Please give a detailed description of the layers of the finish. For which components / package types are these finishes available?

2. How big is the share of these finishes compared to the total amount of components (in %)? How will this share change in the next 2 to 4 years?

3. What other finishes have you already evaluated ? For which reasons did you reject these types? Which additional materials are you planning to evaluate / introduce in the near future? (When?)

4. As a reaction to the upcoming legislation (banning of lead in all electronics from 2004 on), when will you offer **all your components** lead-free? What finish will be used from todays point of view ?

5. Can you supply qualified lead-free samples of your components? (Which types?)

6. Can you provide us with references of companies who are already using your components with alternative (lead-free) finishes in volume?

7. Which of your components contain lead, other than in the finish? Where is the lead located?

8. Do you have publications, reports or presentations from your company on the topic ‘lead-free soldering’? (Please send copies if possible.)

9. Do you have components where in your opinion avoiding the use of lead is impossible? Which components are these? What reasons do you see for requiring to use lead in these components?

10. For which components do you define a maximum heat resistance that is below 260° C ? What is the maximum temperature for these components? How long may the component be exposed to this temperature ? (What are the physical reasons for these values?)

11. What activities do you plan to get the components mentioned in point 10 above ready for the modified process parameters of lead-free solders (liquidus temperature of the solder ~220°C, i.e. soldering temperature >240°C) ?

12. What are the restrictions concerning the storage time of alternative finishes? (reduction of solderability?)

13. Please give a comment on compatibility using SnPb- as well as lead-free solder alloys an different finishes.

14. Do you see yourself / your company as a leader in environmental concerns? Which of your competitors might have an advantage in this area?

Bibliography

[BAS97] C. Bastecki, A benchmark process for the lead-free of mixed technology PCB´s, Veröffentlicht von Alpha Metals, Inc., 1997

[BER98] R. Bergmann, Untersuchungen zum Einsatz höherschmelzender bleifreier Weichlote für Elektronik- und Mechatroniksysteme, Lehrstuhl für Fügetechnik, TU München, 1998.

[BIR97] A. Birolini, Qualität und Zuverlässigkeit technischer Systeme, 3.Auflage, Springer Verlag, 1997.

[DEM98] P. Demmer, Anwendung innovativer Basismaterialien, GMM-Fachbericht 24 Bd.1, 1998, S. 187ff

[DEN99] J. Denzel et al., Schlüsseltechnologien für die Elektronikproduktion von morgen, Präsentation auf der SMT 1999 Nürnberg, http://www.et.tu-dresden/mtp/diskurs.htm

[HAM93] W. B. Hampshire, The Search for Leadfree Solders, „Soldering and Surface Mount Technology“ No.14, MCB University Press 1993, S. 49-52.

[HUA97] F. Hua, J. Glazer, Lead-free solders for electronic assembly, Design & Reliability of solder and solder interconnections, veröffentlicht von TMS, 1997

[ITR99] NPL, ITRI, Lead-free Soldering – An analysis of the current status of lead-free soldering, April 1999, S.11

[JBC99] JBCE, Impact of Substance Bans on Electrical and Electronic Components – Comments from JBCE on the Draft WEEE Directive, 8 June 1999

[KLE91] R.J. Klein-Wassink, Weichlöten in der Elektronik, 2.Auflage, Eugen Leuze Verlag 1991

[LEE97] N.-C. Lee, Getting Ready for Lead-free Solders, MCB University Press, „Soldering & Surface Mount Technology“ No.26, 1997, S.65-69.

[MIR97] A. Miric, A. Grusd, Bleifreie Lotlegierungen, „productronic“ 11/97, Hüthig Verlag Heidelberg, S.34-43.

[MIR99] A. Miric, Firmenmitteilung W.C. Heraeus GmbH, PDF, 1999

[NCM97] N.N.: Lead-Free Solder Project - Final Report, NCMS Report 0401RE96, Ann Arbor, 1997.

[NEM98] NEMA’s letter to US Government officials opposing directive, September 9, 1998, http://www.nema.org/papers/letter.html

[NEM99] NEMI Forms Lead-Free Readiness Task Force, May 3, 1999, http://www.nemi.org/Facts/PressReleases/PR050399.html

[ORG99] Restrictions on the use of substances – Orgalime Position, 28. July 1999, http://www.orgalime.org

[RAH95] A. Rahn, R. Diehm, E. Beske, Bleifreie Lote?, „productronic“ 2/95, Hüthig Verlag Heidelberg, S.18-23.

[RAY94] U. Ray, I. Artaki, H.M. Gordon, The influence of temperature and humidity on printed wiring board surface finishes: Immersion tin vs organic azoles, Seite 779-785, Journal of electronic materials, Volume23, Nummer 8, August 1994.

[REI88] H. Reichl, Hybridintegration, Heidelberg, Hüthig-Verlag, 1988.

[SCH97] W. Scheel „Baugruppentechnologie der Elektronik“ 1. Aufl., Berlin, Saulgau 1997, S.510

[STR98] G. Strelow, Lötbarkeitsuntersuchungen mit verschiedenen Leiterplatten-Oberflächen, GMM-Fachbericht 24 Bd.1, 1998, S. 271ff

[WEG98] S. Wege, Zuverlässigkeit alternativer Lotwerkstoffe unter Temperaturwechselbeanspruchung, SMT/ES&S/Hybrid ’98, Nürnberg, 1998

[WEG99] S. Wege, R. Bergmann, Bleifreie Weichlote – Prozeßfähigkeit und Zuverlässigkeit, Technologieforum Leiterplatte 11./12.03.99

List of abbreviations used

AOI	Automatic Optic Inspection
BE	Bauelement (component)
BGA	Ball Grid Array
DSC	Differential Scanning Calorimetry
EPA	Environmental Protection Agency
FT	Fourier-Transformation
FTE	Research and Technological Development)
HASL	Hot Air Solder Levelling
IDEALS	Improved Design Life and Environmentally Aware Manufacturing of Electronics Assemblies by Lead-Free Soldering
IEC	International Electrotechnical Commission
IR	Infrared
ITRI	International Tin Research Institute
JBCE	Japan Business Council in Europe
JEDEC	Joint Electronic Devices Engineering Council
MELF	Metal Electrode Face
NCMS	National Center of Manufacturing Sciences
NEMI	National Electronics Manufacturing Initiative
NEMA	National Electrical Manufacturers Association
NMRC	National Microelectronics Research Centre
NPL	National Physical Laboratory
OSP	Organic Solderability Preservation
PLCC	Plastic Leaded Chip Carrier
QFP	Quad Flat Pack
SMD	Surface Mounted Device
SMT	Surface Mount Technology
SOIC	Small Outline Integrated Circuit
SOJ	Small Outline J-Lead
Tg	Glass transition temperature
TGA	Thermal Gravimetric Analysis
THD	Through Hole Device
THT	Through Hole Technology
UV	Ultraviolet

Used chemical symbols:

Ag	silver
Au	gold
Bi	bismuth
Cd	cadmium
Cu	copper
In	indium
Ni	nickel
Pb	lead
Pd	palladium
Sb	antimony
Sn	tin
Zn	zinc

Authors:

Dr. Jan Benzler	Robert Bosch GmbH (speaker)
Dr. Harald Dauner	Alcatel SEL AG
Dr. Bernhard Diegner	ZVEI
Dr. Michael Kaiser	Siemens AG
Dr. Franz Kaspar	AMI DODUCO GmbH
Dr. Ralf Luchs	TEMIC TELEFUNKEN microelectronic GmbH
Peter Peetz	Solectron GmbH