Roadmap for Lead-free Transition in the European Space Sector

MPTB/CTB Joint Task-Force on Pb-free transition

April 2020

Participant	Organisation	Signature
Agustin Coello-Vera	REACHLaw	
Marc Lambert	TAS	
Raphael Bolinches	TAS	
Jussi Hokka	ESA	
Liam Murphy	ESA	
Gianni Corocher	ESA	
Daniel Caterbow	DLR Technical Advisor	
Hans-Dieter Herrmann	DLR	
Catherine Munier	Airbus	
Réka Simon-Bálint	RUAG	
Thierry Battault	CNES	
Cathy Barnes	UKSA	
Stefan Hanigk	ArianeGroup	

Disclaimer

The information in this letter reflects the opinion of members of the Task Force. It is not considered a requirement and any action to the described issue is subject to project or programme decision, nor a comprehensive treatment of the subject matter. The information is intended for guidance only and whilst it is provided in utmost good faith and has been based on the best information currently available and adequate technical standards, is to be relied upon at the user's own risk. No representations or warranties are made with regards to its completeness, or accuracy and no liability will be accepted by the participants nor any organisation they represent for damages of any nature whatsoever resulting from the use of or reliance on the information

Table of Contents

1. Introduction

The European Space Sector can no longer avoid the need to plan and implement a managed transition to lead-free electronics. This stimulus comes from two fronts: Regulatory and Market pressures.

In the Regulatory front while the Space Sector was out of scope of the RoHS Directive, a new front has recently opened with REACH. Lead (Pb, CAS 7439-92-1) has now been included in the ECHA Registry of SVHC Intentions and in 2018 it has been included it in the REACH Candidate List of SVHC for Authorisation. While we cannot preclude the final outcome of the process, there is a clear risk for the Space Sector which may have to resort to future Requests for Authorisation to continue using lead.

The Sector is also subjected to increasing Market pressures. Due to the overall transition of the Electronics Industry worldwide to a Pb-free realm, the Space Industry is more and more confronted with a situation where they cannot avoid using EEE parts with Pb-free coatings and they need to manage the associated risk of tin whisker growth. This is becoming more and more important due to the increased interest on COTS (Commercial Off-The-Self) for a wide range of projects.

The REACH regulatory pressure may also result on difficult market availability of leaded solder paste which means going to lead-free soldering, an extensive and very expensive undertaking for the European Space Industry.

These considerations have prompted the ESCC SCSB to launch a joint task force consisting of MPTB and CTB members. This decision is recorded in the minutes of the 52nd SCSB, and the actions were introduced in the 21st MPTB and 55th CTB

2. Task Force Mission

The Working Group should set itself the necessary objectives in order to fulfil the following strategic goals:

1. In the domain of EEE components, electronic assembly technologies and PCBs, ensure a successful industry-wide transition to a Pb-free technology while preserving or improving current level of quality and reliability, including but not limited to:
    a. Tin-whisker mitigation and risk assessment
    b. Lead-free solders and assembly processes
    c. Accelerated tests for verification of Pb-free materials and processes and qualification of components
    d. Acceptance criteria for Pb-free materials, processes and components
2. In the domain of alloys containing Pb-metal, such as free cutting Cu-alloys, record the alternatives and the way forward for a successful industry-wide transition to a Pb-free technology while preserving or improving current level of quality and reliability.
3. In the domain of solid lubrication achieved by Pb-metal, record the alternatives and the way forward for a successful industry-wide transition to a Pb-free technology while preserving or improving current level of quality and reliability.

In order to meet these goals, willingness of the agency and industry members to share any pertinent experiences, information and test data is vitally important.

3. Membership

The Members of the Task Force are listed in the table in page 1. The Task Force has also invited observers from other Industry Sectors

4. Objectives and Schedule

For the first strategic goal the first phase of the work should be the formation of a “Roadmap and Plan for Pb-free transition”, which shall include:

1. Necessary activities and objectives to fulfil the before mentioned strategic goals,
    a. with measurable outcomes indicating successful completion (e.g. TRL[1]),
    b. including schedules and budgets,
    c. and their interconnections and dependencies.
2. A lead-free transition plan composing of
    a. Materials and EEE parts selection
    b. Supplier compliance and guidelines for procurement
    c. Changes in assembly processes
    d. Reliability assessment and key reliability risks in lead-free electronics

The first version of this roadmap and lead-free transition plan shall be presented no later than Q2/2020

For the second and third strategic goals, the working group should record the way forward in completing the Pb-free transition, including identifying the work being done elsewhere such as harmonization and non-space industry activities.

5. Regulatory pressure

In the Regulatory front the Space Sector (i.e. “equipment designed to be sent into space”) was out of scope of the RoHS Directive (but faces commercial threat of obsolescence due to the abandon of lead in some other sectors).

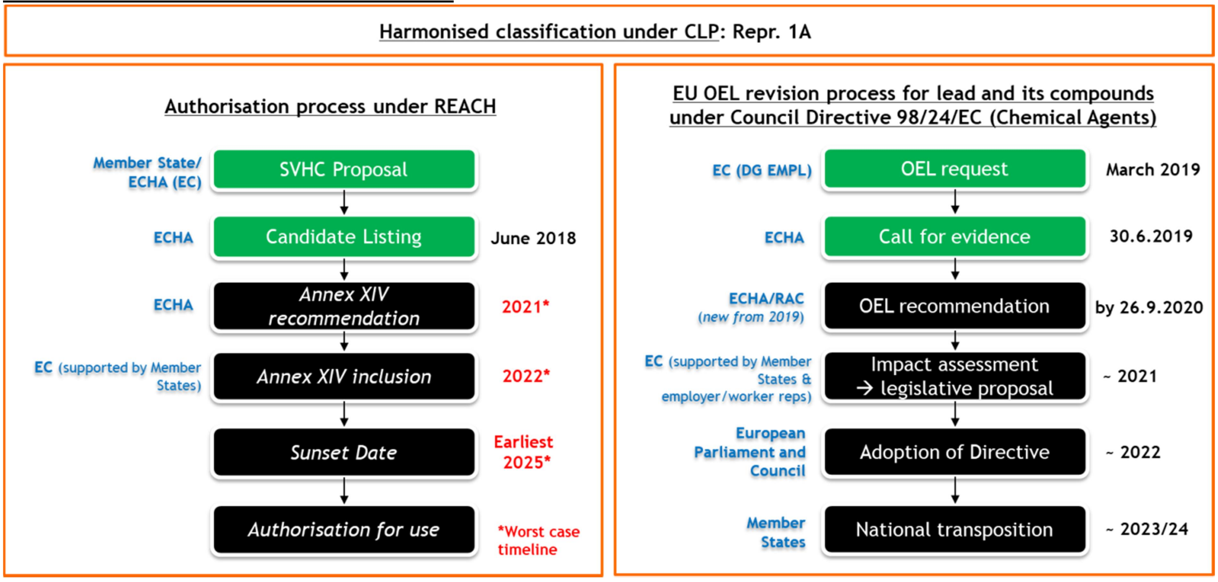
Today a new front has recently opened with REACH. Lead (Pb) has been included in the REACH Candidate List of SVHC for Authorisation.

At the same time the EC has initiated a review of lead in the frame of the EU OSH (Occupational Safety and Health legislation). ECHA RAC has been requested by EC DG EMPL in January 2019 to update the existing health-based bOEL (air) and biological limit value (blood) for lead and its compounds under the Chemical Agents Directive (CAD). RAC is expected to issue an opinion by September 2020). The update is expected to be completed within 3 years (-2022), Member States transposition by mid-2023 at the earliest. The updating under OSH as a regulatory risk management tool could have a deprioritisation effect for lead under REACH authorization, but this is not certain.

This situation, as of March 2020, is summarized in the table below:

---

[1] ECSS-E-AS-11C – Adoption Notice of ISO 16290, Space systems – Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment



Today we cannot preclude the final outcome of the process, it could be either complying with OEL requirements at the workplace only (as is already the case today) or also to resort to Requests for Authorisation. If Lead proceeds via the Authorisation Process, there is a clear risk for the Space Sector which may have to resort to future Requests for Authorisation to continue using lead. If it keeps going via the OSH legislation only, supplemented by tailored REACH restrictions not directly affecting Space, then the Space Sector, as long as it fulfills the OSH requirements, may continue using lead.

6. Discussion

During its first meeting the Task Force acquiesced that the Members did not have the expertise to deal with strategic goals 2 and 3 and decided that it will focus on goal 1. The composition of the Task Force would need to be expanded in order to deal with the other goals; this could be initiated after completions of goal 1. The identified uses that will be treated later under goals 2 and 3 are:

- Massive shielding with lead structures for X-Ray functions etc.
- Partially shielding by lead containing tape
- Use in ceramics for sensors/actuators purposes
- Lead batteries
- Solid lubrication etc.

In relation to EEE Parts lead is used today in:

Finishes for parts terminations
Solder alloys
Surface finishes on PCBs
Others (columns, BGAs, etc.)

Each use will be analyzed separately. The risk of Tin whiskers is present when pure Tin is used and thus applies to all four uses. Tin whiskers will form a separate section of the Roadmap.

7. Electronics manufacturing

7.1 Market and regulatory pressure

As explained in the introduction the two driving forces to the transition to lead-free are Regulations and Market pressure. The general Regulatory situation was introduced and analyzed in section 5.

Past experience related to Applications for Authorisation (AfAs) within REACH indicates that when and if Pb-metal enters the Annex XIV of the REACH regulation and is given a sunset date, it is likely that an Authorisation is granted, if and when:

- The scope is sufficiently narrow, such as use for defined space flight applications,
- There is a sufficient level of detail in the AfA reports (including the Chemical Safety Report, Analysis of Alternatives and Socio-Economic Analysis) justifying the need for continued use beyond the Annex XIV sunset date, and
- The authorization application contains a substitution plan with a realistic timeline, if alternatives to lead are available in general, but not technically or economically feasible for the applicant.

In fact, out of 188 applications for Authorization received by ECHA in the 7 years the process has been functional they have all been approved by ECHA and granted by the European Commission except in one case (which concerned a special case for an intended new use).

Authorisation review periods can vary from 4 to 12 years from the sunset date of the substance. Applications for Authorisation originated from downstream users in the Aerospace Sector have typically been granted the requested review period up to the maximum period of 12 years in recognition of the demanding reliability and safety requirements of the sector. The review itself is a process similar to the initial authorisation and subject to the same conditions. Hence, if the continued use is justified, the authorisation will be prolonged.

Concerning market pressure, and based on market knowledge of the participants, the TF concurred that in the short/medium term (<10 years) the commercial obsolescence risks for lead-tin solder paste are low.

Based on the above mentioned data and assumptions we can project that the time-scales from the regulatory side and from the obsolescence risk concerning the pressure to change solder alloys are:

- In the short term (< 5 years): no risk associated with regulation or obsolescence of SnPb solder
- In the medium term (< 10 years): very low risk from Regulation and very low risk associated with SnPb solder obsolescence
- In the long term (> 10 years): low risk from the Regulatory side and potential risk associated with SnPb materials obsolescence.

Market pressure to transition to Pb free is not only due to possible obsolescence of products but also due to the advent of New Space and the race to achieve costs reductions by equipment manufacturers. Consumer and automotive electronics are the driving force for the development of new components and chip sets and are already using Pb free technology, due to this it can be expected that the use of Pb based alloys can become a limit for space equipment manufacturer in the development of new products.

This trend is already resulting in opening the possibility to use COTS and it is known that Pb free processes are already used in some launcher applications and in low cost constellation programmes. In addition, the development of Mega constellations with a different approach to reliability of the systems is revolutionising the manufacturing process of satellites and is likely to open the door to the utilization of Pb free in space. These constellations relies on the high numbers of satellites (operating and spare) in order to be tolerant to failures rather than on the high reliability of components and assembly.

Taking this into account the TF agreed that the Space Sector is not constrained to abandon lead based solders in the short/medium term due to regulation.

From the regulatory point of view there is no immediate requirement to transition to Pb free. However the However the pressure to introduce COTS in the space projects is already forcing the transition and this is anticipated to accelerate significantly in the near/medium term. European space manufacturers and Space Agencies need to prepare for this in order to maintain their competiveness in the future.

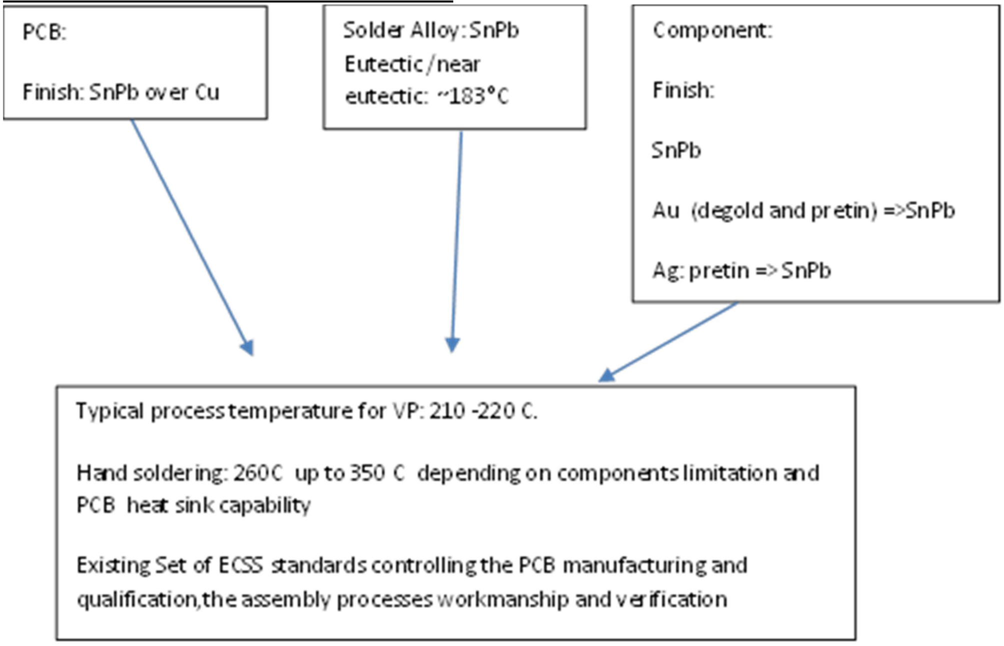
7.2 Overview

Pb is used in all the elements of an electronic assembly: EEE terminations and finishes, PCB surface finishes, and solder alloys.

SnPb alloys have a good resistance to oxidation and corrosion making them suitable as finish of PCB and components terminations. The low melting point (~183°C) and the good wettability of the near eutectic SnPb alloys makes them ideal for soldering. This has also been a driver in the development of PCB materials and components which have to be exposed to the assembly temperature.

The creep and stress relaxation properties of these alloys provides a mean to manage the stresses induced by the differences in CTE (Coefficient of Thermal Expansion) between components and PCB during operation and are a defining factor in the reliability of an electronic assembly.

Space industry is using SnPb alloys in electronics manufacturing since its beginning. The space sector heavily relies on the knowledge of these alloys for the production of electronics that are able to operate in harsh environment meeting the high reliability requirements of space applications. This knowledge is reflected in a series of ESCC/ECSS standards which are managing PCBs, components manufacturing & qualification and the assembly workmanships & processes verification.



Typical process temperature for VP: 210 -220 C.

Hand soldering: 260C up to 350 C depending on components limitation and PCB heat sink capability

Existing Set of ECSS standards controlling the PCB manufacturing and qualification,the assembly processes workmanship and verification

Figure 1

The flow in Figure 1 shows the use of Pb containing alloys in the current space electronics manufacturing chain. All components of an electronics assembly are designed to withstand manufacturing with the use of tin/lead solder. One of the advantages of the current system is the fact that SnPb alloys are used for the PCB finish, as solders and as well the component terminations are either SnPb finished or pretinned before the assembly. This results in uniform starting condition for the assembly, reduces the process variability and results in similar metallurgy and basic properties of the solder joint and all this aspect are controlled in a system of established ECSS standards.

As will be shown in the following paragraphs the Pb free technology introduces the use of several different finishes and alloys system with impacts at all levels of the electronic manufacturing from the choice of the solder alloys to the workmanship and process standards.

However, since 2006, a lot of industries have switched toward lead-free technologies. And, the compatibility between components, PCB and assembly is possible, sometimes with precautions.

8. Finishes for parts terminations

The finish of the components termination has the main scope to ensure the solderability and provide good wetting of the terminations during assembly.

Components finishes are controlled under the requirement of the ESCC 23500, (REQUIREMENTS FOR LEAD MATERIALS AND FINISHES FOR COMPONENTS FOR SPACE APPLICATION). Various ECSS standards identify pure Sn as forbidden finish and provides requirements for the processing of components which have terminations with finishes different from SnPb (for example Au). In the current scenario (SnPb solder) components with finishes different from SnPb are submitted to pre-tinning before assembly in order to eliminate or re-alloy any finish different from SnPb.

The transition to Pb free technology will require assessment of other finishes, in addition to the current standard. Initial candidates for assessment may be hot dipped SnAgCu and Matte Sn with Ni underplating. Other finishes may be added as required.

As of today several TF Members are already using COTs with lead-free finishes in some of their Space programmes. They are not applying the relevant ECSS/ESCC standards because those standards do not allow for those lead-free finishes. They agree with their customers, on a case by case basis, using the reliability data in their possession. These TF members believe that the existing data is good enough to proceed with the update of the standards. However, there is an open question regarding availability of the data as recalled by other TF members. In order to resolve this point, **the TF agreed on the need to analyse existing data on reliability of SnPb solder joints of EEE Parts with lead-free finishes and completed studies in order to identify gaps (gap analysis) and necessary additional studies needing to be performed.**

Once a first assessment of available data is completed, it will be possible to define what, if any, additional activities are necessary for the characterization and for the definition of requirements for the procurement of parts with Pb free finishes and for assembly processes.

The lists of standards which are affected and will eventually need to be updated follows:

1. ESCC 23500, REQUIREMENTS FOR LEAD MATERIALS AND FINISHES FOR COMPONENTS FOR SPACE APPLICATION

2. ESCC-Q-ST-70-61C, High reliability assembly for surface mount and through hole connections, says that Components lead materials and their finishes shall be selected in compliance with requirements from clause 3 of ESCC23500. However Section 7 (Preparations prior to mounting and soldering) would need to be reviewed

3. ECSS-Q-ST-60-13C Commercial electrical, electronic and electromechanical (EEE) components

4. ECSS-Q-ST-70C Rev.1 Materials, mechanical parts and processes (Sn >97% shall not be used)

5. ECSS-Q-ST-70-71C – Materials, processes and their data selection (Sn >97% shall not be used)

6. ECSS-Q-ST-70-60C Qualification and procurement of printed circuit boards (Pure tin finish with > 97 % purity shall not be used, referring to ST-70)

7. ECSS-Q-ST-70-18C Preparation, assembly and mounting of RF coaxial cables. (what solders that can be used and also that pure tin finished connectors can't be used)

Other lower level standard and requirements will also be affected. The update for the relevant standards will be under the responsibility of the PSWG, which is the ESCC body in charge of standards.

All Industry members of the TF have clearly underlined the urgency of this branch of the roadmap since there is today a strong demand from projects to use COTs.

9. Solder alloys

As explained in the previous section SnPb soldering has been the backbone of electronics assembly for space hardware since the beginning of the space age. Changing to lead-free solder and reaching the same level of reliance that the Space Sector had with leaded solders is going to be a major undertaking. **In addition, it is going to be an expensive transition requiring the setup of new assembly lines (both tin/lead, for old designs, and lead-free, for new designs, lines will run in parallel) and the requalification with the new solder of all EEE parts used**.

Pb free soldering technology is widely used today in commercial electronics, automotive and in some high reliability electronic applications since introduction of the RoHS legislation in 2006. A vast amount of activities to characterize the lead-free solder materials have been performed especially on SAC alloys (based on Tin, Silver and Copper) in particular on SAC305 (96.5% tin, 3% silver, and 0.5% copper) by various consortia in US and in Europe with focuses in the industrial, automotive and defense sectors.

Currently the best candidate Pb free alloy for use in space application is SAC305 as confirmed by one TF Member which informed that they have already started to assemble space hardware using lead-free solder, SAC 305, for a specific constellation project using an external subcontractor. CNES also informed to have funded a study on the reliability of SAC 305 for space applications. Other non-Space French consortia, Geamcos (Airbus, EADS, Cassidian, Actia, TechCI) and Amelie (Solectron, IMS, Thales) have generated reliability data. Two French MoD projects: CATS and COSAC, have been completed with additional data. From the US we also have plenty of data from large undertakings like: JGPP (Lead-free solder testing for high reliability), Manhattan project Managed by PERM (Pb-free electronic risk management), and CALCE. It needs to be stressed that the data from several of these studies are not publicly available and probably need to be confirmed.

The existing knowledge from other sectors, as well as the results (if available) of the studies above mentioned, are a good base for developing the space sector capability and expertise; It will probably require a further effort in order to characterize the solder alloys in the environmental conditions typical of space application. The understanding of the behaviour, degradation and failure mechanisms of the solder alloys (including Tin pest) in the operative environment is the base for the development of accelerated test models, manufacturing and workmanship standards which are the tools needed to manage processes for space applications ensuring the correct level of reliability.

As previously stated the most commonly used solder in commercial/industrial applications is SAC 305. This alloy is widely available and is not restricted by any patent but is showing drawbacks, which are currently leading the commercial industry to explore alternative alloys

High temperature applications (>120°C) currently use Pb based alloys and also in this case there are no readily available Pb free candidate alloys for this use.

Another issue is with the InPb solder alloy used for optoelectronic assembly. Today, there is no candidate identify for the replacement.

10. PCB Materials and Surface Finishes

10.1 Use with standard SnPb Assembly Process

The surface finish of a PCB provides a number of functions, with impacts starting at the point of design and continuing through the life of the assembled product. PCBs with fused tin-lead (SnPb) are, manufactured qualified, procured and used for space applications. However, fused tin-lead is not sufficiently planar for fine-pitch applications and the need to obtain better signal performance in RF applications driving the use of novel PCB surface finishes.

Pb free surface finishes have impact on the solder joint reliability and their manufacturing processes need to be carefully controlled.

Pb-free printed circuit finishes, like ENIG, have been used for more than 20 years in other industrial sectors giving entire satisfaction in terms of robustness and accumulating substantial heritage. This serves as a base for the Space sector which is looking to finishes with the same robustness as SnPb finishes. In particular, space industry needs finishes with a long shelf life (storage) to support low volume manufacturing and multiple repairs.

Three lead-free PCB surface finishes with substantial experience and market share in high reliability and commercial applications are currently available from established Space suppliers: ENIG (Electroless Nickel Immersion Gold), ENEPIG (Electroless Nickel Electroless Palladium Immersion Gold) and ENIPIG (Electroless Nickel Immersion Palladium Immersion Gold). The impact of the surface finish on the solder joint depends on the finish build up, surface cleanliness, process bath chemistry, chemical and thermal stability and pad geometry. The challenge is to find out failure root causes, to develop and investigate process technologies and to improve the process reliability.

Many TF members concurred that there is enough data that shows that the level of quality of ENIG, ENEPIG and ENIPIG lead-free PCBs proposed by some Space qualified suppliers is already acceptable for many applications and some of them are already using them for selected space projects. However other TF members believe that an assessment of the surface finishes, their process control and relevant test methods is still necessary for space applications. This includes, for example, robustness in harsh environments, solderability after aging, corrosion resistance.

The benefit of possible other finishes, such as EPIG (Electroless Palladium Immersion Gold), is to have a solder joint to copper and copper-tin intermetallic layer, whereas the previous mentioned surface finishes give a solder joint to nickel. This is similar to SnPb finish and therefore the fatigue mode of assembly may be easier understood. However, the EPIG finish has limited use.

The current ECSS approach for verification of assembly process, as per ECSS-Q-ST-70-60C standard (which replaced standards ECSS-Q-ST-70-10C, ECSS-Q-ST-70-11C, ECSS-Q-ST-70-11C), considers the PCB finish, the solder alloy and the component terminations variables which if individually changed require a new verification of the assembly process. This is in line with the approach used in any manufacturing process where a change of one of the main materials requires the reverification of the process. Part of the industry is already asking if the same approach will be applicable in Pb free technology knowing that the possible combinations of PCB finishes and solder alloys might results in a more frequent need of soldering verification than today.

With today limited knowledge of the alloys systems that will be used and of the reliability of the processes it is not possible to answer this question. It can be anticipated that at least in the initial stages of the transition the same approach used today will be applied so to avoid to overlook major issues. Nevertheless this question needs to be considered in the definition of the activity of the road map aiming to assess if similarity among different finishes can be identified and/or simplified test approach can be defined to reduce the impact of a change of one of these materials in the assembly process.

10.2 Use with Lead-free Assembly Process

Different problems need to be considered when using lead-free solders for the assembly. Lead-free solder alloys, like SAC 305, require higher assembly and repair temperatures exceeding the glass transition temperature (Tg) of the PCB materials. This has severe impact on the PCB integrity:

- Defects in the dielectric may appear (like measling, cracks, Conductive Anodic Filament)

- Defects in the metallization (barrel cracks, interconnect defects)
- Defect at interface of dielectric and metallization (pad lift, delamination)
- Warpage

The melting temperature and processing temperatures of tin-lead alloys previously used are also generally higher than the TG value of PCBs. However, there are PCB materials with a TG value of up to 400°C for critical applications on the market. The CTE values of these materials are almost identical to ceramic materials for EEE components

Therefore, when studying the impacts of the new solders, an assessment of the new assembly processes on the currently used PCB technologies (in particular High Density Interconnect) is needed. This can potentially lead to the need for more robust materials and processes, without forgetting that some of the problems arise from the chemical formulation changes in the different bathes due to REACH and not specifically to lead-free alloy. The road map for lead-free solder introduction shall investigate new materials and modified PCB manufacturing processes to achieve better thermal robustness.

11. Lead-free Interconnects

Lead-free flip chip is needed for DSM chip packaging. At the European level there are the results of recent CNES study with Microchip. The recommendation for the roadmap is:

- Study the reliability of lead-free flip chip as a continuation of CNES study Evaluation of lead-free (pure tin alloy>97% tin content) bumping solution for 65nm flip-chip assembly

Lead is also used in SnPb columns and InPb solder. For both cases the TF concurred that there is no need to go lead-free. In both cases there are no alternatives and their use is for very narrow, niche applications. The TF does not see any risks in the medium/long term. It should also be noted that the ceramic packages that require the SnPb columns are hermetic ceramic packages and they will likely be replaced by plastic packages (BGAs) with SAC solder balls (new generation of FPGA or ASIC components). However these BGA packages with SAC solder balls need to be assembled with lead-free solder.

12. Assembly

12.1 Possible Scenarios

As it is clear from the previous sections, the lead-free transition may result in **different scenarios** encountered by Space Industry for Electronics Assembly in Space hardware:

1. EEE parts with lead-free finishes assembled with SnPb solder on PCBs with SnPb coatings known as backward assembly/process
2. EEE parts with SnPb finishes assembled with SnPb solder on PCBs with lead-free coatings
3. EEE parts with lead-free finishes assembled with SnPb solder on PCBs with lead-free coatings
4. EEE parts with Sn-Pb finishes assembled with lead-free solder on PCBs with SnPb coatings known as forward assembly/process

5. EEE parts with lead-free finishes assembled with lead-free solder on PCBs with lead-free coatings

All of these scenarios may happen independently throughout the transition period that may span many years.

The first 3 scenarios can be managed within the current rules of verification of the assembly processes defined in the ECSS standards for soldering. The main criticality is the management of Pure Sn finishes of components in all those cases where pre-tinning of the component cannot be performed (risk of damage to the devices). The assembly may need a backward process when lead free parts are used (case 1 and 3).

For scenarios 4 and 5 it is important to know that the melting point of the commonly used Pb free solder alloys is higher than the near eutectic SnPb solder. The consequent higher assembly process temperature has effects on:

- Activation and efficiency of the fluxes currently used (Rosin based). Different types of flux will have to be used leading to changes on cleaning materials and procedure currently in use.
- Higher stress on the PCB during assembly and in case of rework /repair. This will have to be taken into account in the frame of qualification of PCB suitable for Pb free processes.
- Higher thermal stress on components during assembly increasing risk of damage due to thermal shock. This is already an issue for certain type of components (for example ceramic capacitors) when SnPb solder is used. Suitability of components to the assembly temperature will have to be considered as part of definition of ESCC requirements and in the qualification of components.

A result of the use of Pb free technology is the variety of finishes for PCB and components and the possible variety of solder alloys leading to various possible combinations in solder joints which, by consequence will have different metallurgy, properties and reliability. This will have to be considered in the characterization of the alloy systems. Compatibility of finishes (of PCB) with SnPb alloys will also have to be assessed as it can be anticipated that there could be products using Pb free PCB but still implementing SnPb based assembly processes.

12.2 Other Impacts

The transition to Pb-free solder alloy will have a dramatic impact on the **assembly and workmanship standards**. Lead free solder is known to have a different appearance to SnPb which produces smooth and shiny joints. This characteristic of the solder joint is the base for the visual inspection in SnPb systems as it allows identifying defect and discontinuity with relative ease. In the case of Pb free, SAC alloys are known to generate solder joints with superficial cracks due to hot tearing during solidification. Establishment of criteria for inspection shall be one of the road map final objectives.

The current approach for use of Pb free PCB finishes within ESA project requires the performance of the verification test using boards from the same batch of boards used for the FM and effectively this means to repeat a reduced verification test for each new batch of manufacturing in case of repeated production. The use of Pb free finishes PCB will result in this requirement being applied unless a good knowledge of the finishes , their process control and their impact of the reliability of the assembly is acquired.

Pb free solder alloys have different properties than the SnPb ones therefore approach to **solder verification** used in the current ECSS standards might not be any longer suitable. Pb free systems are susceptible to additional or different failure mechanism. The different creep and stress relaxation characteristic of these alloys means a different behavior under the same test conditions used for SnPb, in particular the impact of dwell times and rate of temperature change will need to be understood in order to be able to properly compare the reliability of these alloys. Similarly, the accelerated test model used for SnPb alloy will have to be reconsidered and a new model will have to be developed.

To summarize, from an assembly process point of view the transition to Pb free for the space industry requires a good basic knowledge of the alloys systems , the reliability characteristics of the joints, development of suitable test methodology and models. This set of information will be the base for the development of workmanship and standards suitable to introduce and manage this technology in a reliable and cost effective way.

13. Tin Whiskers

13.1 Introduction

Whiskers are hair-like, metallic crystals that unpredictably grow out from a metal surface. They could be straight or kinked filaments, nodules, odd-shaped eruptions. Filaments usually have uniform cross section along entire length. Tin, Zinc and Cadmium coatings are most common sources. Whiskers are also less frequently seen on metals like Indium, Silver, Lead, Gold and other metals. Not all Tin, Zinc or Cadmium Surfaces will grow whiskers.

Absence of growth may last hours to years. The growth occurs by accretion of metal ions at base of whisker not at tip. Typical growth rate is less than 1 mm/yr although up to 9mm/yr has been reported. Log-normal distribution is ~1 mm or less (typical), rarely up to 10 mm or more. Typical thickness is a few microns.

Current theories on formation and growth, and associated test methods do not have predictive power of the time-dependence of whisker density, length or thickness distributions. A useful theory should identify what we must control to make confident predictions and develop accelerated tests. Such a theory has remained elusive although some progress has been reported in the last 10 years.

13.2 History

In 1946 H. Cobb (Aircraft Radio Corp.) published earliest known account of cadmium whiskers on cadmium-coated variable air capacitor plates. Cd whiskers induced electrical shorting in military aircraft radio equipment. These events occurred during WW II (~1942 –1943. After learning of electrical failures from Cd whiskers, Bell Labs opted to use Tin and Zinc coatings. But then Compton, Mendizza, and Arnold reported shorting caused by whiskers from these coatings too.

During the 1950s and 60’s Bell Labs worked through the periodic table to determine whether co-deposition of some element with Tin would “inhibit” whiskering. They found that adding 0.5 -1% by weight or more of Lead (Pb) into tin was effective inhibiting whiskering and that alloying with metals other than Pb sometimes enhances whiskering. As a result since the 1990s to inhibit whiskers most

US MIL and European ESCC standards require adding Pb to tin coatings used near electronics. For design margin, greater than 2% to 3% Pb by weight is usually specified.

13.3 Mitigation

The restriction of Pb and the associated lead-free transition by many part and board suppliers (from tin-lead surface finishes to pure tin or other Pb-free finishes), means that Sn whiskers are once again a potential cause of failure. Whiskers can cause electrical failures, ranging from parametric deviations to catastrophic short circuits, and may interfere with sensitive optical surfaces or the movement of Micro-Electro-Mechanical Systems (MEMS). Lacking an accepted theory for formation and growth, user industry is managing the risk through mitigation.

A lot of work has been performed, mainly in the US, on different kinds of mitigation approaches and the results have been embodied in several standards widely used by European companies using lead-free parts and assemblies:

- GEIA-STD-0005-2, Standard for Mitigating the Effects of Tin Whiskers in Aerospace and High Performance Electronic Systems
- JESD22-A121A, Test Method for Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes
- JESD201, Environmental Acceptance Requirements for Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes

The TF debated whether the US standards mentioned above can be referenced in European standards as such, or whether we need to develop European versions. At the end the consensus was that, at the moment, there is no need to develop European version of them.

There is an actual European standard existing regarding whisker test methods namely IEC 60068-2-82:2019 “Environmental testing - Part 2-82: Tests - Test Xw1: Whisker test methods for components and parts used in electronic assemblies”.(Preview to standard IEC60068-2-82:2019).

Nevertheless it is also acknowledged that, currently, among the TF members, there is an uneven level of experience applying and using the above mentioned standards and need of additional requirements of tailoring cannot be excluded.

There are questions on the applicability of these standards to high reliability, mission critical systems. In particular, it is necessary to acquire a better understanding of the limitations of the test approach provided in the JEDEC standard and the susceptibility of the various Sn based solder alloys being considered needs to be assessed as well as their capability to inhibit whiskers growth if used to re-alloy pure Sn finishes.

14. Lead-free Transition Roadmap Definition

As it has been explained in the text, the overall roadmap is composed of several branches addressing specific needs for the Lead-free transition.

Taking into account the extent of the topic and the fact that it is affecting the whole chain of manufacturing of space electronics a novel approach in the managing and coordinating the activity is also proposed.

The coordination of the implementation of the road map via the **formation of a specific Consortium** with the participation and contribution of space Agencies and Industry is envisaged. The formation of such consortium, open but not limited to the entire European space electronics manufacturing, will allow to generate a much larger amount of data in shorter time. Under this approach all companies will be asked to contribute samples for testing at the various stages of the road map. The Consortium will operate under ESCC umbrella and will report both to CTB and MPTB. The roadmap main objective is the generation of data for the understanding of the reliability of Pb free technology, development or modification of actual available standards for workmanship and for the industrialization of the Pb free technology. To this scope the road map approach is the definition and use of standardized test vehicles and methods from a wide group of manufacturer rather than supporting testing of specific application of a single company.

As confirmed by the majority of the TF members the confidentiality concerns of the companies involved in assembly of electronic is an obstacle to the share of data and information in the frame of working groups resulting in limited cooperation and coordination across industry and to an inefficient use of resources. This approach aims to removes the confidentiality barriers typical of activities involving assembly companies by focusing exclusively to the development of the basic knowledge understanding of alloy systems, main process parameters and reliability models. This approach van also make the activity interesting for the European aerospace and defense industry in general and the creation of a European standard for Pb free could be envisaged.

The formation of a consortium with the scope to manage the funding and ensure the coordination of the activity with complete and transparent share of the results among all the entities is proposed. Through the optimization of the use of available resources and the involvement of European electronic assembly chain (including medium and small enterprises) it will be possible to develop industrial experience with Pb free technology and to build the necessary knowledge at agencies level for definition of requirements and standards. The success of such approach and road map is conditional to the best effort commitment of all actors, industrial and institutional, but above all to the will of the MPTB and CTB to innovate the model of running and implementing a road map for the benefit and competitiveness of the whole European space and Aerospace sectors.

The budgets and duration for each of the Roadmap lines shown below represent the best guess from the members of the Task Force based on their experience and comparable studies already undertaken in the Aerospace and Defence sectors. They will be reviewed as required by the

Consortium after they have analyzed and consolidated the nature of existing, available and reusable information.

14.1 Roadmap for using COTs with the standard SnPb Assembly Process on standard leaded PCBs

From the discussion in section 8 this branch of the roadmap will be defined by the Roadmap Consortium. The Consortium will have to assess whether or not there is enough reliability data, available to everybody, in order for the PSWG to proceed with the updating of the relevant standards. If the answer is yes, then the PSWG will be tasked to initiate the updating of the relevant standards. If the answer is no, the Roadmap Consortium will define the necessary activities to be undertaken in order to generated the missing reliability data. The scope of this study will be the evaluation of different component finishes to assess the degradation due to storage, by checking wettability and other possible deterioration:

14.2 Roadmap for using lead-free PCBs with the standard SnPb Assembly Process

From the discussion in section 10, this branch of the Roadmap will consist of:

> Evaluation of different PCB finishes aimed assessing the degradation due to storage, wettability, and assess test methods for the process control.
>
> - Design of the standard test vehicle and definition of evaluation test approach
> - Test vehicles manufacturing
> - Testing
> - Assessment of results and identification of PCB finishes to be used in continuation of road map and candidate for qualification.
> - Assessment of pressfit and solderless connectors
> - Investigate the behavior of press-fit connectors on Pb-free finished PCB
>
> Task duration 12 months
>
> Cost: 250K euro (TBD)

14.3 Roadmap for the introduction of lead-free solder alloys

Changing the solder alloy is a major disruption that will require the modification of the whole Assembly Process and the verification of everything to take into account the new composition of the alloy and the modified process parameters including temperature.

Phase 1 Alloys selection and preliminary characterization

Scope of this phase is to select the lead-free soldering alloys that will replace SnPb technology. This phase is divided in two steps:

Step 1.1 Alloys Screening

Scope: Bibliography research in order to identify the most suitable candidates Pb free alloys for manufacturing. Method of assessment based on reliability test of standardized test vehicles submitted to thermal cycling under electrical monitoring. One of the alloys shall be SAC305, target is to select a minimum of 3 alloys.

Task duration: 12 months

Cost: 750K euro

Step 1.2 Preliminary Alloys Characterization

Scope: to characterize the selected alloys and acquire data for the development of accelerated test models. The available data should be reused as much as possible if relevant.

Two paths of characterization:

1) Basic characterization using elementary sample of the alloys. Testing using techniques as DMA, XRD, metallography to assess:

- Creep behaviour
- Stress relaxation behaviour
- Metallurgy of joint on different substrate, Intermetallic compounds characterization
- Evolution of intermetallic compounds under thermal aging.

2) Reliability characterization using standard test vehicles as the one developed in phase 1 test aimed to assess impact of the following parameters on reliability. SnPb to be also tested as comparison/control sample:

- Temperature range
- Max temperature
- Min temperature
- Dwell time
- Ramp rate
- Alternative/Different PCB finishes

In parallel a test activity aimed to assess the capability of the PCB materials to sustain the process temperatures required by Pb free assembly processes shall be performed. This activity will also be aimed to identify necessary changes to the PCB manufacturing and qualification standards.

Outcome: confirmation of the candidate alloys of reduction to a minimum of two alloys for complete development. Definition of accelerated test parameters for the continuation of activity

Task duration: 24 months.

Cost: 2 M€

Phase 2: Full characterization and reliability model development

Scope: To acquire data on the reliability of different families of components, assess the various soldering process (machine soldering versus hand soldering). To add mechanical stress to the test regime (shock and vibration).

Assessment is based on use of reliability test samples developed in phase 1. Parameters to be assess in this phase:

- Impact of Shock and vibration on reliability
- Impact of soldering process: machine reflow, IR, HS
- Impact of stand –off
- Introduction of leaded component in the test
- Impact of different PCB finish: solderless and pressfit connectors
- Introduction of conformal coating in the test.

Outcome:

Confirmation of the accelerated test parameters. Understanding of impact of various process parameters on reliability.
Establishment of guidelines for use of lead free soldering technologies on noncritical units under project level approval (RFA)
Gathering of industry experience from the manufacturing of the test vehicle in order to start drafting assembly standard.

Task duration 36 months (TBC)

Cost: 3 M€

Phase 3: Consolidation

Scope: Definition of workmanship standard. ECSS standard for assembly affected by the introduction of lead-free alloys

ECSS working group formation.

Gathering of all data from the previous phase and to analyse if further test combination are needed to confirm or complement the data pool.
Testing of repair configurations.
Confirmation of model by performance of a life test at unit level.
Establishing a data base in order to collect data from assembly verifications with the aim to define rules allowing the minimum effort for verification of an assembly process.

Task duration: 24 months

Cost: 2 M€

Phase 4: Component types and effects

Given the phased approach identified above. The following cascade of work is required to run in parallel to phases 1 and 2 but focused more towards the component technologies:-

Scope of this phase is to identify and select the (ESCC qualified) component types that will be affected by changes to the solder assemble technology. This phase is divided in two steps:

Step 1.1 Component types with internal impacts

Task 1.1.1: Identification of components that have internal features, terminations or constructions that will be affected by the change to lead free solder alloys.

- Bibliography & existing parts lists / databases Drawings and manufacturers data to establish types of construction and limitations to applications of lead free assembly
- Feed findings into phase 1 of the solder assessment above.

Task 1.1.2: Identification of components that have external features or terminations that will be affected by the change to lead free solder alloys.

- Bibliography & existing parts lists / databases to establish types of and limitations to applications of lead free assembly
- Feed findings into phase 1 of the solder assessment above.

Task duration for step 1.1: 6 - 9 months

Cost: 300K euro

Step 1.2 Component internal construction effects evaluation

Scope: Evaluation of component with lead free internal construction to assess the degradation due to lead free solder processing during PCB assembly.

- Identify and obtain suitable samples (identified in step 1.1) and define of evaluation test approach
- Test in accordance with the defined evaluation test approach
- Assessment of results and identification issues or effects of

Task duration: 12 months

Cost: 500K euro

The content of this Phase 4 could be adjusted if the Roadmap Consortium assess that some of the required results are already available.

14.4 Roadmap for assessment of Sn whisker mitigation approach

From the discussion in section 8 and section 13 the scope of this task is the assessment of the current methods and standards for the screening of the susceptibility pure Sn finish to the development of Sn whiskers and the management of the associated risk.

Step 1.1

Scope: Definition of a test approach for the screening of susceptibility to whiskers development. Identification of types of pure Sn finishes based on their susceptibility to develop whiskers

- Identification of the different types of pure Sn finishes available: Matt Sn, reflowed, thermal treatments, with Ni underlayer etc…
- Definition of test regimes: Thermal cycling, thermal aging, Humidity exposure, TVAC...
- Definition of assessment methods: Residual stresses, SEM inspections, DPA.
- Testing of Pb free finished parts assembled with SnPb alloys
- Testing of mitigation methods (conformal coatings)

Task duration: 36 months

Cost : 750 KE

Step1.2:

Scope of the activity: Identification of limitation for use of finishes or alloys and definition of mitigation actions (pre-tinning, use of coating, PCB design rules, etc..)

- Continuation of testing from previous phase
- Testing of Pb free assemblies to assess the susceptibility to whiskers growth of the various alloys identified for assembly.
- Definition and Assessment of mitigation measures

Task duration: 24 months

Costs: 750 KEuro

ANNEX 1: On-going R&D contracts awarded by Space Agencies on subjects relevant to the content of this Roadmap:

Agency: ESA

Title: Reliability of Lead free/pure tin component terminations

Funding: €300K

Contractor: Not disclosed

Scope: This activity will demonstrate that the application of Lead free solder mounting and the mitigation methods described in the non-flight industry documents provide a reliable mitigation against tin whisker growth and other mechanical failure modes when tested in a space flight environment. This shall be achieved by manufacturing completed PCB assemblies, and exposing then to harsh environment testing. The contractor will select, describe, justify and deploy methods of mitigations.

Due to budget constraints, the Contractors will use an existing design/product that includes pure tin finished components, a proven solder technology (as far as possible), and the mitigation methods described in the reference documents.
The design shall include a selection of component types to include both chip & leaded devices, which feature tin finishes, which are assembled using surface mount technology. At least 6 different component types shall be included. For clarity, examples of a component type are: Chip Capacitor, Chip Resistor, SOT 23, Dual in Line, Inductor, LCC, Connector, etc.

Status: Contract Kicked off Feb, 2020. Paralell contract Due for KO June, 2020.

Agency: CNES

Title: Lead Free solder alloy and high reliability for SMT process

Funding: 120K€

Contractor: AIRBUS Defense and Space Elancourt
Scope: The objective of the study is to improve the reliability of soldered joints and thus be able to increase the dimensions and the variety of components to be mounted on PCB (leadless packages, ceramic substrate…). The expected results are the evaluation of lead-free alloys aimed at improving the flexibility of sensitive CMS assemblies. We propose to orient ourselves towards “doped” SAC families and to compare the possible benefit that they could bring compared to a conventional SAC alloy like SAC305.
These study is divided in 3 steps :

- Bibliographic study
- Design and Manufacturing of test vehicles
- Evaluation tests

Status: T0 : 15 January 2020; duration : 15 months