Lead Free Electronics Manhattan Project Phase 2

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LEAD FREE ELECTRONICS MANHATTAN PROJECT PHASE 2 REPORT

I Foreword

II Executive Summary

Phase 1 of the Pb-Free Electronics Manhattan Project consisted of capturing and documenting the current best aerospace and defense (A&D) industry practices to deal with the multiple technical and business issues from the commercial industry transition to Pb-free electronics. The set of Pb-free electronics best practices contained in the report constitute the current baseline practices as determined by the assembled team of nationally-recognized subject matter expert scientists and engineers. "Current baseline practice" is defined as a practice that describes the current state-of-the-art as a baseline against which future improvement can be measured. Known issues with the current baseline practices and technical gaps are also identified in the Phase 1 report.

Phase 2 of the Pb-Free Electronics Manhattan project focused on the development of a time-phased roadmap, including a detailed technical approach, to deal with the multiple technical risks and knowledge gaps identified during Phase 1. The three-year roadmap and supporting details contained in this Phase 2 report define the Phase 3 research and development (R&D) recommended by the team of subject matter experts to deal with those issues. The rough order of magnitude (ROM) cost to complete the R&D is estimated to be $105M in 2010 dollars, and includes a 10% factor for the cost of the government contract administration effort. To convey the scope and purpose of the needed R&D, Phase 3 has been named the Pb-Free Electronics Risk Reduction Program.

During the preparation of the Phase 2 Roadmap, the team reaffirmed its fundamental findings from Phase 1:

- The use of Pb-free electronics in products whose life-cycle includes operation in harsh environments poses technical risks leading to degraded reliability and reduced lifetimes.
- Quantification of these technical conclusions within valid statistical confidence bounds remains a gap.
- Further data is needed to converge existing reliability prediction methodologies and provide acceptable accuracy.
- Continued "point solution" projects will not adequately address the spectrum of gaps that exist in the current body of knowledge on Pb-free electronics.

It is therefore strongly recommended that the subsequent Pb-Free Electronics Risk Reduction Program be fully implemented to ensure that the risks imposed by Pb-free electronics in high-reliability, high-performance applications (especially in extreme environments) become fully articulated, quantified, and bounded to ensure viable product design, manufacturing, test, delivery, and sustainment at an affordable cost. As noted by the team during its Phase 2 deliberations, the fundamental objective of the focused three-year effort is to continue the intelligent and safe use of commercial off-the-shelf (COTS) electronics in future A&D products.

III Acknowledgements

The Pb-Free Electronics Research Manhattan Project team wishes to acknowledge the U.S. Navy Office of Naval Research (ONR), the ONR Office of Transition and its Manufacturing Technology (ManTech) Directorate, the Joint Defense Manufacturing Technology Panel, and the Navy ManTech Benchmarking and Best Practices Center of Excellence (B2PCOE) for their continued financial and logistic support in providing the resources to complete Phase 2 of the Lead Free Electronics Manhattan Project (LFEMP). The team also wishes to acknowledge ACI Technologies for providing the appropriate facilities and process leadership in the development of the Phase 2 Roadmap. The authors of this report would also like to thank the Pb-free Electronics Risk & Mitigation Council for their proactive role in advisement and contribution to the Pb-free mitigation knowledge base.

Once again, the team leadership would like to acknowledge the dedicated scientists and engineers who assiduously worked together in an integrated team environment to produce the LFEMP Phase 2 roadmap.

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1.0 Introduction

1.1 The Current Electronics Business Environment

As stated in the Lead-Free Electronics Manhattan Project – Phase 1 Report, the worldwide electronics supply industry is adopting lead-free materials and processes in their manufactured and assembled electronics products. Ultimately, these Pb-free electronic assemblies are being introduced into the inventories of original equipment manufacturers (OEMs) who must make a determination as to whether to use, reject, or rework them. This decision process is driven by the fact that the use of Pb-free electronics poses a potential product risk and could compromise end item product reliability when subjected to harsh environments and long service life-times. On the other hand, the growing proliferation of commercial off-the-shelf (COTS) electronics that are only available without lead is making it increasingly difficult and expensive to continue to use tin-lead (SnPb)-based electronics.

Since releasing the Phase 1 Report, additional troubling information has emerged regarding the reliability of Pb-free electronics operating in harsh A&D environments. A team of technical experts assigned to create a handbook, "Reliability Assessment for Aerospace and High Performance Electronics Containing Lead-Free Solder," for the Pb-Free Electronics Risk Management (PERM) Consortium have declared that they are unable to complete the handbook due to a lack of sufficient reliability test data.

Consequently, Aerospace & Defense (A&D) OEMs are ultimately being forced to severely limit the use Pb-free electronics to benign operating environments, or implement costly processes to ensure they are suitably screened to prevent entry through the SnPb product stream. Either option has an impact on product acquisition and total ownership cost (TOC). Denial of Pb-free electronics will restrict the use of COTS and increase platform cost. Admission of Pb-free electronics into the build of material will require re-qualification of the manufacturing processes and products, further increasing platform cost. Either option increases the end-item's TOC since sustainment of platforms necessitates greater attention to manage and control electronics inventories. Additionally, the use of specialized rework and repair processes to maintain a "Pb-only" baseline or to permit a mix of Pb-based and Pb-free components will be required.

1.2 Lead-Free Electronics Manhattan Project

The Pb-Free Electronics Manhattan Project was motivated by the desire to mitigate the increasing risk associated with the proliferation and use of commercial Pb-free electronics in OEM products. The concept for the Pb-Free Electronics Manhattan Project was initialized, formulated, and "socialized" across industry and the customer community in order to obtain sponsorship and general consensus. The project was envisioned as a single, fully-funded team of nationally recognized scientists and engineers working cooperatively over a three-year period, focused on addressing the use of Pb-free electronics in A&D products.

The project has been segmented into three phases with the primary funding (estimated to be $105M) expected in Phase 3 (which has been renamed to the "Pb-free Electronics Risk Reduction Program" to

better convey its intent). Phase 1 established the baseline in terms of documented current practices used across industry and the identification of the issues and gaps associated with those practices. Phase 2 articulates the roadmap for the future work required to mitigate those issues and close the gaps in order to reach an acceptable risk level. These two phases form the basis for Phase 3 which will focus on specific technical research and development tasks that address the identified technical knowledge gaps. Phases 1 and 2 were planned as distinct, two-week projects, conducted in a single geographical location, such as a national lab, using a skilled set of recognized scientists and engineers.

The Phase 2 R&D Roadmap, including a detailed Technical Approach, is the subject of this report.

2.0 Pb-free Overview – Update

2.1 Overview of the current state

The restriction and elimination of lead (Pb) in electronics products was initiated by legislation enacted within the European Union (i.e., Restriction of Hazardous Substances [RoHS] in Electrical and Electronic Equipment, and Waste from Electrical and Electronic Equipment [WEEE]) and Pacific Rim regions (circa 2006). Many non-U.S. countries have followed suit in order to restrict the disposal of electronics products containing Pb within their boundaries. The U.S. does not have existing federal legislation, but several states have adopted laws restricting Pb content in electronics manufacture and their disposal. To date, Aerospace and Defense OEMs are exempt from this legislation.

However, there have been recent reports that the European Union (EU) is formulating plans for a RoHS2 that will potentially expand the scope of RoHS to all electrical and electronic equipment sold in the EU, including A&D products.

The general definition of Pb-free is described as packages which contain solder and other materials that have a maximum of 0.1% Pb (by weight). Legislation to restrict Pb content in electronics led to a technology shift in the global electronics supply chain. For a myriad of reasons, including increasing their capture of market share, suppliers have been transitioning to using Pb-free processes and supplying Pb-free materials. This shift in the supplier baseline has altered the fundamental process of how electronics assemblies are built and qualified, and has led to a technology disruption and potential risk at the A&D OEM product level.

A&D OEMs had established their product designs and builds predicated upon the use of a stable SnPb baseline. As suppliers have changed to a Pb-free baseline, OEMs have been driven to increase the awareness of Pb-free use, understand its impact upon their product performance, and establish risk mitigation processes. Exacerbating this pervasive issue is the fact that there is no “drop-in” replacement that can be substituted for the legacy SnPb baseline. In fact, the opposite situation exists since there are a myriad of Pb-free materials which are being supplied and used as replacements across the worldwide supplier community. Furthermore, the Pb-free materials demand by commercial consumers has contributed to the proliferation as consumer and commercial OEMs have determined that Pb-free materials were adequate for their markets.

The primary issue associated with the use of Pb-free materials is that the reliability is un-quantified for A&D products built using this technology in typical “harsh environments.” It does not have the legacy of over 50 years of supporting performance data as in the case for SnPb. A&D product lives are often measured in decades compared to the typically short commercial product lives measured in months or a few years. These factors contribute to the risk associated with Pb-free electronics and the uncertainty of how to adequately address it within current product life cycles. Engineers using SnPb electronics have evolved to be good rule followers. However; in this new paradigm, Pb-free electronics will require engineers to create new rules-of-thumb involving the total array of system issues associated with Pb-free materials.

The customer base has a general awareness of Pb-free electronics use, but reliance upon performance-based procurements has shifted the requirements driven burden to the A&D OEMs to be aware of and

mitigate the risk in their products, without the appropriate qualification standards for Pb-free. Unfortunately, without a uniform approach and existing standards to guide the OEMs, a current state exists where A&D OEMs can deliver mixed SnPb and Pb-free or wholly Pb-free products based upon their own preferred approach. The end result will be a set of products that the customer must ultimately maintain which contain product pedigrees which to some extent are unknown and whose build of materials vary widely. This situation greatly impacts product sustainability and leads to a high total ownership cost and a logistical quagmire. Extrapolation of this situation leads to a state of unrestrained cost growth.

Major Risks Associated with use of Pb-free Electronics

The major risks confronting systems which introduce Pb-free electronics into their build of material may be divided into two categories: product reliability and product sustainment. Product reliability encompasses those risks which impact the reliability of the product required to operate as desired in defined environmental applications for its contractual service life. The primary product reliability risks related to Pb-free electronics are the premature failures of the Pb-free interconnects and functional failures caused by tin whiskers. Both reliability risks are addressed in detail in this document. Product sustainment includes those risks which impact the projected lifetime of the product to include its availability and total ownership costs. These general risks may be further subdivided into the following risk factors.

Product Reliability Risk Factors	Product Sustainment Risk Factors
COTS/GOTS	Configuration management
PCB design and finishes	Repair level and instructions
Solder attachments and finishes	Inventory management
Component finishes to include Sn whisker issues	Availability of correct parts & solders
Mechanical parts and finishes to include Sn whiskers	Training of depot personnel
Reliability demonstration (test or analysis)	Documentation (e.g. technical baseline)
Product manufacturing processes to include rework and test	Compatibility of SnPb and multiple Pb-free alloys

Table 2.1 - Pb-free Electronics Risk Factors. Use of Pb-free electronics pose a risk to product reliability and sustainability. Shown are those risk factors which must be addressed in the life cycle.

Relevance to Warfighter

The warfighters that defend the United States expect and deserve weapon systems and equipment that have superior technical performance and unquestioned reliability. This demand is accelerated by the unique applications required in urban warfare against terrorists imbedded in civilian populations, and is critical that the weapons and equipment function correctly and without failures. To minimize collateral damage, the numbers of weapons used against an urban target have been reduced, further mandating that each weapon perform flawlessly. Product failures in the midst of a battle can have catastrophic results, jeopardizing the outcome of a conflict and exposing our warfighters to needless injury and even loss of life.

The systems must also be sustainable in the field and be quickly and easily and cost effectively repaired when needed to bring a system back on line that experienced damage in the field.

Given the high reliance on electronics in weapon systems and military equipment, it is paramount that the issues and technical risks from Pb-free electronics, highlighted in Figure 2-1, be fully understood and mitigated.

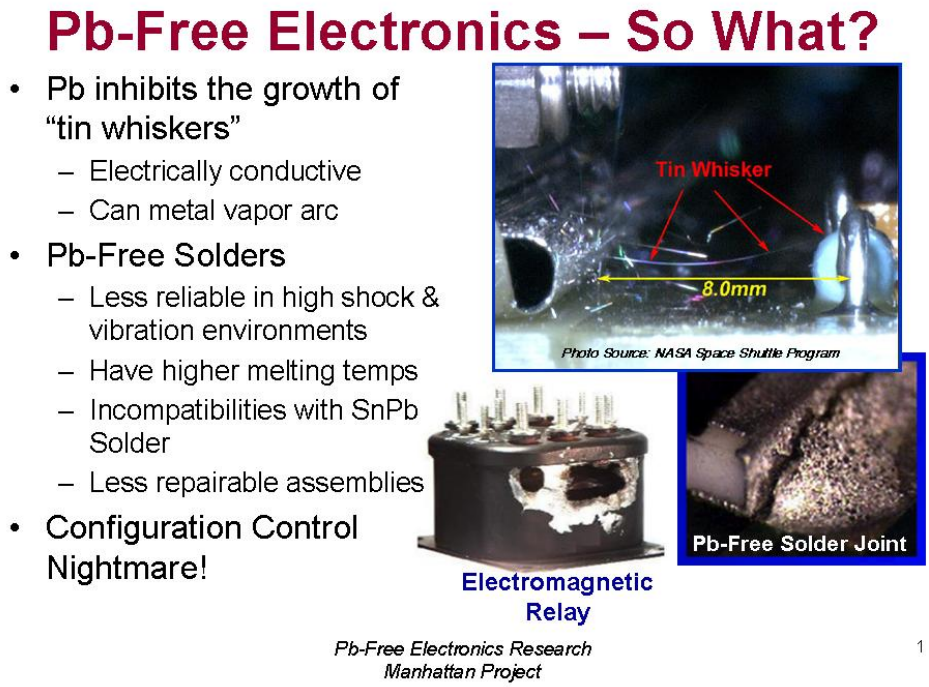


Figure 2.1 - Sample of Pb-free electronics issues. Focused R&D is required to maintain unquestioned reliability when using Pb-free electronics in warfighter weapon systems and equipment.

2.2 Remediation of Risks

The transition to Pb-free materials by electronics suppliers initiated a movement among the OEMs to recognize it as a pervasive issue and acknowledge that a collective approach was necessary to manage

and mitigate its risk. After reviewing the situation, it was concluded that the risk remediation solution set was viewed as being non-competitive since it involved the synthesis of numerous data sources. In addition, single company investment strategies to achieve this state were deemed to be cost prohibitive. Hence, early on in the awareness and risk mitigation approach to Pb-free electronics, the industry sought to develop inclusive collaborations to address and manage the risk. Initial collaborations across industry, DoD, NASA, and FAA, resulted in the Lead-free Electronics in Aerospace Project (LEAP) and the Executive Lead-Free Integrated Process Team (ELF IPT) projects. LEAP focused on development of standards and their publication. The ELF IPT focused on awareness, training, and policy.

These groups continued to work together for several years before uniting under the current Pb-free Electronics Risk Management (PERM) Consortium structure as displayed in Figure 2-2. The shift to the more robust PERM Consortium framework was driven by a clear sense that although both groups were doing good work to deal with the Pb-free electronics issues, our overall national strategic response was inadequate and poorly coordinated. The PERM Consortium concept was briefed to the Aerospace Industries Association's Technical Operations Council (AIA TOC) in December 2008 and was formally endorsed in January 2009.

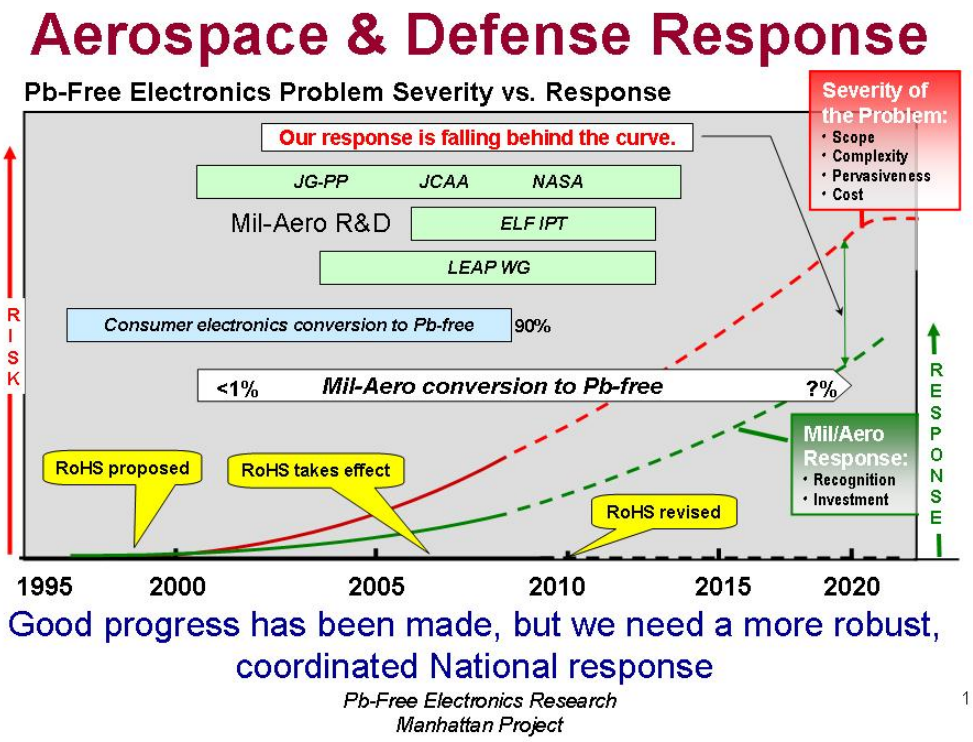


Figure 2.2 - A&D Response to Pb-free electronics. Good progress was made through 2008, but a more robust national strategic response was needed to deal with the risks posed by Pb-free electronics.

The PERM Consortium strategic management framework shown in Figure 2-3 represents an organizational construct that integrates the myriad of Pb-free electronics activities (existing and proposed) into organized subsets of related activities. These activities include the industry, academia, consortium, and government sponsored projects which become united under the PERM structure into a single organizational architecture.

The PERM Consortium framework includes a Research Coordination Task Team chartered to define, develop, and maintain an overall systematic, coordinated plan to provide the necessary research and development (R&D) to address all the critical needs of the aerospace and defense community regarding the global transition to lead-free electronics. Comprised of volunteer members from government, industry, and academia, the Research Coordination Task Team has no current budget or funding capabilities, and is only able to coordinate known and recommended R&D activities and endeavor to minimize overlap and duplication of efforts across the participating organizations. As portrayed in Figure 2-3, the team will include the Lead-free Electronics Risk Reduction Program as one of the R&D activities that it coordinates, in addition to other government, industry, and academia Pb-free electronics R&D projects that are either underway or being planned.

To accelerate the incremental proliferation of findings from the Pb-free Electronics Risk Reduction Program, results will be provided to the appropriate PERM Consortium Task Team for incorporation into standards, handbooks, and training.

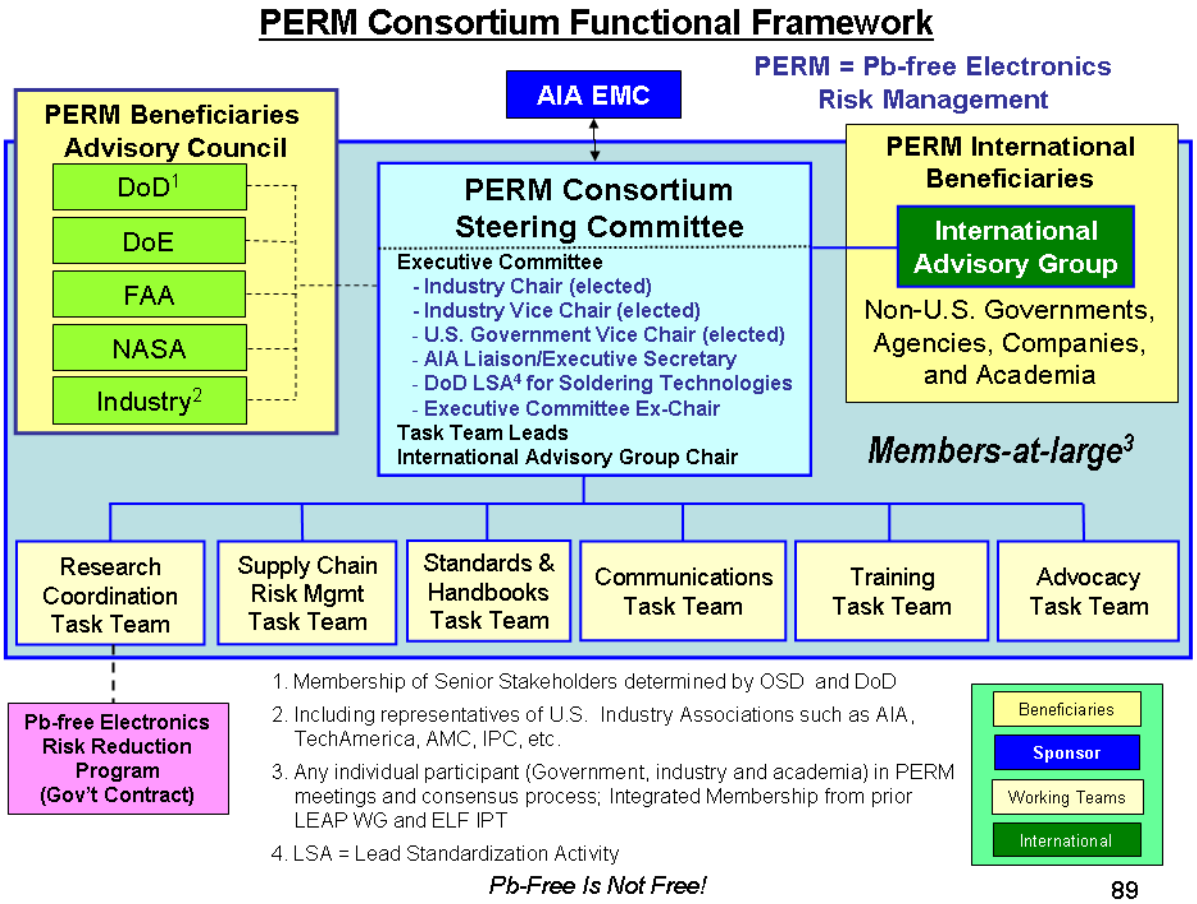


Figure 2-3 - PERM Consortium Strategic Framework. The Pb-free Electronics Risk Management (PERM) Consortium is comprised of government, industry, and academia representatives focused on mitigating Pb-free electronics risks.

The Pb-free Electronics Research Manhattan project was planned as a multi-phased R&D project. The Phase 1 report identifies the current baseline practices in use to deal with Pb-free electronics. Phase 2, the subject of this report, developed a three-year roadmap of the time-phased, risk reduction, R&D tasking recommended for execution during Phase 3. The roadmap further articulates the gaps that exist in relation to the risks associated with the use of Pb-free electronics and recommends the necessary R&D tasks required to fill those gaps. The Phase 2 roadmap presents an integrated approach to deal with the multiple and complex Pb-free electronics technical knowledge gaps facing the aerospace and defense community today. Government funding is needed to initiate and execute the Phase 3 effort for the common benefit.

Pb-free Electronics Cultural Issues

Adding to the Pb-free electronics challenges, there are cultural issues which are as complex as the technical issues. Due to the cross-cutting, multi-faceted technical issues, the first cultural issue encountered is that "this is everyone's problem, therefore it's no one's problem." As a result, finger-pointing ensues and mitigation time is lost as impacted organizations attempt to identify who should be responsible for dealing with the multiple Pb-free electronics issues, including who should provide requisite funding.

Other fundamental Pb-free electronics cultural issues are embodied in the captured actual quotes of leaders in both government and industry:

"I have more important, immediate problems."
"I cannot obtain funding for a research project for which there is no clear solution, no definitive schedule, and no grasp of the total funds required."
"Show me the recent evidence that this is a problem that merits my attention." versus "We cannot share this with anyone."

During recent months, an additional cultural issue has emerged – battle fatigue. The community of technical subject matter experts is growing weary of the problems, and those in management positions are becoming impatient and are in some cases, withdrawing their support for on-going R&D funding.

Each of these perspectives is an additional excuse for inaction, perhaps hoping that the problem will just go away. Regrettably, doing nothing is not deemed to be the right answer.

3.0 Integrated Research and Development Roadmap

3.1 Methodology

To produce the Phase 2 Roadmap defining the R&D technical approach to deal with the technical issues and knowledge gaps identified during Phase 1, the Phase 1 team of subject matter experts reconvened in August of 2009. Their first step was to update the list of gaps based on new information and insights regarding the use of Pb-free electronics in harsh A&D operating environments. Over 100 gaps were identified, including gaps that were non-technical, such as the need for robust awareness training covering the Pb-free electronics risks. Appendix A documents the updated list of technical knowledge gaps that need to be addressed. Non-technical gaps that were passed to the PERM Consortium for their action are presented in Appendix B, as well as the planned handling of technical findings from the Phase 3 R&D that are to be incorporated into standards, handbooks, and training courses as appropriate. Appendix D contains a Gaps Key that was used in the development of the detailed Technical Approach to ensure that all gaps were fully addressed.

The second major step was to develop a top-level strategic approach to deal with the multiple technical knowledge gaps. After much deliberation, the team identified five major R&D project areas to efficiently deal with the gaps. As shown in Figure 3.2, the project areas are: Tin Whiskers, Assembly, Solder Joints, Printed Circuit Boards, and Components. The Assembly project area addresses manufacturing and sustainment issues.

Once the five major project areas were identified and characterized, multiple subordinate projects were defined following a simple work breakdown structure (WBS) and a standard technical approach template. The resulting technical approach documented in Appendix C was then used to develop a time-phased roadmap of the R&D that needs to be conducted to mitigate the risks from the multiple knowledge gaps.

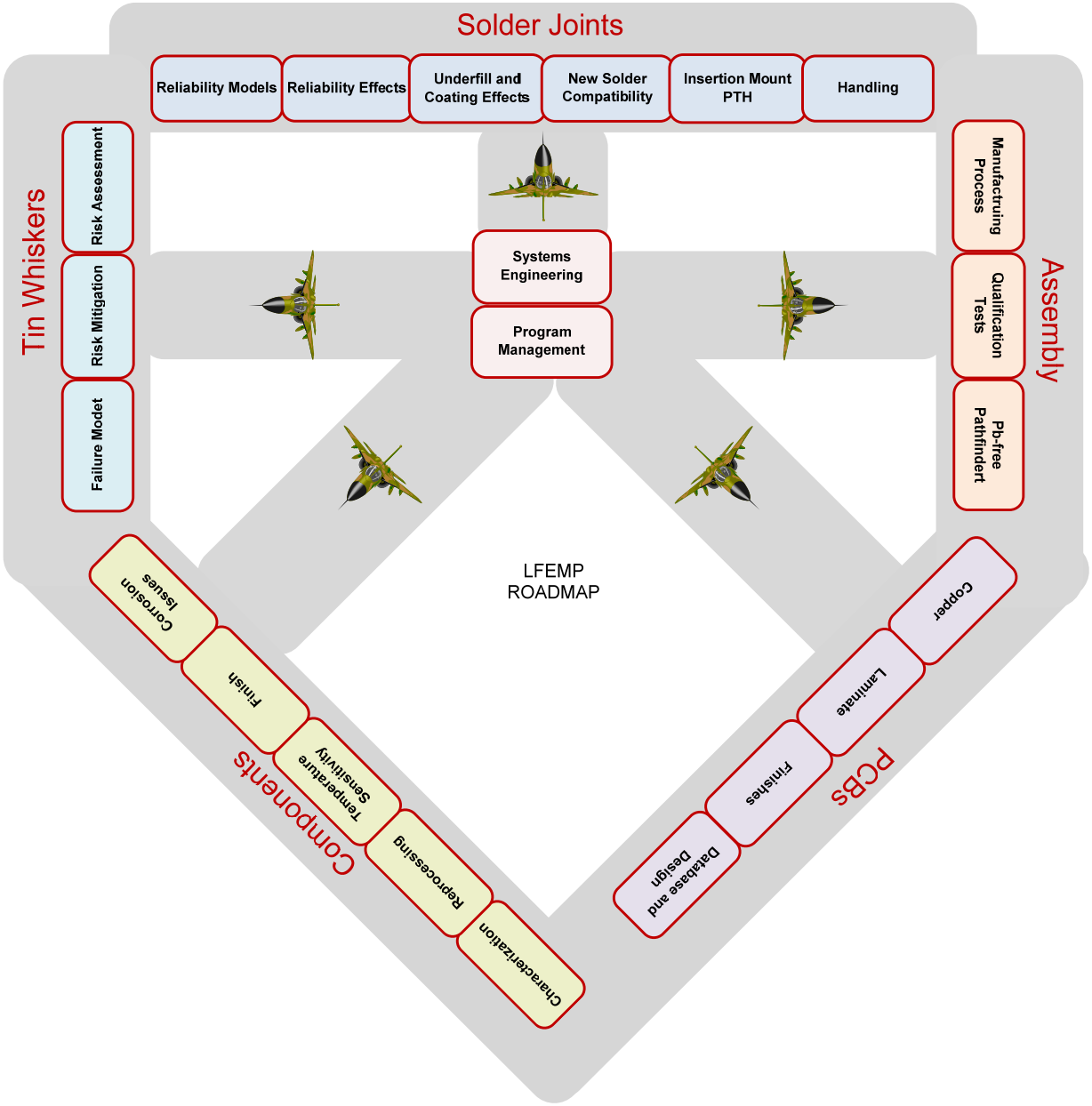
To capture rough order of magnitude (ROM) cost estimates to complete each of the defined R&D projects, a standard cost estimating worksheet was developed. The worksheet contains standardized labor and overhead rates to ensure consistent cost estimation calculations.

Section 3.2 summarizes the Roadmap and Technical Approach developed by the team of deep subject matter experts. It is important to note that the methodology included multiple peer reviews drawing on the expertise and experience across the team to refine the Roadmap with its Technical Approach and ROM cost estimate.

3.2 Pb-free electronics Risk Reduction Program

The Roadmap is essentially divided into what will be referenced as the five Level 1 technical areas, where project activities and tasks have been identified as being crucial to the Phase 3 Pb-free risk reduction strategy. The Level 1 areas can be considered basic areas for the subsequent technical projects. These are disseminated, in many cases, to six levels of granularity designed to define very specific tasks required to the address the respective technological gaps. The level of detail for all of the projects can be viewed in the Appendix C portion of the report. Central to all project endeavors, is the program management and systems engineering team projected to coalesce, gather, organize, and disseminate project activities into one central repository. Here, interactions and correlated activities between project participants can be managed on a programmatic scale.

3.3 Technology Roadmap



3.3.1 Roadmap Summary

The Phase II Pb-free Manhattan Project has identified the weaknesses and gaps suggested during the documentation of Best Practices in the Phase 1 of the Pb-free Manhattan Project. A roadmap of potential future projects has been outlined to resolve the disparities in the Pb-free mitigation strategy. The studies have ranged from package and PWB designs, to material, manufacturing, and reliability issues. From this roadmap, a benchmarking metric can be established that will produce criteria for assessing and prioritizing Pb-free projects.

The Pb-free Manhattan Project concept is to establish a more effective manner to deal with the introduction of Pb-free materials into the product stream by:

- Aggressively investigating the best mitigation strategies currently available
- Analyzing the deficiencies in the present state of Pb manufacturing and technology
- Creating a strategic roadmap for the effective insertion of projects needed to fill the gaps
- Create a benchmarking metric for the viability of Pb-free projects

All of these issues have been addressed in the LFEMP phase 2 efforts. Figure 3.1 illustrates the sequence of events needed to attend to the technical gaps in the mitigation of Pb-free electronics.

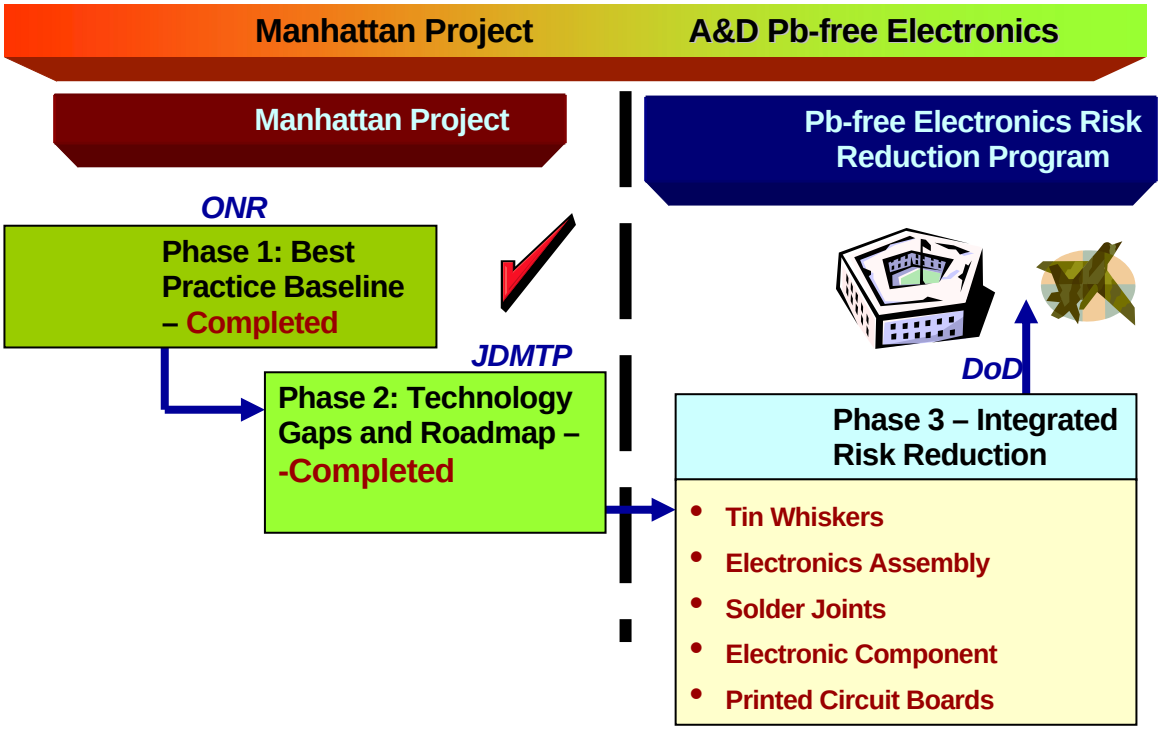


Figure 3.1 - Pb-free mitigation phases

The cost of mitigation and the existing technical gaps in Pb-free are two major considerations when assessing the impact of the Pb-free transition to the DoD. Both are critical to the success of the mitigation efforts. Phase II of the Pb-free Manhattan Project has identified and recommend remedial procedures to help reduce costs and diminish the technology gap that presently exists with Pb-free.

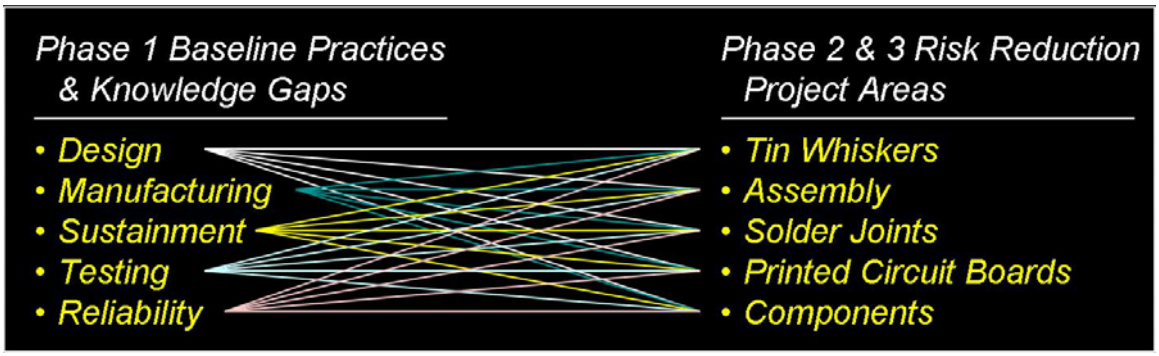


Figure 3.2 - Interaction between Phase 1 and 2

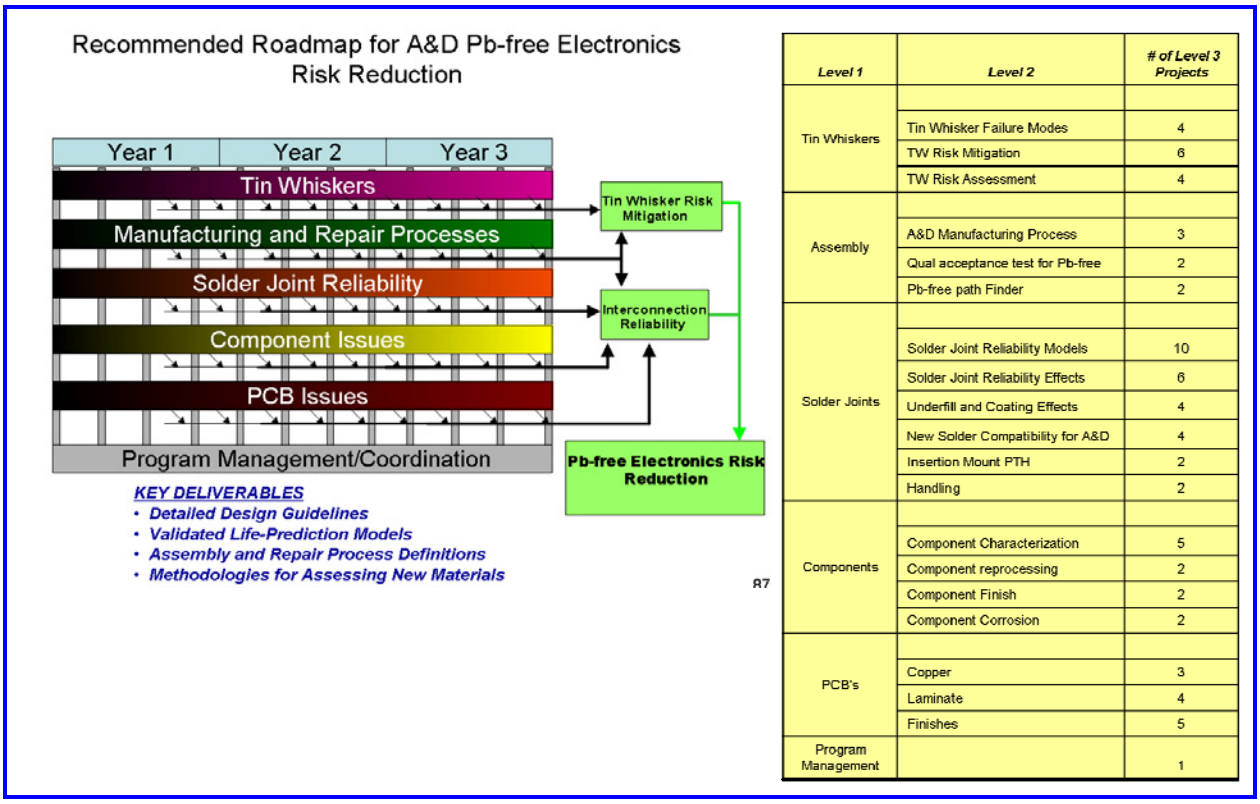
Figure 3.2 shows the complex interlocking relationship among the knowledge gaps that were established, and the various project areas needed to be addressed. Some observations included:

- Serious technical gaps exist for Pb-free electronics that have to be overcome for use in A&D harsh environment
- Quantification of degraded reliability and lifetimes is a significant gap
- The three-year Pb-free Electronics Risk Reduction Program schedule is aggressive, but realistic
- Phase 3 execution will require and draw on the best available talent in the A&D community
- Phase 3 will benefit any A&D or commercial product that relies on Pb-free COTS electronics and operates in extreme or harsh environments

Five major technical areas have been identified as pivotal in addressing the current Pb-free mitigation gaps (Fig 3.3). The level 1 technical areas are prescribed as a high level overview that are further disseminated within each technical section to five sublevels. For the sake of conciseness and clarity, this report will focus primarily on the technical approaches that have been filtered down through to level 3 activities. The complete section on technical approaches is located in Appendix C.

Some key deliverables from the completion of the technical projects outlined in this report include:

- Detailed design guidelines
- Validated life prediction models
- Assembly and repair process definitions
- Methodologies for assessing new materials
- A sustainment strategy



Level 1	Level 2	# of Level 3 Projects
Tin Whiskers		
	Tin Whisker Failure Modes	4
	TW Risk Mitigation	6
	TW Risk Assessment	4
Assembly		
	A&D Manufacturing Process	3
	Qual acceptance test for Pb-free	2
	Pb-free path Finder	2
Solder Joints		
	Solder Joint Reliability Models	10
	Solder Joint Reliability Effects	6
	Underfill and Coating Effects	4
	New Solder Compatibility for A&D	4
	Insertion Mount PTH	2
	Handling	2
Components		
	Component Characterization	5
	Component reprocessing	2
	Component Finish	2
	Component Corrosion	2
PCB's		
	Copper	3
	Laminate	4
	Finishes	5
Program Management		1

Figure 3.3 - Recommended risk reduction Pb-free roadmap

3.3.2 The Pb-free Technology gap

Virtually any manufacturing process can be refined to produce the efficiency needed to control and mitigate the costliness of accommodating Pb-free assemblies. However, the existing gap in Pb-free technology becomes a primary impediment in the predicting lifetime reliability of assemblies utilizing Pb-free material sets. From a historic perspective, SnPb alloys have been utilized in electronics well before the advent of Pb-free, and consequently, the amount of reliable data gathered for Pb-free is limited. Some of the factors that affect reliability and are in need of further research are:

- **Tin whisker control**
- **Package design**
- **Component selection**
- **Solder alloy**
- **Substrate materials**

General Gap Areas

<u>Commercial vs. Military</u>

Participants in recent studies acknowledged the difficulty in making conclusions without more empirical evidence about Pb-free in the areas of reliability, especially long term reliability greater than 10 yrs. While some commercial telecom products specify lifetimes of 10 yrs, the Joint Strike Fighter military airplane, for example, specifies a 40 year life.

Technical Knowledge

A good deal of confidence has been placed by the general electronic manufacturing industry on the published findings by the various consortia and other entrepreneurial driven efforts by industry and academia, as being representative of the state of technology in regards to Pb-free. While there is a contribution to the overall Pb-free knowledge base, it is still very limited, sparse, and often disconnected to the reliability requirements of the DoD.

Field Failure

Field failure information regarding Pb-free assemblies at this juncture is very sporadic since no substantial data is available to accurately extract this often classified and/or proprietary information. More critically, it is still not fully understood what mechanisms are responsible for failure when it occurs, or how to mitigate them. This increases the potential risks associated with the inadvertent contamination of Pb-free components into military hardware.

Process Control

Data to assess reliability of one specific Pb-free manufacturing system over others can be difficult to interpret since many of the manufacturing variables are not consistent from one process to another. The Pb-free Electronics Manhattan Project has identified the best manufacturing practices to date that will mitigate the effects of Pb-free. More work needs to be done to assess the various manufacturing technology gaps that exist, to produce greater process efficiency and controls that will reduce cost and increase military hardware reliability.

Reliability models

One major shortcoming in the validation of existing Pb-free reliability models to predict potential field failure, has been the use of a scatter shot approach, which frequently cannot account for many of the factorial interactions. The lack of cohesiveness for these efforts can be attributed to the limitation of any one industrial organization to incorporate all of the relevant factors in a manner consistent with a more comprehensive approach. One of the goals of the Pb-free Manhattan Project is to integrate the activities around modeling lifetime reliability of Pb-free electronic assemblies in a manner consistent with best know practices.

Various Pb- free consortia have undertaken studies at a considerable cost, designed to narrow the field of acceptable Pb-free material sets, process conditions, and testing environments to demonstrate the comparative effects of assemblies processed under what was then, the best known Pb-free technology. The studies proved effective to a certain degree, and have been used as advantage points for further Pb-free mitigation studies; however, consortium results are largely proprietary and made available to only participating members. Virtually every subject matter expert on Pb-free mitigation technologies, agrees that a more inclusive and thorough roadmap needs to be implemented, but more importantly, orchestrated in an organized fashion to carefully select the appropriate parameters for research, ascertained as critical, by a thorough GAP analysis

Timelines

As noted in the Figure 3.2 risk reduction roadmap, a minimal of three years is a needed for the major mitigation efforts. Chart 3.1 shows the completion of the major projects disseminated down to the subprojects on a 4 year or 16 quarter timescale.

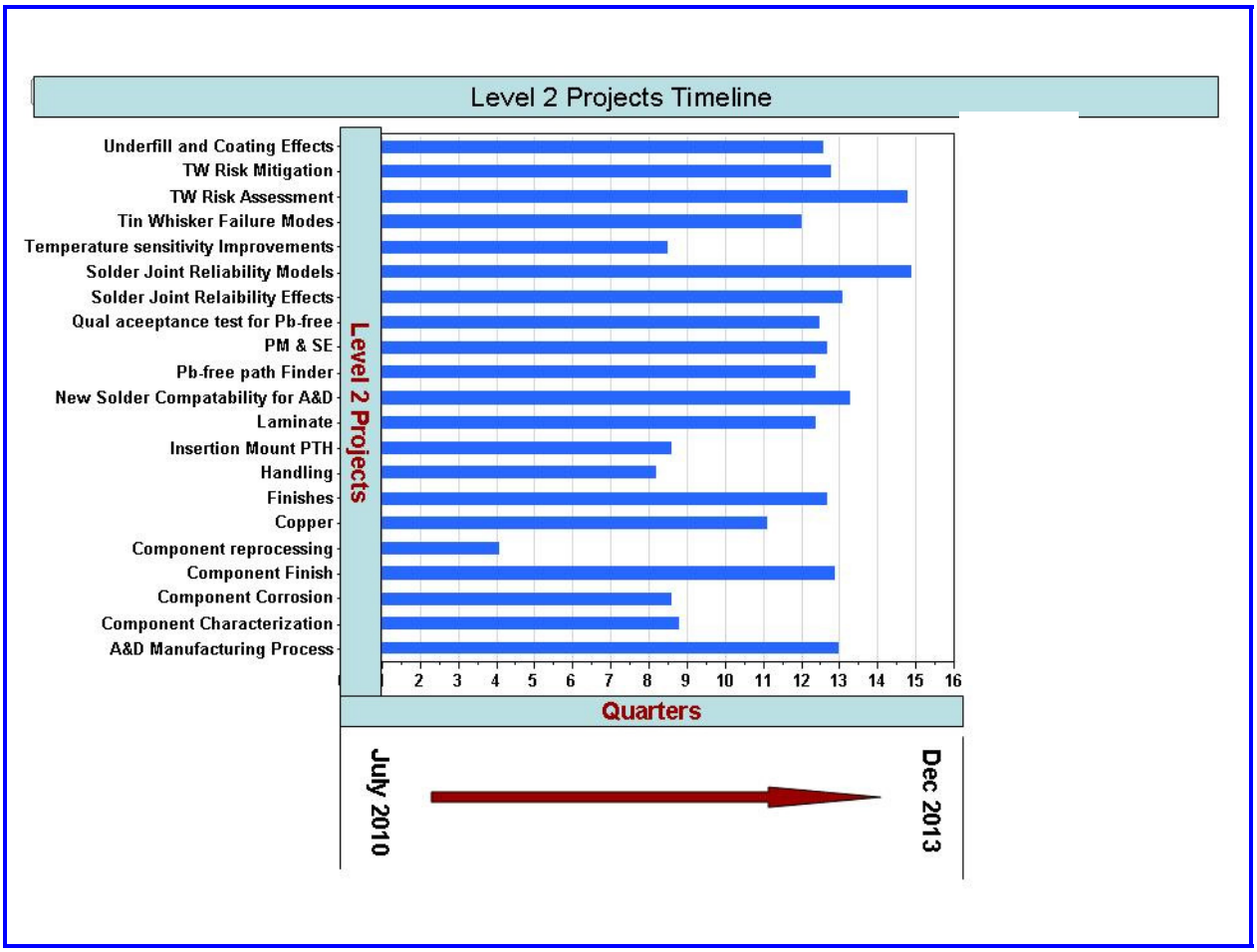


Chart 3.1 - Level 2 project timeline

The WOW Points

Chart 3.2 outlines the deliverable "gold nuggets" that can be extracted from the Phase 3 Pb-free electronics risk reduction efforts. Most of the projects that feed the golden nuggets have multiple project independencies associated with them and rely on predecessors and successor projects to complete or validate the results.

	LFEMP Roadmap
	WOW Points - The Gold Nuggets
Tin Whiskers	◆ Greatly enhanced mitigators for management of tin whisker risks for long term system reliability ◆ Validated Test methods to accelerate tin whisker growth in a quantifiable manner ◆ Validated life prediction tools that permit prediction of parts and assemblies of tin whisker induced reliability
Assembly	◆ A defined set of Pb-free process guidelines for A&D manufacturing ◆ Guidelines for rework and repair of A&D assemblies ◆ Qualification and acceptance test parameters based on field life data ◆ Field performance data for Pb-free assembly
Solder Joints	◆ A qualified set of materials for use in A&D applications ◆ Models for assessing life and reduction in life due to exposure to environmental stress screens ◆ A consistent set of models and data for assessing life expectancy of qualified set of solder materials ◆ Soldered assembly handling guidelines ◆ A material science based qualification method for any Pb-free solder
Components	◆ Receiving inspection guidelines and incoming requirements for components ◆ Methods to assess cost and schedule impact of component refinishing ◆ Storage requirements for unassembled components
Printed Circuit Boards	◆ Design rules for reducing or eliminating CAF in Pb-free electronic designs ◆ Quanitfy critical Pb-free PWB finish attributes after assembly ◆ Review PCB finish solderability and corrosion in the context of Pb-free use in A&D harsh and long term environments for long term sustainment

Chart 3.2 – LFEMP Roadmap deliverables

3.3.3 Cost of Pb-free mitigation to the A&D Industry

Virtually all industries supplying military and mission critical hardware to the DoD have enacted infrastructural changes to accommodate the potential for restricted material entering the product stream. A recent study conducted over the past few years has shown substantial expenditures of resource and investment in this area by individual industry providers. It follows naturally that these Pb-free electronics costs are passed on to the DoD customer in prices of acquired goods.

Cost Drivers:

In this very direct way, the impact of Pb-free mitigation affects the cost of military hardware. The costs incurred by the major OEM's supplying DOD electronic assemblies fall into three categories.

Preventive Measures
To ensure that Pb-free materials do not enter the supply chain in Pb-free restricted projects, most OEM's have implemented a project plan to deal with prohibited materials and are in various stages of completion. It should be noted that the cost of configuration has gone up dramatically. As an example, hundreds of thousands of piece parts have changed from SnPb finishes to pure tin finishes or other Pb-free materials externally, and to Pb-free solders and finishes internally. This puts the burden on OEM's to differentiate between "good "and "bad materials.

Validation of Pb-free Processes
The second category, and complementary to the prohibited material strategy, are the Pb-free transitional projects designed to introduce and validate Pb-free processes into the manufacturing facility. These measures are intended to reduce the cost to the DoD by utilizing COTS materials wherever introduction of these materials is not a liability to performance and reliability. The incurred cost for both prohibited and transitional projects ranges from $10M to $35M for one OEM facility over a 2 to 3 year period (depending on the size of the facility). These costs are subsequently passed on to the DoD in the form of increased product prices.

Non-recurring costs typically amount to 70% of the total cost, which includes capital, labor, and materials for the implementation of a prohibited material process. The transitional cost to a Pb-free process is about 30% of the prohibited material process, but both must be implemented to be effective.

Cost of Confusion
Many "Box" system requirements and piece part specifications were created before the advent and introduction of Pb-free materials into the product mix. Program managers are led to believe that reliability requirements (MTBF, FAA) have been flowed down, as they always have been. However, the basis for making reliability prediction in DoD systems does not exist, and furthermore, the methodologies for making Pb-free reliability predictions have not been developed.

Chart 3.3 is an example of a typical flow chart implemented by many of the DoD providers.

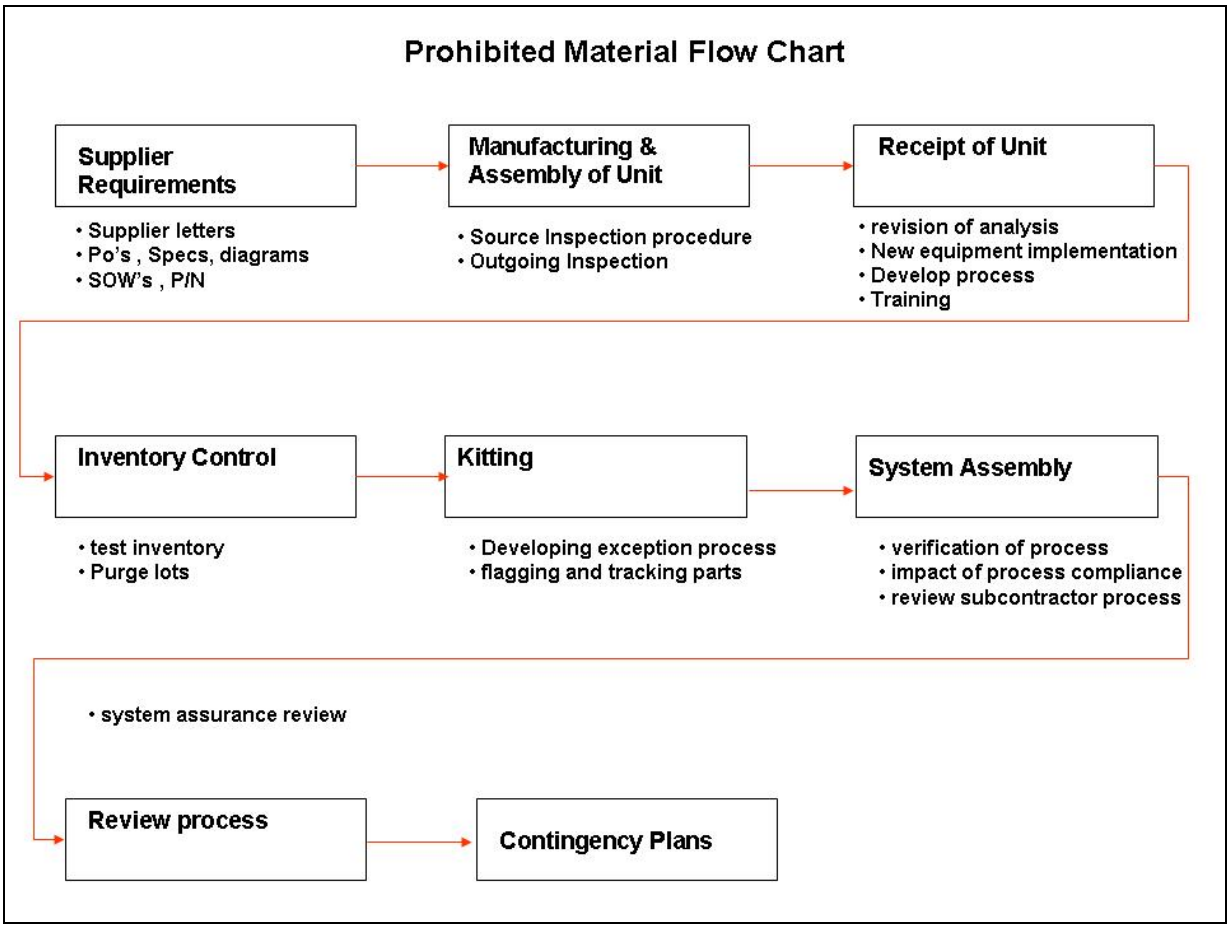


Chart 3.3 - OEM system requirements prohibitive material flow chart

The cost of doing business in Pb-free will revolve mainly around the expenses of prohibited materials and ensuring that suppliers comply with Pb-free restrictions. Because many of the suppliers, both distributors and manufacturers, have changed their COTS availability from SnPb to Pb-free, the sense of urgency by COTS vendors to form cooperative strategies to prevent Pb-free from entering the DoD product stream is not necessarily a top priority.

Chart 3.4 is an example of the mitigation costs implemented by one specific manufacturing facility.

Cost of Lead-Free Mitigation										
			Year 1			Year 2			Year 3	
	hrs	Labor cost	Materials	hrs	Labor cost	Materials	hrs	Labor cost	Materials	Totals
Organizing team	2800	$ 616,000		2800	$ 616,000		2800	$ 616,000		$ 1,848,000
industry participation	10400	$ 2,288,000		16600	$ 3,652,000		24960	$ 5,491,200		$ 11,431,200
Consortium activities	4160	$ 915,200		4160	$ 915,200		4160	$ 915,200		$ 2,745,600
Engineering	1040	$ 228,800		1040	$ 228,800		1040	$ 228,800		$ 686,400
Automation and process control	16600	$ 3,652,000		16600	$ 3,652,000		16600	$ 3,652,000		$ 10,956,000
Whisker Monitoring	2080	$ 457,600		4160	$ 915,200		14560	$ 3,203,200		$ 4,576,000
BOM analysis		$ -			$ -		2080	$ 457,600	$ 175,000	$ 457,600
Lead-free testing	2080	$ 457,600	$ 5,000.00	2240	$ 492,800	$ 45,000.00	2080	$ 457,600	$ 190,000	$ 1,408,000
										$ -
Subtotal	39160	$ 8,615,200	$ 5,000.00	47600	$ 10,472,000	$ 45,000.00	68280	$ 15,021,600	$ 365,000	$ 34,108,800
Total cost		$ 34,639,680								

Chart 3.4 - Example of cost mitigation - OEM

3.3.4 Phase 3 ROM Costs

The approximate cost to resolve the technical gaps in each of the individual areas is outlined in chart 3.5. The collective efforts will take at least three years to complete. The fundamental objective of the Phase 3 efforts, is to resolve the knowledge gaps for the use of Pb-free electronics in A&D products as quickly as possible.

A	Tin Whiskers	$ 6.3	$ 6.8	$ 6.5	$ 19.7
B	Assembly	$ 3.2	$ 4.0	$ 3.0	$ 10.2
C	Solder Joints	$ 13.9	$ 19.4	$ 13.3	$ 46.6
D	Components	$ 1.2	$ 2.6	$ 2.1	$ 5.9
E	Printed Circuit Boards (PCBs)	$ 3.9	$ 5.2	$ 3.5	$ 12.6
	TOTAL	$ 28.5	$ 38.0	$ 28.5	$ 95.0
	Total with 10 % Contract Administration Cost	$31.4	$ 41.8	$ 31.3	$ 104.5

Chart 3.5 - Phase 3 ROM cost estimates

The Observations from the project cost analysis indicated:

- The Pb-free electronics technical knowledge gaps & risks for A&D applications are bigger than anticipated, impacting the Risk Reduction Program cost
- The resulting ROM cost estimate is higher that expected, but is not unreasonable based on the scope of the required 36-month risk reduction effort

Chart 3.6 shows the percentage of resource distributed for each major (Level 1) technical area for the implementation of projects during the three year duration of the Phase 3. The PM-SE section indicates the allocated distribution of program management and system engineering distributed across the three year project cycle.

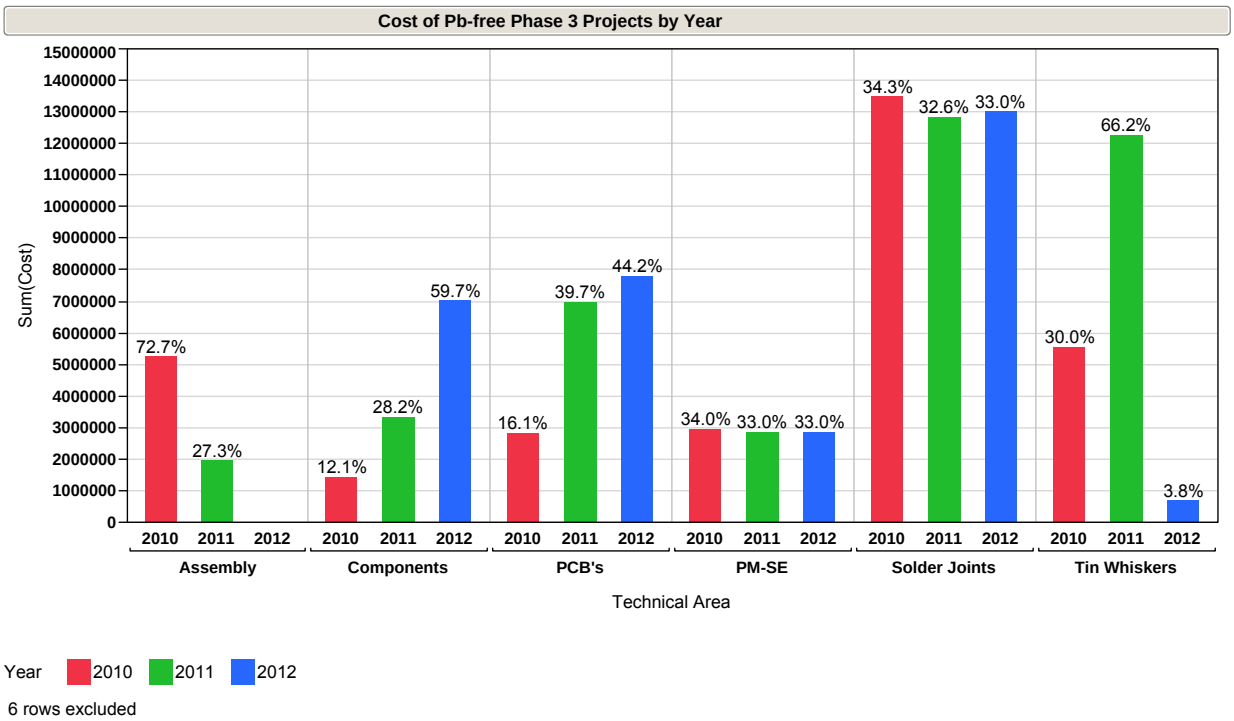


Chart 3.6 - The cost of Phase 3 projects within each major technical area

The timeline for these events may extend into a three and half year period to produce the final reports from each of the respective technical areas by the centralized program management team.

The Level 2 costs are further disseminated in the graph below (Chart 3.7) in the form of a Pareto chart. It can be seen that the development of solder joint reliability models, followed by tin whisker risk mitigation, requires the most resource to adequately address the underlying pervasive issues in the Pb-free mitigation efforts. It is important to note that each Level 2 technical area is supported by subprojects in Level 3. The number of projects associated with each level 3 project is notated in the chart. As mentioned previously, in some cases, 5 levels of detail are needed to delineate the specific tasks for each project. For simplicity sake, only level three projects will be detailed for this report.

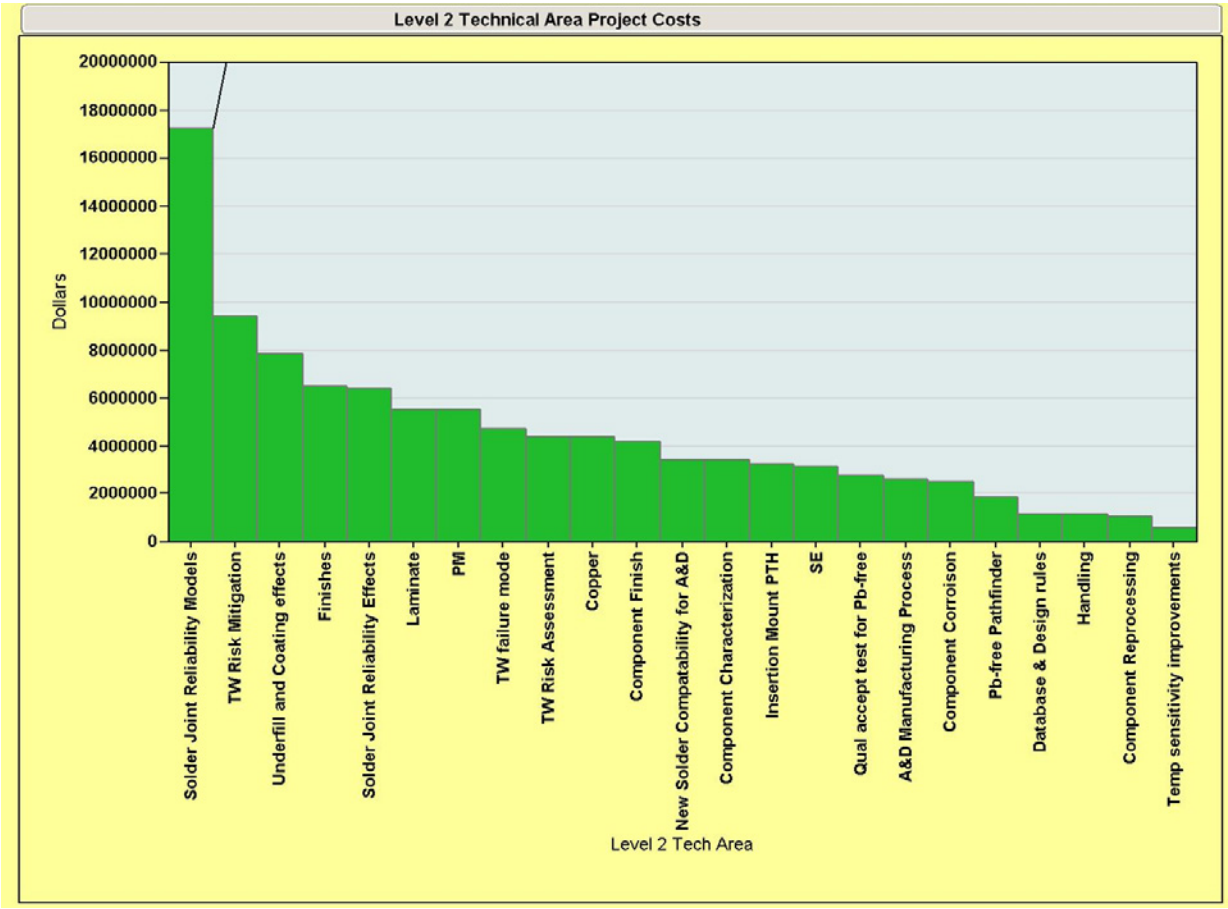


Chart 3.7 – The cost of phase 3 projects within each level 2 technical area

3.3.5 The Cost of Retaining SnPb

The cost of identifying the current production impact has been massive. An estimation of $54M or 270,000 labor hours will be required on current and legacy assemblies to evaluate the proximity of tin to adjacent conductors. An example of one part change is shown below in Figure 3.5

- **OnSemi Product Change Notice (PCN)**
  - Product Change Notice PCN 16389
    - 4Q09 (4th QUARTER 2009) Product Discontinuance Notice
    - LAST BUY DATE: 21-Jul-2010
    - LAST SHIP DATE: 21-Jan-2011
  - 672 parts obsolete
    - 456 parts have a pure tin finish replacement
    - 96 parts have no replacement
    - 120 Pb-free parts have another Pb-free replacement
  - 60 of the 672 part numbers are used in production
    - Matte tin, JESD 201 class 2 tested
    - None have a nickel underplate
    - 23 parts have Tin over copper
    - 35 parts have Tin over Alloy 42 (Fe42Ni)
    - 2 unpublished base metal

			PLATING							
			Sn [%]	Pb [%]	Ag [%]	Cu [%]	Pd [%]	Au [%]	Ni [%]	Weight [mg]
Base part	Part	Status	7440-31-5	7439-92-1	7440-22-4	7440-50-8	7440-05-3	7440-57-5	7440-02-0	
1.5SMC47A	1.5SMC47AT3	Lifetime	80.00	20.00						2.51
1.5SMC47A	1.5SMC47AT3G	Active	100.00							2.51
	SZ1.5SMC47AT3	Obsolete	80.00	20.00						2.51
	SZ1.5SMC47AT3G	Active	100.00							2.51

- **PCN estimated to impact 27,000 assemblies**
  - **With multiple parts typically used on each assembly**
- **One part with high usage**
  - **Used on 1908 assemblies**
  - **Impacting 105 programs and/or program variants**

Figure 3.5- Product Change Notice Cost

The combined current annual spending for the eight large industry OEM's for mitigation investments has approached about $12M a year. This figure does not represent the reoccurring and non reoccurring cost for implementation of Pb-free mitigation measures in the respective manufacturing facilities.

DoD and COTS electronic dependency

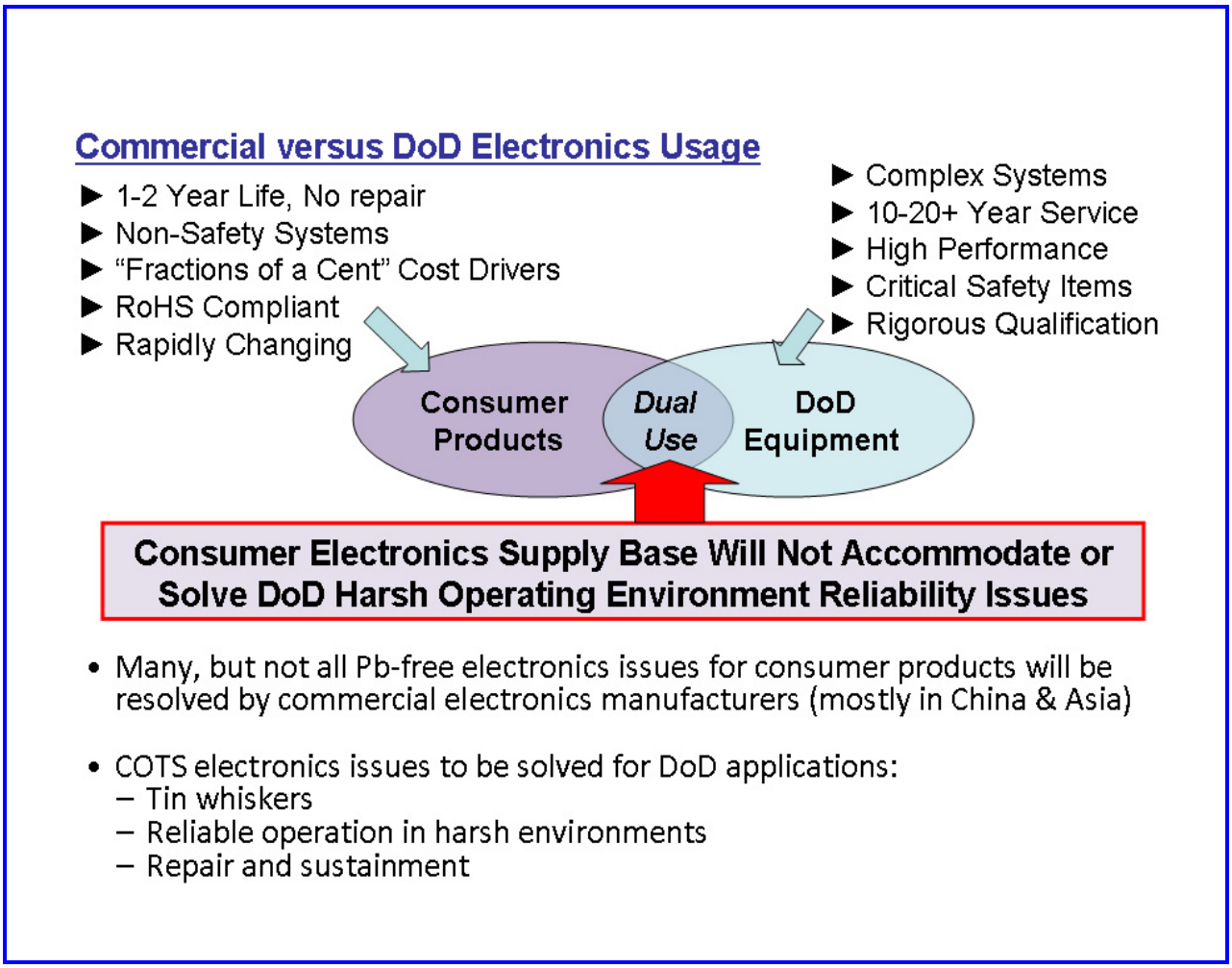


Fig 3.6 - The requirements of DoD versus COTS

The impact of the Pb-free transition extends beyond the component configuration issues to performance requirements that are considerably more stringent for the DoD as outlined in Figure 3.6. Component distributors have frequently not differentiated between similar components having different lead finishes. This has prompted contract manufactures to diagnostically check all component lead metallurgy to ensure compliancy to RoHS, and conversely, as a mitigation effort to prevent the introduction of Pb-free components into the A&D product stream. The cost of regulating in-coming materials constitutes a large portion of the overall Prohibited Material process flow, followed by inventory testing, and the subsequent purging of Prohibited Material lots identified. The recurring cost estimates should diminish over time as the transitional process becomes more mature and high risk commodities are purged from the inventory.

DoD Return on Investment Analysis

The cost of inaction to properly mitigate the introduction of Pb-free materials can be potentially substantial (Figure 3.7) on A&D systems if the current issues around tin whiskers and reliability are not resolved.

Forecasted Future Annual DoD O&S Repair Cost from Pb-free Electronics Failures

(Does not include mission impact cost or loss of platforms)

- **Current Defense Electronics Infrastructure: ~$50B fielded inventory**
  - **Defense electronics procurement of $10B/year with electronics average life >5 years = $50B**
  - **>5M LRUs fielded at an average value of <$10K = $50B**

- **Assumptions**
  - **Additional 1% failure rate per year without R&D mitigations**
    - **"One OEM has recently indicated privately that their returns are already up more than 3% compared to products produced with traditional solders"** - Global SMT & Packaging, April 2006
  - **$1K repair cost per LRU failure**
  - **All failed Pb-free LRUs are repairable**

- **Increased Repair Cost at Full Pb-free Electronics Introduction: $50M/year**

Figure 3.7 - Cost of Pb-free failures

Things never seen before with Pb-free

More work has probably been done characterizing the bulk physical properties and behavioral attributes of Pb-free solders than any other aspect of the Pb-free transition. Some general characterizations can be made on the subject.

- Most Pb-free alloys that are applicable for electronic packaging have higher melt points than the eutectic SnPb
- Many of the Pb-free alloys are non-eutectic, and therefore the individual solder constituents will reach liquidus and solidus phases at different rates
- This creates possibilities of varying intermetallic compound (IMC) formations (Figure 3.8), both compositional and quantitatively. For tertiary compounds, the IMC formations can be complex and difficult to characterize
- Some of the visual techniques used to characterize morphological changes to the crystalline structure of SnPb after environmental stressing, can not be used for Pb-free alloys

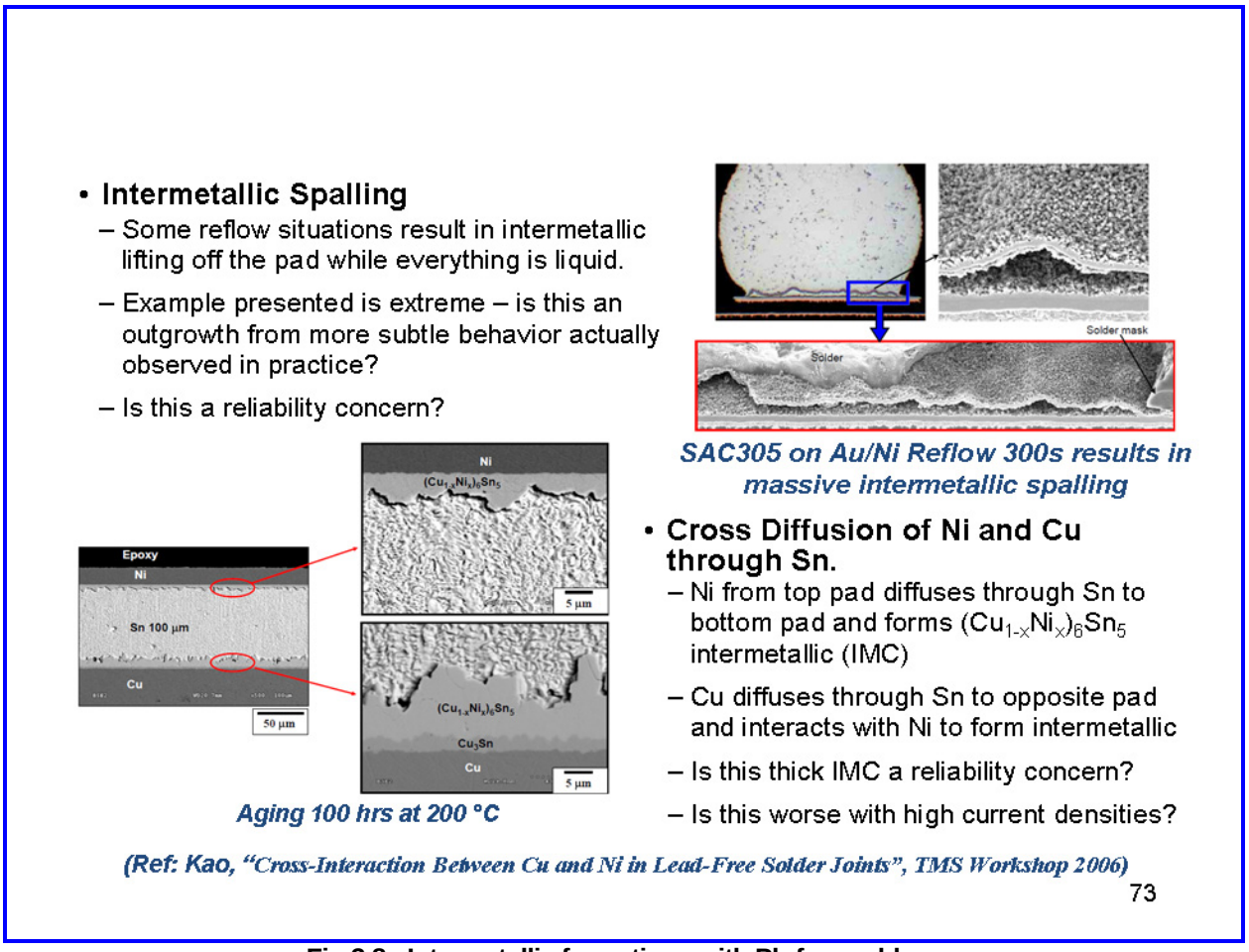


Fig 3.8 - Intermetallic formations with Pb-free solders

Intermetallic structures in solder joints are intrinsic and necessary to the formation of a reliably strong bond between the solder and the connective joint, or pad. Without the complex interaction of metals forming the physical structures responsible for the "adhesive" properties of the alloy, there would be a lack of anchoring sites needed for proper bonding. Compositionally, the intermetallics arise from the elemental constituents of the alloy into a variety of oxidation states, which migrate during the various stages of heating and cooling. As a consequence, the same mechanisms responsible for creating a robust connection can also result in the development of joint embrittlement. In the case of Pb-free, a whole new array of intermetallic possibilities have been introduced, along with the embrittlement potentials (Figure 3.9).

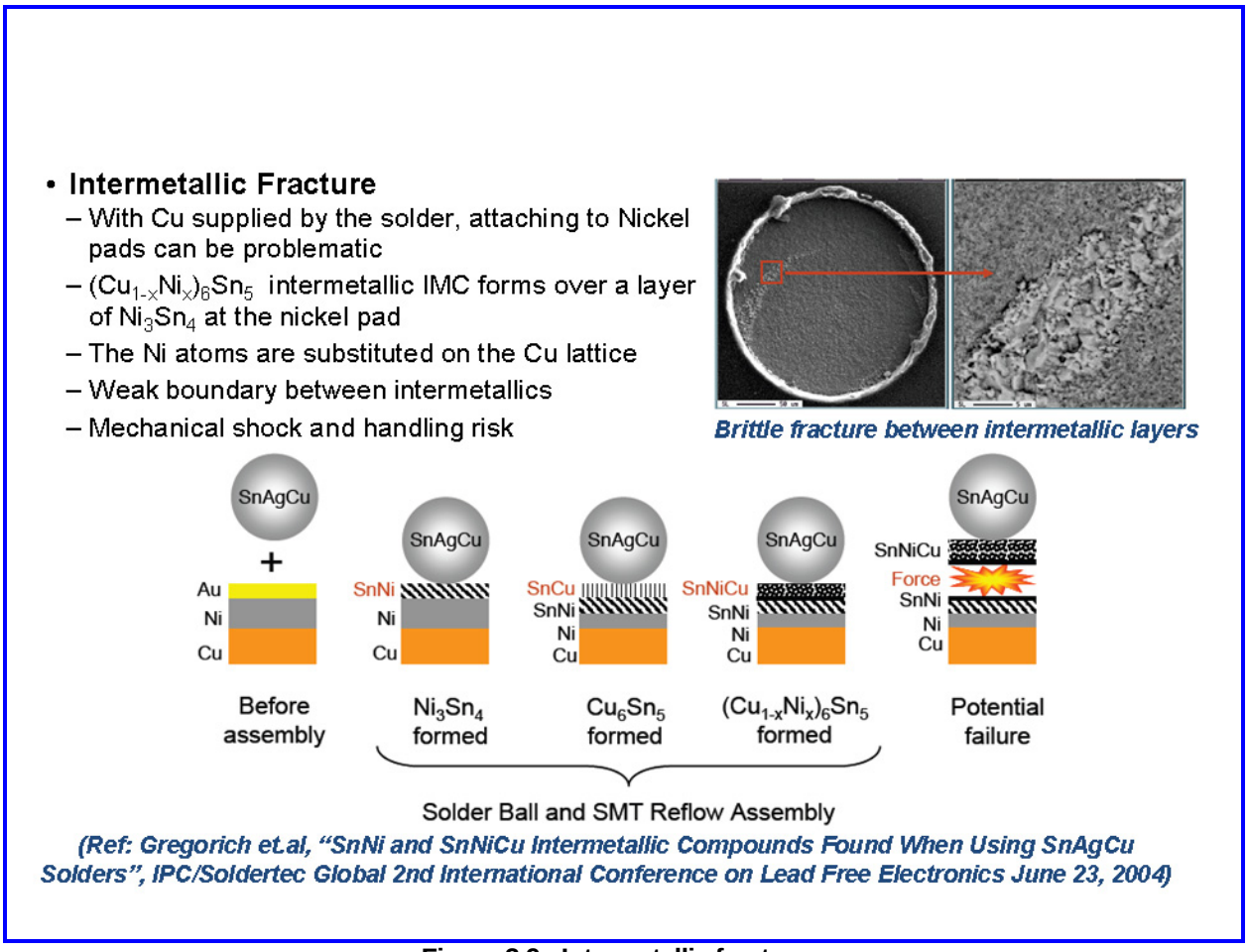
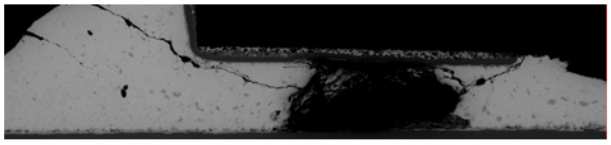


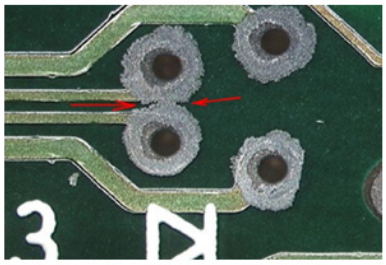
Figure 3.9 - Intermetallic fractures

Solder voids are much more prevalent using Pb-free solders, than SnPb. This seemingly intrinsic manufacturing flaw may meet the IPC 610 solder voiding spec, but the detrimental effects may manifest themselves under Pb-free accelerated conditions (Figure 3.10) that may be difficult to detect during typical environmental stress screening. Additionally, the introduction of immersion silver as a major PCB finish has exacerbated the concerns for silver migration and tin whiskers.

- **Solder voids suspected to significantly reduced thermal cycling life.**
  - Failure occurred after 85 cycles (approximately 5 days of accelerated thermal cycling)
  - Will SnPb environmental stress screening be effective for Pb-free?
  - What about other Pb-free alloys?
  - What about vibration and shock?



Sn0.7Cu0.5Ni0.05Ge chip resistor cross-section after thermal cycling. (Ref. CALCE)



Schueller, "Creep Corrosion of Lead-Free PCBs," SMTA Conf. Proc. 2007

- **Silver + Sulfur = Corrosion**
  - Immersion silver is a leading Pb-free circuit board finish
  - Concerns in sulfur and high humidity environments include Cu corrosion, electrochemical migration and silver whiskers
  - Will existing MIL-STD-810 salt fog tests catch this?
  - MIL-STD-810 does not include sulfur environments

Fig 3.10 – Potential voiding and corrosion issues with Pb-free

Many of the standard coating conformal coating materials have been established for a number of years. Research and investigations have found that tin whiskers have the capability to breach the coatings (Figure 3.11), especially in areas where the deposits are thin. There are other promising coating materials and deposition methods that show the potential to mitigate the advancement of tin whisker growth, but the cost is still prohibitive for a mainstream process and the manufacturing readiness level is still not yet mature.

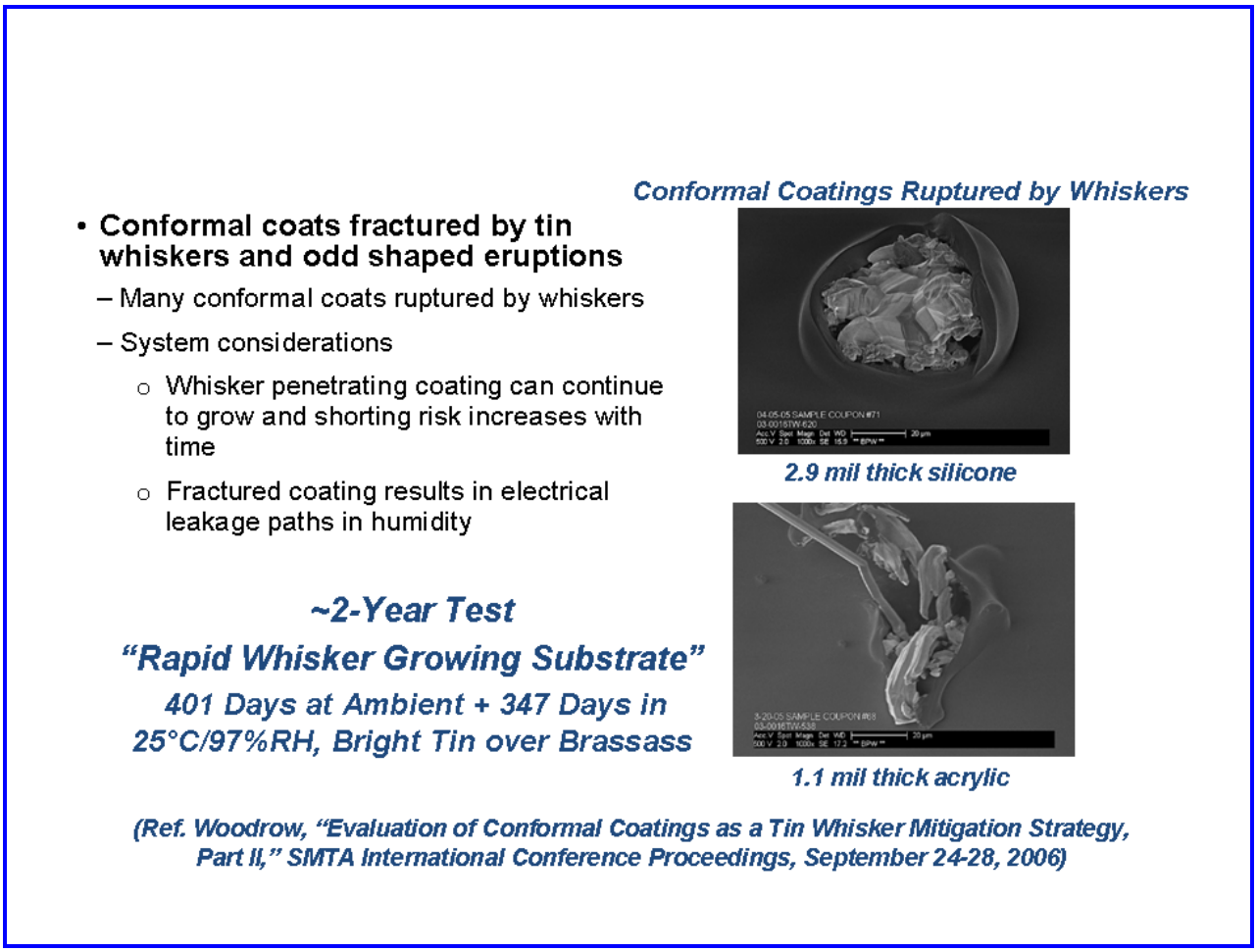
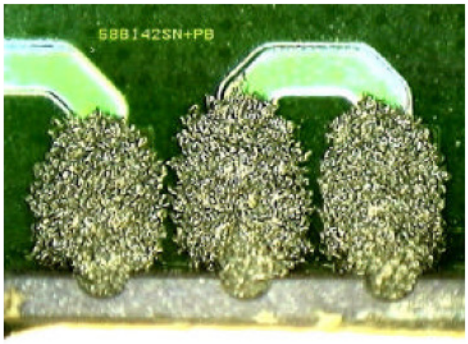


Fig 3.11 Tin whiskers rupturing the conformal coating

An unintended consequence of the elimination of Pb from the electronic assembly product stream, is that small incremental traces of Pb and bismuth containing Pb-free alloys can produce a low melting ternary alloy with an unacceptably low eutectic temperature. This has resulted in catastrophic failure during environmental testing (Figure 3.12).

- **Mixing SnPb alloys with Bismuth bearing Pb-free solder joints can spell trouble**
  - Trace amounts of lead (Pb) can decrease the reliability of bismuth–containing solders
  - The effects of trace amounts of lead on 58Bi42Sn are catastrophic
    - Solder joints essentially turned to powder during thermal
  - **Important because SAC Bismuth alloys have demonstrated the best reliability**
  - **DoD sustainment infrastructure will have SnPb for many more years, probably forever**



58Bi42Sn Joints contaminated with Pb (after 835 Thermal Cycles -55 to +125 °C) Suspect issue with SnPbBi ternary eutectic (T_{melt} = 96 °C)

(Ref. Woodrow, "The Effects of Trace Amounts of Lead on the Reliability of Six Lead-Free Solders," IPC Proceedings of the 3rd International Conference on Lead-Free Components and Assemblies, San Jose, CA April 23-24 (2003)

Fig 3.12 - Bismuth alloys with traces of Pb

Things that have challenged us before with SnPb

Electromigration due to increased copper dissolution (Figure 3.13), especially at higher current densities experienced with smaller joints, has been a problem with both SnPb and Pb-free. The dissolution with Pb-free solder is worse than heritage SnPb solder because of the higher processing temperatures associated with Pb-free solder and greater solubility limits of copper in Pb-free solder. The heritage SnPb design rules for surface copper and plated through holes are insufficient for Pb-free use in A&D products that must be capable of long-term service, rework, and repair.

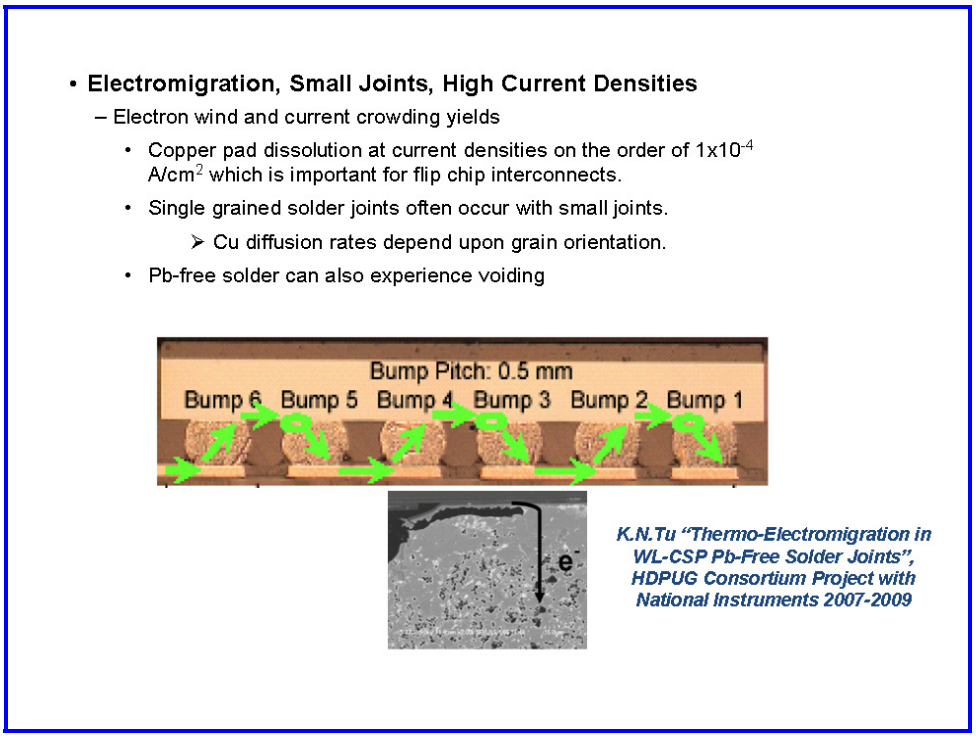


Fig 3.13 - Electromigration

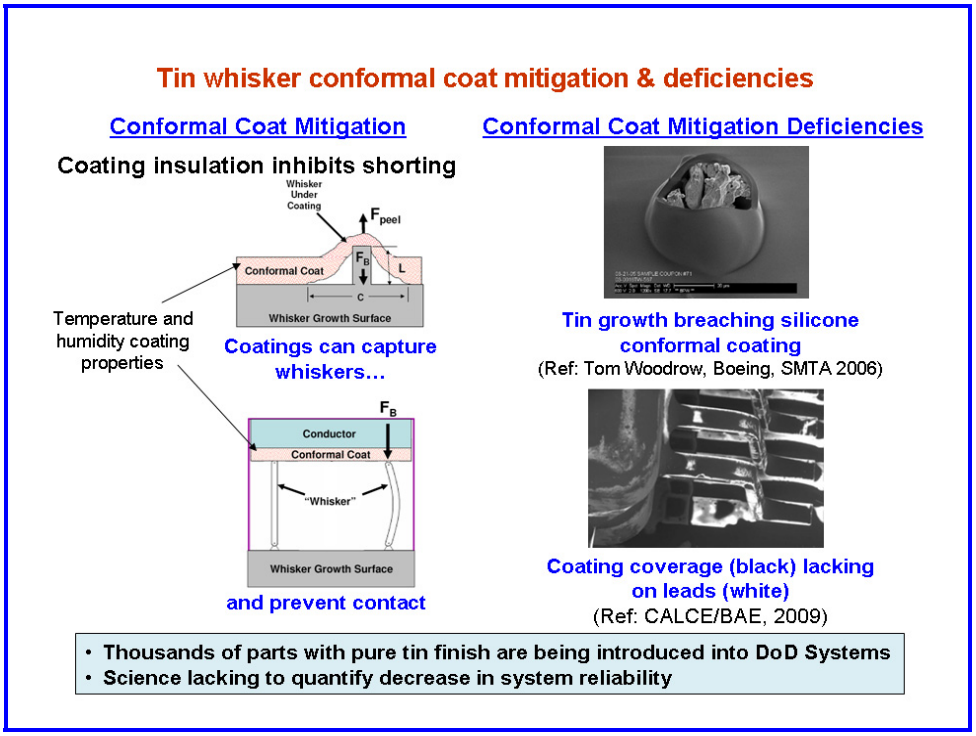


Figure 3.14 - Conformal coating issues

Conformal Coating issues have been prevalent even with SnPb solders to prevent the growth of whiskers. Whiskers have been known to grow through various types of coating (Figure 3.14) and are exacerbated with the increased incidence of Sn based finishes. The addition of Pb to solder has a mitigating effect in curtailing the length of the whiskers.

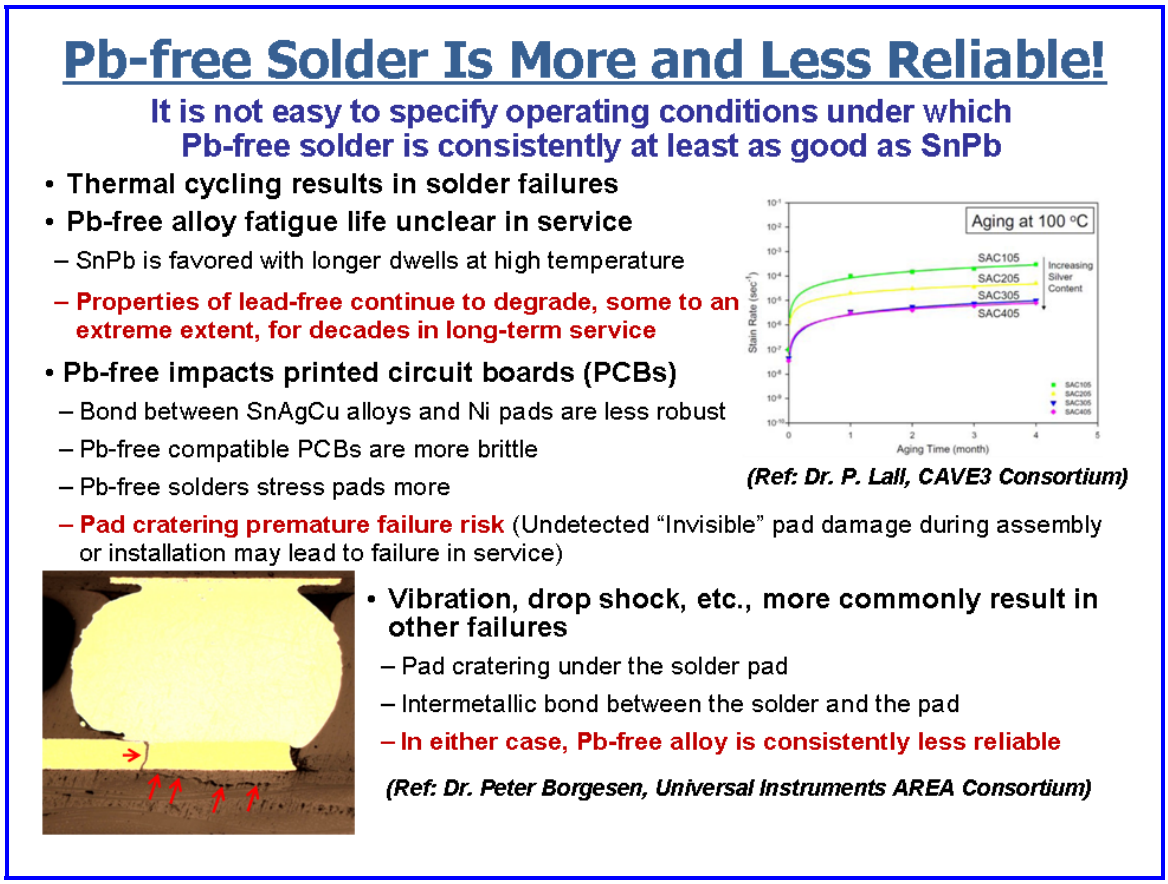


Figure 3.15 - Pb-free reliability

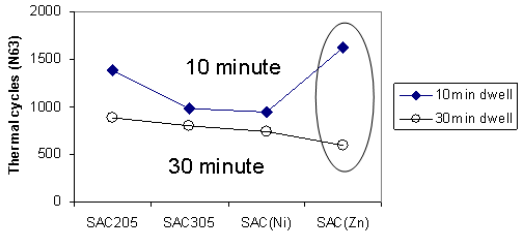
Predicting Reliability

The correlation of Pb-free alloys to SnPb alloy solder joint reliability is controlled, in part, by the mechanical creep properties, which are quite different between the two, and usually vary from one Pb-free alloy to another Pb-free alloy. The elastic behavior and hysteresis are also substantially different and behave in a non-linear fashion. These differences contribute to specific uncertainties in the attempt to determine the appropriate factors for simulation of long term reliability. Thermal cycling and shock are cases where Pb-free alloys do not behave consistently (Figure 3.15).

Importantly, the design community must consider interfacial brittle fractures associated with Pb-free assemblies that generally do not exist with the softer, more compliant SnPb solders. With such a broad range of metallurgical selections for solder, PCB finishes, substrates, component types, and component finishes, there is a need to extract reliability information to pose as a guideline for Pb-free packaging at various levels. The matrix of packaging possibilities and materials highlights the fact that predicting reliability (Figure 3.16) involves greater complexity over that of SnPb.

Predicting Reliability

- **SnPb materials properties are largely independent of joint size**
  - Vast accelerated test data bases could be scaled onto 'Master curves' based on modeling of mechanics
  - Decades of field experiences offered sanity checks for extrapolations of test data
- **Lead free solder properties vary with joint size, processing, history, and alloy dopants**
  - 'Master curves' are missing or misleading
  - No field experience to offer verification…First alloys have only been in service for a few years and are already being displaced by newer ones



- **Models can't even interpret comparisons**
  - Current thermal cycle models cannot account for one SnAgCu alloy being **best** in test with 10 minute dwell but **worst** with 30 minute dwell
  - **Depending on service conditions predictions of current models may easily be in error by 1-2 magnitudes (life of 1 year vs. 100 years)!**

Predicting Reliability (Cont'd)

- **Errors may be *even greater* because of aging & cycling effects**
- **Also not accounted for:**
  - Ongoing coarsening of secondary precipitates gives strong solder properties changes
  - Strain enhanced coarsening and dislocation structure formation make properties vary with joint location
- **Cannot rely on Mil-HBK-217, Military Handbook for "Reliability Prediction of Electronic Equipment" to assess system reliability**
- **As of January 2010, technical consensus lacking to complete draft GEIA-HB-0005-4, "*Reliability Assessment for Aerospace and High Performance Electronics Containing Lead-free Solder*"**

"It is the judgment of the team that the use of Pb-free electronics in products whose life-cycle includes operation in and through harsh environments, poses technical risks that can lead to degraded reliability and reduced lifetimes. Quantification of these technical conclusions within valid statistical confidence bounds remains a gap. Further reliability data is needed in order to unite the existing prediction methodologies, and provide acceptable modeling accuracy."

– Manhattan Project Phase I Report, December 2009

Fig 3.16 - Predicting Reliability

Qualification Protocol

There are no qualification protocols (Figure 3.17) designed to validate the effectiveness and reliability of a Pb-free design or material against the previously used SnPb assemblies. Because of the fundamentally different material characteristics between SnPb and Pb-free, there is no certainty that the robustness of A&D products assembled with Pb-free will equate to SnPb.

Qualification Protocols

No validated lead-free electronics qualification methods

- **Qualification is used to compare to previous design or material**
  - Just as good, or good enough **in terms of robustness or life in service**
  - Decades of experience and reproducibility of SnPb properties offer some degree of confidence **for SnPb**
  - However, **current lead free solders are fundamentally different**

Using existing SnPb electronics qualification protocols for Pb-free electronics will yield erroneous reliability and service life predictions

- **Qualification for Pb-free should consider:**
  - Joint composed of 1-3 Sn grains: **extreme anisotropy** results in strength and failure distribution outliers **unlikely to be captured** by current empirical sampling
  - Comparison of alloys and processes varies with thermal cycling conditions
  - **Effects of aging** on vibration and shock vary strongly among Pb-free alloys

Qualification Protocols (Cont'd)

- **PCB robustness qualification of new lead-free compatible laminates should consider:**
  - Temperature, aging and humidity changing properties
  - Latent failure risk of repairs
- Realistic **service** environments all involve **combinations of loading**, and **damage doesn't add up** (commonly much greater or smaller than predicted)

Life of SnAgCu Joints in Vibration

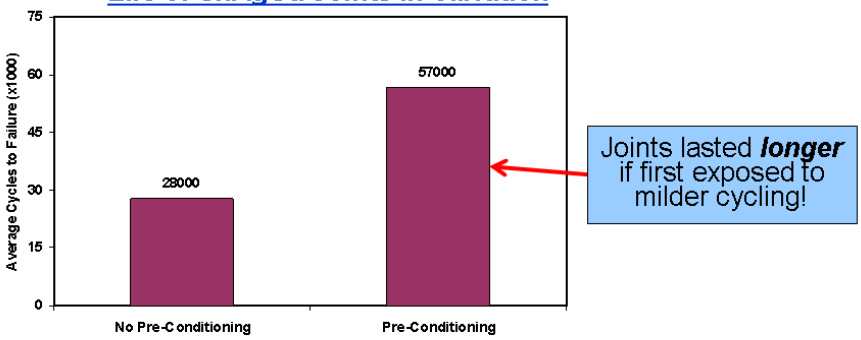


Figure - 3.17 - Qualification protocol

Component Issues

Generally speaking, in addition to the various component attributes (Figure 3.18), the reliability of component connections are confounded by the other factors such as board finish, substrate materials, solder selection, environmental conditions, and manufacturing process parameters.

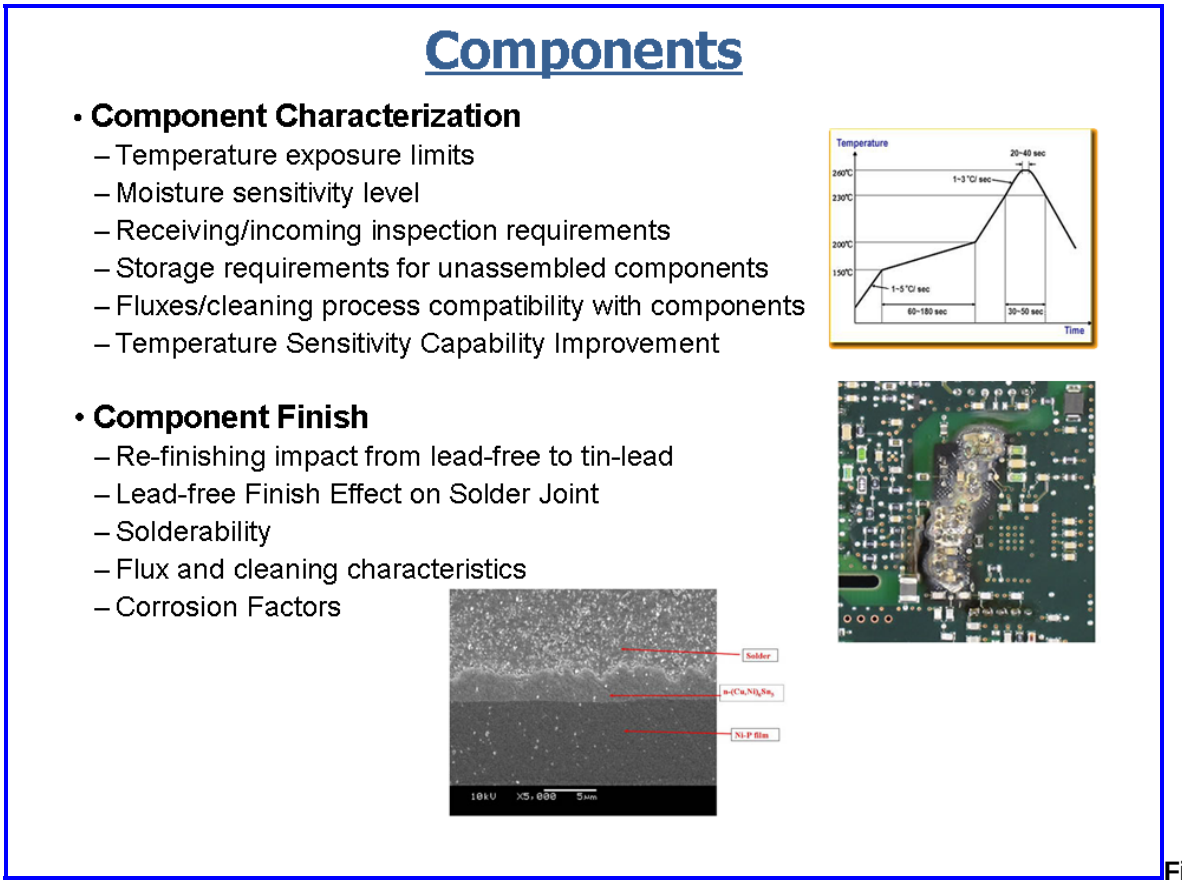
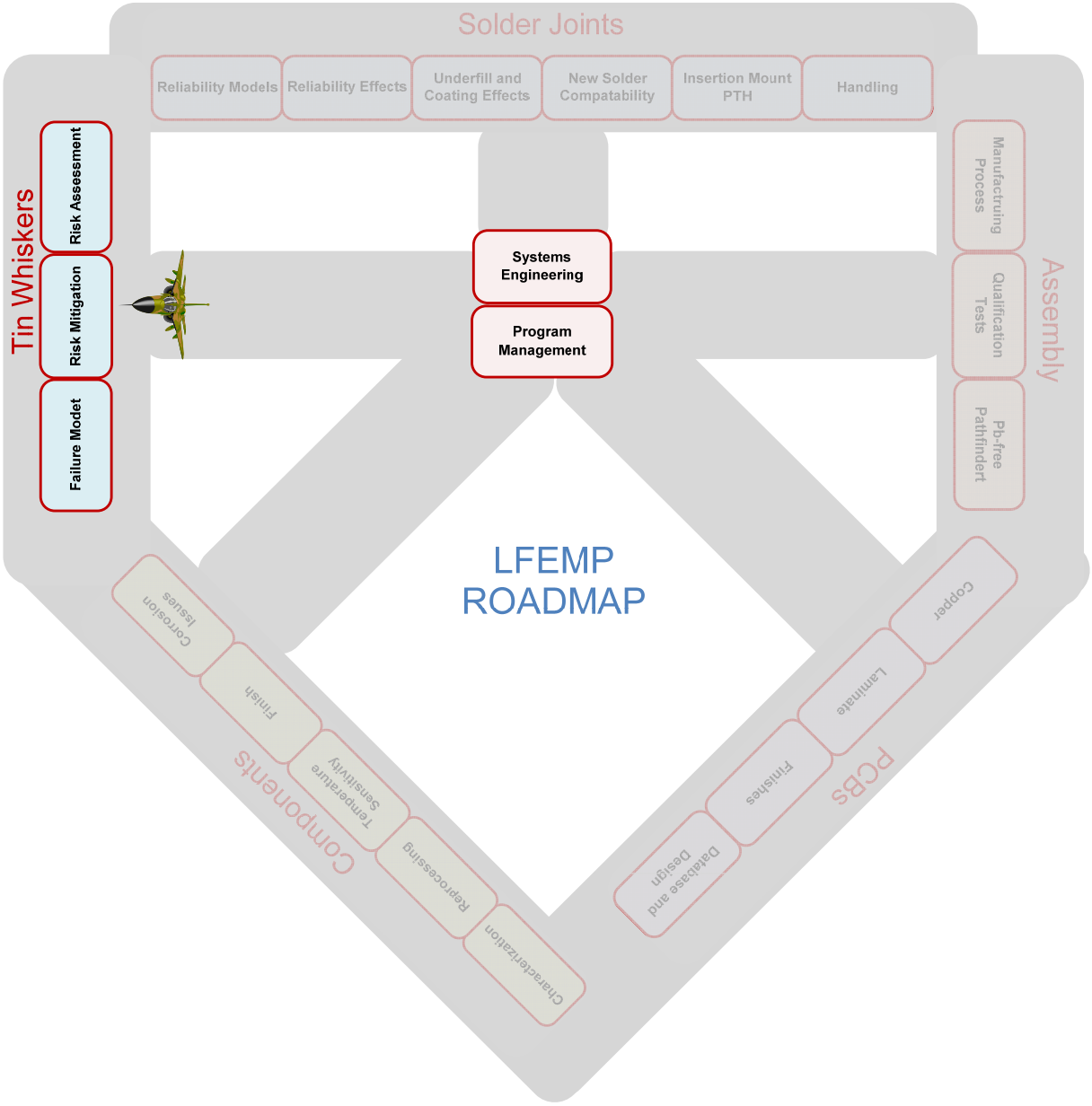


Fig 3.18 - Component issues

3.4 Tin Whiskers



3.4.1 Summary Description

The greatest reliability risks associated with lead-free electronics are the formation of tin whiskers, solder joint failures due to mechanical vibration and shock, and the lack of validated models required to design tests and predict field lifetimes for these failure modes. A lack of these validated test procedures are exacerbated by the harsh environments of A&D applications and by the impact of failure on critical systems.

The formation of tin whiskers threatens the reliability of A&D systems that use Pb-free surface finishes and solders. Current tin whisker testing methods cannot predict whether a finish or solder will grow tin whiskers, nor can they identify what additional whisker mitigation strategies are needed for a particular part or assembly. Existing strategies are only partially effective, leaving a significant gap with respect to protecting the most vulnerable circuits.

A comprehensive approach to design rules for tin whisker mitigation is needed that includes strategies from circuit analysis, design, and component placement, to the tin material behavior, the component mitigations used, and board-level mitigation such as coatings applied directly to assemblies. Reliable whisker test methods for parts and assemblies, mitigation strategies, and a lifetime prediction model need to be developed based upon a fundamental knowledge of the relationships between whisker formation and the parameters that are under the control of the A&D industry. A direct linkage between field failure root cause analysis, lifetime prediction models, test methods, and design rules will be essential to assess the validity of such tests and models. The expected result of the R&D program area described here is a significant reduction in risk of tin whisker-induced failure in A&D applications.

3.4.2 Technical Brief

Tin whiskers have been a known source of reliability issues for a number of years. A massive amount of effort has been initiated in predicting, preventing, or mitigating the growth of tin whiskers. The rapid transition of electronics to tin rich Pb-free solders and finishes, and the miniaturization of electronic circuitry to fit smaller and smaller devices, increase the likelihood of the occurrence of tin whiskers causing malfunctioning equipment in A&D related programs. There is a great degree of knowledge on the various attributes of tin whiskers, but some of the fundamental science still needs to be explored and a concerted effort to bridge the existing gaps in whisker mitigation techniques need to be addressed.

The knowledge of the fundamental growth mechanisms and failure modes will be a critical input to create valid test methods for screening parts and assemblies for whisker risk. This will determine which assemblies and what levels of additional tin whisker risk mitigation is needed. The materials, part manufacturing processes, and assembly, rework, and repair conditions that create different levels of risk for Pb-free parts and assemblies, will be identified.

Examples of Tin Whiskers

Figures 3.19 to 3.24 show examples of tin whiskers that have caused electrical shorts.

- Figure 3.19 shows tin whiskers on tin plated connector pins
- Figure 3.20 shows a tin whisker coming from a tin plated shield near connector pins
- Figure 3.21 shows tin whiskers bridging between a tin plated bracket and a plated through hole component
- Figure 3.22 shows a whisker from a tin plated lead that shorted to the case
- Figure 3.23 shows a whisker in an oscillator, bridging between the crystal and the side wall
- Figure 3.24 shows a cross-section of a whisker and a hypothesis is proposed on how the whisker is formed through compressive stress

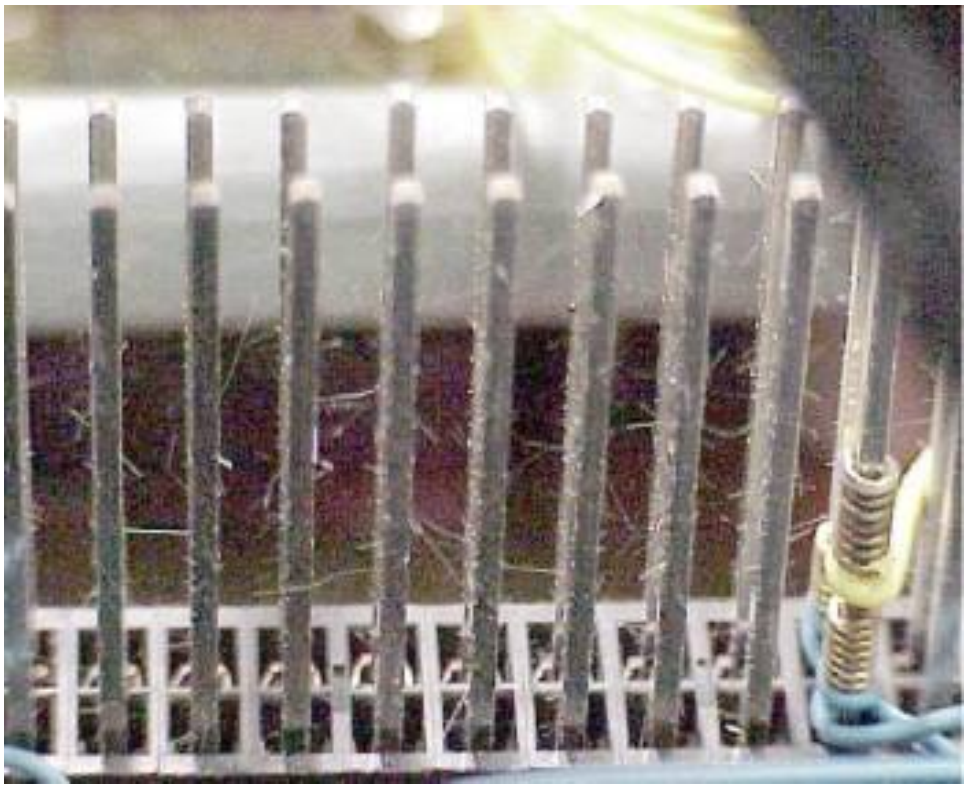


Figure 3.19 - Pure tin plated connector pins after 10 years in the field (Reported in 2000; Courtesy of NASA Goddard)

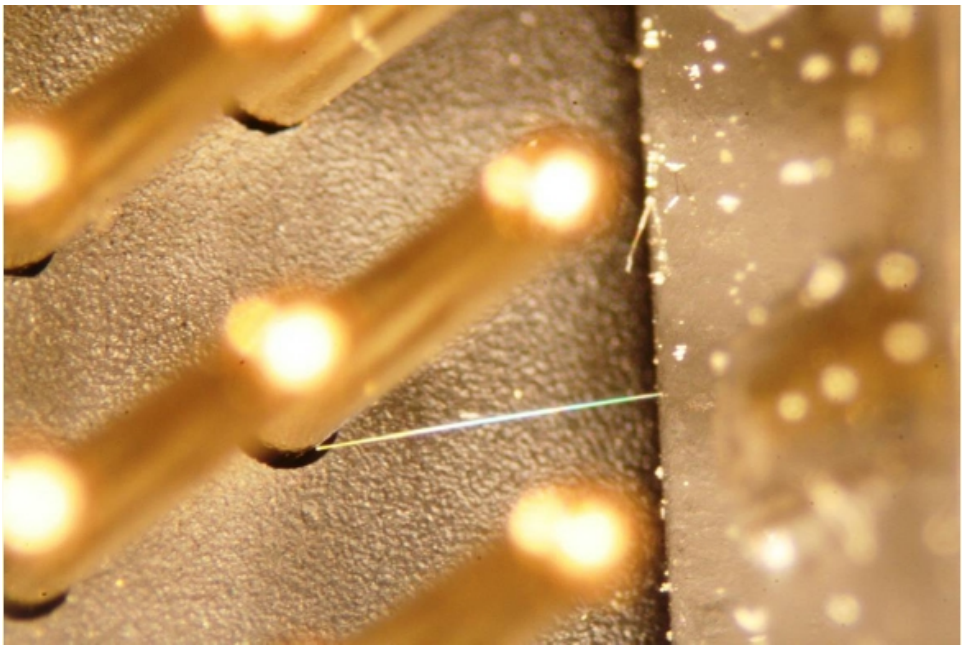


Figure 3.20 - Actual whisker short caused by growth from the bright tin shield on a D-Sub connector Bright Ni should be used for connector shields (courtesy of Emerson)

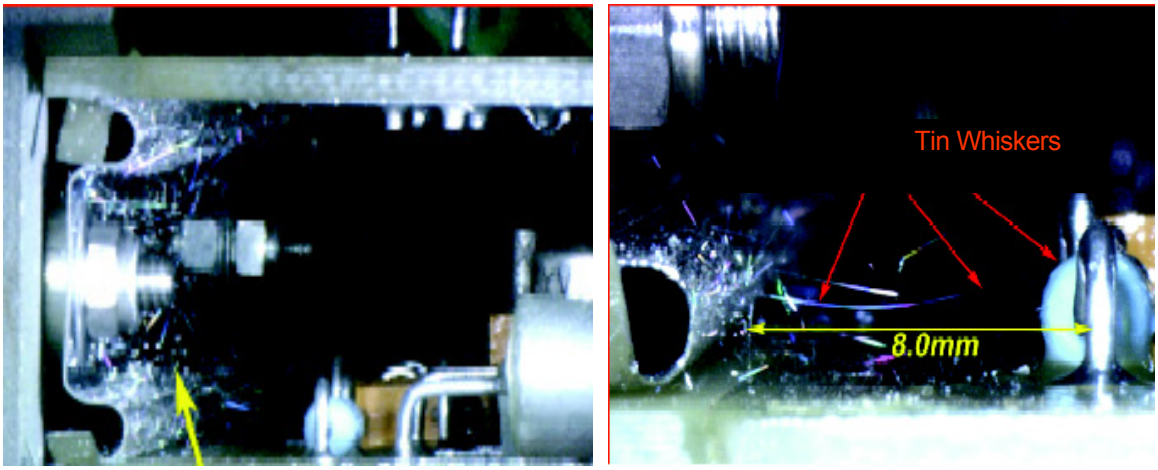


Figure 3.21 Tin whiskers bridging between a tin plated bracket and a plated through hole component (H. Leidecker, J. Brusse, "Tin Whiskers: A History of Documented Electrical System Failures", Technical Presentation to Space Shuttle Program Office, NASA April 2006.)

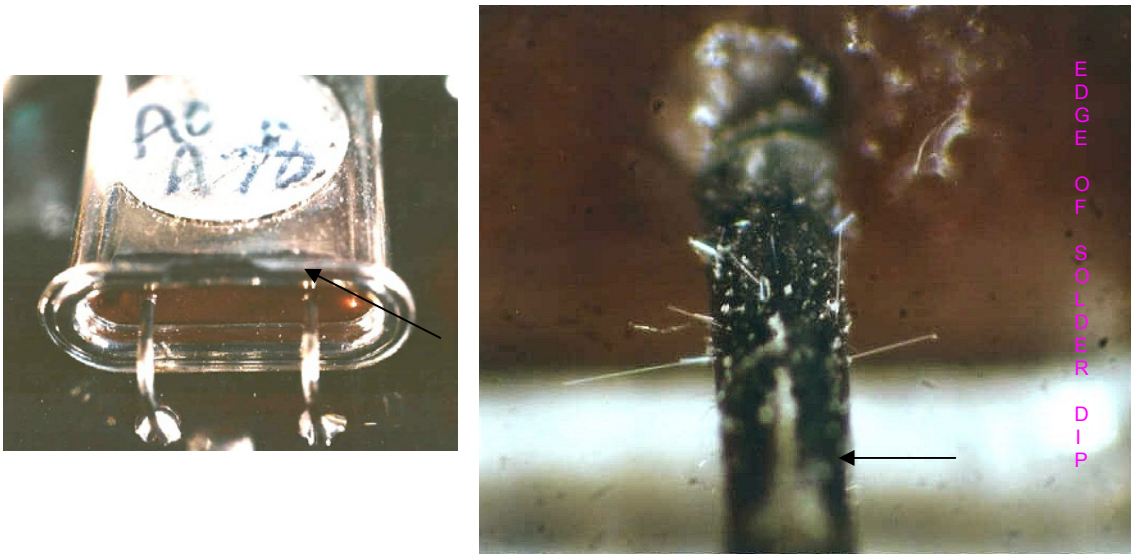


Figure 3.22 - Tin whisker growth noted from seal to about 20 mils from edge of solder coat Electrical failure was traced to a 60 mil whisker that shorted the lead to the case

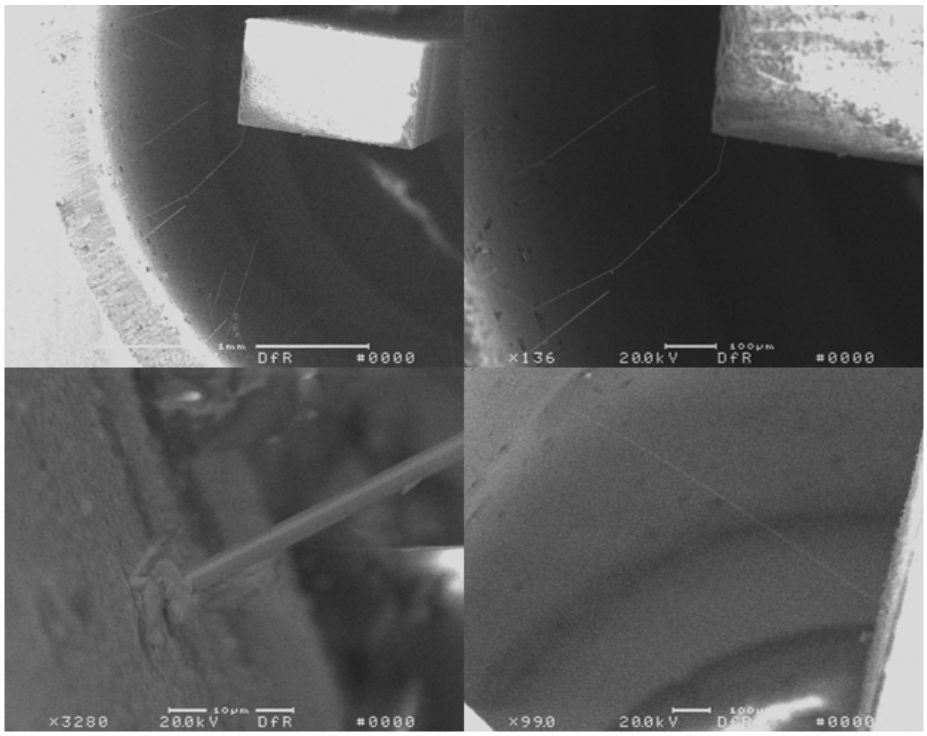


Figure 3.23 - SEM images of an oscillator in which one tin whisker is clearly bridging between the side wall and the crystal (Courtesy of DfR Solutions)

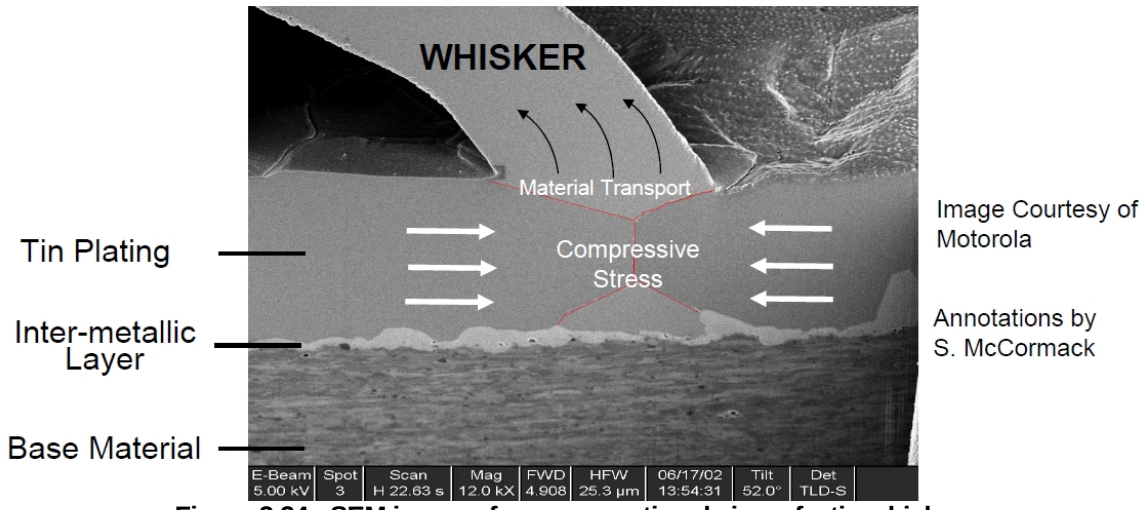


Figure 3.24 - SEM image of a cross-sectional view of a tin whisker.
One hypothesis is that whiskers are formed to relieve compressive stress

Managing the Risks

Effective management of tin whiskers should include an assessment of product design and its susceptibility to whisker induced failure. The execution of an unsuitable design could have potential consequences, particularly at a system level. Design trades and changes (Figure 3.25) when selecting an appropriate level of mitigation will result in a more balanced cost effective design.

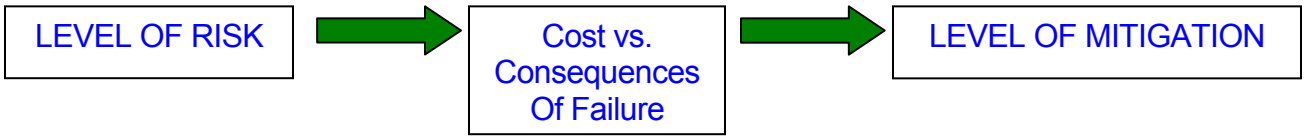


Figure 3.25 – Risk versus mitigation

The technical approach for the phase three research program divides the effort into three main areas:

- Failure modes
- Mitigation
- Risk assessment

3.4.3 Recommended Tin Whisker Projects and Gaps Addresses

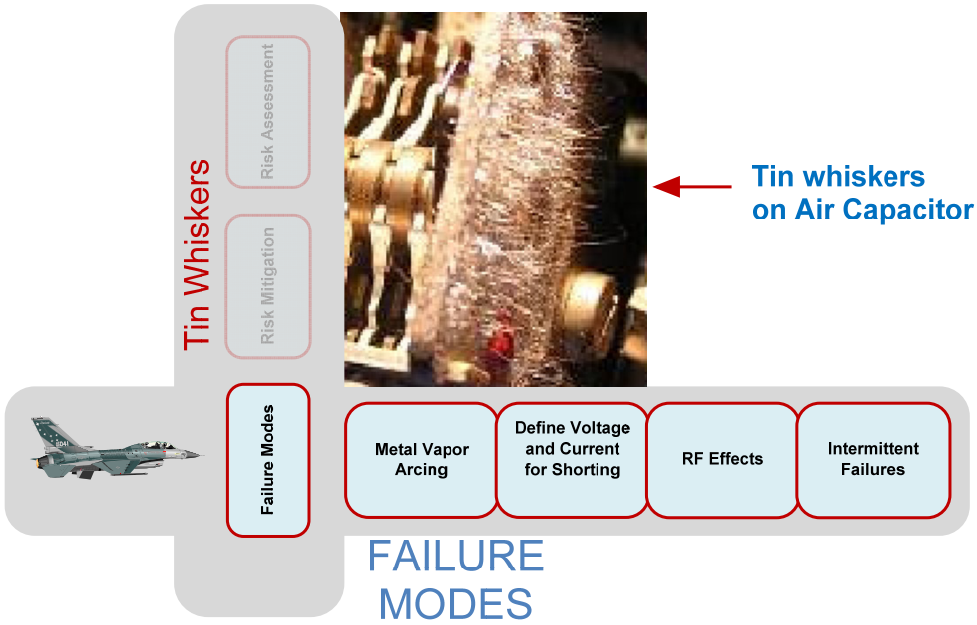
Hyperlink to Gap key

I	Technical Area	II	Techical Area	III	Technical Area		start	duration	GAPS Addressed
A	TIN WHISKERS	AA	Tin Whisker Failure Modes	AAA	Metal Vapor Arcing		1	12	D31
				AAB	Define Voltage and Current Conditions for Whisker Induced Electrical Shorting		1	15	D43
				AAC	RF Effects of Whiskers		1	12	D42
				AAD	Detection of Intermittent Tin Whisker Field Failures		18	15	S15
		AB	Tin Whisker Risk Mitigation	ABA	Automate Spacing		1	36	D45
				ABB	Design Rules for Tin Whisker Risk Mitigation		1	24	D30
				ABC	Conformal Coating Whisker Mitigation		1	36	M03
				ABD	Test Method for Tin Whisker at the Part Level for A&D Electronics		1	36	D41
				ABE	Test Method for Tin Whisker Risk at the Product Level for A&D Electronics		1	36	D46
				ABF	New Mitigations		1	36	D48
		AC	Tin Whisker Risk Assessment	ACA	Develop Techniques and Procedures to Identify Tin Whiskers on Field Returned Hardware		1	9	S12
				ACB	Circuit Analysis for Tin Whisker Risk Assessment		18	12	M16
				ACC	Tin Whisker Life Prediction		6	24	M16
				ACD	Fundamental Research for Tin Whisker Risk Assessment		1	36	R01

Table 3.1 – Tin whisker technical chart

* Note - Table 3.1 shows the specific level 3 technical approaches for tin whiskers along with the specific gap referrals. The full array of technical approaches can be found in Appendix C.

Tin Whisker Failure Modes Projects



Failure Modes	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Metal Vapor Arcing																
Define voltage and current conditions for TW shorting																
RF Effects of Whiskers																
Detection of Intermittent Tin Whisker Field Failures																

Metal Vapor Arcing

This project characterizes the conditions under which tin whisker induced shorts can result in metal vapor arcing events. As a minimum, the conditions with respect to applied current and voltages (DC and AC), atmosphere, temperature and humidity, and conductor spacing will be investigated.

- **Gap Addressed**
  - Based on experience with SnPb programs, existing heuristic rules for metal vapor arcing used by electrical and mechanical designers may be insufficient to ensure reliability of Pb-free product.

Define Voltage and Current Conditions for Whisker Induced Electrical Shorting

This project defines the conditions under which whiskers can induce electrical shorts by bridging two conductors and defines circuit model elements that cover all possible voltage and current conditions resulting in a tin whisker.

- **Gap Addressed**

  - There is insufficient information on how and when tin whiskers can impact circuit performance of high frequency RF circuits

RF Effects of Whiskers
This effort will determine the effects of tin whisker growth on the RF performance of devices, packages, assemblies, and systems. The results will be communicated in a form that can be used in subsequent circuit and system risk analysis.

- **Gap Addressed**

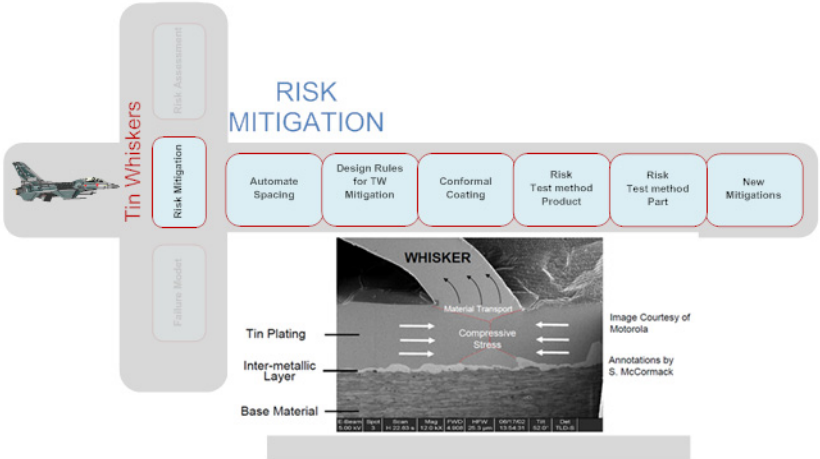
  - No existing mitigation practice is universally implementable and definitively prevents the occurrence of tin whiskers in high frequency RF circuits

Detection of Intermittent Tin Whisker Field Failures
The ability of current field return systems to detect intermittent faults resulting from tin whiskers will be analyzed and modifications to the current processes, protocols, and equipment will be recommended to improve detection of intermittent faults due to tin whiskers.

- **Gap Addressed**

  - The field service data feedback requirements, process, and content definition are not adequate to capture the most prevalent issues around Pb-free assemblies in the field

Tin Whisker Risk Mitigation Projects



Risk Mitigation schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Automate Circuit Spacing Analysis																
Conformal Coating for TW Mitigation																
Test method for TW Risk at Product Level																
Test method for TW Risk at Part Level																
Fundamental Research TW Mitigation																
New Mitigations																

Automate Circuit Spacing Analysis

This project will mitigate whisker risk by developing a critical design process to implement spacing at the circuit and circuit card assembly (CCA) level. The circuit design and reliability analysis needs to determine the acceptable risk related to hazard level or mission criticality requirements. This includes whisker shorts from component lead-to-lead spacing and inter-component CCA spacing. New rules for part selection based on lead-to-lead spacing and the CCA layout rules for separation will be defined and incorporated into the board design section of existing tin whisker standards.

- **Gap Addressed**

  - Based on experience with SnPb programs, existing heuristic rules for metal vapor arcing used by electrical and mechanical designers may be insufficient to ensure reliability of Pb-free product

  - Electrical design practice does not provide guidance regarding physical separation between critical devices (e.g., components from different critical functional elements or redundancy to reduce whisker risk)

Design Rules for Tin Whisker Mitigation

This project will develop a set of design rules that can be implemented across the A&D industry to provide adequate control of the risk of tin whisker induced failures in a cost-effective manner. Since restricting the use of tin always involves some additional cost, the goal is to identify the widest range of conditions under which the use of tin can be reliably proven consistent with system-level performance requirements. These design rules must be based upon the full set of quantitative and qualitative information available during the course of the project.

Design rules must include considerations of all levels of product integration (plating level, component level, assembly level, and module level through system level). These design rules should take into account all relevant environments (manufacturing environment, storage environments, transportation environments, and field service environments), as applicable. These design rules should provide for assured compliance with a specified maximum probability of failures as a function of time and environmental exposures. Additionally, design rules shall be formulated both in the written form and embodied in an algorithm or other suitable software tool.

Gap Addressed

- No single source exists for the A&D community to select tin whisker risk mitigation activities based on cost, availability, and degree of mitigation

Conformal Coating Whisker Mitigation

This effort will enable the reduction of tin whisker failures by the application of specified types and thicknesses of conformal coatings to circuit card assemblies.

Gap Addressed

- The conformal coating processes lack objective evidence for tin whisker mitigation capability

Test Method for Tin Whisker at the Part Level for A&D Electronics

Develop a test method to rapidly identify tin whisker risk at the part level for all classes of parts (mechanical and electrical), including printed circuit boards. This test method will determine the propensity for whisker growth on mechanical and electrical parts in less than six months.

Gap Addressed

- No current test method exists for determining whether a mechanical or electrical part is whisker prone over its lifetime. An industry standard test method is needed to rapidly identify tin whisker risk for mechanical and electrical parts

- **Test Method for Tin Whisker Risk at the Product Level for A&D Electronics**
  The project will identify and validate test methods for accurately determining if an electronic product will form whiskers, and asses the effect of these whiskers during its service lifetime.

  - **Gap Addressed**

    - Existing tests for design verification or product qualification used by the A&D community may not be valid for Pb-free products

- **Fundamental Research for Tin Whisker Risk Assessment**

  A project will be needed to research the fundamental understanding of tin whisker growth mechanisms so the extreme variations in the propensity of tin film deposits to grow whiskers can be understood from first principles. This fundamental understanding will be linked to the development of test methods for parts and assemblies, life prediction models, and to design new mitigation strategies and materials. The result is expected to help mitigate the effects of tin whiskers by choosing designs, materials, and processes with lower propensities for whisker formation after rework and repair.

  - **Gap Addressed**

    - There is a lack of understanding of fundamental whisker growth mechanisms

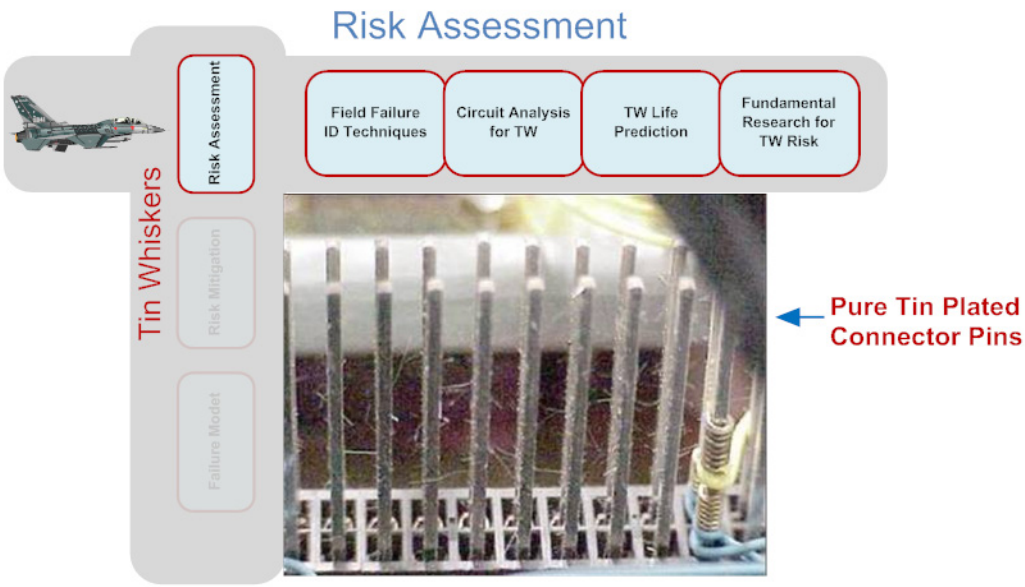
- **New Mitigations**

  The project will identify and quantify the effectiveness of new mitigation technologies for preventing whisker formation and growth on A&D products.

  - **Gap Addressed**

    - No existing mitigation practice is universally implementable and definitively prevents the occurrence of tin whiskers

Tin Whisker Risk Assessment



Tin Whisker schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Field Failure ID Techniques																
Circuit Analysis for TW Assessment																
TW life prediction																

Develop Techniques and Procedures to Identify Tin Whiskers on Field Returned Hardware

This project will address the lack of standards and requirements for incoming inspection upon receiving field hardware. This will be part of resolving the sustainment situation that presently exists for tin whisker identification of returned hardware.

- **Gap Addressed**
  - There is a lack of standards/requirements to address receiving inspection in sustainment situations for tin whisker identification

Circuit Analysis for Tin Whisker Risk Assessment

This project will incorporate results from tin whisker failure mode activity into an open source software tool that will allow the circuit designer to identify tin whisker risks. The mechanism will be based on the failure modes initiated by electrical connections between various nodes and other aspects of the system design.

- **Gap Addressed**
  - The current industry components are not capable of surviving lead-free soldering processes

Tin Whisker Life Prediction

This project will develop methodologies and tools that will predict the likelihood of tin whisker induced failures.

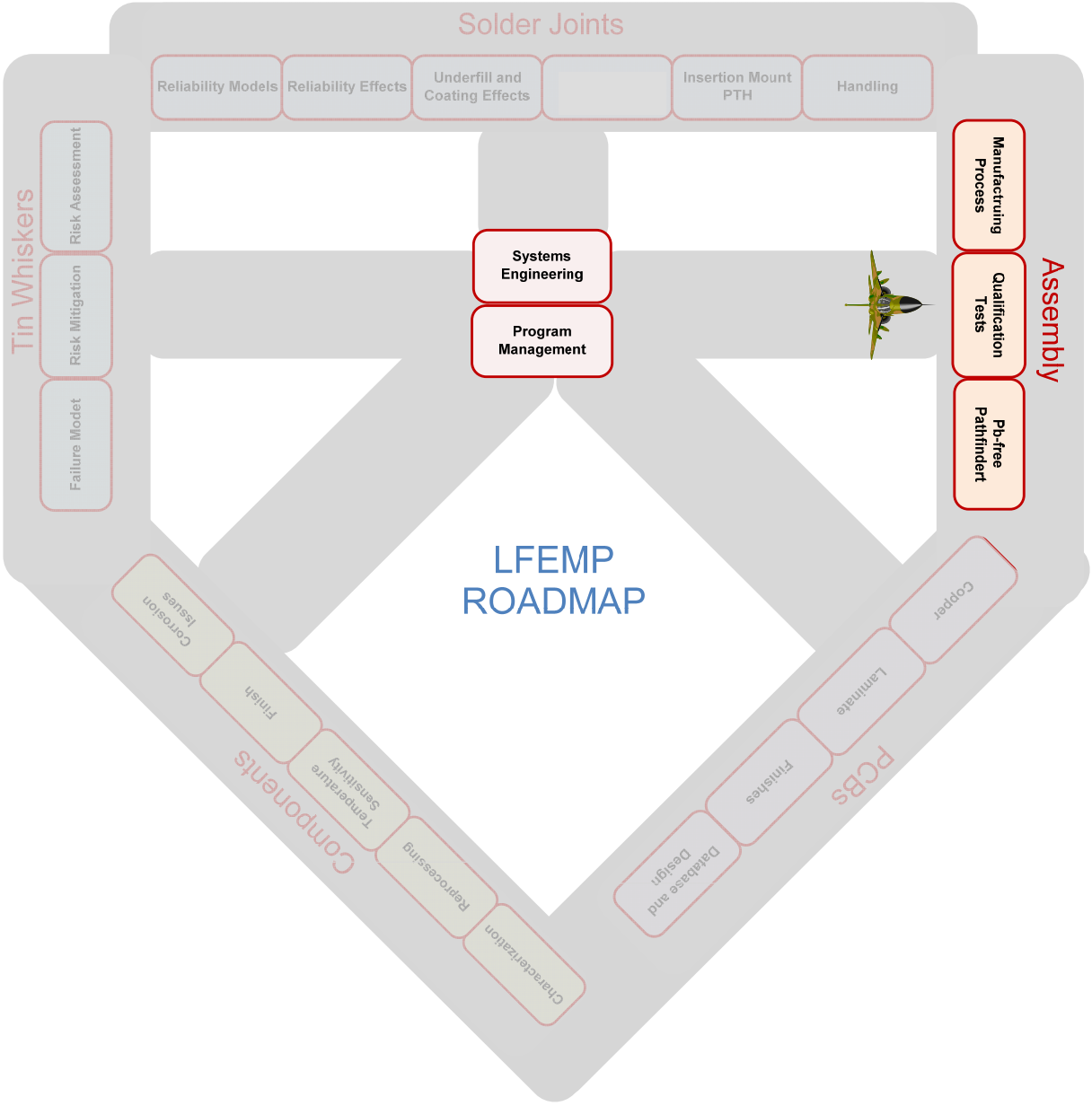
- **Gap Addressed**
  - The current industry components are not capable of surviving lead-free soldering processes

3.4.4 Expected Outcome

- A set of greatly enhanced tools for management of tin-whisker risks will be developed. This will decrease costs through more efficient targeted application of costly mitigations while providing greater assurance of long-term system reliability
- Defining the probability of a tin whisker induced metal vapor arcing event as a function of a clearly defined set of conditions of interest to the A&D community
- Defining the probability of a tin whisker induced short circuit event as a function of a clearly defined set of conditions of interest to the A&D community
  - **NOTE: This presumes the existence of a tin whisker between two conductors but adds the set of conditions that result in an actual electrical short**
- A quantitative description of the effects that the growth of tin whiskers will have on the RF performance of components, assemblies, and systems
- Inspection methods for intermittent field failures should be able to identify root causes and provide valuable input to improve design rules and lifetime prediction models (since the current field return systems are able to detect faults for only half of returned systems). In order to improve reliability and sustainment, intermittent faults caused by tin whiskers will be associated with their specific root cause
- New cost-effective and implementable tin whisker risk mitigation techniques will be provided. Newly developed and validated test methods usable on components and on systems will be defined. An implementable set of design rules for tin whisker risk mitigation will be provided that permit tin whisker risk to be controlled to quantifiable levels in a cost-effective manner. Specific modifications to existing standard design tools will be defined
- Design rules and tools that use spacing as a Sn whisker mitigation strategy in the formalized design process are expected
- A set of design rules that can be readily implemented across the A & D community so that the risk of tin whisker induced failures can be managed in a cost-effective manner are expected
- Verification and tabulation of tin whisker mitigation effectiveness of selected conformal coatings is expected. This would enable valid design rule development since no single source currently exists for the A&D community to select tin whisker risk mitigation activities based on cost, availability, and degree of mitigation

- Test methods that reduce the time required to evaluate electroplated tin surface finishes for whisker growth are expected
- Standards to address receiving inspection at the depot level for tin whisker identification are expected
- An automated tool that will allow the circuit designer to identify tin whisker risks based on the failure modes initiated by electrical connections between various nodes and other aspects of the system design is expected
- Software module development that will provide the A&D community the ability to predict the reliability and lifetime based on tin whisker failure modes and perform tradeoff analysis for various whisker mitigations
- Higher fidelity test methods are expected for tin whisker formation that provides required algorithms for development of design rules and life prediction models for tin whisker risk mitigation
- An open source software tool that will allow the circuit designer to identify tin whisker risks based on the failure modes initiated by electrical connections between various nodes and other aspects of the system design is expected

3.5 Electronic Assemblies



3.5.1 Summary Description:

A&D products have unique manufacturing process parameters resulting from the program critical and safety critical nature of the product use environments. They are comprised of printed wiring assemblies with unique geometric and highly complex construction attributes that do not exist in the industrial electronic product base. This requires specific critical Pb-free process parameters for the A&D electronics product segment. A&D products can also be characterized as having significantly longer product life cycles and sustainment cost value in comparison to the industrial electronic product segment. The rework/repair manufacturing processes have a major impact in terms of potential latent field defects and product degradation. This section of the report focuses on the need for supplying manufacturing guidelines for Pb-free, qualifying and validation of processes, and producing actual A&D units that will be fielded for failure studies.

3.5.2 Technical Brief

The A&D Manufacturing Process Project is comprised of three work packages:

- The first package defines the critical Pb-free process parameters for each of the major process elements producing a defined set of guidelines for the A&D manufacturing sector. This will also encompass the use of a cost decision matrix comparing the relative cost of a current tin/lead solder process versus a proposed Pb-free solder process
- The second package evaluates and assesses the rework & repair of A&D assemblies in terms of critical Pb-free process parameters. This includes a measure of the maximum degradation of threshold limits in order to gauge the repeatability & reproducibility of the rework & repair process. Additionally, produce a cost decision matrix comparing the relative cost of the current SnPb process, versus the Pb-free rework & repair solder process
- The third package should incorporate a "State of the Art" technology assessment for non-solder attachment technologies. The resulting list of proposed alternate attachment technologies should be evaluated on the manufacturing and performance viability as a suitable technology replacement for A&D attachments on printed circuit assemblies

The project for development, qualification, validation, and acceptance of Pb-free assemblies for Pb-free products, establishes qualification and acceptance test parameters to determine the reliability of Pb-free products at the time of assembly, capturing all relevant failure modes. Field failure data will be acquired, including functional failures (electrical and mechanical) as well as associated failure modes, to validate the analytical and computational models and optimize their prediction fidelity for determining the qualification and acceptance test parameters for Pb-free product.

The Pathfinder project will take 3 yrs for its implementation and completion, but the overall assessment for lifetime reliability will need approximately 10 years to complete. This can be considered an option if further studies are warranted. This project was designed to build a prototype assembly of an actual aerospace and defense product using a Pb-free solder. The entire manufacturing procedure will be exercised at a predetermined manufacturing facility. The hardware will be fielded, and where necessary, returned to the depot to record the failure and failure mode as well as effect repairs and replacement of the unit in order to place it back into the field.

3.5.3 Recommended Assembly Technical Projects and Gaps Addressed

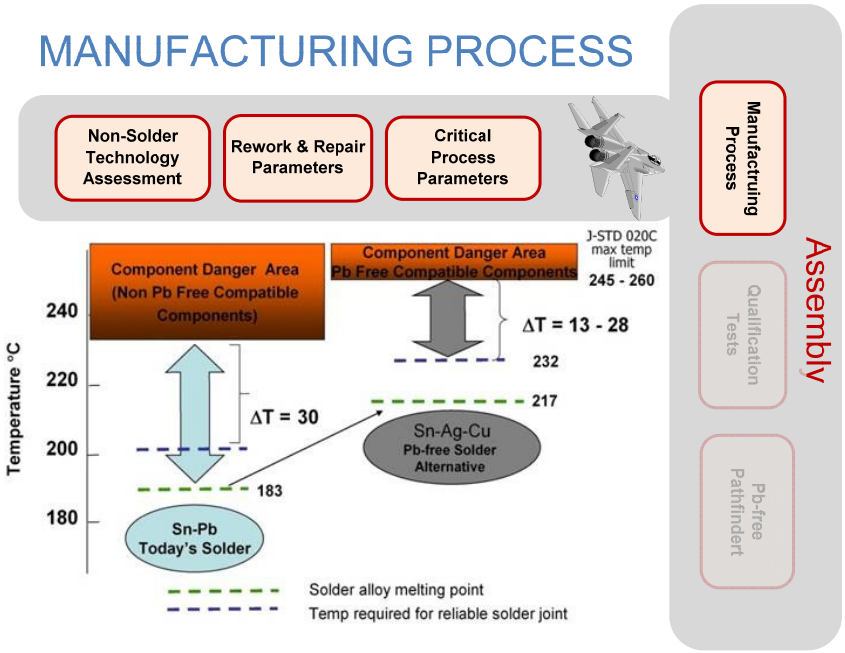
Hyperlink to Gap key

	I	Technical Area	II	Techical Area	III	Technical Area		start month	duration	GAPS Addressed	
	B	ASSEMBLY	BA	A&D Manufacturing Process	BAA	Critcal Process Parameter Development		1	36	M01, M02, M04, M07, M08, M09, M10, M12, M13, M18, D09, D58	
					BAB	Rework & Repair Critical Process Parameter Development		1	36	M02, M04, M11, M18, S01, S05, S06, D10, D56	
					BAC	State of the Art Assessment of Non-Solder Attachment Technologies		1	8		
			BB	Development and Validation of Qualification and Acceptance Tests for Pb-Free	BBA	Method for Determining Qualification and Acceptance Test Parameters		1	36	D05, D27, D28, D29	
					BBB	Field Life Data for Validating Qualification and Acceptance Test Predictions		1	36	S02, S07, S15, D04, D59	
			BC	Pb-Free Pathfinder	BCA	Fabrication of Ten (10) Prototype Units and Two (2) Spare Units		1	12	S19	
					BCB	Assessment of Fielded Pb-Free Products		1	12	S19	

Table 3.2 - Assembly Technical chart

Table 3.2 shows the specific level 3 technical approaches for the assembly projects along with the specific gap referrals. The full array of technical approaches can be found in Appendix C.

A&D Manufacturing Process



Process Schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Define the critical Pb-free process parameters																
Evaluate/assess the rework/repair of A&D assemblies																
Conduct a "State of the Art" technology assessment – non solder attachment																

Critical Process Development

The objective of this work package is to define the critical Pb-free process parameters for each of the major process elements. This activity will require characterization and an assessment of the Pb-free solder process for A&D assemblies and will produce a defined set of manufacturing process guidelines. A test vehicle comprised of the necessary internal structures, thermal capacity, and component technologies will be used to investigate four Pb-free solder alloys. A cost decision matrix comparing relative cost of a current tin/lead solder process versus a proposed Pb-free solder process assessing each major element of the solder processes shall be produced.

➢ Gap Addressed

- Lead-free assembly cleaning processes are not clearly defined in terms of materials compatibility and contamination
- Conformal coating processes compatibility is poorly defined for materials compatibility with lead-free processes
- Surface mount assembly process placement accuracy and placement vision capability requires improved Gauge Repeatability & Reproducibility (R&R)

- Industry defined requirements for cross contamination limits for shared assembly processes do not exist
- Lack of industry defined requirements for equipment and component placement for Pb-free circuit card assembly singulation
- Current industry vapor phase process chemistry and thermal load parameters are not robust for A&D
- Lead-free laser soldering processes are undefined for A & D products
- Current lead-free soldering equipment thermal capability and profile parameters are unspecified to meet solder joint integrity requirements for A&D
- Current cleaning technologies have unproven lead-free soldering process flux residue removal performance for A&D
- The A&D community is unable to accurately assess the costs of maintaining SnPb or transitioning to Pb-free materials and assembly. Insufficient information on assembly costs
- In PCB design, there is a risk that heritage SnPb solder geometries or solder stencil designs will need to change to adjust the solder volume and geometry for Pb-free solder that are currently based on thermal cycle test results and neglect shock/vibration considerations
- Industry rework equipment and processes are not capable of supporting lead-free A&D product demands
- Current cleaning technologies have unproven lead-free soldering process flux residue removal performance for A&D

Rework and Repair

This project is designed to evaluate and assess the rework/repair of A&D assemblies in terms of critical Pb-free process parameters, maximum degradation threshold limits, rework/repair process repeatability/reproducibility, and associated Pb-free specific root cause solder defects. A test vehicle comprised of the necessary internal structures, thermal capacity, and component technologies will be used to investigate four Pb-free solder alloys. A cost decision matrix comparing relative cost of a current tin/lead versus Pb-free shall be produced assessing each major element of the rework/repair solder process and the rework/repair Gauge Reproducibility & Repeatability study.

Gap Addressed

- A lack of maximum reflow cycles control and requirements (part/component limitations on repair/rework cycles)
- A lack of understanding of materials and process compatibility issues that affect repair
- A lack of understanding of repair/rework stresses
- The A&D community is unable to accurately assess the costs of maintaining SnPb or transitioning to Pb-free materials and assembly. Insufficient information on sustainment costs
- Rules of thumb for manufacturability and rework/repair must be re-examined for Pb-free solder to ensure that manufacturing process variation is minimized

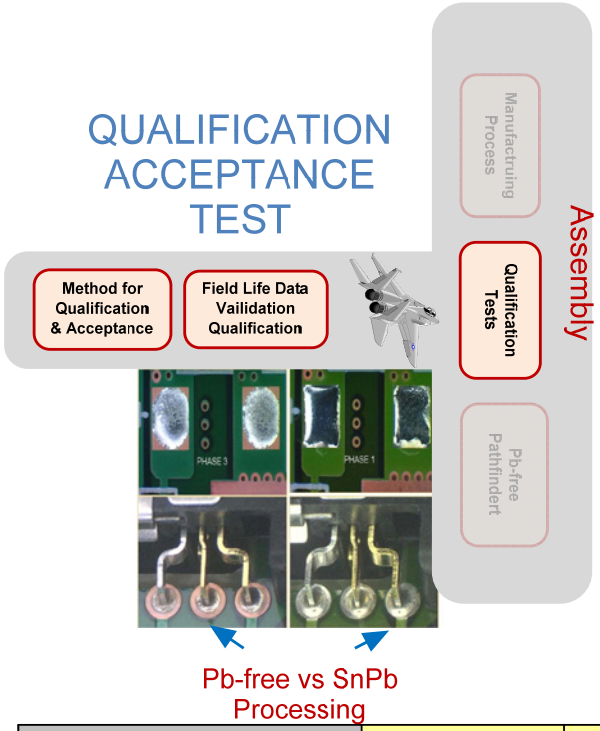
Non Solder Technologies

The objective of this work package is to conduct an industry assessment of the "State of the Art" for non-solder attachment technologies. Academia, industry consortia, Department of Defense, Department of Energy, Department of Commerce, Federal Aviation Administration, NASA, industry publications, and private industry will be surveyed for applicable technologies that could replace soldering as the primary printed circuit assembly attachment methodology.

Gap Addressed

- A&D products have traditionally utilized soldering as a printed circuit assembly attachment technology. However, this has several material and process limitations
- A review of non-solder printed circuit assembly attachment technologies should be conducted as part of an "out of the box" thought process in addressing the topic of Pb-free soldering technology impact on A&D products

Development and Validation of Qualification and Acceptance Tests for Pb-free



Qualification Schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Method for Determining Qualification and Acceptance Test Parameters																
Field Life Data for Validating Qualification and Acceptance Test Predictions																

Method for Determining Qualification and Acceptance Test Parameters

This project establishes qualification and acceptance test parameters to determine the reliability of Pb-free products at the time of assembly, capturing all relevant failure modes. Field failure data will be acquired (including electrical and mechanical functional failures) with associated failure modes to validate the analytical and computational models. This will optimize their prediction fidelity for determining the qualification and acceptance test parameters for Pb-free product.

Gap Addressed

- Introduction of Pb-free materials may increase the occurrence of intermittent failures during operation
- Existing design verification tests (HALT / HAST) used by the A&D community may not be valid for Pb-free product. Subsequent model development is difficult since fatigue constants and stress states of board traces are different
- Existing product qualification tests (MIL-STD-810, DO-160) used by the A&D community may not be valid for Pb-free product

- Existing environmental stress screening (ESS) tests (design verification, product qualification) used by the A&D community may not be valid for Pb-free product

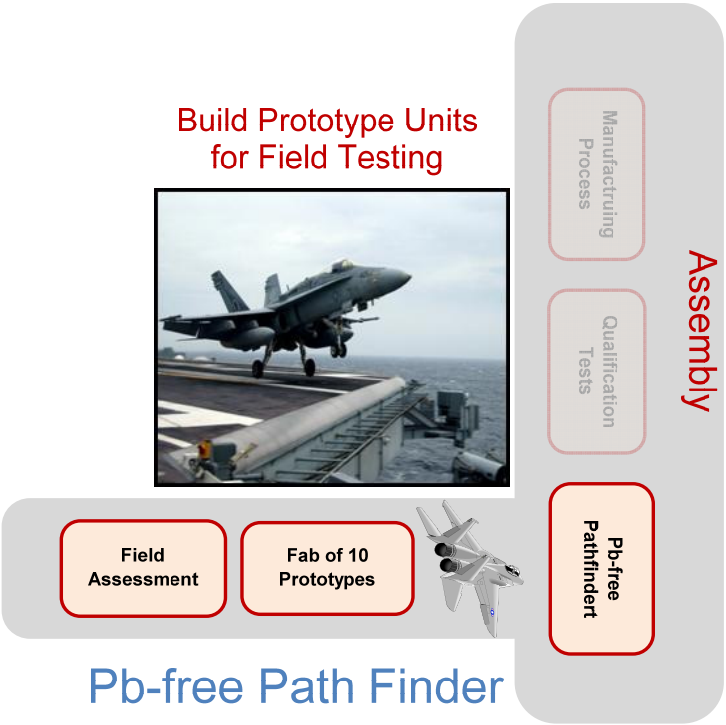
Field Life Data

This project will establish the logistics needed to acquire field failure data, including functional failures (electrical and mechanical) and associated failure modes. This will validate the analytical and computational models that will establish qualification and acceptance test parameters.

Gap Addressed

- A lack of configuration control to address material compatibility issues
- A lack of field service data feedback requirements, process, and content definition are not adequate
- An understanding of reliability degradation from storage, use, and repair stresses
- The long-term field performance of A&D product with Pb-free materials is critical in assessing the validity of failure models. Currently, there is insufficient field failure data to make determinations of long term reliability
- There is a lack of suitable diagnostic and prognostic processes to address Pb-free solder joint failure modes. There is also an absence of non-destructive failure analysis techniques to detect pad cratering or tin whisker occurrences

Pb-Free Path Finder



Path Finder Schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Fabrication of ten (10) prototype units																
Assessment of Fielded Pb-free Products																

* Note. The Pathfinder project will take 3 yrs for its implementation and completion, but the overall assessment for lifetime reliability will need approximately 10 years to complete.

Fabrication of 10 Prototype Units, Two Spares, and Assessment of Fielded Pb-free products

This project will perform a prototype assembly build of an actual aerospace and defense product using a Pb-free solder. The entire manufacturing procedure will be exercised at a predetermined manufacturing facility. The hardware will be fielded and returned to the depot (when necessary) to record the failure and failure mode, as well as affect repairs and replacement of the unit, in order to place it back into the field.

The test vehicle will be down-selected from candidate hardware for fabrication. Materials, components, printed circuit boards, and structural members will be procured (including surface finish alteration if necessary). It will be assumed that relevant vendors have already been identified.

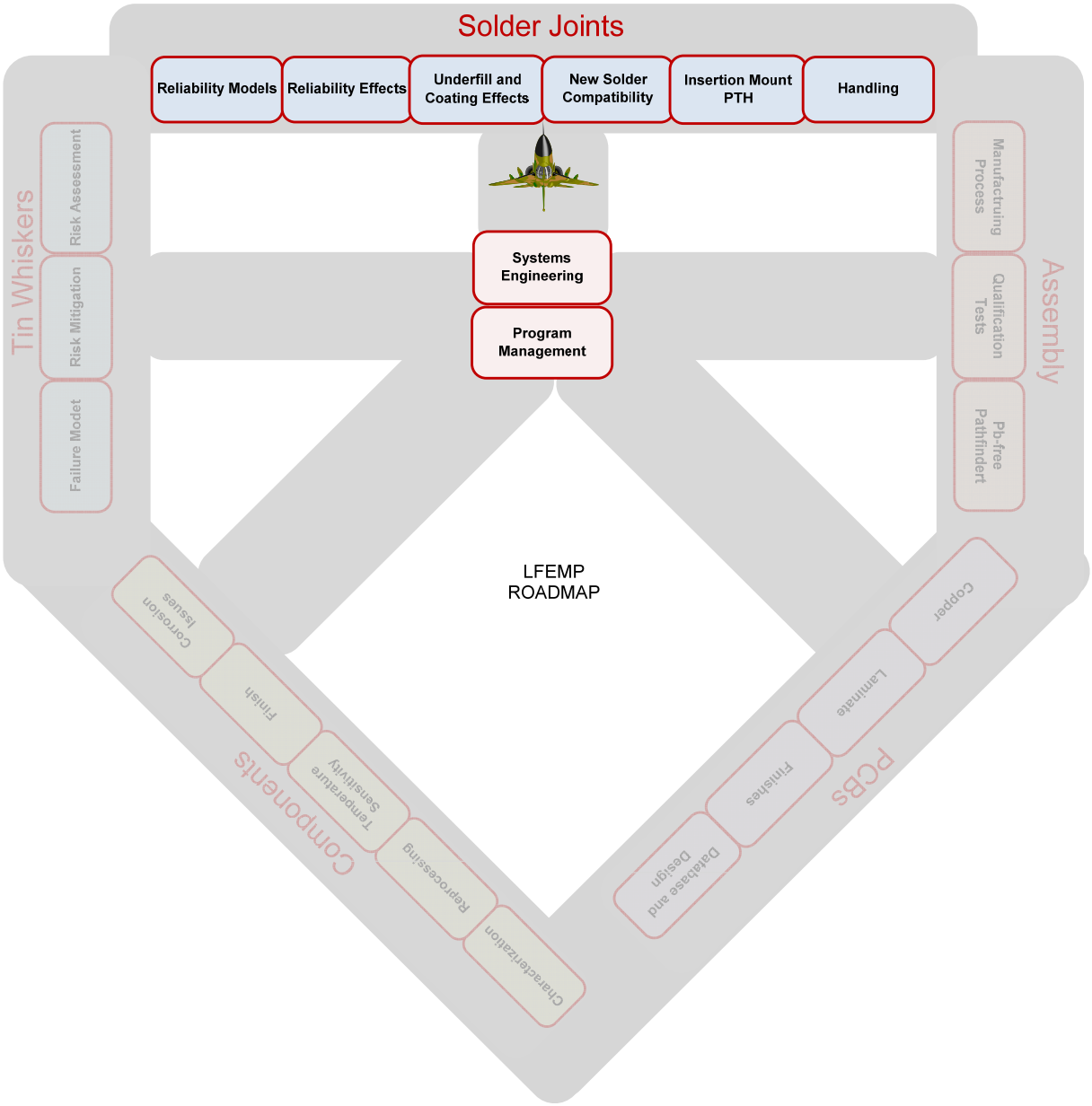
- **Gap Addressed**

  There have been very few public studies which document challenges of the assembly of an actual A&D product with Pb-free solders. There is little or no experience with the sustainment stage of a Pb-free product lifecycle, including the number of field failures in as-manufactured Pb-free product, failure mode documentation, repair, and the service life of repaired hardware

3.5.4 Expected Outcome:

- A Pb-free process guideline document base-lining the critical process parameters and root cause solder defects for each major assembly process element for A&D product manufacturing
- A cost decision matrix comparing relative cost of a current tin/lead solder process versus a proposed Pb-free solder process assessing each major element of the solder processes. The cost matrix will be formatted in categories of costs associated with each major assembly process element
- A rework/repair process guideline document base-lining the critical Pb-free process parameters and root cause defects for use by A&D product manufacturing
- A cost decision matrix comparing relative cost of a current tin/lead versus Pb-free assessing each major element of the rework/repair solder process. The cost matrix will be formatted in categories of costs associated with each major assembly process element
- An information data set of specific critical process parameters applicable to IPC High Performance Class 3 products that can be used to revise/supplement current IPC specifications and standards
- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly
- A relative cost decision matrix comparing tin/lead solder versus Pb-free solder processes
- A report documenting suggested changes for IPC-AJ-820 handbook (Pb-free critical solder process parameters), IPC-JSTD-001 specification (solder joint criteria), and IPC-A-610 specification (Pb-free specific solder defects)
- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, root cause solder defects for the rework/repair process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free rework/repair process baseline for A&D product assembly
- A report documenting the rework/repair solder process Gauge Reproducibility & Repeatability study defining process procedures/protocols for specific rework/repair methodology
- A relative cost decision matrix comparing tin/lead solders versus Pb-free rework/repair processes
- A report documenting suggested changes for IPC 7711/7722 specification (rework/repair critical process parameters) and IPC-A-610 specification (Pb-free specific solder defects)

3.6 Solder Joints



3.6.1 Summary Description

A major project was formulated in terms of a set of strongly interdependent tasks to develop the capabilities to assess and predict the reliability of lead free solder joints in service. A few alloys and mixtures of alloys shall be selected based on common usage and availability. Acceleration factors and actual reliability models shall be validated, emphasizing long term service applications by establishing a quantitative understanding of the underlying mechanisms.

A set of representative, generic service scenarios shall be identified and the capabilities developed to assess service life. Available data shall be collected and carefully assessed for use in model validation. Suitable test vehicles shall be designed and assembled for use in thermal cycling, vibration, shock, and drop testing ensuring comparability across tasks. Accelerated testing will be conducted for a carefully selected range of test parameters and the results used to develop convenient expressions for the acceleration factors to service.

Modeling and extrapolations are greatly complicated by the sensitivity to design and process parameters and the continuous variation of solder properties during loading and long term aging. Each of these factors is taken into account through the development of dynamically adaptive constitutive relations based on correlations between microstructure and properties quantified during testing.

The ultimate goal is the development of a comprehensive solder reliability model accounting for failure due to thermal fatigue, vibration, drop, shock, creep rupture, and combinations of these. The effects of combinations are the subject of a separate task.

3.6.2 Technical Brief

A number of conditions play a role in solder joint reliability. Work package CA (see appendix C) addresses the primary recognized and tested conditions and provides a detailed research plan to provide data and models to allow for reliability production in A&D applications. This work package is designed to complement CA and examine other detrimental factors to solder joint reliability that are not characterized. With close examination of phenomenon identified in this work package, unexpected and unpredicted earlier failures may occur in A&D applications. Areas of concern include:

- The role of electrical current
- The role of elevated corrosive environments
- The role of rework/repair
- The role of board material and finish
- The role of solder paste
- Factors influencing the formation of tin pest

Projects expectations:

- Document the impact of underfill on solder joint life of lead-free assembled area array packages relevant to A&D environments
- Document the impact of staking on solder joint life of lead-free assembled surface mount parts relevant to A&D environments
- Document the impact of conformal coating on solder joint life of lead-free assembled surface mount parts relevant to A&D environments
- Document the material behavioral properties of underfill, staking, and coating components relevant to the development of models assessing solder joint life expectancy
- Detail a modeling approach suitable for commercial finite element analysis software for predicting life expectancy of underfilled, staked, and conformally coated lead-free assembled surface mount parts
- Develop an analytical modeling approach suitable for spreadsheet implantation for predicting life expectancy

This project will also be evaluating manufacturability and reliability in harsh environments of standard SnPb and Sn-Ag-Cu lead-free solders (SAC) with lead-free BGA (ball grid array) ball materials. The BGA ball materials will include the widely used SAC405, SAC305, SAC105, and low Ag solders with additives such as Ni, Mn, and rare earth elements that were introduced by component manufacturers to improve the mechanical performance. The process parameters that provide high reliability in harsh environment will be defined.

The project also will be evaluating the reliability of some of the new lead-free solders in harsh environments. Several compositions with Bi, In, or combinations of Bi, Ni, and Sb additives are proposed, which may provide long term reliability performance for both high mechanical and high thermal stress conditions. The project will deliver data on the new solders' compatibility with new and existing lead-free components using different assembly parameters. The performance in harsh environment, mechanical and thermo mechanical conditions will be tested and the results delivered. The best performers will be recommended for further qualification in the A&D industry.

In this project, the new rework solution using low melt solder (which demonstrated good electrical properties and higher reliability than pure SnPb joints in computer/networking operating environments) will be evaluated for performance in the harsher A&D operating conditions.

Current IPC-610 barrel fill specifications were originally established in the 1970s using a 0.062" thick board and SnPb alloy. The requirements have not been updated for today's thicker boards and the use of lead free alloys. The specification requirements can be unnecessarily challenging, especially considering the size (>0.120" thick), complexity, and multiple ground connections of some of today's highly complex products. Recent literature within the industry has shown that barrel fill requirements should be based on the wetted pin length, as opposed to a percentage fill. It states that a board up to a thickness of 0.130",needs to obtain only 36% barrel fill to establish a suitably strong joint to survive both thermal and mechanical environments.

This project will address two main concerns with respect to plated through-hole (PTH) devices. The first objective is to assess the reliability performance of PTH SAC 305 solder joints in a harsh

environment when hole fill levels do not reach current IPC-610 class 3 requirements for a PCB thickness equal to or greater than 120 mils. The second objective is to assess the impact of high levels of copper dissolution on the thermal reliability, shock, and vibration robustness of PTH connections.

In addition to these two main objectives, the project will also characterize the impact of solder bath contamination levels on the final barrel fill and copper dissolution rates, evaluate the effect of certain wave solder process parameters (e.g., preheat/pot temperatures and flux chemistries), and evaluate the impact that certain key board design features have on obtaining barrel fill (e.g., pin to hole aspect ratio, thermal connection, and relief designs).

The goal is to establish rules for the maximum PCB deflection allowed only once or a relatively few times in handling. Conservative estimates will be based on how much lead free solder joints, integral pads, and their attachment to laminates can be loaded a given number of times without having a significant effect on subsequent assembly reliability.

Assembly and individual solder joint testing will be employed to quantify the acceptable loads; subjecting assemblies to thermal cycling, vibration, shock, drop, and flexural loading to quantify subsequent life. Results will be compared to the life obtained without preconditioning. Specific test parameters will be selected based on available mechanistic understanding (to be as sensitive as possible to projected differences in service life).

Limits will first be quantified in terms of loads and strains on the solder joints. Simple mechanical analysis will then be employed to convert these into practical limits on PCB deflection, surface strain, and strain rate for various critical component types, with the intent of generating strain rate dependent process limits for surface strain. Modeling and calculations will be based on the constitutive relations developed under another task.

Examples of Solder Reliability Issues

- **Mixed Solder Ball Process**

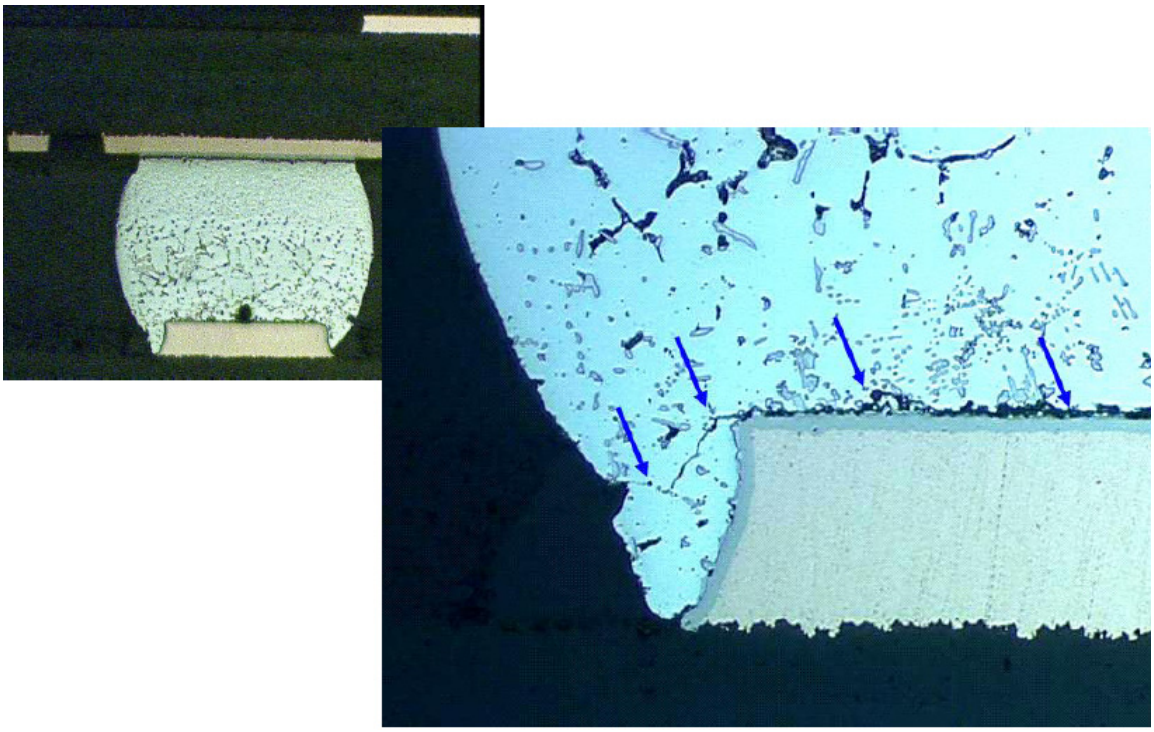


Figure 3.26 - Lead-free bumped array assembled with tin-lead solder paste (Mixed) (Courtesy Hillman, Wells, Cho)

Figure 3.26 shows a lead free BGA (that was assembled using a conventional Sn63Pb37 solder process) after less than 150 temperature cycles. The cracking at the pad to BGA interface, shown by the blue arrows, indicates a weakness in the adhesion between the solder ball and pad surface. This type of defect could escape current screening practices and result in aborted or failed missions.

- **Tin-Silver-Copper-Solder Process**

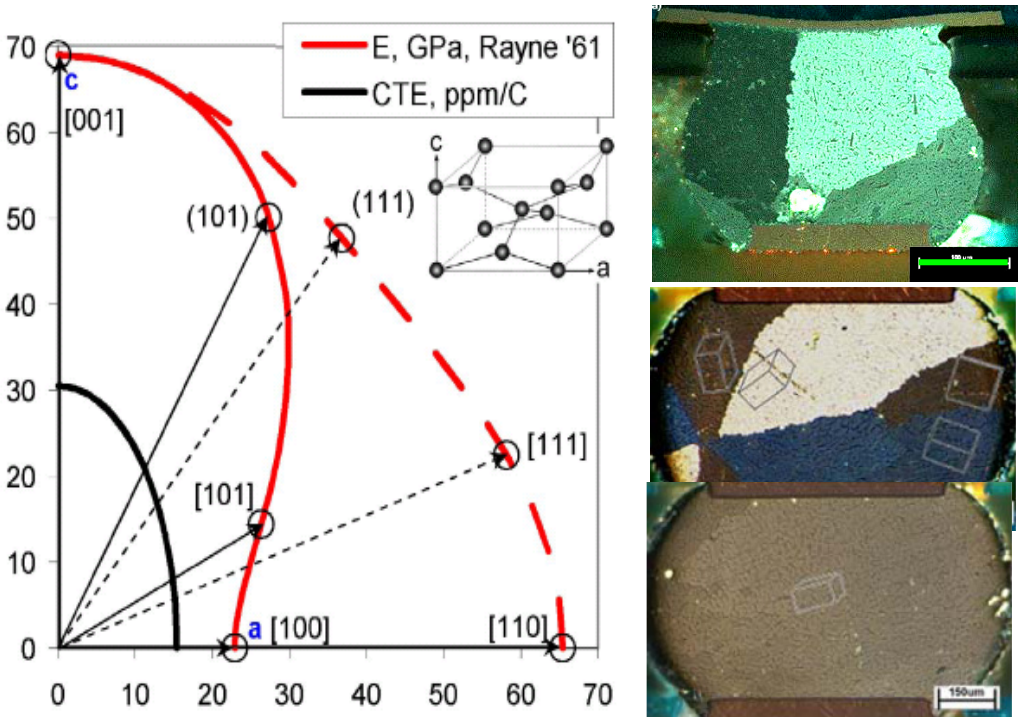


Figure 3.27 - SAC grain structures

Sn-Ag-Cu alloys have gained market share as a lead free replacement for tin-lead solder. The SAC compositions have been studied extensively, but reliability concerns have prompted continued research into alternate compositions. Significant scatter is expected in SAC properties because of heterogeneity and uniqueness caused by a few large anisotropic Sn grains. Figure 3.27 shows the isotropic direction of Sn crystals at various orientations within a single solder ball. This situation can be particularly damaging if the Z-expansion falls parallel to pad surfaces.

- **Influx of Solder Alloys**

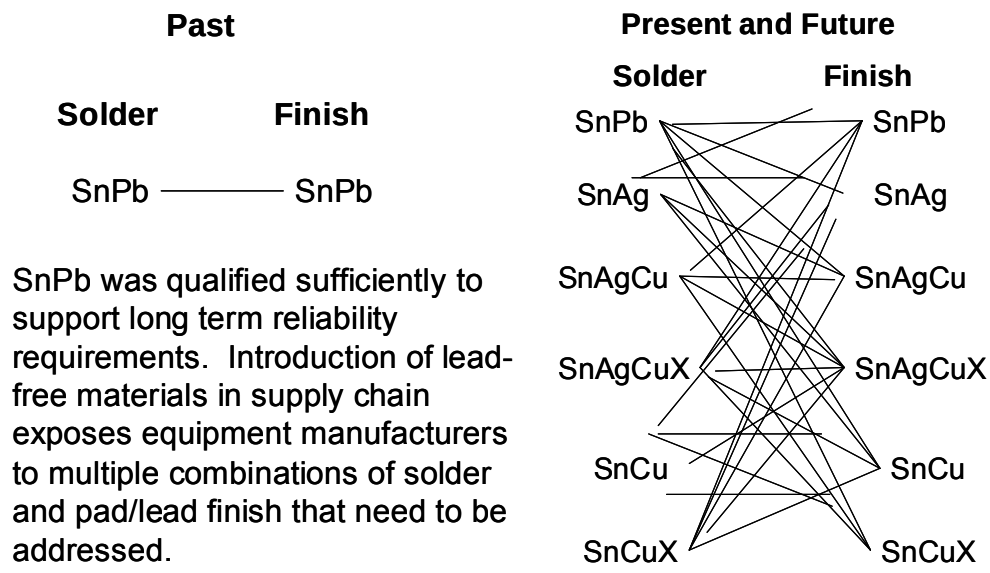


Figure 3.28 - Illustration of Solder to Surface Finish combinations

The possible permutations and combinations of solder alloys and pad finishes as illustrated in Figure 3.28 can be the sources of great uncertainty in solder joint reliability.

Fatigue Damage Evolution

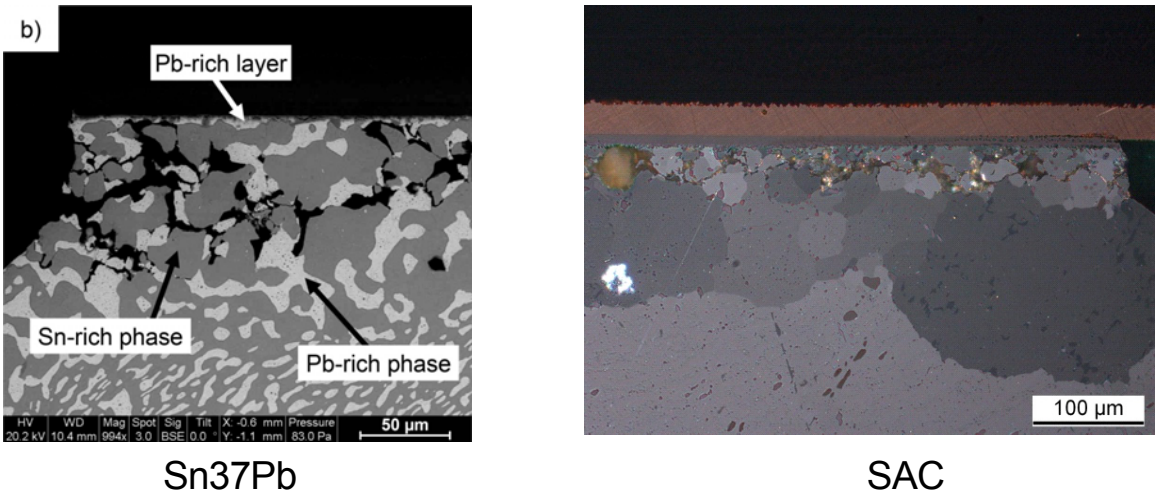
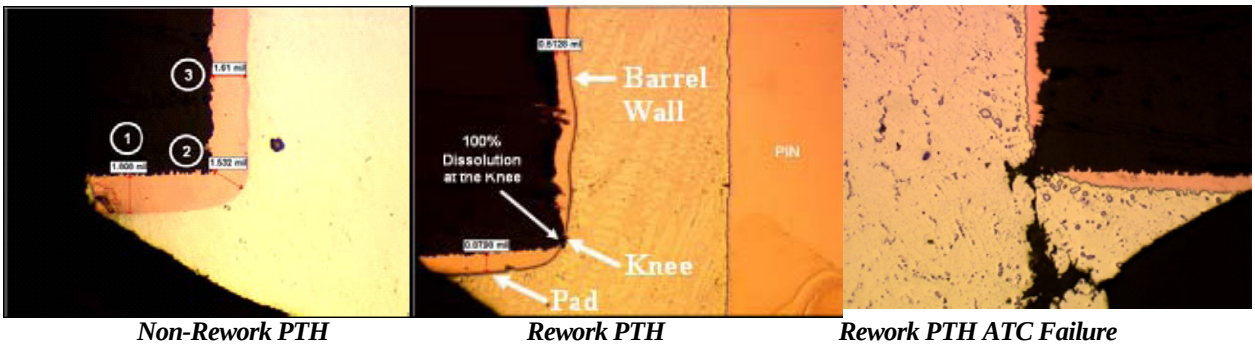


Figure 3.29 - SAC and SnPb grain structure under cyclic stress (Courtesy CALCE U of MD)

Under cyclic stress, SnPb exhibits grain coarsening (Figure 3.29) or enlargement which results in crack formation and growth. For Pb-free SAC solder, the structure exhibits grain formation due to re-crystallization which results in finer grains that separate at grain boundaries resulting in crack growth. Due to anisotropic behavior and random dispersion of intermetallic compounds in the solder, material behavior exhibits a greater degree of randomness than occurred with SnPb.

PTH Insertion Mount Issues



Non-Rework PTH *Rework PTH* *Rework PTH ATC Failure*

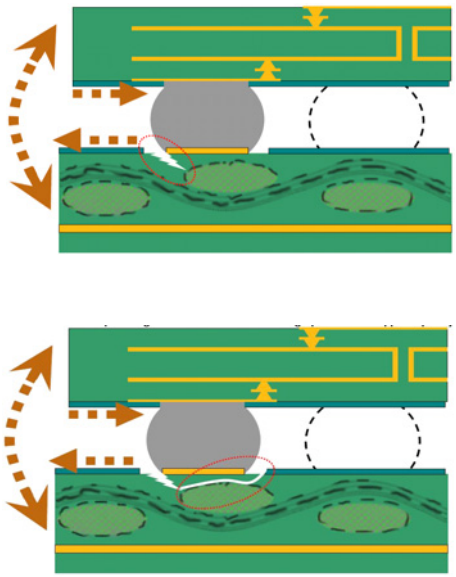
Figure 3.30 - PTH failure after rework (Courtesy of Celestica)

Copper dissolution impacts the hole wall integrity and reliability of insertion mount interconnects (Figure 3.30). Efforts to resolve this issue should include:

- Defect generation
- ATC stress tests
- Analysis of test results

A guideline should be produced for A&D applications on the acceptance of partially filled holes and acceptable copper barrel loss.

- **Handling Guidelines**



*Images courtesy of Celestica

Figure 3.31 - Illustration of cracking mechanism during handling

Due to the stiffness of Pb-free solders, new handling procedures must be produced to avoid damage of electronic equipment in manufacturing assembly, storage, and use. These efforts will include tests for assessing handling stress and strain limits, life loss, and models to predict the damage. Guidelines will be needed for allowable tolerances on maximum loads during assembly and storage to prevent early life failures of lead free and mixed solder joints. Figure 3.31 shows the results of shear and tensile forces that may be applied during handling.

3.6.3 Recommended Solder Joint Technical Projects and Gaps Addressed

Hyperlink to Gap key

I	Technical Area	II	Techical Area	III	Technical Area		start month	duration	GAPS Addressed
C	SOLDER JOINTS	CA	Solder Joint Reliability Models	CAA	Test Vehicle Design and Fabrication		1	24	
				CAB	Validation Data Collection and Assessment		1	8	D03, D14
				CAC	Materials Properties & Constitutive Relations		1	33	D01, D14, D24, D25, D32, R04, R06, D53, T05, S07
				CAD	Thermal Cycling Induced Fatigue		1	36	D03, D14, D24, D53, R06
				CAE	Vibration		1	36	D03, D14, D15, D24, D53, R06, D33, R04
				CAF	Combined Loading		1	36	D03, D14, D24, D29, D53, R06, D18, D22
				CAG	Shock and Drop		1	24	D03, D16, D17, D24, D34, D53, D58, R06, R04
				CAH	Creep Rupture		1	36	D01, D24, R05
				CAI	An Optimized Test Approach for Additional Alloys		25	6	D01, D03, D13, D14, D17, D23, R06
				CAJ	Reliability Modeling		1	36	D14, D15, D16, D17, D18, D20, D21, D24, D25
		CB	Solder Joint Relaibility Effects	CBA	Current Density Effects		1	24	D19
				CBB	Corrosion		1	24	D52
				CBC	Reflows and Repair and Board/Finish Impact		1	12	S01, S05
				CBD	Wave Solder Contamination Effects		25	12	D25
				CBE	Solder Paste Efffects		13	24	
				CBF	Tin Pest		1	36	S12, T02

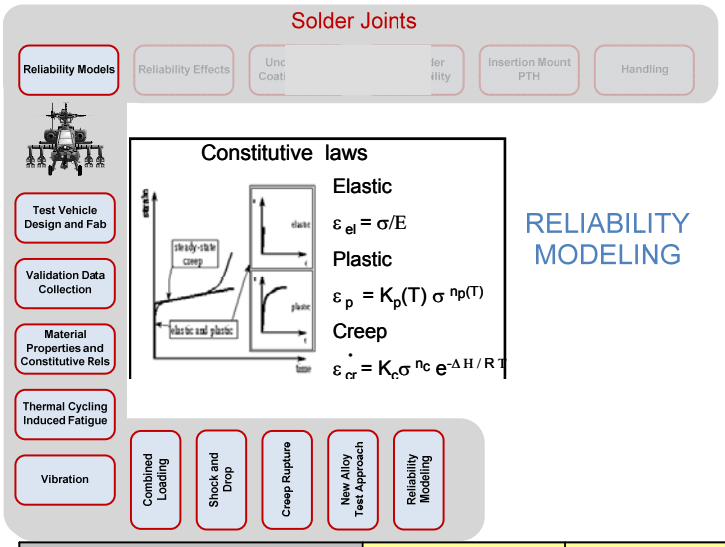
Table 3.3 - Solder joint technical chart

I	Technical Area	II	Techical Area	III	Technical Area		start month	duration	GAPS Addressed
C	SOLDER JOINTS	CC	Underfill, Staking, and Coating Effects	CCA	Underfill Life Testing		1	24	R02
				CCB	Staking and Coating Life Testing		1	24	D14, D35, M17, R02, R03
				CCC	Properties and Property Degradation		3	24	D14, D35, M17, R02, R03, S20
				CCD	Solder Joint Life Models for Underfilled, Staked, and Coated Surface Mount Parts		12	24	D14, D35, M17, R02, R03
		CD	New Solders and Compatibility for A&D	CDA	Compatibility Study of SnPb Solder Pastes and Pb-Free Component		1	24	D53, M14, D01, D03
				CDB	Compatibility Study of Exisiting Solder Pastes and New Component Materials		1	36	D11, D01, DO3, D55, D53, M14, M19
				CDC	New Solder Qualifications		1	36	D13, D01, D03, D55
				CDD	Low Melt Solder Rework		13	24	D13, D44
		CE	Insertion Mount (PTH)	CEA	Reliability of PTH Solder Joints as a Function of Remaining Cu Plating Thickness after Assembly and Rework		13	18	D20
				CEB	Shock and Vibration		13	24	D50
		CF	Handling	CFA	Handling and ICT Testing		13	24	M24, D57, T7, S17
				CFB	Handling Assessment Models and Guide		13	24	M24, D57, T07, S17

Table 3.3 - Solder joint technical chart (cont)

Table 3.3 shows the specific level 3 technical approaches for the assembly projects along with the specific gap referrals. The full array of technical approaches can be found in Appendix C.

Solder Joint Reliability Models



Reliability Modeling Schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Test Vehicles and Data Collection																
Validation Data Collection and Assessment																
Materials Properties & Constitutive Relations																
Thermal Cycling Induced Fatigue																
Vibration																
Combined Loading																
Shock and Drop																
Creep Rupture																
Reliability Modeling																

Test Vehicle Design and Fabrication

This project will serve as a shared support for a number of other tasks. Common test vehicles shall be employed in these other projects to the greatest extent possible. The subprojects will be disseminated as follows.

1. Daisy-chained model components shall be designed to simulate BGAs, CSPs, flip chips and LGAs and passives, effectively spanning the relevant range of solder microstructures and resulting properties. The BGA, chip scale packaging (CSP), and flip chip designs will be produced with solder balls of SAC305, SnAg, SAC105, and SnPb.
2. A representative range of commercial (daisy-chained) components shall be procured for cross checking and calibration of results achieved with the model components. These shall include components known to have particularly limited life such as passives and thin small outline packages (TSOPs).
3. A range of different PCB designs shall be developed in collaboration with the other tasks to accommodate thermal cycling, cyclic bending, drop, and vibration testing. The pad

designs shall normally be optimized to favor solder failure, as opposed to pad cratering or intermetallic bond failure. A special solder mask defined design shall be developed to allow the study of intermetallic bond failures.

4. Components and PCBs shall be thoroughly characterized in terms of effective modulus and CTE vs. temperature, above and below T_g, as well as warpage vs. temperature during reflow and thermal cycling.
5. Test vehicles shall be assembled with two different reflow profiles and both SAC305 solder paste and two different volumes of SnPb solder paste each. In addition, passives shall also be assembled with SN100C paste to simulate wave-soldered assemblies.

➢ **Gap Addressed**

- Currently there is no capability to predict the reliability of lead free solder joints under realistic long term service conditions with the necessary degree of fidelity. Even which set of materials, design, or process alternatives will perform best in service is unknown
- A large number of projects addressing critical gaps need similar test vehicles. Standardization will help quantify interactions and relations, as well as saving money

Validation Data Collection and Assessment

Available solder joint reliability test data shall be collected with all possible experimental details, component and PWB properties, and other factors affecting reliability. The credibility and completeness of the available information shall be carefully assessed and uncertainties assigned to the data. Contact shall be made with the original experimenters and owners of the data for verifications and further details.

➢ **Gap Addressed**

- A shortage of test data for Pb-free assemblies renders the attempts to validate failure models (solder, pad cratering, and trace cracking), more difficult and inconclusive
- There is an absence of predictive models of solder joint fatigue, along with insufficient materials properties data for the model inputs
- The list of appropriate computational models needed include: thermo mechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration
- Test vehicles to gather the required data and other information such as underfill, staking methods, preconditioning environments, stress screening environments, and field conditions, all need to be developed

Materials Properties & Constitutive Relations

Constitutive relations shall be developed that describe the evolution of deformation and damage propagation (damage resistance) properties as a function of time, temperature and

loading history. Credibility of extrapolations shall be established through a quantitative relationship between the solder properties and fundamental materials features and mechanisms. All data generated under other tasks shall be incorporated to minimize the current task. Mixing lead free joints with SnPb solder will change the properties to a degree that varies strongly with the specific Pb concentration, i.e. general constitutive relations will not be meaningful, but two examples will be considered.

- **Gap Addressed**

  - Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. One of the material sets includes solder where existing and future Pb-free alloys to formulate failure models is lacking (solder, pad cratering, and trace cracking)
  - There is an absence of predictive models of solder joint fatigue, along with insufficient materials properties data for the model inputs. The list of appropriate computational models needed include: thermo mechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration
  - Test vehicles to gather the required data and other information such as underfill, staking methods, preconditioning environments, stress screening environments, and field conditions, all need to be developed
  - The influence of preconditioning or storage of Pb-free materials prevents the creation of appropriate and validated failure models for failure prediction, test development, and creation of heuristic rules
  - There is a lack of appropriate and validated failure models, which prevents accurate failure prediction, test development, and creation of heuristic rules on assemblies which have been influenced by prior events, such as environmental stress and field conditions
  - Existing heuristic rules for Combined Environments used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product
  - Behavior of Pb-free solder interconnects under shock and vibration at low temperatures (sub zero) is not adequately characterized
  - Current Pb-free materials are insufficient for A&D products. This includes solders, laminates, and other materials that comprise Pb-free electronic assemblies.
  - There are no rules for mixed solders, "SnPb+Pb-free" joints or "Pb-free-Pb-free" alloys
  - There are no standardized tests for simulated solder joints. There is little test data and no standardized specimen geometries and test methods for evaluating the effects of Pb-free solder specimen size in relation to microstructure on the mechanical and physical properties of the interconnections
  - There is a lack of understanding of reliability degradation from storage, use, and repair stresses

Thermal Cycling Induced Fatigue

A database of systematic and comprehensive accelerated thermal cycling results shall be established which can serve as the basis for validation of solder joint fatigue models and determination of acceleration factors in thermal cycling induced fatigue failure. This database shall include the statistical distributions of solder failure, failure mode, and the associated evolution of solder microstructure. Additionally, the database will include creep properties as a function of stress and time, and the physical and mechanical properties of the components and the circuit boards required as critical input into solder joint fatigue models. Accelerated test protocols and acceleration factors applicable to long-term service under representative conditions shall be developed based on this database. This shall include guidelines to ensure that the solder failure mechanism is the same in service and test (that both are equally affected by recrystallization).

- **Gap Addressed**

  - Shortages of test data for Pb-free assemblies renders the attempts to validate failure models more difficult and inconclusive (solder, pad cratering, and trace cracking)
  - There is an absence of predictive models of solder joint fatigue along with insufficient materials properties data for the model inputs. The list of appropriate computational models needed include: thermo mechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration
  - Test vehicles need to be developed to gather the required data and other information such as underfill, staking methods, preconditioning environments, stress screening environments, and field conditions
  - The influence of preconditioning or storage of Pb-free materials prevents the creation of appropriate and validated failure models for failure prediction, test development, and creation of heuristic rules
  - There are no rules for mixed solders, "SnPb+Pb-free" joints, or "Pb-free-Pb-free" alloys
  - Current Pb-free materials are insufficient for A&D products. This includes solders, laminates, and other materials that comprise Pb-free electronic assemblies

Vibration

A systematic database of the statistical distributions of solder failure in accelerated vibration testing shall be established. These shall be correlated with solder microstructure and creep properties for use in reliability model development. Accelerated test protocols and acceleration factors applicable to long-term service under representative conditions shall be developed. This shall include guidelines to ensure that the solder failure mechanism is the same in service and test.

- **Gap Addressed**

- A shortage of test data for Pb-free assemblies renders the attempts to validate failure models (solder, pad cratering, and trace cracking), more difficult and inconclusive
- There is an absence of predictive models of solder joint fatigue, along with insufficient materials properties data for the model inputs. The list of appropriate computational models needed include: thermo mechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration
- Test vehicles to gather the required data and other information such as underfill, staking methods, preconditioning environments, stress screening environments, and field conditions, all need to be developed
- There is a lack of appropriate and validated failure models, which prevents accurate failure prediction, test development, and creation of heuristic rules for solder failure models requiring vibration
- The influence of preconditioning or storage of Pb-free materials prevents the creation of appropriate and validated failure models for failure prediction, test development, and creation of heuristic rules
- There are no rules for mixed solders, "SnPb+Pb-free" joints, or "Pb-free-Pb-free" alloys
- Current Pb-free materials are insufficient for A&D products. This includes solders, laminates, and other materials that comprise Pb-free electronic assemblies
- Existing heuristic rules for vibration used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product
- Behavior of Pb-free solder interconnects under shock and vibration at low temperatures (sub zero) is not adequately characterized

Combined Loading

A systematic database of the statistical distributions of solder failure under various combinations of loading shall be established. These shall be correlated with solder microstructure and creep properties for use in reliability model development. Accelerated test protocols and guidelines for the assessment of damage accumulation shall be developed. This shall include guidelines to ensure that the solder failure mechanism is the same in service and test.

Gap Addressed

- A shortage of test data for Pb-free assemblies renders the attempts to validate failure models (solder, pad cratering, and trace cracking), more difficult and inconclusive
- There is an absence of predictive models of solder joint fatigue, along with insufficient materials properties data for the model inputs. The list of appropriate computational models needed include: thermo mechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration. Test vehicles to gather the required data and other information such as

- The influence of preconditioning or storage of Pb-free materials prevents the creation of appropriate and validated failure models for failure prediction, test development, and creation of heuristic rules
- Existing tests (design verification, product qualification) and screens used by the A&D community may not be valid for Pb-free product undergoing Environmental Stress Screening (ESS)
- There are no rules for mixed solders, "SnPb+Pb-free" joints, or "Pb-free-Pb-free" alloys
- Current Pb-free materials are insufficient for A&D products. This includes solders, laminates, and other materials that comprise Pb-free electronic assemblies
- The predicted reliability of solder joints using combined environmental tests lack the appropriate and validated failure models for accurate failure prediction, test development, and creation of heuristic rules
- The lack of appropriate and validated failure models prevents accurate failure prediction, test development, and creation of heuristic rules for tin whiskers

Shock and Drop

A systematic database of the statistical distributions of solder failure in selected shock and drop tests shall be established. These shall be correlated with solder microstructure and creep properties for use in reliability model development. Test protocols together with guidelines for the generalization of test results to all the variations of conditions encountered under typical service conditions shall be recommended.

Gap Addressed

- A shortage of test data for Pb-free assemblies renders the attempts to validate failure models (solder, pad cratering, and trace cracking), more difficult and inconclusive
- There is a lack of appropriate and validated failure models, which prevents accurate failure prediction, test development, and creation of heuristic rules for solder failure models requiring mechanical shock
- High G pyrotechnic mechanical shock requirements for solder joints, which are differentiated from other mechanical shock tests, do not have predictive models for Pb-free materials. The absence of materials properties, validation and High G failure mode data, make computational models difficult to ascertain
- The influence of preconditioning or storage of Pb-free materials prevents the creation of appropriate and validated failure models for failure prediction, test development, and creation of heuristic rules
- Existing heuristic rules for mechanical shock used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product
- There are no rules for mixed solders, "SnPb+Pb-free" joints, or "Pb-free-Pb-free" alloys

- In PCB design, there is a risk that heritage SnPb solder geometries or solder stencil designs will need to change to adjust the solder volume and geometry for Pb-free solders. Geometries are currently based on thermal cycle test results and neglect shock/vibration considerations
- Current Pb-free materials are insufficient for A&D products. This includes solders, laminates, and other materials that comprise Pb-free electronic assemblies
- Behavior of Pb-free solder interconnects under shock and vibration at low temperatures (sub zero) is not adequately characterized

Creep Rupture

Guidelines shall be developed for the rapid prediction of time to creep rupture failure under various conditions of load, temperature, and thermo mechanical history and relevant materials data quantified.

Gap Addressed

- Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. One of the material sets includes solder where existing and future Pb-free alloys to formulate failure models (solder, pad cratering, and trace cracking) is lacking
- The influence of preconditioning or storage of Pb-free materials prevents the creation of appropriate and validated failure models for failure prediction, test development, and creation of heuristic rules
- Existing heuristic rules for creep rupture used by electrical and mechanical designers based on experience with SnPb programs, may be insufficient to ensure reliability of Pb-free product

An Optimized Test Approach for Additional Alloys

The available results and conclusions from the other solder joint testing projects shall be carefully reviewed. A new and reduced test plan sufficient for testing additional solder alloys shall be the defined basis of test reviews. Current lead free solder alloys may be inappropriate for some A&D products, as the consumer electronics industry continues its search for better materials. There is a clear need for an affordable approach to the assessment and characterization of additional alloys.

Gap Addressed

- Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. One of the material sets includes solder where existing and future Pb-free alloys to formulate failure models (solder, pad cratering, and trace cracking) is lacking

- A shortage of test data for Pb-free assemblies renders the attempts to validate failure models (solder, pad cratering, and trace cracking), more difficult and inconclusive
- There is no known Pb-free alloy that meets or exceeds SnPb assembly and reliability performance
- There is an absence of predictive models of solder joint fatigue, along with insufficient materials properties data for the model inputs. The list of appropriate computational models needed include: thermo mechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration. Test vehicles to gather the required data and other information such as underfill, staking methods, preconditioning environments, stress screening environments, and field conditions, all need to be developed
- High G pyrotechnic mechanical shock requirements for solder joints, which are differentiated from other mechanical shock tests, do not have predictive models for Pb-free materials .The absence of materials properties, validation and high G failure mode data, make computational models difficult to ascertain
- There is no means to predict the effects of soldering process variations (workmanship) on long-term joint reliability for Pb-free. The absence of computational models that can address changes to the solder joint caused by multiple reflows, solder volume, and fillet/joint geometry, make reliability predictions difficult
- Current Pb-free materials are insufficient for A&D products. This includes solders, laminates, and other materials that comprise Pb-free electronic assemblies

Reliability Modeling

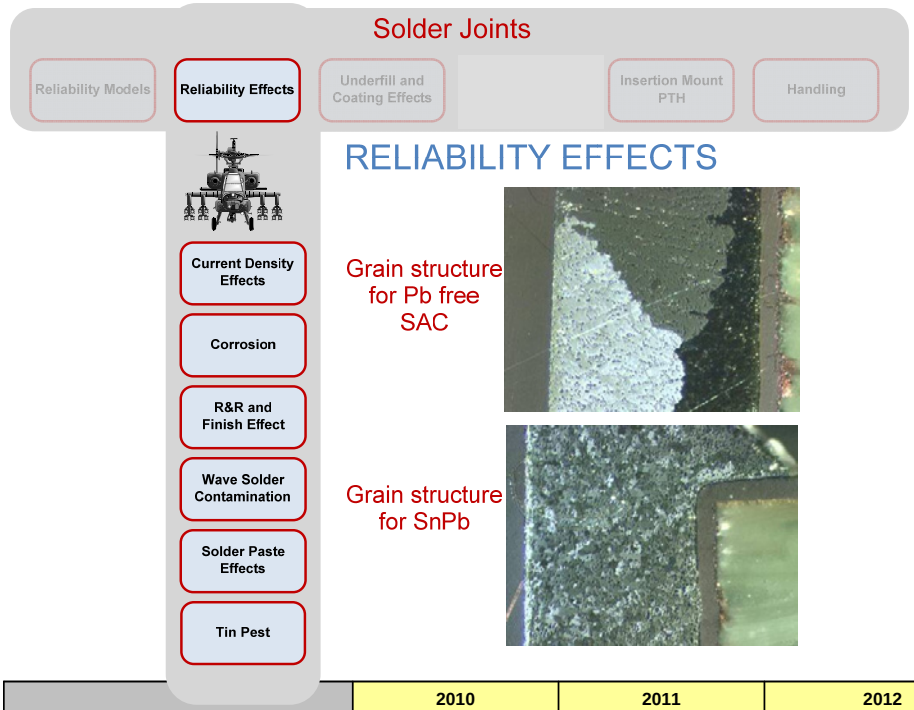
Individual life prediction models for different failure modes shall be developed and combined into a comprehensive computational model predicting failure rates and life under conditions of thermal fatigue, vibration, shock and drop, creep rupture and combinations of these.

- **Gap Addressed**

  - There is an absence of predictive models of solder joint fatigue along with insufficient materials properties data for the model inputs. The list of appropriate computational models needed include thermo mechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration. Test vehicles to gather the required data and other information such as underfill, staking methods, preconditioning environments, stress screening environments, and field conditions, all need to be developed
  - There is a lack of appropriate and validated failure models, which prevents accurate failure prediction, test development, and creation of heuristic rules for solder failure models requiring vibration
  - There is a lack of appropriate and validated failure models, which prevents accurate failure prediction, test development, and creation of heuristic rules for solder failure models requiring mechanical shock

- High G pyrotechnic mechanical shock requirements for solder joints, which are differentiated from other mechanical shock tests, do not have predictive models for Pb-free materials. The absence of materials properties, validation and high G failure mode data, make computational models difficult to ascertain
- The predicted reliability of solder joints using combined environmental tests lack the appropriate and validated failure models for accurate failure prediction, test development, and creation of heuristic rules
- There is a lack of appropriate and validated failure models which prevents accurate failure prediction, test development, and creation of heuristic rules in plated through-holes (PTH)
- PCB pad cratering and trace cracking lacks the sufficient data on material properties to formulate failure models. No test vehicle has been developed for model validation and failure mode analysis
- The influence of preconditioning or storage of Pb-free materials prevents the creation of appropriate and validated failure models for failure prediction, test development, and creation of heuristic rules
- There is a lack of appropriate and validated failure models, which prevents accurate failure prediction, test development, and creation of heuristic rules on assemblies which have been influenced by prior events, such as environmental stress and field conditions

Solder Joint Reliability Effects



Reliability Effects Schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Test Approach for new Alloys																
Current Density Effects																
Corrosion																
R&R board and finish report																
Tin Pest																

A number of conditions play a role in solder joint reliability. Work package CA addresses the primary recognized and tested conditions and provides a detailed research plan to provide data and models to allow for reliability production in A&D application. This work package is designed to complement the CA and examine other detrimental factors to solder joint reliability that are not characterized and that may be detrimental to solder joint reliability. With close examination of phenomenon identified in this work package, unexpected and unpredicted earlier failures may occur in A&D applications.

Areas of concern include:

- The role of electrical current
- The role of elevated corrosive environments
- The role of rework/repair
- The role of board material and finish
- The role of solder paste
- The factors influencing the formation of tin pest

Current Density Effects

This project will incorporate the following technical approaches:

- A summation of literature on current density and electromigration on solder joint life expectancy
- A defined test plan to determine time and current level influence on electromigration for SAC305, SnAg, SAC105, and SnPb solder spheres attached with SAC305 and SnPb solder paste, with bare copper and nickel over copper lands. Solder spheres < 350 micron and > 600 microns will be used. The plan shall include period microstructural evaluation.
- Development of a test plan approval for electromigration onset tests
- The execution of electromigration onset tests
- Correlate the microstructural changes with the onset of electromigration and define the model to assess electromigration over a range of test materials
- Define a test plan to assess influence of elevated current density (AC and DC) on solder joint failure due to temperature cycling and mechanical cycling.
- Execute the test plan and conduct failure analysis to identify failure location
- Provide project management including planning, reporting, coordination, and collaboration

Gap Addressed

- Predictive models of the solder joint electromigration phenomenon under high current density conditions are not well understood for Pb-free alloys. This is a lack of understanding on how the correlation between the solder alloy and test condition will affect the results

Corrosion

- This project will conduct a review for existing literature on corrosion impact on solder joint life under relevant field conditions including temperature cycling, vibration, and shock. Based on the data retrieved, test plan will be developed for assessing impact of corrosive environments and contamination on solder joint reliability

Gap Addressed

- The Pb-free material corrosion rates and how they correlate to service environments is not fully understood, resulting in increased reliability risk. This includes corrosive interactions with solder, PCB finishes, and component finishes, under powered and off storage conditions within A&D environments

Reflow and Repair Impact

An existing literature review will be needed on reflow/repair impact on solder joint life under relevant field conditions including temperature cycling and repetitive shock. Based on the findings, a test plan shall be developed to evaluate the impact of the rework/repair process on solder joint reliability subject to repetitive shock and temperature cycling.

- **Gap Addressed**

  - There is a lack of understanding on what the additional stresses of rework/repair will do to Pb-free assemblies
  - There is no defined specification for the maximum amount of reflow cycles and limitation requirements for each part/component that undergoes repair/rework cycles

Wave Solder Contamination Effects

This project will determine the effect of solder bath contamination on the long term reliability on solder joints and will collaborate with the studies conducted on the influence of contaminated wave solders on Pb-free assemblies.

- **Gap Addressed**

  - There is a lack of appropriate and validated failure models which prevents accurate failure prediction, test development, and creation of heuristic rules on assemblies which have been influenced by prior events, such as environmental stress and field conditions

Tin Pest

This project will develop a protocol and subsequent test method for visually indentifying and confirming tin pest, based on the review of existing tin pest research. The factors affecting tin pest will be identified and subsequent experiments will be conducted to ascertain the factors contributing to tin pest formation.

- **Gap Addressed**

  - There is a lack of standards/requirements to address receiving inspection in sustainment situations for tin whisker identification
  - The current Pb-free materials are insufficient to test for tin pest on A&D products

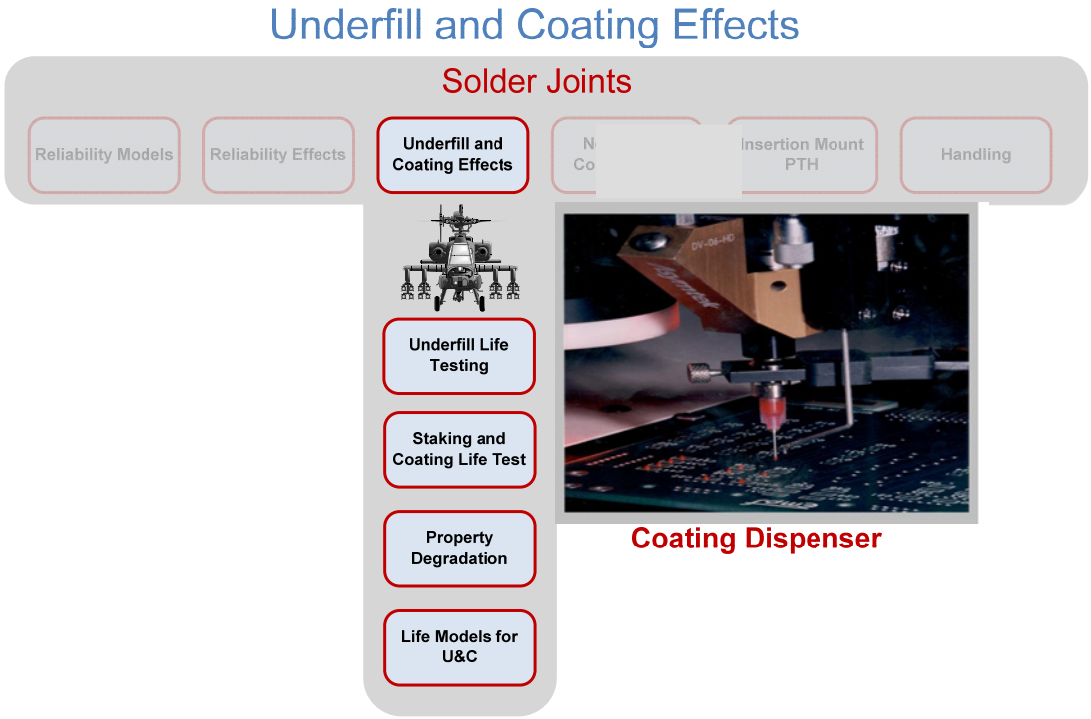
Solder Paste Effects

This project will define test vehicle and test plan for evaluating variation due to solder paste. The plan shall include ESS evaluation of a least four clean and no-clean solder pastes suppliers, and various SMT components common to the CCA test vehicle specimens.

- **Gap Addressed**

  - The variation in solder joint reliability can arise from a variety of sources. Presently there is no reliable method of assigning cause to the large variation in reliability for Pb-free solders

Underfill, Staking, and Coating Effects



Underfill & Coating Schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Underfill life testing																
Staking and Coating																
Property Degradation																
Solder Joint Life Models																

These projects will ascertain the reliability and effects of underfill on Pb-free solder joints. The project will achieve the following:

- Document the life impact of underfill on solder joint life of lead-free assembled area array packages relevant to A&D environments
- Document the life impact of staking on solder joint life of lead-free assembled surface mount parts to A&D environments
- Document the life impact of conformal coating on solder joint life of lead-free assembled surface mount parts to A&D environments
- Document the material behavioral properties of underfill, staking, and coating components relevant to development of models to assess solder joint life expectancy
- Provide a detailed modeling approach suitable for commercial finite element analysis software for predicting life expectancy of underfilled, staked, and conformally coated lead-free assembled surface mount parts
- Provide and analytic modeling approach suitable for spreadsheet implantation for predicting life expectancy of underfilled, staked, and conformally coated lead-free assembled surface mount parts

Underfill Life Testing

This project will summarize underfill research related to solder joint reliability, and create a test plan including test specimen design and failure criteria. At a minimum, the test specimens shall include 6 candidate underfills (2 reworkable, 4 non-reworkable). Parts will include two area array packages (<350 and > 600 micron solder spheres) with four solder sphere alloys and one surface mount perimeter leaded package. Parts will be assembled with either SnPb or SAC305 solder paste; both clean and no-clean pastes will be used. A board for temperature cycling and mechanical cycling will be defined. The test board designs will be created in collaboration with test vehicle design and fabrication activity. Environmental tests will include two temperature cycles, two vibration conditions, and two drop shock tests. Precondition will include ambient storage, elevated temperature and humidity storage, and elevated temperature storage. The test specimen count will be sufficient enough determine the effect of precondition, underfill, and solder volume. Pilot tests will also be conducted to assure significant relevant failure within the test scope.

Gap Addressed

- Life test data is not readily available for the interconnect life of staked and underfilled components

Staking and Coating Life Testing

This project will summarize staking and coating research related to solder joint reliability and create test plan including test specimen design and failure criteria. The test plan will be similar in nature to that of the underfill project notated above.

Gap Addressed

- There is an absence of predictive models of solder joint fatigue, along with insufficient materials properties data for the model inputs. The list of appropriate computational models needed include: thermo mechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration. Test vehicles to gather the required data and other information such as underfill, staking methods, preconditioning environments, stress screening environments, and field conditions, all need to be developed
- Existing heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free products using encapsulants, staking compounds, and underfill
- There is no proven durability and compatibility of adhesives/coatings/underfill materials with lead-free soldering processes
- Life test data is not readily available for the interconnect life of staked and underfilled components

- Effectiveness of modeling techniques for estimating life expectancy of interconnections of staked or underfilled over long-term operation has not been satisfactorily documented. These include the Solder Failure Models for Thermal Cycling, Vibration, and Mechanical Shock.

Properties and Property Degradation

This project entails obtaining a list of underfill, staking, and coating compounds to collaborate with modeling activity and material properties to be measured and characterized. The envisioned properties will include glass transition temperature, elastic modulus, Prony series, Poisson's ratio, shrinkage, and adhesion properties. The property measurements will be made *as cured* and under aging conditions to coordinate with testing groups. The adhesion properties tests will be conducted over the respective PCB areas on copper and solder mask utilizing the various types of solder paste.

Gap Addressed

- There is an absence of predictive models of solder joint fatigue, along with insufficient materials properties data for the model inputs. The list of appropriate computational models needed include: thermo mechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration. The test vehicles to gather the required data and other information such as underfill, staking methods, preconditioning environments, stress screening environments, and field conditions, all need to be developed
- Existing heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free products using encapsulants, staking compounds, and underfill
- There is no proven durability and compatibility of adhesives/coatings/underfill materials with lead-free soldering processes
- The life test data is not readily available for the interconnect life of staked and underfilled components
- Effectiveness of modeling techniques for estimating life expectancy of interconnections of staked or underfilled over long-term operation has not been satisfactorily documented. These include the Solder Failure Models for Thermal Cycling, Vibration, and Mechanical Shock
- There is a limited understanding of underfill reparability and potential degradation in storage conditions

Solder Joint Life Models for Underfilled, Staked, and Coated Surface Mount Parts

This endeavor will summarize the existing modeling approaches to underfill, staking, and coating. Subsequent models will be developed with detailed approaches for assessing the impact of underfill, staking, and coating on solder interconnect life of lead-free solders under various ESS testing. The model will be developed based on the constitutive and

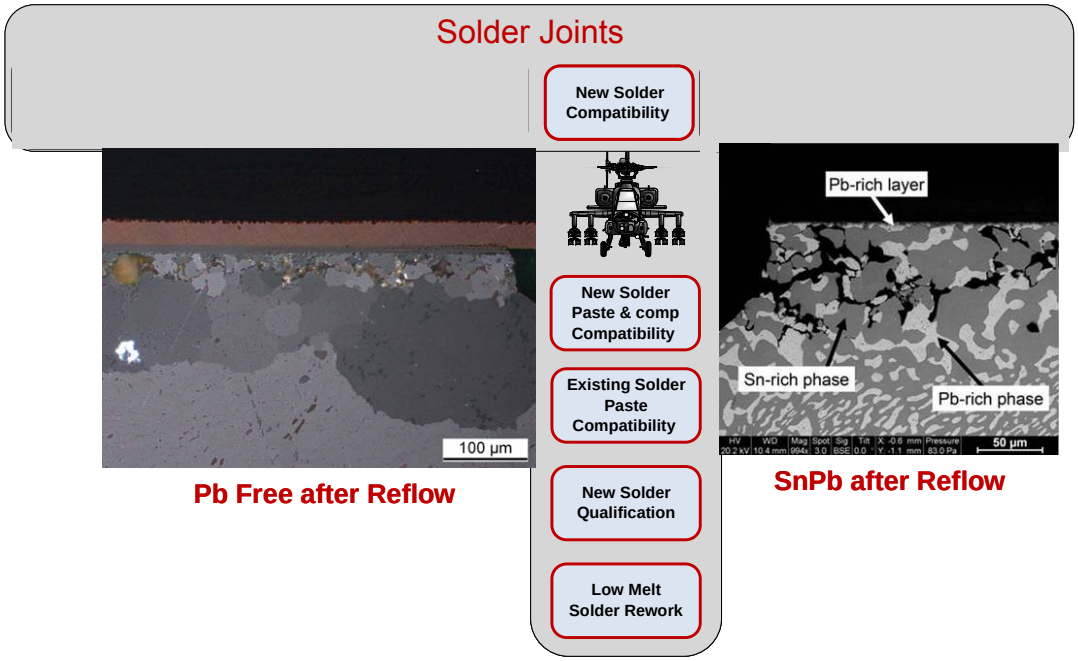
compound properties detailed in other studies to produce a predicative life expectancy for underfilled, staked, and coated surface mount parts.

- **Gap Addressed**

  - There is an absence of predictive models of solder joint fatigue, along with insufficient materials properties data for the model inputs. The list of appropriate computational models needed include: thermo mechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration. Test vehicles to gather the required data and other information such as underfill, staking methods, preconditioning environments, stress screening environments, and field conditions, all need to be developed
  - Existing heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free products using encapsulants, staking compounds, and underfill
  - There is no proven durability and compatibility of adhesives/coatings/underfill materials with lead-free soldering processes
  - Life test data is not readily available for the interconnect life of staked and underfilled components
  - Effectiveness of modeling techniques for estimating life expectancy of interconnections of staked or underfilled over long-term operation has not been satisfactorily documented. These include the Solder Failure Models for Thermal Cycling, Vibration, and Mechanical Shock

New Solders and Compatibility for A&D

NEW SOLDER COMPATIBILITY FOR A&D PRODUCTS



New Solder Compatibility	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Compatibility study New Materials																
Compatibility study Existing Materials																
New Solder Qualification																
Low Melt Solder Rework																

This project will be evaluating manufacturability and reliability in harsh environment of standard SnPb and Sn-Ag-Cu lead-free solders (SAC) with lead-free BGA ball materials. The BGA ball materials will include the widely used SAC405, SAC305, SAC105 and Low Ag solders with additives such as Ni, Mn, and rare earth elements that were introduced by component manufacturers to improve the mechanical performance. The process parameters that provide high reliability in harsh environment will also be defined.

Additionally, the project will also be evaluating the reliability of some of the new lead-free solders in harsh environments. Several compositions with Bi, In, or combinations of Bi, Ni, and Sb additives are proposed, which may provide long term reliability performance for both high mechanical and high thermal stress conditions. The project will deliver data on the new solders' compatibility with existing and new lead-free components using different assembly parameters. The performance in harsh environment, mechanical, and thermo mechanical conditions will be tested, and the results delivered. The best performer/ performers will be recommended for further qualification in the A&D industry.

Compatibility Study of SnPb Solder Pastes and Pb-free Components

This project will be evaluating the manufacturability and reliability of SnPb solders with lead-free BGA ball materials. Incorporating lead-free BGAs in tin-lead solder using conventional process may or may not allow full mixing; a resulting microstructure may not be uniform and could cause a reduction in reliability. The solder joint quality, microstructure, manufacturing parameters, and long-term reliability in harsh environments will be systematically studied for different mixture levels of SnPb solder with lead-free components including SAC105 and its modifications.

Gap Addressed

- There are no rules for mixed solders, "SnPb+Pb-free" joints, or "Pb-free-Pb-free" alloys
- Industries lacks knowledge about the relationship between solder alloys and solder processes/equipment to produce acceptable solder joint microstructure
- Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. One of the material sets includes solder where existing and future Pb-free alloys to formulate failure models (solder, pad cratering, and trace cracking) is lacking
- A shortage of test data for Pb-free assemblies renders the attempts to validate failure models (solder, pad cratering, and trace cracking), more difficult and inconclusive

Compatibility Study of Existing Solder Pastes and New Component Materials

This project will be evaluating the manufacturability and reliability of industry accepted SAC305 and SnPb solders with new lead-free BGA ball materials. Low Ag solders with additives such as Ni, Mn, and rare earth elements were introduced by component manufacturers to improve the mechanical performance of consumer electronics. The melting temperature of these new solders are higher then SAC305. The solder joint quality, microstructure, manufacturing parameters, and long-term reliability in harsh environments are unknown

Gap Addressed

- Current Pb-free materials are insufficient for A&D products. There is no known component plating finish that meets or exceeds SnPb assembly and reliability performance
- Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. One of the material sets includes solder where existing and future Pb-free alloys to formulate failure models (solder, pad cratering, and trace cracking) is lacking
- A shortage of test data for Pb-free assemblies renders the attempts to validate failure models (solder, pad cratering, and trace cracking), more difficult and inconclusive

- When multiple solders are used in assembly, certain combinations of solders are incompatible or have a narrow process window
- There are no rules for mixed solders, "SnPb+Pb-free" joints, or "Pb-free-Pb-free" alloys
- Industries lacks knowledge about the relationship between solder alloys and solder processes/equipment to produce acceptable solder joint microstructure
- There is a lack of manufacturing protocols and procedures to mitigate solder defects resulting from lead-free solder processes

New Solder Qualification

This project will be an evaluation of new lead-free solders with high reliability in harsh environments. Several compositions with Bi, In, or combinations of Bi, Ni, and Sb additives were proposed for these new lead-free solders, which may provide long term reliability in high mechanical and thermal stress conditions. The data on solder compatibility with existing and new lead-free components, assembly parameters, and thermo mechanical performance are needed.

Gap Addressed

- There is no known Pb-free alloy that meets or exceeds SnPb assembly and reliability performance
- Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. One of the material sets includes solder where existing and future Pb-free alloys to formulate failure models (solder, pad cratering, and trace cracking) is lacking
- A shortage of test data for Pb-free assemblies renders the attempts to validate failure models (solder, pad cratering, and trace cracking), more difficult and inconclusive
- When multiple solders are used in assembly, certain combinations of solders are incompatible or have a narrow process window

Low Melt Solder Rework

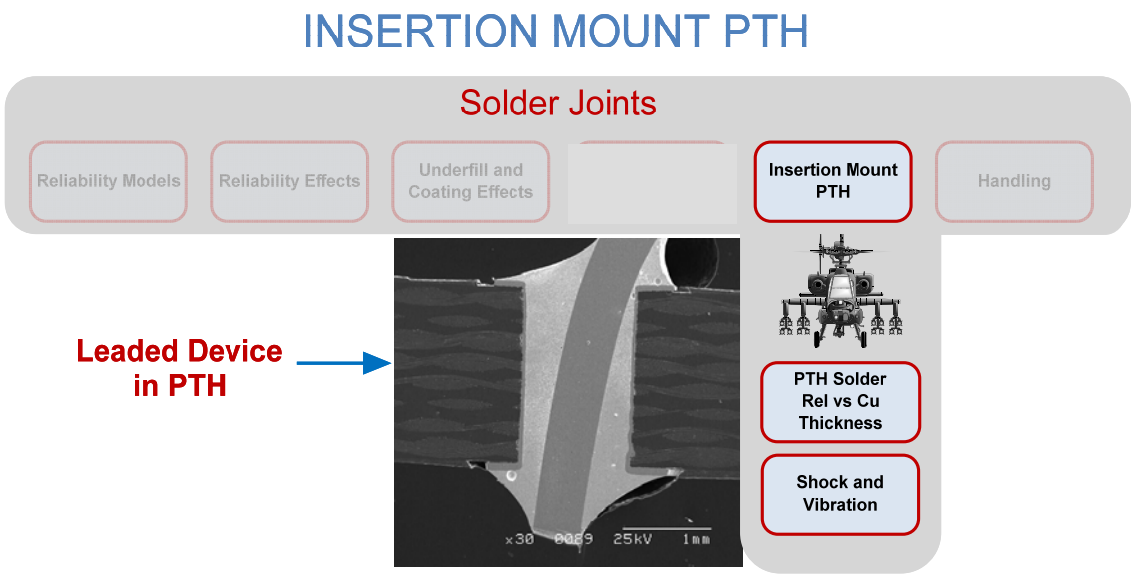
A new solder and rework process with a peak reflow temperature not higher than 217 + 2°C is proposed. The reduced process temperature avoids component overheating, reduces board warpage and cratering, and protects neighboring components from thermal damage. The new rework solution demonstrated good electrical properties and higher reliability than pure SnPb joints in 0°C to 100°C cycling. This project will be evaluating -55°C to 125°C thermal cycling, vibration and drop/shock performance of reworked solder joints using this new solder

Gap Addressed

- There is no known Pb-free alloy that meets or exceeds SnPb assembly and reliability performance

- Current PCB laminate materials formulated for Pb-free assembly have unknown risks in regards to assembly and reliability performance under A&D required environmental conditions.

Insertion Mount



Insertion Mount PTH Schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
PTH solder reliability and Thickness																
shock and Vibration - PTH																

Current IPC-610 barrel fill specifications were originally established in the 1970's considering a 0.062" thick board and SnPb alloy, and the requirements have not been updated to suit today's thicker boards and use of lead free alloys. The specification requirements, especially considering the size (>0.120" thick), complexity and multiple ground connections of some of today's high complexity products, can be unnecessarily challenging. Recent literature within the industry has shown that barrel fill requirements should be based on the wetted pin length, as opposed to a percentage fill. It states that a board up to a thickness of 0.130", only needs to obtain up to 36% barrel fill to establish a suitably strong joint to survive both thermal and mechanical environments.

This project is proposed to address two main concerns with respect to pin-through-hole (PTH) devices. The first objective is to assess the reliability performance of pin-through-hole SAC 305 solder joints in a harsh environment when hole fill levels do not reach current IPC-610 class 3 specification levels on a printed circuit board equal to or greater than 120 mil in thickness. The second objective is to assess the impact of high levels of copper dissolution on the thermal reliability and Shock and Vibration robustness of PTH connections. In addition to these two main objectives, the project will also characterize the impact which contamination levels of the solder bath have on the final barrel fill and copper dissolution rates. The project will also evaluate the effect of certain wave solder process parameters (e.g. preheat/pot temperatures and flux chemistries) and evaluate the impact that certain key board design features have on obtaining barrel fill (i.e. pin to hole aspect ratio, thermal connection and relief designs, etc…).

Reliability of PTH Solder Joints as a function of Copper

The process issues relating to high copper dissolution rates have been well documented within the industry. The copper dissolution rates of SAC305/405 plus many of the leading alternative lead-free wave alloys has been characterized and pin through-hole rework process windows assessed. One remaining gap within the A&D industry is the understanding of how copper dissolution or thinning of the through-hole barrel wall/knee locations affects the thermal reliability, under harsh environment and mechanical reliability of a pin through-hole joint. This project will provide attempts to assess the impact of high levels of copper dissolution on the thermal reliability and Shock and Vibration Robustness of PTH connectors.

Gap Addressed

- There is a lack of appropriate and validated failure models which prevents accurate failure prediction, test development, and creation of heuristic rules in Plated through Holes (PTH)

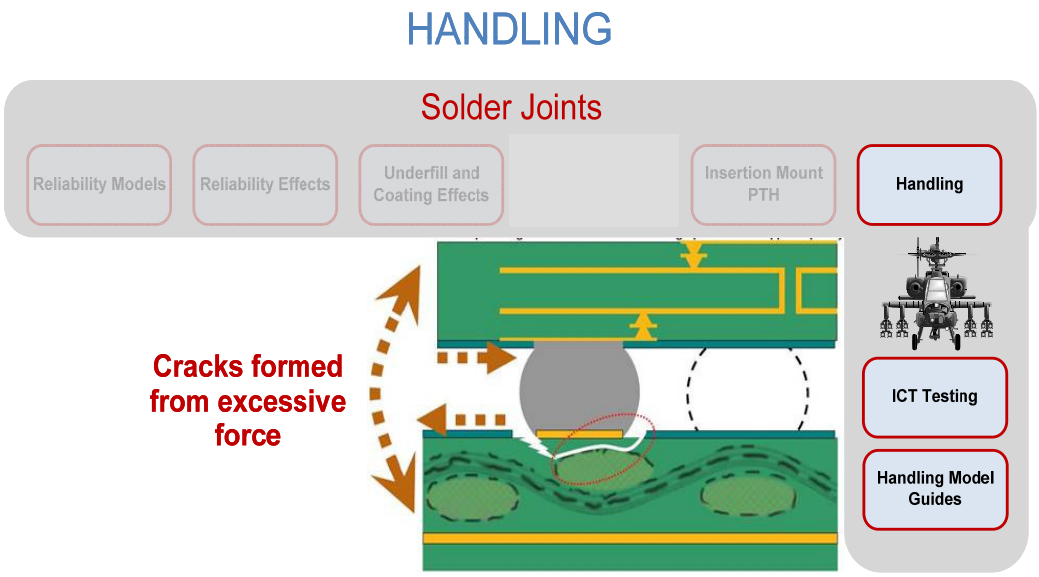
Shock and Vibration

The majority of work conducted to date on lead-free PTH thermal-mechanical reliability assessment has focused on maximizing hole fill on ground and signal leads. Assembly materials and processes have been optimized to achieve 100% barrel fill with subsequent reliability assessment. This project is proposed to assess the reliability performance of PTH solder joints in harsh environments when optimized hole fill is not achieved on thicker PCB cross sections. The goal would be to better understand the thermal-mechanical reliability performance of partially filled PTH barrels.

Gap Addressed

- Existing heuristic rules used for PTH solder fill by electrical and mechanical designers based on experience with SnPb programs, may be insufficient to ensure reliability of Pb-free product. There are no established (thermal cycling, vibration, shock) correlations on the reliability of solder joints of PTHs that are 25 to 75% partially filled with Pb-free solder

Handling



Solder Joint Handling Schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Handling and ICT Testing																
Handling assessment Model Guides																

The goal is the establishment of rules for the maximum PCB deflection allowed once or relatively few times in handling, ICT, etc. Conservative estimates will be based on how much lead free solder joints, integral pads and their attachment to laminates can be loaded a given number of times without having a significant effect on subsequent assembly reliability.

Handling and ICT Testing

Assembly and individual solder joint testing will be employed to quantify the acceptable loads, subjecting assemblies to thermal cycling, vibration, shock, drop and flexural loading to quantify subsequent life. Results will be compared to the life obtained without preconditioning. Specific test parameters will be selected based on available mechanistic understanding to be as sensitive as possible to projected differences in service life.

Limits will first be quantified in terms of loads and strains on the solder joints. Simple mechanical analysis will then be employed to convert these into practical limits on PCB deflection, surface strain and strain rate for various critical component types with the intent of generating strain rate dependent process limits for surface strain. Modeling and calculations will be based on the constitutive relations developed under another task.

- **Gap Addressed**

- The current ICT capability is not optimized for the processing of lead-free assemblies
- The current practice of designing in SnPb solder stress conditions for Pb-free designs will not necessarily result in satisfactory life in high stress environments. New test parameters need to be determined specifically for Pb-free materials
- There needs to be defined detection limits for Pb-free assemblies to prevent damage during handling, assembly, and test. Due to their stiffness, Pb-free alloys require additional precautions during handling and/or performing failure mode analysis
- Shipping and handling procedures do not presently address Pb-free factors, such as handling and storage conditions

Handling Assessment Models and Guide

This project shall summarize the critical handling inducted failures and input conditions, structures, models, and material properties necessary for assessing identified failures.

- **Gap Addressed**

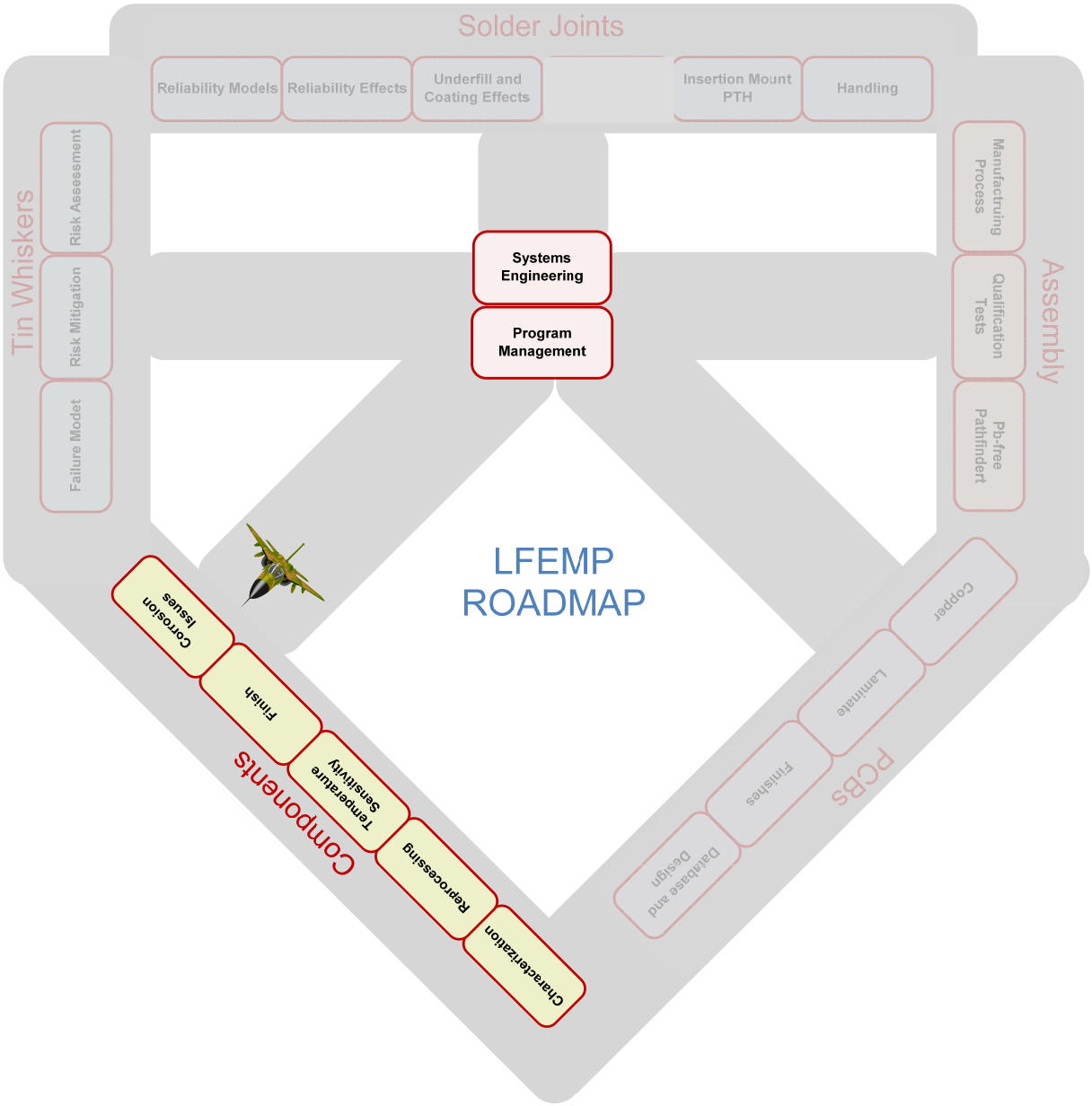
  - The current ICT capability is not optimized for the processing of lead-free assemblies
  - The current practice of designing in SnPb solder stress conditions for Pb-free designs will not necessarily result in satisfactory life in high stress environments, therefore new test parameters need to be determined specifically for Pb-free materials
  - There needs to be defined detection limits for Pb-free assemblies to prevent damage during handling, assembly, and test. Due to their stiffness, Pb-free alloys require additional precautions during handling and/or performing failure mode analysis
  - Shipping and handling procedures do not presently address Pb-free factors, such as handling and storage conditions

3.6.4 Expected Outcomes

- Qualified set of materials for use in A&D applications
- Models for assessing life and reduction in life due to exposure to environmental stress screens
- Solder qualification requirements
- A consistent set of models and data for assessing life expectancy of qualified set of solder materials
- Order of magnitude ranking for influences of:
  - Electromigration
  - Corrosion
  - Board Finish/Multiple reflows
- Tin pest modeling procedure

- Solder acceptance screening requirements
- Insertion mount fill requirements and rework limits
- Soldered assembly handling guidelines

3.7 Electronic Components



3.7.1 Summary Description:

To assure reliability in A&D applications requires more insight into component properties relevant to Pb-free assembly processes and requirements. This project element will design and conduct experiments, interpret results, and recommend program requirements to assure that components meet system requirements through storage, use, and possible repair actions. While technical considerations addressed elsewhere in the project may require refinishing of component interconnects, this project will also determine impact of refinished components on cost and schedule. Due to the degradation impacts of the elevated reflow temperatures required by most Pb-free solders, this project will evaluate new materials, design, and construction for components to improve temperature sensitivity.

Since component finishes have significant effects on solder joints for A&D applications, this project will develop approaches to evaluate the performance of Pb-free component finishes, considering factors such as assembly robustness, gold and palladium embrittlement, copper-nickel-tin failures, Kirkendall voiding, and identification of new problems. The degradation mechanisms must account for assembly stresses (e.g., multiple reflows), and environmental and operating stresses. The project will also develop approaches to evaluate the solderability performance of component finishes for A&D applications. Since Pb-free electronics introduces many new materials combinations, it will be necessary to characterize corrosion rates for Pb-free assembly materials and develop mitigation techniques.

3.7.2 Technical Brief

Components have become a major issue for providers of A&D products because of the likelihood that Pb-free materials, and especially components will filter their way through the product stream. Even with proper diagnostic systems to detect the occurrences of Pb-free entry, the probabilities of integration into the A&D product stream seem inevitable. Some of the issues left to be resolved are:

1. Component Characterization
    a. Temperature exposure limits
    b. Receiving/incoming inspection requirements
    c. Storage requirements for unassembled components
    d. Component properties database
    e. Fluxes/cleaning process compatibility with components
2. Component Refinishing/Reprocessing
3. Temperature Sensitivity Capability Improvement
4. Component Finish
    a. Finish Solder Joint Effect
    b. Solderability
5. Component Corrosion
    a. Corrosion Acceleration Factors
    b. Corrosion Mitigation

Examples of Component Issues

1. Component Characterization

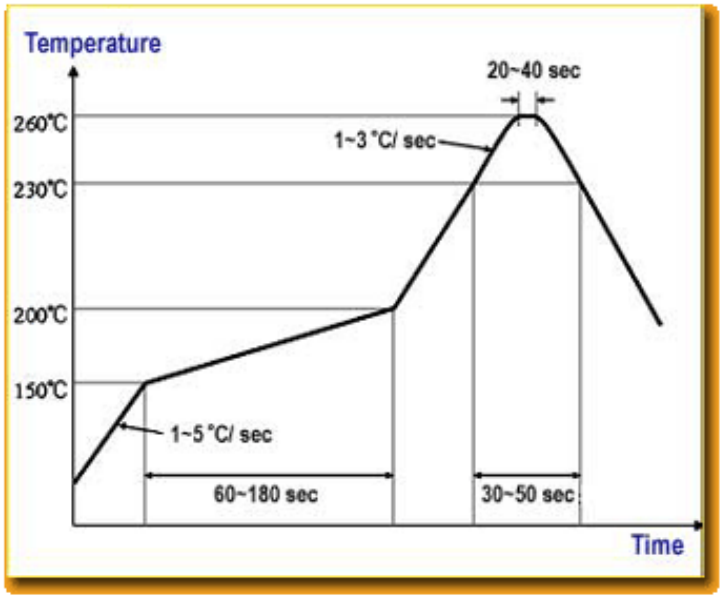


Figure 3.32 - Pb-free reflow Profile

There are prevailing issues regarding the effect of Pb-free on the various aspects of component characterization for A&D applications. These include:

- Receiving/incoming inspection requirements
  - Develop incoming component test/identification screening protocol for A&D products to preclude introduction of improper materials
  - Define inspection equipment capabilities to provide adequate performance in identifying finish properties (e.g., elements, thickness)
  - Consider issues related to source of supply (integrity of supplier, and component history within supply chain), cost of inspection (sampling approaches provide cost effective information), and prevalence of unwanted finishes for particular components

- Temperature exposure limits
  - Characterize components capability to survive soldering process temperatures to determine maximum number of permissible exposures to solder process reflow cycles (fig 3.32)
  - Consider degradation and introduction of latent defects due to assembly rework, field storage and use, and rework, and refinished components.
  - Aid establishment of A&D Pb-free assembly process margins and practices

- Storage requirements for unassembled components
  - Perform testing and evaluation to confirm long-term storage effects on Pb-free finish solderability, and that established requirements (time limits, and environment levels) control component degradation

- Develop storage requirements that address factors such as humidity and temperature, and gases that can affect solderable finish integrity.

- Component properties database
  - Characterize coefficient of thermal expansion and flexural modulus (component body and leads), and other information as indicated by the collaboration effort
  - Characterize the change in component characteristics after exposure to assembly/repair processes

- Fluxes/cleaning process compatibility with components
  - Determine component compatibility with Pb-free fluxes and cleaning processes to meet A&D life cycle requirements

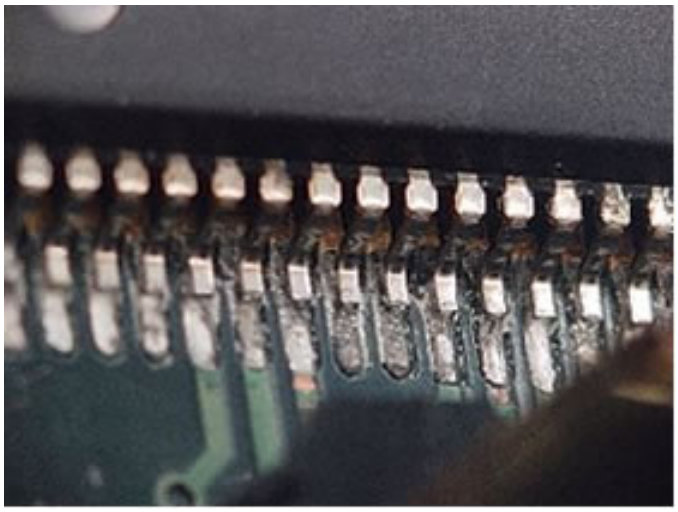


Figure 3.33 - Reworked leads on QFP

2. Component Refinishing and Reprocessing

There are prevailing issues regarding the effect of Pb-free on the various aspects of component refinishing and reprocessing for A&D applications. These include:

- The Cost and schedule impacts for solder compatibility refinishing
- The methodology to assess cost and schedule impact of damaged components and/or latent field failures induced by component refinishing, including impact of repair, rework, and replacement. This methodology will require risk assessment for ball grid array solder ball reprocessing to replace Pb-free balls with SnPb balls, as well as cost and schedule impact for components subjected to GEIA-STD-0006 requirements.

3. Component Finishes

The issues affecting Component finishes are the following:

- Development of higher process temperature tolerance

- Develop materials changes/component redesigns to improve thermal degradation sensitivity to assure A&D application reliability. Target improvement for component families most sensitive to Pb-free process reflow high temperatures. Collaborate with components manufacturers, as allowed. Apply J-STD-075 methodology, and note any required improvements. Evaluate performance of proposed changes with life cycle stress testing that includes assembly, repair/rework, and life cycle environmental and use stresses

- Finish Solder Joint Effect
  - Characterize performance of Pb-free finishes (e.g., Sn, SnBi, SnAg, SnCu, SAC dip, Au) in A&D applications, including contribution to solder joint integrity. Develop approach and test methods to characterize life cycle (primarily, temperature cycle, vibration, and shock effects) performance of Pb-free finishes with key solder alloys to address failure mechanisms related to finish.

- Solderability
  - Establish approaches to test for whether part finishes meet A&D requirements for solderability. Determine design characteristics that affect solderability performance, and establish finish requirements to meet different performance levels (including solder joint integrity). Evaluate suitability of existing solderability test requirements for A&D applications. Coordinate DDA finish testing for solder joint integrity to evaluate relationship between solderability and solder joint integrity.

4. Component Corrosion

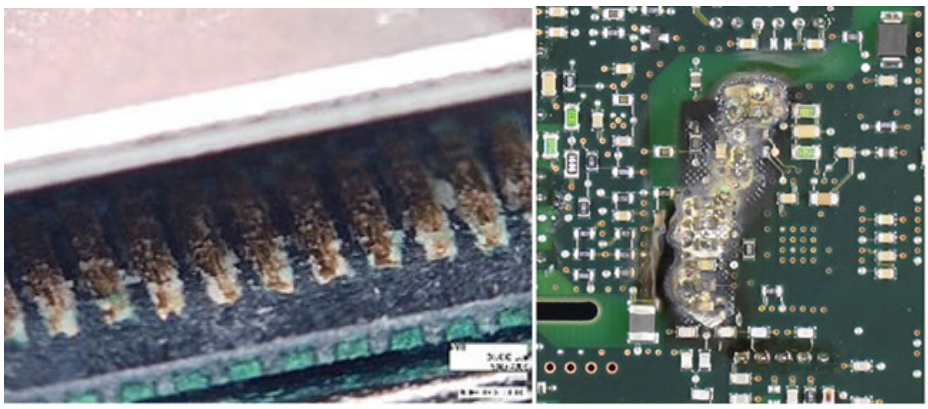


Fig 3.34 examples of corrosion of leaded devices

The issues affecting corrosion include:

- Corrosion Acceleration Factors
  - Establish corrosion (such as electrochemical, dendritic, galvanic) acceleration factors, for common Pb-free finishes (e.g., Sn, SnBi, SnCu, SnAg, SAC dip) on component

- Corrosion Mitigation (fig 3.34)
    - Develop and demonstrate design practice mitigation techniques, such as conformal coating and cleaning, to preclude corrosion effects. Assess life cycle environmental effects on the mitigation technique, compared to non-mitigated conditions

3.7.3 Recommend Components Technical Projects and Gaps Addressed

Hyperlink to Gap key

I	Technical Area	II	Techical Area	III	Technical Area		start month	duration	GAPS Addressed
D	COMPONENTS	DA	Component Characterization	DAA	Temperature Exposure Limits		1	24	M16, S05, S07
				DAB	Receiving / Incoming Inspection Requirements		1	6	M25
				DAC	Storage Requirements for Unclassified Components		13	12	M16
				DAD	Component Properties Database		1	24	D02
				DAE	Fluxes/Cleaning Process Compatability with Componenents		7	12	M16, S06, S07
		DB	Component Refinishing / Reprocessing	DBA	Component Refinishing / Reprocessing		13	12	M23
		DC	Temperature Sensitivity Capability Improvements	DCA	Temperature Sensitivity Capability Improvements		13	24	D51
		DD	Component Finish	DDA	Finish Solder Joint Effect		7	30	D11, M16
				DDB	Solderability		1	18	D47
		DE	Component Corrosion	DEA	Corrosion Acceleration Factors		13	24	D52
				DEB	Corrosion Mitigation		19	18	D52

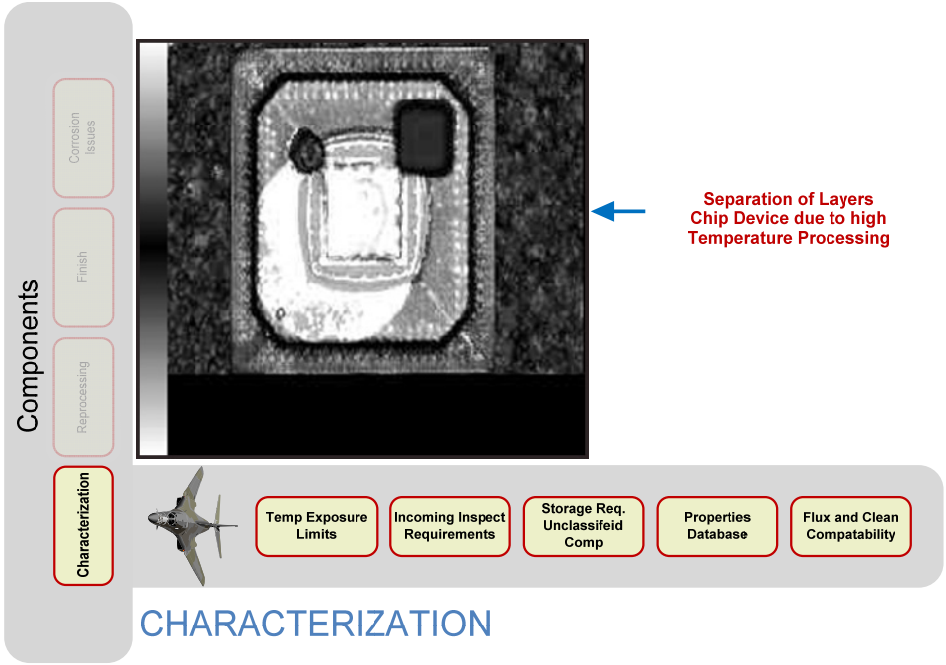
Table 3.4 - Components technical chart

Table 3.4 shows the specific level 3 technical approaches for the assembly projects along with the specific gap referrals. The full array of technical approaches can be found in Appendix C.

Currently available components do not consistently provide the robustness to support higher Pb-free processing temperatures, and the capability to survive multiple reflow cycles is not sufficiently characterized. There is a lack of current industry standard incoming screening procedures for components to assure proper finishes, as well as gap in the current industry standard procedures for storing components before assembly. Pre assembly procedures are necessary to assure solderability and capability to survive Pb-free soldering processes. Insufficient information on existing and future

Pb-free components structural properties prevents the formulation and validation of appropriate failure models. Lack of understanding of component and process compatibility issues that cause reliability degradation and latent defects from Pb-free soldering processes.

Component Characterization



Component Characterization Schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Temperature Exposure Limits																
Incoming Inspection Requirements																
Component Properties Database																
Flux and Cleaning compatibility with Comp																
Storage requirements for unclassified components																

This section of projects will characterize component properties relevant to Pb-free assembly processes and requirements. It will include the design and implementation of experiments, interpretation of results, and recommend program requirements to assure that components meet system requirements through storage, use, and possible repair actions.

Temperature Exposure Limits

This project will investigate thermal durability/survivability of current component families to establish A&D Pb-free assembly process margins and practices. This effort will characterize components capability to survive soldering process temperature excursions to determine the maximum number of permissible exposures to solder reflow cycles. The characterization will consider degradation and introduction of latent defects due to assembly rework, field storage and use, and rework, and include refinished components

- **Gap Addressed**

  - The current industry components are not capable of surviving lead-free soldering processes
  - There is no defined specification for the maximum amount of reflow cycles and limitation requirements for each part/component that undergoes repair/rework cycles
  - There is a lack of understanding of reliability degradation from storage, use, and repair stresses

Receiving and Incoming Inspection Requirements

This project will establish incoming inspection approaches to assure that components finishes correspond to the design requirements.

- **Gap Addressed**

  - There is a lack of current industry standard component incoming screening procedures

Storage Requirements for Unclassified Components

This endeavor shall develop environmental requirements for storage conditions of components before assembly

- **Gap Addressed**

  - Current industry components are not capable of surviving lead-free soldering processes.

Component Properties Database

This project will characterize component properties relevant to Pb-free assembly processes and requirements. This will involve the design and administration of experiments, interpretation of results, followed by recommend program requirements to assure that components meet system requirements through storage, use, and possible repair actions.

- **Gap Addressed**

  - The development of new laminate materials used for Pb-free processing has necessitated a compulsory examination of laminate properties and their effect on future Pb-free materials. The lack of data prevents the formulation and validation of appropriate failure models

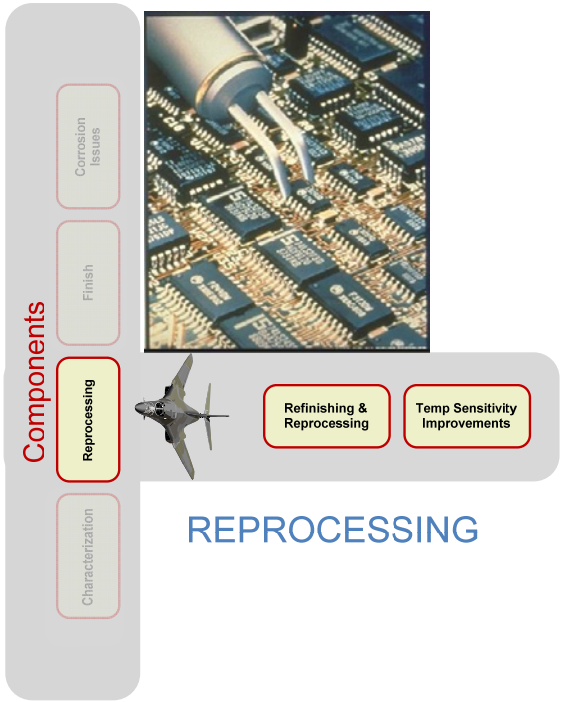
Fluxes/Cleaning Process Compatibility with Components

This project will determine the component compatibility with Pb-free fluxes and cleaning processes to meet A&D life cycle requirements.

- **Gap Addressed**

  - The current industry components are not capable of surviving lead-free soldering processes
  - There is a lack of understanding of how materials and process compatibility issues affect repair
  - There is a lack of understanding of reliability degradation from storage, use, and repair stresses

Component Refinishing/Reprocessing



Component Reprocessing schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Comp. Refinishing and Reprocessing																
Temp Sensitivity Capability Improvements																

This section of projects will determine the impact of refinished components on manufacturing, repair and rework costs and delivery schedule.

Component Refinishing/ Reprocessing

This project will produce a methodology to aid decision on refinishing/reprocessing components to balance risk of whiskers (pure tin finishes) and unreliable solder joints (ball replacement). This will assist in determining the impact of refinished components on cost and schedule.

- **Gap Addressed**
  - The current component reprocessing procedures can result in component degradation

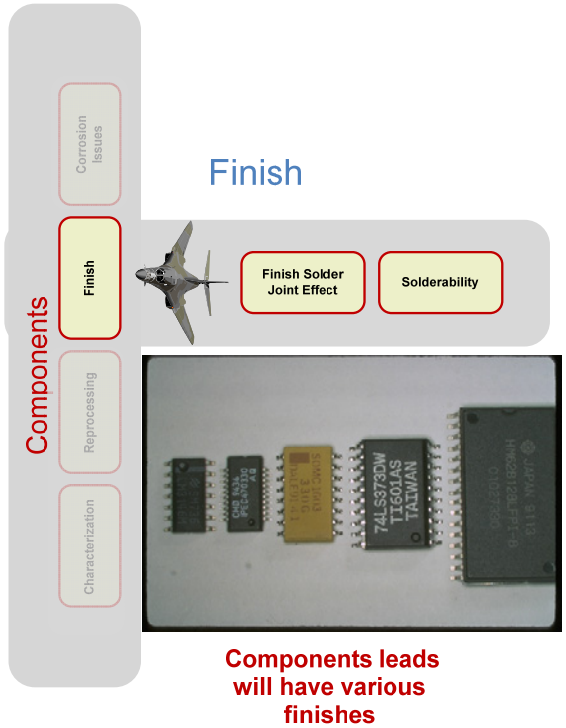
Temperature Sensitivity Capability Improvements

This project will evaluate new materials, design, and construction for components to improve temperature sensitivity incurred by the higher process temperatures

➢ Gap Addressed

- There have been premature failures of temperature sensitive passive components, particularly capacitors, subjected to Pb-free solder process temperatures that resulted in reduced defects, infant mortality, and reliability reductions. The root cause for these failures, have yet to be determined

Component Finish



Component Finish schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Solderability																
Finish Solder Joint Effect																

These component finish project will produce:

1. Test Methods and requirements to evaluate component finishes for Pb-free solder applications
2. Characterization data for current finishes and interaction with key solders
3. Solderability evaluation test method and requirements
4. Solderability characterization data for various finishes and solders

Finish Solder Joint Effect

These projects will focus to develop an approach to evaluate the performance of component finishes for A&D applications. This will establish approaches to test whether part finishes meet A&D requirements for assembly robustness, gold embrittlement, copper-nickel-tin failures, Kirkendall voiding, and new problems. The degradation mechanisms must account for assembly stresses (e.g., multiple reflows), and environmental and operating stresses.

Gap Addressed

- Current Pb-free materials are insufficient for A&D products
- There is no known component plating finish that meets or exceeds SnPb assembly and reliability performance
- The current industry components are not capable of surviving lead-free soldering processes

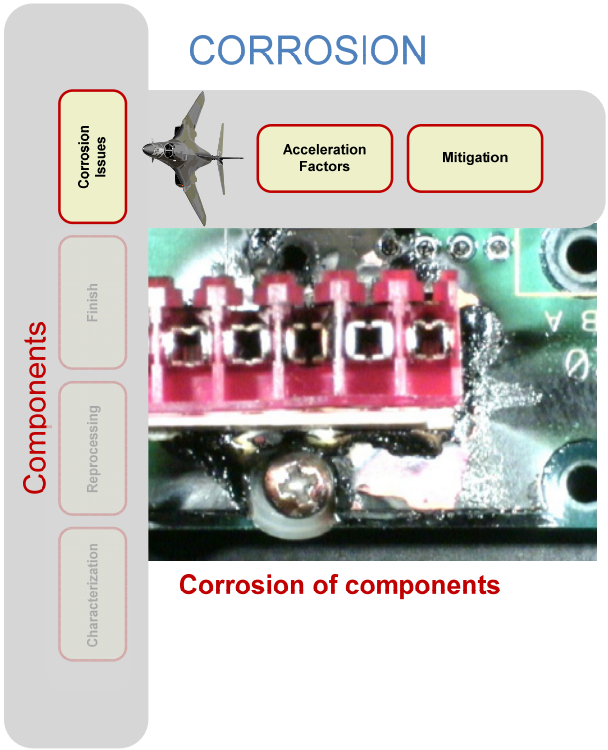
Solderability

This project will establish approaches to test for whether part finishes meet A&D requirements for solderability, determine design characteristics that affect solderability performance, and establish finish requirements to meet different performance levels (including solder joint integrity). The outcome is also to evaluate suitability of existing solderability test requirements for A&D applications, and coordinate finish testing for solder joint integrity.

Gap Addressed

- Existing heuristic rules on the solderability of finishes used by electrical and mechanical designers based on experience with SnPb programs, may be insufficient to ensure reliability of Pb-free product

Component Corrosion



Component schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Corrosion Acceleration Factors																
Corrosion Mitigation																

Corrosion Acceleration and Mitigation Factors

This project will characterize the corrosion rates for Pb-free assembly materials and develop mitigation techniques. It will also define and demonstrate design practice mitigation techniques, such as conformal coating and cleaning, to preclude corrosion effects.

➢ Gap Addressed

- The Pb-free material corrosion rates and how they correlate to service environments is not fully understood, resulting in increased reliability risk. This includes corrosive interactions with solder, PCB finishes, and component finishes, under powered and off storage conditions within A&D environments
- There is a lack of validated corrosion mitigation methods for Pb-free assemblies in A&D service environments. This has the effect of increased reliability risk

3.7.4 Expected Outcomes

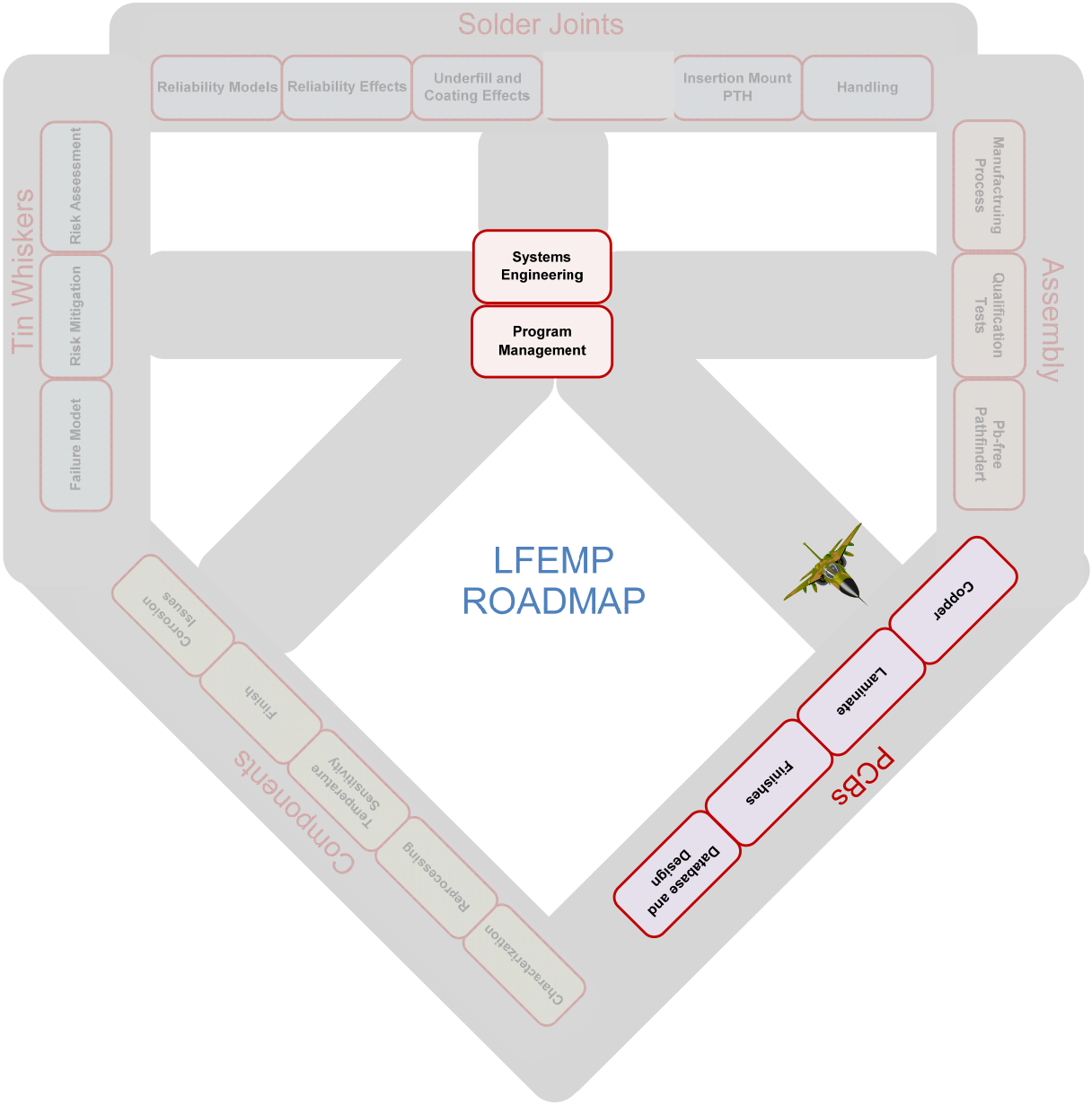
- A set of component requirements to assure compatibility with assembly processes to reduce defects and field failure rate. The requirements will include:

  - Component temperature reflow cycle limits
  - Receiving inspection protocol and requirements
  - Storage requirements for unassembled components in Pb-free applications
  - Component properties database
  - Flux compatibility and cleaning requirements for components
  - A methodology to aid decision on refinishing/reprocessing components to balance risk of whiskers (pure tin finishes) and unreliable solder joints (ball replacement).
  - Metrics and tools to aid decision on refinishing components
  - Components technology that reduces degradation of component performance due to thermal exposure to Pb-free assembly processes
  - Materials, design and construction techniques to reduce thermal degradation of components

- Provide the methodology to evaluate existing and new component finishes, and provide characterization data of existing finishes, as well as requirements to specify solderability for Pb-free applications. This includes:

  - Test Methods and requirements to evaluate component finishes for Pb-free solder applications Characterization data for current finishes and interaction with key solders
  - Solderability evaluation test method and requirements
  - Solderability characterization data for various finishes and solders
  - Capability to characterize corrosion susceptibility and design mitigation practices. These are:
  - Corrosion rate models for Pb-free materials and assemblies (Month 36)
  - Corrosion mitigation techniques (Month 36)
  - Receiving inspection guidelines and incoming requirements fro components
  - Component properties database for assembly requirements and reliability modeling
  - Temperature sensitivity qualification for Pb-free
  - Characterization models of components finish effects on solderability and solder joints reliability
  - Methods to assess cost/schedule impact of component refinishing
  - Flux and cleaning characteristics
  - Determination of flux compatibility with components
  - Circuit card assembly cleaning requirements and corrosion/degradation impacts
  - Storage requirements for unassembled components

3.8 Printed Circuit Boards



3.8.1 Summary Description

There are significant reliability and sustainment issues associated with the effects Pb-free made to the printed circuit board copper structures, laminate material integrity, surface finishes and design rules, that will be detailed further in the chapter.

3.8.2 Technical Brief

There are many new Pb-free materials which have been introduced into the product streams of electronic assemblies and used for A&D applications. The number of new solders, laminates, finishes, components, processes, and manufacturing chemicals for Pb-free continues to grow. The effects these new materials have on reliability and performance of A&D products is not always apparent and virtually no data exists on long-term sustainability in harsh environmental conditions. A great deal of research remains to be done to ascertain the effects that these new materials have on ongoing and future A&D programs. Additionally, research projects dealing with new materials are often being done on an isolated basis, not taking into account possible interactions between various materials sets. The scope of the investigations to satisfy statistically valid protocol, require a concerted and organized effort across many disciplinary fields of material technology.

- <u>Design</u>

  - There is no known PCB plating finish that meets or exceeds SnPb assembly and reliability performance
  - Current PCB laminate materials formulated for Pb-free assembly have unknown risks in regards to assembly and reliability performance under A&D required environmental conditions

- <u>Manufacturing</u>

  - The electronics manufacturing industries lacks knowledge about the relationship between PCB finish, solder alloys and solder processes/equipment to consistently produce acceptable solder joint to PCB intermetallics
  - The many current A&D printed wiring board materials are not capable of surviving Pb-free soldering processes with a known understanding of the reliability impacts
  - Pb-free assembly cleaning processes are not clearly defined in terms of material compatibility and contamination testing since the majority of commercial Pb-free soldering processes use “no-clean” flux technologies
  - Conformal coating process compatibility is poorly defined for material compatibility with lead-free processes

- <u>Reliability</u>

  - There is a lack of understanding of fundamental whisker growth mechanisms for tin rich PCB finishes
  - Current Pb-free materials are insufficient for A&D products. This includes solders, laminates, and other materials that comprise Pb-free electronic assemblies

- Sustainment

  - There is a lack of understanding on what the additional stresses of rework/repair will do to Pb-free assembly PCB structure reliability
  - Shipping and handling procedures do not presently address Pb-free factors, such as storage for long-term (3 + years) solderability, pre baking prior to rework, etc
  - There is a limited understanding of underfill reparability and potential degradation in storage conditions
  - There is no defined specification for the maximum amount of reflow cycles and limitation requirements for each part/component location on the PCB that undergoes repair/rework cycles
  - There is a lack of understanding of how materials and process compatibility issues affect long term PCB repair in terms of CAF, dielectric behavior, and insulation resistance
  - There is a lack of understanding of reliability degradation from storage, use, and repair stresses

- Test

  - Current Pb-free materials are insufficient to test for copper dissolution on A&D products
  - Current Pb-free PCB finishes may negatively impact in-circuit test of the electronic assembly due to voiding or brittle intermetallic formations fracturing as the PCB bends during “bed of nails” testing

3.8.3 Recommended PCB Technical Projects and Gaps Addressed

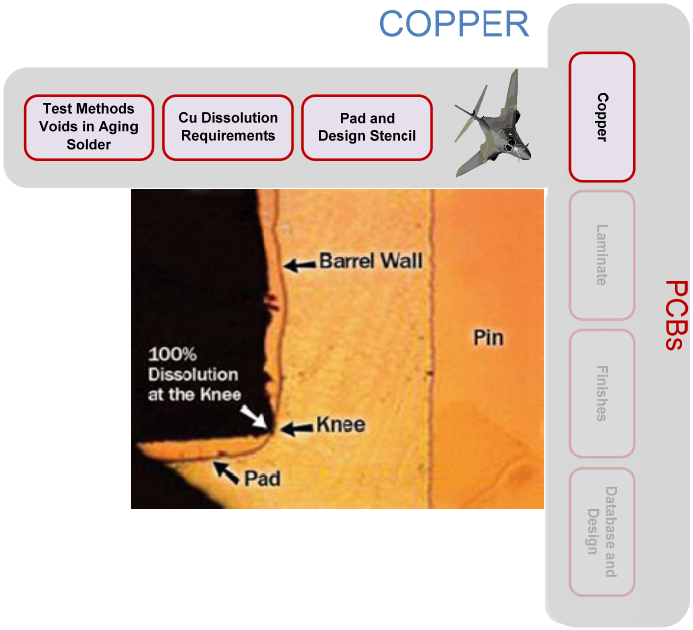
Hyperlink to Gap key

I	Technical Area	II	Techical Area	III	Technical Area		start month	duration	GAPS Addressed
E	PRINTED CIRCUIT BOARDS	EA	Copper	EAA	Pad Design / Stencil Design Assessment and Confirmation		1	12	D58
				EAB	Copper Requirements and Copper Dissolution		13	18	T04, M15, D54, D15, D03
				EAC	Acceptance Test Methods for Void Formation Assocaited with Aging of Solder / Copper Plated Structures		13	8	D20
		EB	Laminate	EBA	Thermal Robustness of Laminate Material		1	18	D36, D44, M15, D02, S05
				EBB	Pad Cratering		6	24	D36, D44, D02, S05, D15, D16, D17, D18, S11, D21, D27, D38, R04, S07
				EBC	Conductive Anaodic Filament (CAF)		13	15	D39, D02
				EBD	Development of New Laminate Material		18	18	D12, D47, D52
		EC	Finishes	ECA	Surface Finish Evaluation		1	36	D12, D47, D52
				ECB	Surface Finish Test Methods		1	12	D12, D47, D52
				ECC	Development of New PCB Plating Material		18	18	D12, D47
				ECD	Sporadic Brtttle Failure of Pb-Free Solder due to Nickel Plating		1	36	D12, D47, D52
		ED	Database and Design Rules	EDA	Database and Design Rules		1	36	

Table 3.5 – PCB technical chart

Table 3.5 shows the specific level 3 technical approaches for the assembly projects along with the specific gap referrals. The full array of technical approaches can be found in Appendix C.

Copper



PCB – Copper schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Pad design/ stencil Design assessment																
Copper requirements and Copper dissolution																
Acceptance test methods for voids in aging solder- Cu dissolution																

The printed circuit board copper structures and material must be evaluated when using Pb-free in A&D applications. Currently there are few A&D applications, starting at inception, that have been designed to be Pb-free. As a result, the copper PCB design rules have not yet been proven, especially with respect to vibration, shock and rework. Furthermore, plated-through-hole design and copper dissolution for Pb-free assemblies must be understood to ensure reliable repair. In addition, the interaction between Pb-free solder and copper plated structures has made a voiding condition worst that can adversely affect mechanical reliability.

Pad Design / Stencil Design Assessment and Confirmation

This project will review failure modes in conjunction with IPC pad design rules for A&D products, and validate pad and stencil design rules using "Design of Experiment". The factors include solder alloys and flux to demonstrate solder joint quality/ strength using pad and stencil design rules. An A&D Pb-free test vehicle can be utilized for thermal cycle, vibration and shock environments.

- **Gap Addressed**

- In PCB Design, there is a risk that heritage SnPb solder geometries will need to change, or solder stencil designs will need to change to adjust the solder volume and geometry for Pb-free solders. IPC geometries are currently based on thermal cycle test results and neglect shock/vibration or rework/repair considerations

Copper Requirements and Copper Dissolution

This project will provide the A&D community with design rules, test methods, and Pb-free solder process parameters to improve the durability and integrity of printed circuit board copper structures after assembly and rework. Additionally, it will provide a way to mitigate problems caused by copper dissolution and plated through-hole copper cracking during service and/or repair.

Gap Addressed

- Current Pb-free PCB manufacturing quality assurance coupons are insufficient to test for copper dissolution on A&D products
- Many of the current A&D printed wiring board materials are not capable of surviving Pb-free soldering processes
- There are no design rules for copper dissolution
- There is a lack of appropriate and validated failure models, which prevents accurate failure prediction, test development, and creation of heuristic rules for PCB solder failure models, especially during vibration and shock
- A shortage of test data for Pb-free assemblies renders the attempts to validate failure models, such as solder, pad cratering, and trace cracking, more difficult and inconclusive
- There is a lack of appropriate and validated rules in plated thru holes

Acceptance Test Methods for Void Formation Associated with Aging of Solder / Copper Plated Structures

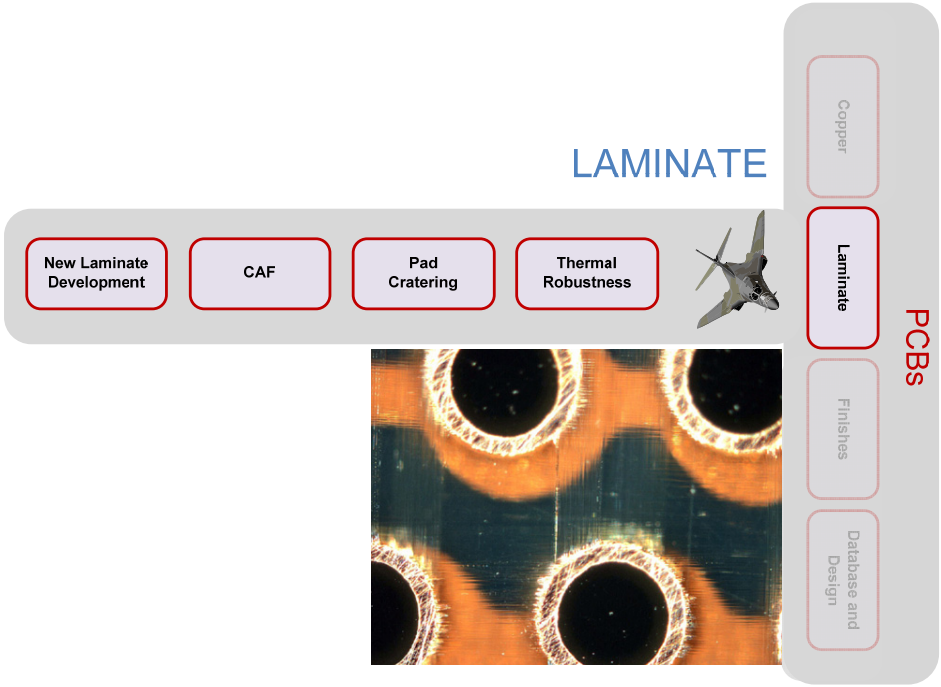
This endeavor will give the A&D community a standard test method to screen copper platings and copper board structures for void formation during aging of solder/copper structures, and will improve the durability and integrity of printed circuit board solder joints. It is well known that the copper plating process introduces impurities into the copper that can lead to void formation during aging. At a minimum, an acceptance test shall be developed for the copper plating on printed circuit boards with respect to this degradation mode.

Gap Addressed

- The sporadic formation of voids near the interface between copper and the intermetallic bond continues to be underestimated across the industry. The problem is caused by the incorporation of impurities into the copper. Lead-free solder with less ductility can exacerbate the problem of pad integrity during service

- A quantitative understanding of the problematic mechanism, along with how the phenomena is accelerated, has generated some established practical remedies that still need to be implemented in a production environment
- There is a lack of appropriate and validated failure models which prevents accurate failure prediction, test development, and creation of heuristic rules in plated through holes (PTH).

Laminate



PCB Laminate schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Thermal Robustness of Laminates																
Pad Cratering																
CAF																
Development of New Laminate																

The printed circuit laminates used in industry have changed to accommodate Pb-free processing. The performance of laminates claimed to be Pb-free compatible varies widely and little evaluation has been performed with these materials in complex board constructions typical of A&D applications. Some of these laminates are more brittle than the heritage material making them more susceptible to fracturing under the pads, a phenomenon called "pad cratering." In addition, the Pb-free processing makes traditional A&D failures modes such as conductive anodic filament growth worse. There is a need to encourage development of new laminate materials that will provide enhanced thermal robustness and improved vibration/shock/handling performance.

Thermal Robustness of Laminate Material

This project will develop test protocols for evaluating laminate materials for acceptability to meet thermal conditions expected in Pb free A&D manufacturing environments

- **Gap Addressed**

- Existing heuristic rules used for the selection of laminate material by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product
- Current PCB laminate materials formulated for Pb-free assembly have unknown risks in regards to assembly and reliability performance under A&D required environmental conditions
- Many of the current A&D printed wiring board materials are not capable of surviving Pb-free soldering processes
- The development of new laminate materials used for Pb-free processing has necessitated a compulsory examination of laminate properties and their effect on future Pb-free materials. The lack of data prevents the formulation and validation of appropriate failure models
- There is no defined specification for the maximum amount of reflow cycles and limitation requirements for each part/component that undergoes repair/rework cycles
- Current PCB manufacturing criteria for acceptable A&D performance in terms of parameters such as glass transition temperature, time to delamination, decomposition temperature, etc, for Pb-free does not exist.

Pad Cratering

This project will endeavor to develop test protocols and models for evaluating and predicting the propensity of pad cratering during flexure events.

Gap Addressed

- Existing heuristic rules used for the selection of laminate material by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product
- Current PCB laminate materials formulated for Pb-free assembly have unknown risks in regards to assembly and reliability performance under A&D required environmental conditions
- The development of new laminate materials used for Pb-free processing has necessitated a compulsory examination of laminate properties and their effect on future Pb-free materials. The lack of data prevents the formulation and validation of appropriate failure models
- There is no defined specification for the maximum amount of reflow cycles and limitation requirements for each part/component that undergoes repair/rework cycles
- There is a lack of appropriate and validated failure models, which prevents accurate failure prediction, test development, and creation of heuristic rules for PCB and solder failure models, especially vibration and shock
- High G pyrotechnic mechanical shock requirements for solder joints and PCB's, which are differentiated from other mechanical shock tests, do not have predictive

- The predicted reliability of solder joints using combined environmental tests lack the appropriate and validated failure models for accurate failure prediction, test development, and creation of heuristic rules
- There is a lack of diagnostic and prognostic processes to address Pb-free related failure modes, such as tin whisker shorts and solder joint opens, including intermittent failures
- PCB pad cratering and trace cracking lacks the sufficient data on material properties to formulate failure models. No test vehicle has been developed for model validation and failure mode analysis
- Existing tests (design verification, product qualification) and screens used by the A&D community may not be valid for Pb-free product. Design verification (HALT / HAST) and subsequent model development is difficult since fatigue constants and stress states of board traces are different
- The current risk assessments for pad cratering and trace cracking on critical Pb-free failure mechanisms are insufficient in regards to timeliness and accuracy. There currently is no method to rapidly and accurately identify the risk of pad cratering and trace cracking
- Behavior of Pb-free solder interconnects under shock and vibration at low temperatures (sub zero) is not adequately characterized
- There is a lack of understanding of reliability degradation from storage, use, and repair stresses

Conductive Anodic Filament (CAF)

This project will conduct testing to provide a better understanding of the CAF resistance of Pb-free laminates exposed to Pb-free processing conditions.

Gap Addressed

- There currently is little data on the risk of CAF formation within lead-free laminates exposed to lead-free processing temperatures
- The development of new laminate materials used for Pb-free processing has necessitated a compulsory examination of laminate properties and their effect on future Pb-free materials. The lack of data prevents the formulation and validation of appropriate failure models

Development of New Laminate Material

The project addresses the development of new laminate materials that meet the assembly, reliability, and cost expectations of the A&D community.

Gap Addressed

- There is no known PCB plating finish that meets or exceeds SnPb assembly and reliability performance
- Existing heuristic rules on the PCB PTH's used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product
- The Pb-free material corrosion rates and how they correlate to service environments is not fully understood, resulting in increased reliability risk. This includes corrosive interactions with solder, PCB finishes, and component finishes, under powered and off storage conditions within A&D environments

Finishes

PCB finish & design schedule	2010				2011				2012				2013			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Surface Finish Evaluation																
Surface Finish Test Methods																
Nickel Plating embrittlement on Pb-free solder																
New PCB Plating Material																
Database and Design Rules																

The Pb-free printed circuit finishes being used by the consumer industry do not have the same system level performance as heritage tin-lead solder finishes. In particular, A&D needs finishes with a long shelf life to support high mix low volume manufacturing and repair. Many of the finishes that have been developed for consumer electronics may be acceptable as long as they are fully covered with solder during assembly. Unfortunately, there are many instances where the original printed circuit board finish will not be soldered during assembly (e.g. press fit connectors, test points, etc.). There are also failure mechanisms that are exacerbated with the increased rigidity of the Pb-free solder and the intermetallic compounds that can form with some of the Pb-free alloys being considered. In addition, an assessment of the surface finishes and development of test methods for A&D applications is needed.

Surface Finish Evaluation

This project will quantify the following lead-free finish attributes after assembly: robustness in harsh environments, solderability after aging, corrosion resistance, and their resistance to forming tin whiskers.

- **Gap Addressed**

  - There is no known PCB plating finish that meets or exceeds SnPb assembly and reliability performance
  - Existing heuristic rules on the solderability of finishes used by electrical and mechanical designers based on experience with SnPb programs, may be insufficient to ensure reliability of Pb-free product
  - The Pb-free material corrosion rates and how they correlate to service environments is not fully understood, resulting in increased reliability risk. This includes corrosive interactions with solder, PCB finishes, and component finishes, under powered and unpowered storage conditions within A&D environments

Surface Finish Test Methods

The performance of Pb-free PCB finishes is ensured through design, PCB lot testing, and procurement requirements. The existing solderability and corrosion practices (e.g. JEDEC/IPC) shall be reviewed in the context of Pb-free. The applicability standards in the A&D harsh and long service environments are 1 to 3-year shelf life and long-term corrosion resistance. In addition, methods shall be evaluated for the verification of PCB finishes during initial receipt and repair to ensure that the qualified configuration is maintained. Furthermore, tin whisker test methods shall be established to assess the whisker propensity of Pb-free tin rich finishes on PCBs. A database of the information and design rules shall be compiled periodically and in conclusion of the project

- **Gap Addressed**

  - There is no known PCB plating finish that meets or exceeds SnPb assembly and reliability performance
  - Existing heuristic rules on the solderability of finishes used by electrical and mechanical designers based on experience with SnPb programs, may be insufficient to ensure reliability of Pb-free product
  - The Pb-free material corrosion rates and how they correlate to service environments is not fully understood, resulting in increased reliability risk. This includes corrosive interactions with solder, PCB finishes, and component finishes, under powered and off storage conditions within A&D environments

Development of New PCB Plating Material

This project entails the development of new plating material that meets the assembly, reliability, and cost expectations of the A&D community.

- **Gap Addressed**

  - There is no known PCB plating finish that meets or exceeds SnPb assembly and reliability performance

- Existing heuristic rules on the solderability of finishes used by electrical and mechanical designers based on experience with SnPb programs, may be insufficient to ensure reliability of Pb-free product

Sporadic Brittle Failure of Pb-Free Solder Due to Nickel Plating

This project will explore the major intermetallic bond failures in Pb-free solder traced to sporadic problems with the plated nickel (Ni) surface finishes. An effective screening procedure will be identified, and guidelines for electroplating to prevent the problem will be developed.

- **Gap Addressed**

  - There is no known PCB plating finish that meets or exceeds SnPb assembly and reliability performance
  - Existing heuristic rules on the solderability of finishes used by electrical and mechanical designers based on experience with SnPb programs, may be insufficient to ensure reliability of Pb-free product
  - The Pb-free material corrosion rates and how they correlate to service environments is not fully understood, resulting in increased reliability risk. This includes corrosive interactions with solder, PCB finishes, and component finishes, under powered and off storage conditions within A&D environments

Database and Design Rules

Collect all data from project area E Printed Circuit Board and create a database. Develop PCB design rules for Pb-free assembly of A&D products.

- **Gap Addressed**

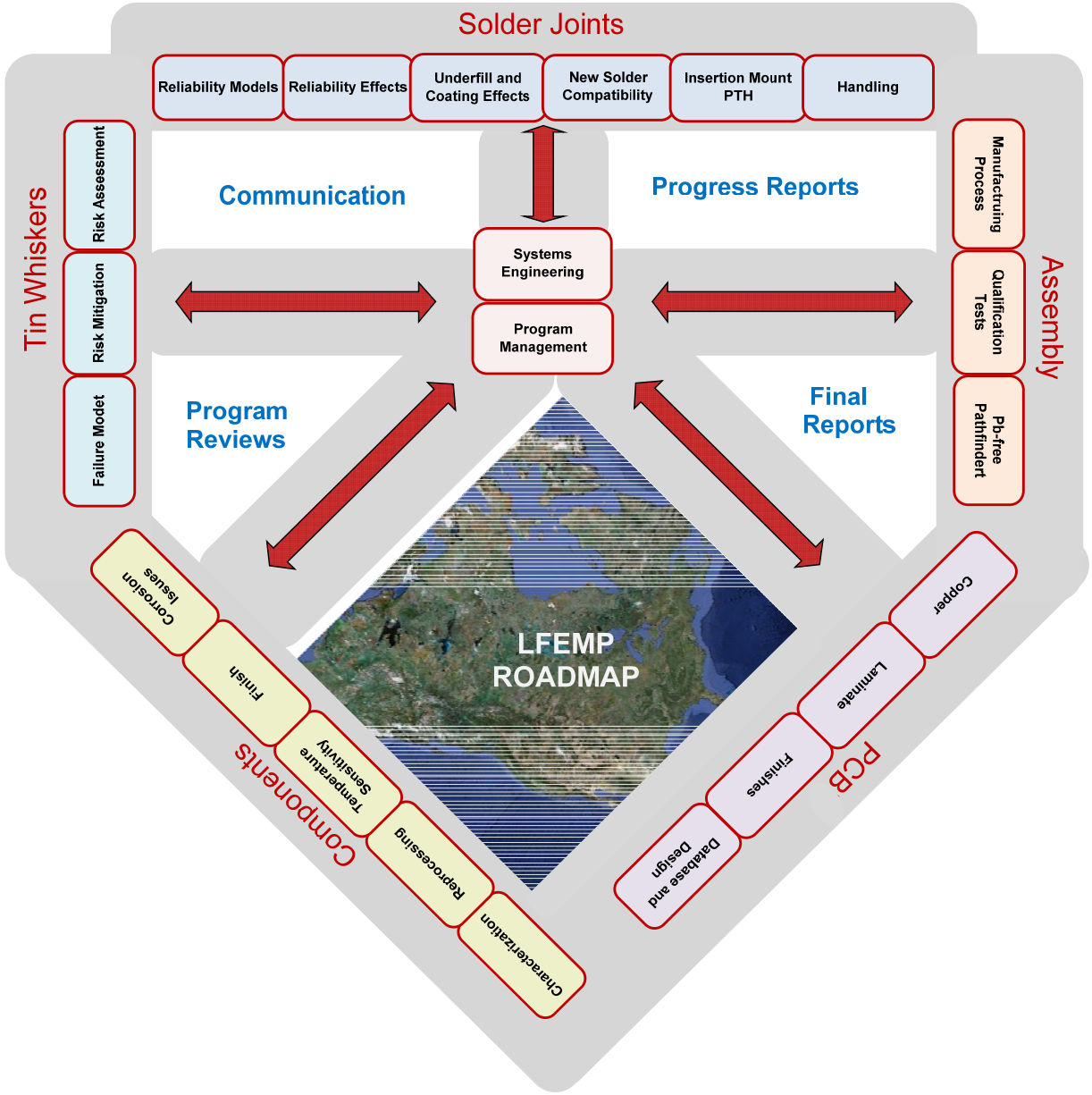
  - Heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product
  - There is a need for a database of new and future materials attributes and compatibilities resulting in design rules for PCBs used in Pb-free assembly of High Performance products

3.8.4 Expected Outcome

- Validated surface mount pad geometries and stencil designs for IPC High Performance Class 3 products are expected.
- Improvement in copper circuit board structures that can withstand Pb-free assembly, rework, and repair processes, resulting in more consistent and higher durability in Pb-free solder assemblies subjected to handling stresses, thermal cycling, vibration, shock, and thermal shock is expected

- A process for identifying the propensity of a PCB assembly to experience thermally-induced cracking or delamination after exposure to a Pb-free manufacturing environment is expected
- A process for evaluating the propensity of a PCB assembly to experience pad cratering during manufacturing, design testing, service and repair is expected
- A new laminate material able to meet assembly, reliability, and cost expectations of the A&D community is expected
- Test methods for solderability, corrosion, finish verification and tin whiskers for PCB finishes are expected
- A new plating material able to meet assembly, reliability, and cost expectations of the A&D community is expected
- A process for preventing brittle failures of solder joints on ENIG or electrolytic Ni pads is expected
- A database of new and future materials attributes and compatibilities resulting in design rules for PCBs used in Pb-free assembly of A&D products are expected

3.9 Program Management and Systems Engineering



3.9.1 Summary Description

Program management and administration for the overall execution of the Pb-free electronics research and development (R&D) Manhattan Project as described in Work Breakdown Structure Elements (WBSE) A through F. WBSE FA includes the management and administration of subcontracts required to execute the R&D tasks described (and funded) in WBSE A through F.

Systems Engineering effort required to manage the technical interdependencies between and within WBSE A through E, including the allocation and closure of identified R&D gaps. WBS FB includes

the development and maintenance of a Systems Engineering Management Plan in contractor format and the conduct of overall Technical Opportunity and Risk Management.
The ONR has maintained a leadership role as the program execution agency, and will continue to act as the executor of the project management team.

3.9.2 Technical Brief

See specific technical area.

3.9.3 Recommended PM and SE Technical Projects and Gaps Addressed

Hyperlink to Gap key

I	Technical Area	II	Techical Area	III	Technical Area		start	duration	GAPS Addressed
F	PROGRAM MANAGEMENT & SYSTEMS ENGINEERING	FA	Program Management	FA	Program Management		1	36	A through E
		FB	Systems Engineering	FB	Systems Engineering		1	36	A through E

Table 3.6 - Tin whisker Failure Mode Projects and Timeline

Table 3.6 shows the specific level 3 technical approaches for the assembly projects along with the specific gap referrals. The full array of technical approaches can be found in Appendix C.

- **Program Management**

  Program management and administration for the overall execution of the Pb-free Electronics Risk Reduction Program as described in the Technical Approaches A through F. Technical Approach FA includes the management and administration of subcontracts required to execute the R&D tasks described (and funded) in Technical Approaches A through F.

  The full-time Program Management team shall consist of a Program Manager, Chief Engineer, Subcontract Manager, and Administrative Assistant. The PM team is responsible for effective communication and coordination with the Government Program Office. Interface with the customer shall include:

  - Communication of program activities, progress, and issues and their resolution
  - The conduct of Quarterly Program Review Meetings
  - The submittal of Monthly Technical Progress Reports and Cost Expenditure Reports
  - The preparation and submittal of a Final Report

The PM team is also responsible for interfacing with the Pb-free Electronics Risk Management (PERM) Consortium's Executive Steering Committee to coordinate an effective hand-off of R&D results to the appropriate PERM Consortium Task Teams. This interface activity includes participation in quarterly PERM Consortium meetings and periodic teleconferences. The Chief Engineer will participate in the PERM Consortium's Research Coordination Task Team meetings and teleconferences.

The PM team will interface with other government, industry and academia groups as warranted to promote collaboration in the R&D required to deal with Pb-free electronics issues impacting the aerospace and defense community.

- **Gap Addressed**
  - This task manages the overall program activities to deal with all identified Pb-free electronics technical Research and Development (R&D) gaps addressed by Technical Approaches A through E

System Engineering

Systems Engineering efforts are required to manage the technical interdependencies between and within Technical Approaches A through E, including the allocation and closure of identified R&D gaps. The technical approach includes the development and maintenance of a Systems Engineering Management Plan in contractor format and the conduct of overall Technical Opportunity and Risk Management.

The Systems Engineering team shall consist of sixteen Pb-free electronics R&D subject matter experts led by the Chief Engineer. Participation in Phase 1 and 2 of the Pb-free Electronics R&D Manhattan Project is not a prerequisite, but is highly encouraged for continuity.

The Systems Engineering team shall participate in the Quarterly Program Review Meetings (Ref: Technical Approach FA) and conduct monthly teleconferences to review and assess the technical progress and closure of identified R&D gaps. Members of the Systems Engineering team may also be engaged in the conduct of the R&D activities contained in Technical Approach A through E.

- **Gap Addressed**
  - This Technical Approach manages the R&D Systems Engineering activities to deal with all identified Pb-free electronics technical gaps addressed by Technical Approach A through E.

3.9.4 Expected Outcome

- Effective management of R&D activities including cost and schedule performance
- Timely dissemination of R&D progress and results to the government customer
- Coordinated hand-off of R&D findings to the PERM Consortium for follow-on dissemination and implementation activities
- Quarterly Program Review Meetings
- Monthly Technical Progress Reports
- Monthly Cost Expenditure Reports
- Final Report
- On-going assessments of technical progress and closure of identified R&D gaps
- Sound, integrated technical approach for the R&D tasks
- Systems Engineering Management Plan in contractor format
- Technical Opportunity and Risk Management

4.0 Conclusions

4.1 Overview

The EU Restriction of Hazardous Substances Directive which banned the use of Pb in commercial electronics sold in the EU has impacted the global COTS electronics market. Some of the unintended consequences included a greater frequency of tin whisker short circuits which are electrically conductive and can cause metal vapor arcing. Additionally, it is not fully understood what the effects will be on reliability and performance from high shock and vibration environments where the incidence of fracture failures have been known to occur. The higher process temperatures and incompatibility with SnPb makes assemblies more vulnerable to rework and repairability problems. Configuration control continues to be an issue with unidentified component alloys and mixed Pb and Pb-free inventories shipping from component distributors. Perhaps the biggest uncertainty and potential hazard for the DoD is the inability to quantify the reliability in harsh operating environments.

Tin whiskers continue to pose potential threats to DoD systems with an already established array of documented occurrence of failures attributed to 1 billion dollars of damage. Recently failures not associated with tin whiskers have become more prevalent and range from “head and pillow” effect , a condition derived from improper amalgamation of dissimilar solders (SnPb and Pb-free), to embrittlement due to excessive intermetallics. Many of the problems recently encountered are insidious in nature because of the protracted time delay that is incurred from an assembly leaving the manufacturing floor to its utilization in an A&D system. Additionally, intermittently functioning devices are becoming more commonplace, and many products with potential defects have already been introduced into the field.

The GEIA standards have been able to offer a good amount of information directed toward dealing with recommended guidelines in order to meet compliancy requirements of A&D systems. The GEIA standards do not presently deal with reliability assessment for aerospace and high performing electronics containing Pb-free materials.

4.2 Tin Whisker Conclusions

- The formation of Sn whiskers can threaten the reliability of A&D systems that use Pb-free surface finishes and solders
- Current tin whiskers testing methods cannot predict whether a finish or solder will grow tin whiskers, nor can they identify which whisker mitigations are needed for a particular part or assembly
- Existing strategies are only partially effective, leaving a significant gap with respect to protecting the most vulnerable circuits in mission critical or certified flight systems
- A comprehensive approach to design rules for tin whisker mitigation is needed, and should define strategies for circuit analysis, hardware design, including PCA component placement, tin plating characteristics, and component and board-level mitigation
- Reliable tin whisker test methods for parts and assemblies along with lifetime reliability models need to be developed
- A direct linkage between field failure root cause analysis, test models, and design rules will be essential to achieving their validation and acceptance

4.3 Assembly Conclusions

- Industries lack knowledge about the relationship between solder alloys and assembly processes and equipment
- The current A&D printed wiring board materials and components are not capable of surviving Pb-free soldering processes
- Pb-free assembly cleaning processes are not clearly defined in terms of material compatibility and contamination testing
- Conformal coating compatibility and coverage capability is poorly defined. The conformal coating processes lack objective evidence for tin whisker mitigation capability
- Need Pb-free solder bath process contamination limits and controls
- Need proven durability and compatibility of adhesive/underfills material with Pb-free soldering processes
- An understanding of the design requirements to optimize lead free footprints , via design, and ground planes are needed
- Pb-free laser soldering processes are undefined for A&D products
- Need soldering equipment with requisites for defining thermal capability
- The current cleaning technologies have no proven Pb-free soldering process flux residue removal performance for A&D
- Inspection method criteria are inadequate in assessing Pb-free joint quality for A&D products.
- The process capability of manual solder tools, equipment, and periodic maintenance is not clearly defined
- The current Vapor phase process chemistry and thermal load parameters are not robust for A&D
- There is a lack of current industry standard component incoming screening procedures and component reprocessing procedures can result in component degradation
- The current ICT capability is not optimized for Pb-free
- There is a lack of manufacturing protocols and procedures to mitigate copper dissolution

4.4 Solder Joint Reliability Conclusions

The majority of electronic parts (memory, logic, passives, etc) manufacturers have converted to parts construction to comply with government regulations. While some still provide SnPb terminations, the ability to obtain original manufactured parts with SnPb is becoming difficult. The largest issue with solder joint reliability is the increased used of large area array packages which are no longer available with SnPb. Mixed solder joints have known reliability issues which are dependant on solder assembly processes, which is further complicated by changes in the electronic part manufactures'. The primary areas of concerns are:

- The need to provide credible models for assessing life expectancy of solder interconnects formed with a set of prevalent solder combinations with optimized test methodology to qualify new solder combinations

- Solder joints and their respective reliability can be expected to be influenced by other factors. With the use on new materials and combination, it is necessary to quantify these impacts to qualify materials for use in A&D applications. An effects study needs to be undertaken
- Due to known shock fragility, underfill and staking will likely be used in greater frequency. Due to threat of tin whiskers, conformal coating will also be used in greater frequency. Models for assessing life impact of underfill, staking and conformal coating will be needed to determine life expectancy of solder interconnects
- There is a need to evaluate new solder materials for potential acceptance for use in A&D applications for selecting solder and solder combinations for qualification in A&D applications
- The impact of copper dissolution and poor hole fill on reliability of insertion mount interconnections is exacerbated by the use of Pb-free solders
- Due to higher stiffness of Pb-free solders, handling rules need to be provided to avoid damage to electronic equipment in manufacture, assembly, storage, and use

4.5 Components Conclusions

- Component Pb-free process/materials compatibility characterized mainly for consumer applications
- Component Assembly Compatibility
    - Moisture Sensitivity Level widely characterized for Pb-free
        - SnPb finishes not characterized for Pb-free process temperatures
    - Temperature Sensitivity per J-STD-075 not universal
    - Storage of components not major concern for most current Pb-free applications
    - No-clean processes for consumer items
- Component Finish Effects on Solder Joint Reliability
    - Short term life generally sufficient for most finish materials
- Assembly Process Temperature sensitivity
- Corrosion sensitivity
    - Flux and cleaning compatibility
- Finish effects on solder joint reliability
- Solderability requirements
- Refinishing cost and schedule impacts
- Storage requirements for solderability maintenance
- Protocols for finish material verification

4.6 Printed Circuit Board Conclusions

The printed circuit board is the foundation for the entire printed circuit assembly – if the PCB integrity is questionable, then all other efforts is a moot point.

- Printed Circuit Board Copper Structures:
    - Pad Design/ Stencil Design Assessment and Confirmation

- Identify pad patterns and stencil designs required for the creation of High Performance solder joint geometries

- Copper Requirements and Copper Dissolution
  - Identify the minimum copper plating requirements for High Performance harsh environment integrity
- Acceptance Test Methods for Void Formation associated with Aging of Solder/Copper Plated Structures
  - Identify test methods provided an assessment of void formation in solder/copper plated structures

- Printed Circuit Board Laminate Materials:
  - Thermal Robustness of Laminate Material
    - Identify the level of laminate robustness is required to avoid thermally induced degradation in High Performance PCB laminates
  - Pad Cratering
    - Characterize, assess and design for a new failure mode in High Performance PCB laminates
  - Conductive Anodic Filament (CAF)
    - Characterize, assess and design for this failure mode in High Performance PCB laminates
    - Development of New Laminate Material
      - Application of High Performance PCB laminate key characteristics for laminate development

  - Printed Circuit Board Surface Finishes:
    - Surface Finish Evaluation
      - Identify Assembly Robustness, Corrosion, Solderability and Tin Whisker characteristics are necessary requirements for High Performance Assembly Processes
    - Surface Finish Test Methods
      - Assess what test methods exist for understanding surface finish characteristics relating to harsh long storage and fielded environments
    - Development of New PCB Plating Materials
      - Development of new plating materials that meets the assembly, reliability, and cost expectations of High Performance products
    - Sporadic Brittle Failure of Pb-free Solder Due to Nickel Plating
      - How do we characterize, assess and design for a new failure mode in High Performance PCB laminates

1) Printed Circuit Board Database and Design Rules:

   a) Heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product.
   b) Provide a database of new and future materials attributes and compatibilities resulting in design rules for PCBs used in Pb-free assembly of High Performance products.

5.0 Recommendations

5.1 Overview

Predicated upon the findings of this report, the following actions are recommended for the phase 3 efforts of the Pb-free electronic risk reduction program:

- A coordinated approach is proposed to achieve technical consensus. This will avoid the past strategy of "going it alone" which has resulted in:
    - Individual industry efforts to figure out unique solutions that has resulted in configuration, contractual, and logistics nightmares
    - The high cost to industry, and subsequently to the DoD for the lack of a cooperative effort
    - DoD readiness and sustainment will be severely impacted by a non-coordinated approach

- There have been 72 integrated project tasks that have been identified and defined as crucial to the Pb-free mitigation efforts. They have been structured to include a Level 1 top organization of five major project areas:

    A. Tin whiskers
    B. Assemblies
    C. Solder Joints
    D. Components
    E. Printed Circuit Boards

    The projects are further sub-divided into 19 intermediate projects, and additional subprojects under each of the intermediate projects that address the respective technical gaps that have been identified in both phase 1 and 2 of the Pb-free Electronic Manhattan Projects. The duration for these projects have been estimated to be between 6 and 36 months, with some residual months left for the program management to gather, and disseminate the resulting data from the respective projects in the form of a reports. Most of the projects at the task level are estimated to require between $500k and $1M .Projects will typically collaborate with at least five other concurrent projects. There will be a Systems Integration team consisting of Subject Matter Experts required for technical coordination and oversight. It is recommended that the ONR be the agent of program execution and program management

5.2 Recommend Level 1 Projects for Tin Whiskers

- Tin whisker failure modes
- Tin whisker risk mitigation
- Tin whisker risk assessment

5.2.1 Outcomes

- Greatly enhanced tools for management of tin-whiskers risks
  - Provide assurance of long-term system reliability
  - Quantify how tin whiskers cause electrical faults
  - Determine how to identify these faults
- Mitigations
  - New mitigation techniques and mitigation verification tests.
    - Accelerated quantifiable tin whisker growth.
  - Integrated design rules
- Life predictions for whisker induced unreliability
  - Validated tools for parts and assemblies
- Understanding whisker induced failure modes
  - Quantification of circuit shorting or degradation condition
  - Detailed functional risk assessments
- Tin whisker Field Assessment
  - Description of the signatures of tin whiskers induced failures
  - Enhancements to data collection protocols
  - Increased detection and identification of tin whisker induced problems
- Tin whiskers risk assessment process
  - Algorithm development
  - Automated circuit analysis
  - New whisker inspection techniques
  - Fundamental whisker formation kinetics research

5.3 Recommended Level 1 Projects for Assembly

- Aerospace and defense (A&D) manufacturing processes
- Development and Validation of qualification and acceptance tests for Pb-free products.
- Pb-free pathfinder equipment field assessment

5.3.1 Outcomes

- Defined set of Pb-free process guidelines for A&D manufacturing
- Guidelines for rework/repair of A&D assemblies
- Recommendations on possible non-solder attachment technologies and alternate printed circuit assembly attachments technologies
- Cost decision matrix comparing relative cost of a current SnPb solder process versus a proposed Pb-free solder process
- Qualification and acceptance test parameters based on field life data
- Field performance data for Pb-free assembly

5.4 Recommended Level 1 Projects for Solder Joints

- Solder joint reliability models

- Effects issue resolution
- Underfill, staking, and coating methods
- Solder selection guidelines
- Insertion mount issue resolution
- Handling guidelines

5.4.1 Outcomes

- Qualified set of materials for use in A&D applications
- Models for assessing life reduction in life due to exposure to environmental stress screens
- Solder qualification requirements
- A consistent set of models and data for assessing life expectancy of qualified set of solder materials
- Order of magnitude ranking for influences of :
    - Electromigration
    - Corrosion
    - Board Finish/Multiple reflows
    - Tin pest
- Solder acceptance screening requirements
- Insertion mount fill requirements and rework limits
- Soldered assembly handling guidelines

5.5 Recommended Level 1 Projects for Printed Circuit Boards

- Printed circuit board copper structures
- Printed circuit board laminate materials
- Printed circuit board surface finishes
- Printed circuit board database and design rules

5.5.1 Outcomes

- Validated surface mount pad geometry and stencil design
- Solder process parameter requirements (reflow, wave, and rework)
    - Control copper dissolution and integrity of copper structures
    - Test methods for void formation at copper/solder interfaces
- Design rules, procurement specifications, and test method development to minimize:
    - Thermal laminate degradation
    - Pad cratering
    - Conductive anodic filament (CAF) formation
- Laminate capabilities and limitation evaluation
    - Assessment of polymer formulation, glass treatments, glass weaves, fillers, and post treatments
- Quantify finish attributes during initial receipt and after assembly
    - Robustness in harsh environments
    - Solderability after aging
    - Corrosion resistance

    - Resistance to forming tin whiskers
- Evaluate methods for the verification of PCB finishes
    - Initial receipt and repair to ensure that the qualified configuration is maintained
- Evaluate suitability of finishes for A&D harsh and long service environments requiring long term corrosion resistance

5.6 Recommended Level 1 Projects for Components

- Component characterization.
- Component refinishing & reprocessing.
- Temperature sensitivity capability improvements.
- Component finish.
- Component corrosion.

5.6.1 Outcomes

- Receiving inspection guidelines and incoming requirements for components
- Component properties database for assembly requirements and reliability modeling
- Temperature sensitivity quantification for Pb-free
- Characterization / models of component finish effects on solderability and solder joint reliability
- Methods to assess cost/schedule impact of component refinishing
- Flux and cleaning characteristics
    - Determination of flux compatibility with components
    - Circuit card assembly cleaning requirements and corrosion /degradation impacts
- Storage requirements for unassembled components.

LEAD FREE ELECTRONICS MANHATTAN PROJECT PHASE 2 REPORT

APPENDIX A

TECHNICAL KNOWLEDGE GAPS REPORT

Executive Summary

The need for the Department of Defense (DoD) to accommodate the global movement to lead (Pb)-free electronics in response to the European Union law known as RoHS (Restriction on Hazardous Substances) has caused the various DoD services and agencies to initiate individual (inconsistent, uncoordinated) approaches to Pb-free electronics. They have taken the form of Mission Assurance Plans (within MDA), Air Worthiness Directives (within Air Force), and other equally uncoordinated reactions. Phase II of the Pb-free Manhattan Project, through Gap analysis and Road-mapping, will better serve the Department of Defense with a methodology to select critical projects in Pb-free electronics leading to a much more consistent approach to this dilemma. This will save significant money and time by allowing the various DoD material suppliers to have a common "open systems" approach to Pb-free electronics for use in the DoD.

Phase II of the Pb-free Manhattan project will assemble the same small group (~15) of recognized experts in Pb-free electronics as were involved in Phase I for an additional very concentrated effort to identify, from the Phase I known best practices documentation, the technological Gaps that introduce risk into each Pb-free best practice. A Roadmap for Pb-free accommodation by the DoD will be generated and documented. Documented Gaps and the Pb-free Roadmap can provide uniform guidance for proposal, funding, and execution of future Pb-free electronics process or materials improvement projects.

Objective

The Phase II Pb-free Manhattan Project will identify the weaknesses and gaps suggested during the documentation of Best Practices in the Phase 1 of the Pb-free Manhattan Project. Once the technology gaps are identified, a roadmap of potential future projects will be outlined to resolve the disparities in the Pb-free mitigation strategy. The studies can range from package and PWB designs, to material, manufacturing, and reliability issues. From this roadmap, a benchmarking metric can be established that will produce criteria for assessing and prioritizing Pb-free projects

The Pb-free Manhattan Project concept is to establish a more effective manner to deal with the introduction of Pb-free materials into the product stream by:

- Aggressively investigating the best mitigation strategies currently available
- Analyzing the deficiencies in the present state of Pb manufacturing and technology(GAP analysis)
- Creating a strategic roadmap for the effective insertion of projects needed to fill the gaps
- Create a benchmarking metric for the viability of Pb-free projects.

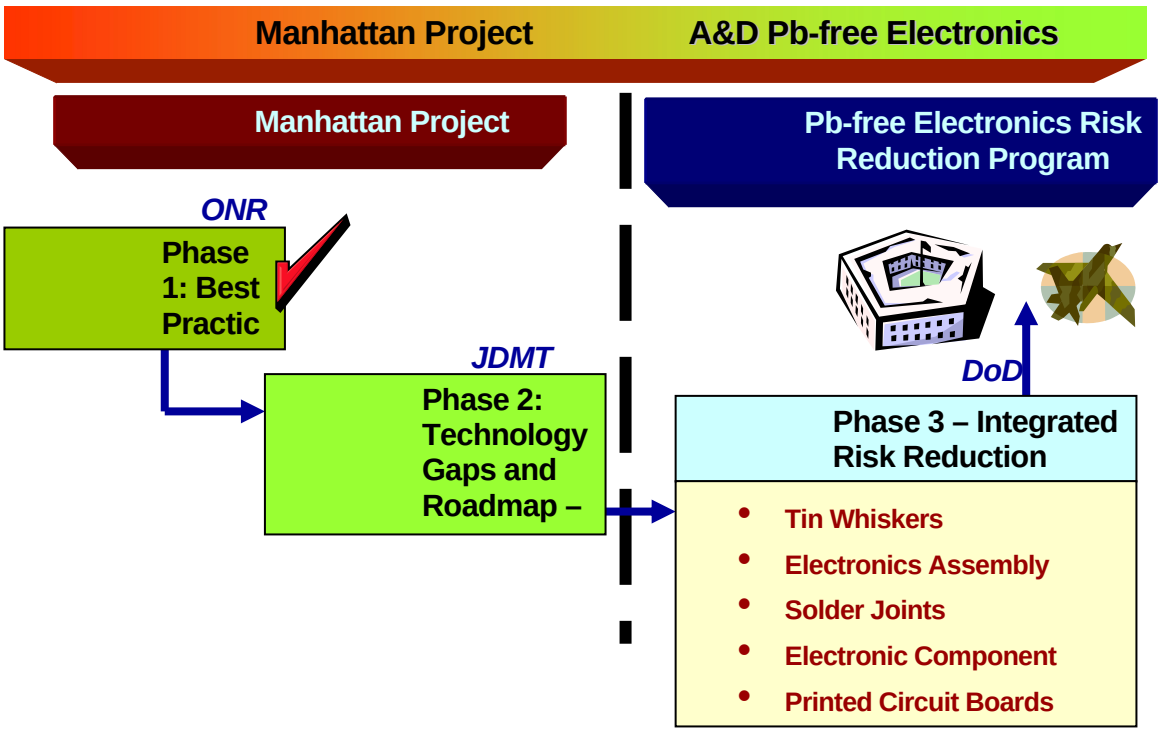


Fig 1 – Summary Approach for A&D Pb-free Electronics Risk Reduction

Figure 1 illustrates the sequence of events needed to address the technical gaps in the mitigation of Pb-free electronics.

Background

The cost of mitigation and the existing technical gaps in Pb-free are two major considerations when assessing the impact to the DoD of the Pb-free transition into the electronics product stream, with both being critical to the success of the mitigation efforts. Phase II of the Pb-free Manhattan Project will attempt to identify and recommend remedial procedures to help reduce costs and diminish the technology gap that presently exists with Pb-free.

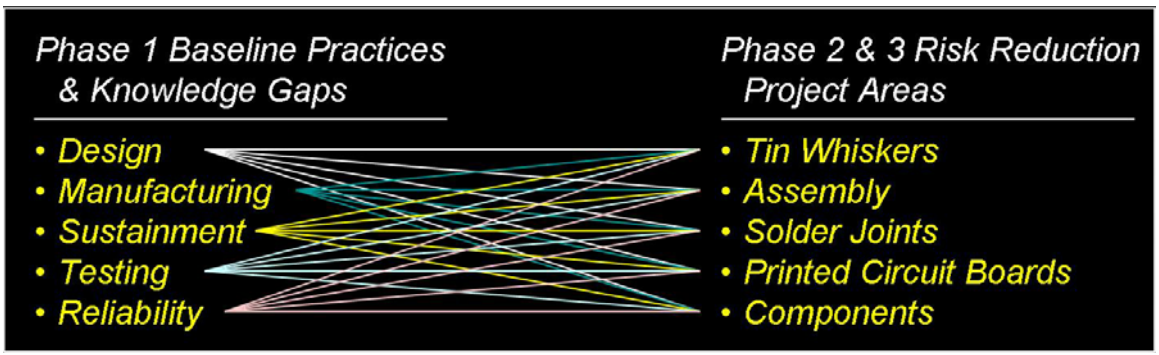


Fig 2 Knowledge Gaps and Project Areas

Fig 2 shows an interlocking relationship the knowledge gaps that were established, and the various project areas needed to be addressed. Some observations included:

- Serious technical gaps exist for Pb-free electronics that have to be overcome for use in A&D harsh environment
- *Quantification of degraded reliability and lifetimes is a significant gap*
- The three-year Pb-free Electronics Risk Reduction Program schedule is aggressive, but realistic
- Phase 3 execution will require and draw on the best available talent in the A&D community
- *Phase 3 will benefit any A&D or commercial product that relies on Pb-free COTS electronics and operates in extreme or harsh environments*

Key Deliverables from the roadmap:

- Detailed design Guidelines
- Validated Life prediction Models
- Assembly and repair process definitions
- Methodologies for assessing new materials

Cost examples of Pb-free mitigation to the A&D Industry

Virtually all industries supplying Military and mission critical hardware to the DoD have enacted infrastructural changes to accommodate the potential for restricted material entering the product stream. A recent study conducted over the past few years has shown substantial expenditures of resource and investment in this area by individual industry providers. It follows naturally that these Pb-free electronics costs are passed on to the DoD customer in prices of acquired goods

Cost Drivers:

In this very direct way, the impact of Pb-free mitigation affects the cost of military hardware. The costs incurred by the major OEM's supplying DOD electronic assemblies falls into two categories.

Preventive Measures

To ensure that Pb-free materials do not enter the supply chain in Pb-free restricted projects. Most OEM's have implemented a project plan to deal with **prohibited materials** and are in various stages of completion.

Validation of Pb-free Processes

The second category, and complementary to the prohibited material strategy are the Pb-free transitional projects designed to introduce and validate Pb-free process into the manufacturing facility.

These measures are intended to reduce the cost to the DoD, by utilizing COTS materials wherever introduction of these materials is not a liability to performance and reliability. The incurred cost for both prohibited and transitional projects ranges from **$10M to 35M** for one type of facility over a 2 to 3 year period depending on the size of the facility. These costs are subsequently passed on to the DoD in the form of increased product prices

Non-recurring costs typically amount to 70% of the total cost, which includes capital, labor, and materials for the implementation of a prohibited material process. The transitional cost to a Pb-free process is about 30% of the prohibited material process, but both must be implemented to be effective.

Below is an example of a typical flow chart implemented by many of the DoD providers.

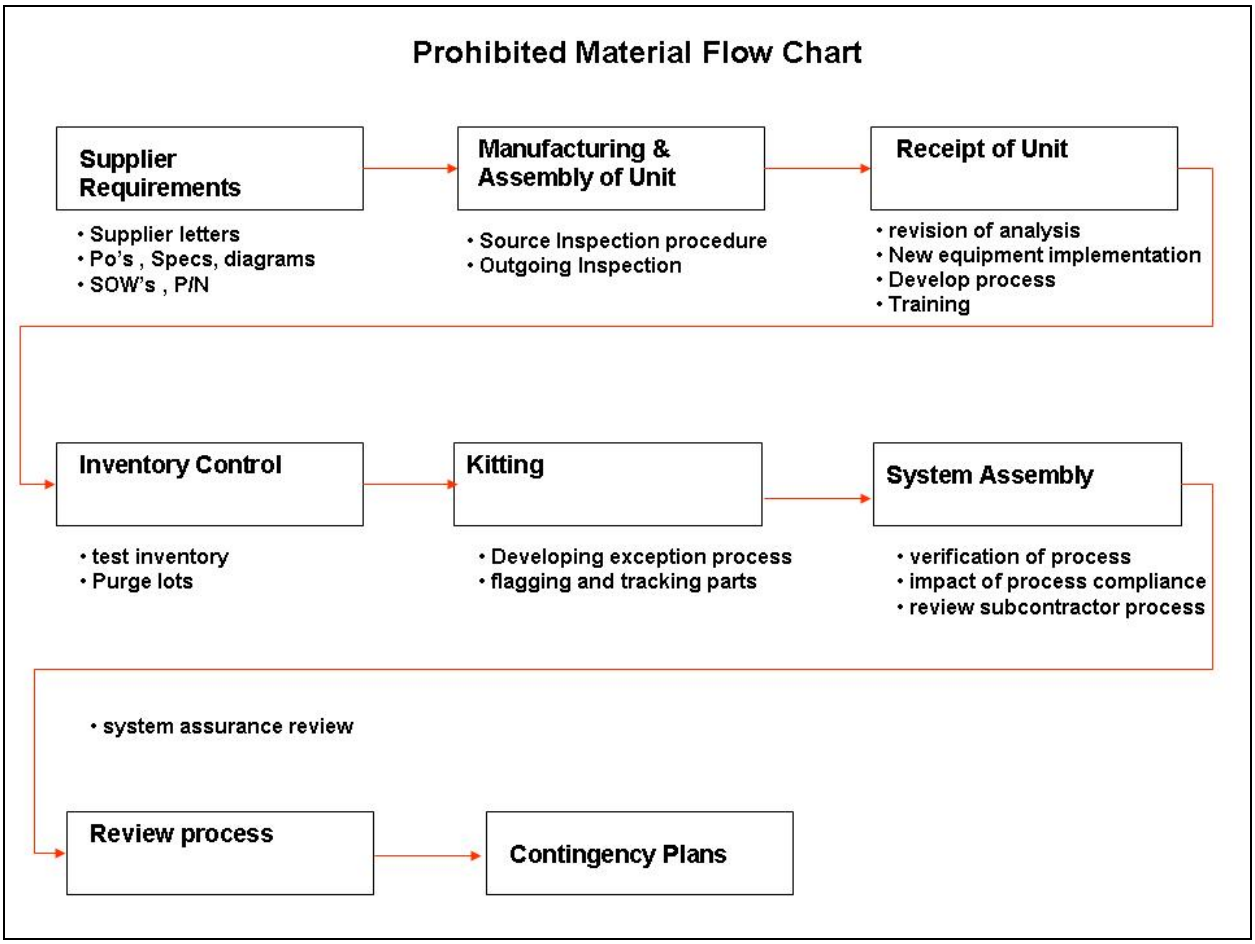


Fig 4: OEM prohibitive material flow chart

The cost of doing business in Pb-free will revolve mainly around the expenses of prohibited materials and ensuring that suppliers comply with Pb-free restrictions. Because many of the suppliers, both distributors and manufacturers, have changed their COTS availability from SnPb to Pb-free, the sense

of urgency by COTS vendors to form cooperative strategies to prevent Pb-free from entering the product stream is not necessarily a top priority.

Below is an example of the mitigation costs implemented by one specific manufacturing facility.

Cost of Lead-Free Mitigation										
	Year 1			Year 2			Year 3			
	hrs	Labor cost	Materials	hrs	Labor cost	Materials	hrs	Labor cost	Materials	Totals
Organizing team	2800	$ 616,000		2800	$ 616,000		2800	$ 616,000		$ 1,848,000
industry participation	10400	$ 2,288,000		16600	$ 3,652,000		24960	$ 5,491,200		$ 11,431,200
Consortium activities	4160	$ 915,200		4160	$ 915,200		4160	$ 915,200		$ 2,745,600
Engineering	1040	$ 228,800		1040	$ 228,800		1040	$ 228,800		$ 686,400
Automation and process control	16600	$ 3,652,000		16600	$ 3,652,000		16600	$ 3,652,000		$ 10,956,000
Whisker Monitoring	2080	$ 457,600		4160	$ 915,200		14560	$ 3,203,200		$ 4,576,000
BOM analysis		$ -			$ -		2080	$ 457,600	$ 175,000	$ 457,600
Lead-free testing	2080	$ 457,600	$ 5,000.00	2240	$ 492,800	$ 45,000.00	2080	$ 457,600	$ 190,000	$ 1,408,000
										$ -
Subtotal	39160	$ 8,615,200	$ 5,000.00	47600	$ 10,472,000	$ 45,000.00	68280	$ 15,021,600	$ 365,000	$ 34,108,800
Total cost		$ 34,639,680								

Table 1: Example of Cost Mitigation - OEM

Phase 3 ROM Costs

WBS	Risk Reduction Project Area	ROM Cost in 2010 $ (M)			
		Year 1	Year 2	Year 3	TOTAL
A	Tin Whiskers	$ 6.3	$ 6.8	$ 6.5	$ 19.7
B	Assembly	$ 3.2	$ 4.0	$ 3.0	$ 10.2
C	Solder Joints	$ 13.9	$ 19.4	$ 13.3	$ 46.6
D	Components	$ 1.2	$ 2.6	$ 2.1	$ 5.9
E	Printed Circuit Boards (PCBs)	$ 3.9	$ 5.2	$ 3.5	$ 12.6
	TOTAL	$ 28.5	$ 38.0	$ 28.5	$ 95.0

Table 2 - Phase 3 ROM Cost estimates

The approximate cost to resolve the technical gaps in each of the individual areas is outlined in the table 2. The collective efforts will take at least three years to complete. The fundamental objective of the Phase 3 efforts, is to resolve the knowledge gaps for the use of Pb-free electronics in A&D products, as quickly as possible

- The Pb-free electronics technical knowledge gaps & risks for A&D applications are bigger than anticipated, impacting the Risk Reduction Program cost
- The resulting ROM cost estimate is higher that expected, but is not unreasonable based on the scope of the required 36-month risk reduction effort

The Pb-free Technology gap

Virtually any manufacturing process can be refined to produce the efficiency needed to control and mitigate the costliness of accommodating Pb-free assemblies. However, the existing gap in Pb-free technology becomes a primary impediment in the predicting lifetime reliability of assemblies utilizing Pb-free material sets. From a historic perspective, SnPb alloys have been utilized in electronics, well before the advent of Pb-free, and consequently, the amount of reliable data gathered for Pb-free is limited. Some of the factors that affect reliability and are in need of further research are:

1. Tin Whisker Control
2. Package Design
3. Component Selection
4. Solder Alloy
5. Substrate Materials

General Gap Areas

Commercial vs. Military
Participants in recent studies acknowledged the difficulty in making conclusions without more empirical evidence about Pb-free in the areas of reliability, especially long term reliability of greater than 10 yrs. While some commercial telecom products specify lifetimes of 10 yrs, the Joint Strike Fighter military airplane, for example, specifies a 40 year life.

Technical Knowledge
A good deal of confidence has been placed by the general electronic manufacturing industry on the published findings by the various consortia and other entrepreneurially driven efforts by industry and academia, as being representative of the state of technology in regards to Pb-free. While there is a contribution to the overall Pb-free knowledge base, it is still very limited, sparse, and often disconnected to the reliability requirements of the DoD.

Field Failure
Field failure information regarding Pb-free assemblies at this juncture is very sporadic since no substantial data is available to accurately extract this often classified and/or proprietary information. More critically, it is still not fully understood what mechanisms are responsible for failure when it occurs, or how to mitigate them. This increases the potential risks associated with the inadvertent contamination of Pb-free components into Military hardware

Process Control
Data to assess reliability of one specific Pb-free manufacturing system over others can be difficult to interpret since many of the manufacturing variables are not consistent from one process to another.

The Pb-free *Manhattan Project* has identified the best manufacturing practices to date that will mitigate the effects of Pb-free. More work needs to be done to assess the various manufacturing technology gaps that exist to produce greater process efficiency and controls that will reduce cost, with results of increased assurances of military hardware reliability

5. Reliability models
One major shortcoming in the validation of existing Pb-free reliability models to predict potential field failure has been the use of a scatter shot approach, which frequently cannot account for many of the factorial interactions. The lack of cohesiveness for these efforts can be attributed to the limitation of any one industrial organization to incorporate all of the relevant factors, in a manner consistent with a more comprehensive approach. One of the goals of the Pb-free Manhattan Project is integrate the activities around modeling lifetime reliability of Pb-free electronic assemblies in a manner consistent with best know practices.

Various Pb- free consortia have undertaken, at a considerable cost, studies designed to narrow the field of acceptable Pb-free material sets, process conditions, and testing environments apropos to demonstrating the comparative effects of assemblies processed under what was then, best known Pb-free technology. The studies proved effective to a certain degree, and have been used as advantage points for further Pb-free mitigation studies. Virtually every subject matter expert on Pb-free mitigation technologies, agrees that a more inclusive and thorough roadmap needs to be implemented , but more importantly, orchestrated in an organized fashion to carefully select the appropriate parameters for research, ascertained as critical, by a thorough GAP analysis

Technical Findings

Gap analysis

The gaps that were identified during the first phase of the LFEMP were categorized and segmented into the following areas: Design Gaps, Manufacturing Gaps, Reliability Gaps, Sustainment Gaps, and Test Gaps. The selection of these gaps were assessed on their insufficient or a total lack of information on the particular technological area as it pertains to the mitigation efforts of Pb-free materials into the Aerospace and Defense industry. Each gap succinctly summarizes the present deficiencies, and is related to specific technical approaches that need to be taken to begin the process of reconciling the disparities between Pb-free and SnPb materials. In the broader context of the Gap analysis, the information obtained from the dissemination process will subsequently produce a technological roadmap designed to provide resolution in addressing the existing gaps, and clarity in the selection process in assessing technological viability for Pb-free projects.

Major Gap Areas.

1 Database and Testing

An extensive amount of information and data is lacking concerning the Pb-free especially when compared to SnPb the databases that are presently available for analytical and modeling purposes. This also applies to test methodologies and standardized procedures used to assess reliability and test performance for assemblies made with Pb-free materials

Design

- Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. One of the material sets includes solder where existing and future Pb-free alloys to formulate failure models (solder, pad cratering, and trace cracking) is lacking.
- The development of new laminate materials used for Pb-free processing has necessitated a compulsory examination of laminate properties and their effect on future Pb-free materials. The lack of data prevents the formulation and validation of appropriate failure models
- A shortage of test data for Pb-free assemblies renders the attempts to validate failure models (solder, pad cratering, and trace cracking), more difficult and inconclusive.
- Long-term field performance of A&D product with Pb-free materials is critical in assessing the validity of failure models. Currently, there is insufficient field failure data to make determinations of long-term reliability.
- There have been premature failures of temperature sensitive passive components and capacitors subjected to Pb-free solder process temperatures, which resulted in reduced defects, infant mortality, and reliability reductions. The root cause for these failures, have yet to be determined.
- The Pb-free material corrosion rates and how they correlate to service environments is not fully understood, resulting in increased reliability risk. This includes corrosive interactions with solder, PCB finishes, and component finishes, underpowered and off storage conditions within A&D environments.
- The current practice of designing in SnPb solder stress conditions for Pb-free designs will not necessarily result in satisfactory life in high stress environments. New test parameters need to be determined specifically for Pb-free materials.

Reliability

- Life test data is not readily available for the interconnect life of staked and underfilled components.
- Behavior of Pb-free solder interconnects under shock and vibration at low temperatures (sub zero) is not adequately characterized

Sustainment

- The field service data feedback requirements, process, and content definition are not adequate to capture the most prevalent issues around Pb-free assemblies in the field.

2 Pb-Free Cost Models

The transition to Pb-free requires extensive research into how the new material and processing requirements will influence the overall cost of manufacturing A&D hardware. There are a few attempts to characterize and develop cost models for commercial applications, but it has been limited concerning the real costs for A&D programs to mitigate the entry of Pb-free material, or transition where it is feasible to Pb-free materials. It is particularly difficult to forecast program costs based on COTS supply chains that have discontinued SnPb inventories, and in many cases in programs that have been qualified with legacy parts. Realistic cost models to suit the requirements of the A&D need to be developed

Design

- The A&D community is unable to accurately assess the costs of maintaining SnPb or transitioning to Pb-free materials and assembly. There is little known on how extensive the sustainment costs can be become with the rapidly demising sources of SnPb materials.
- The A&D community is unable to accurately assess the NRE costs for projects requiring specialized or custom materials and processes suited to maintain the SnPb design specifications.
- Manufacturing costs for maintaining SnPb assemblies becomes more difficult to appraise without accurate information on the availability and acquisition of the required SnPb materials.

3 Materials Research

There are a great deal of new Pb-free materials, which have been introduced into the product streams of electronic assemblies, used for A&D applications. The number of new solders, laminates, finishes, components, process and manufacturing chemicals adapted for Pb-free continues to grow. The effects these new materials have on reliability and performance of A&D products is not always apparent, and virtually no data exists on long-term sustainability in harsh environmental conditions. A great deal of research remains undone to ascertain the effects that these new materials have on ongoing and future A&D programs. Additionally, research projects dealing with new materials are often being done on an isolated basis, not taking into account possible interactions between various materials sets. The scope of the investigations to satisfy statistically valid protocol, require a concerted and organized effort across many disciplinary fields of material technology.

Design

- Current Pb-free materials are insufficient for A&D products. There is no known component plating finish that meets or exceeds SnPb assembly and reliability performance
- There is no known PCB plating finish, which meets or exceeds SnPb assembly and reliability performance.
- There is no known Pb-free alloy, which meets or exceeds SnPb assembly and reliability performance.
- Current PCB laminate materials formulated for Pb-free assembly have unknown risks in regards to assembly and reliability performance under A&D required environmental conditions.

- When multiple solders are used in assembly, certain combinations of solders are incompatible or have a narrow process window.

Manufacturing

- Industries lacks knowledge about the relationship between solder alloys and solder processes/equipment to produce acceptable solder joint microstructure
- The current A&D printed wiring board materials are not capable of surviving Pb-free soldering processes.
- The current industry components are not capable of surviving Pb-free soldering processes.
- Lead-free assembly cleaning processes are not clearly defined in terms of materials compatibility and contamination testing.
- Conformal coating process compatibility is poorly defined for materials compatibility with Pb-free processes.
- Lead-free solder bath process contamination limits and controls are not defined

Reliability

- There is a lack of understanding of fundamental whisker growth mechanisms.
- Current Pb-free materials are insufficient for A&D products. This includes solders, laminates, and other materials that comprise Pb-free electronic assemblies

Sustainment

- There is a lack of understanding on what the additional stresses of rework/repair will do to Pb-free assemblies.
- Shipping and handling procedures do not presently address Pb-free factors, such as handling and storage conditions.
- There is a limited understanding of underfill reparability and potential degradation in storage conditions.
- There is no defined specification for the maximum amount of reflow cycles and limitation requirements for each part/component that undergoes repair/rework cycles
- There is a lack of understanding of how materials and process compatibility issues affect repair
- There is a lack of understanding of reliability degradation from storage, use, and repair stresses.

Test

- The current Pb-free materials are insufficient to test for tin pest on A&D products.
- Current Pb-free materials are insufficient to test for copper dissolution on A&D products.

4 Failure Mode Development

The ability to predict potential problems early on in the product cycle is a critical part in reducing cost, and increasing performance. Unlike many of the physical attributes and predictive behavior known about SnPb, Pb-free materials remain relatively unknown making it difficult to mitigate potential failures.

Design

- There is an absence of predictive models of solder joint fatigue, along with insufficient materials properties data for the model inputs. The list of appropriate computational models needed include thermo mechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration. Test vehicles to gather the required data and other information such as underfill, staking methods, preconditioning environments, stress screening environments, and field conditions, all need to be developed.
- There is a lack of appropriate and validated failure models, which prevents accurate failure prediction, test development, and creation of heuristic rules for solder failure models requiring vibration.
- There is a lack of appropriate and validated failure models, which prevents accurate failure prediction, test development, and creation of heuristic rules for solder failure models requiring mechanical shock.
- High G pyrotechnic mechanical shock requirements for solder joints, which are differentiated from other mechanical shock tests, do not have predictive models for Pb-free materials .The absence of materials properties, validation and High G failure mode data, make computational models difficult to ascertain.
- The predicted reliability of solder joints using combined environmental tests lack the appropriate and validated failure models for accurate failure prediction, test development, and creation of heuristic rules.
- Predictive models of the solder joint electromigration phenomenon under high current density conditions are not well understood for Pb-free alloys. This is a lack of understanding on how the correlation between the solder alloy and test condition will affect the results.
- There is a lack of appropriate and validated failure models, which prevents accurate failure prediction, test development, and creation of heuristic rules in Plated through Holes (PTH).
- PCB pad cratering and trace cracking lacks the sufficient data on material properties to formulate failure models. No test vehicle has been developed for model validation and failure mode analysis.
- The lack of appropriate and validated failure models prevents accurate failure prediction, test development, and creation of heuristic rules for tin whiskers.
- There is no means to predict the effects of soldering process variations (workmanship) on long-term joint reliability for Pb-free. The absence of computational models that can address changes to the solder joint caused by multiple reflows, solder volume, and fillet/joint geometry make reliability predictions difficult.
- The influence of preconditioning or storage of Pb-free materials prevents the creation of appropriate and validated failure models for failure prediction, test development, and creation of heuristic rules.
- There is a lack of appropriate and validated failure models, which prevents accurate failure prediction, test development, and creation of heuristic rules on assemblies which have been influenced by prior events, such as environmental stress and field conditions

- The effect of the most common forms of contamination on the properties of the Pb-free solder is not known. Predictive models derived from validated data and failure mode effects do not exist.
- Lack of pi factors, and the data to develop them, inhibits the ability to assess the influence on Mean Time Before Failure.
- There is a prevalent lack of suitable diagnostic and prognostic processes to address Pb-free solder joint failure modes. There is very little in the way of non-destructive failure analysis techniques to detect pad cratering or tin whisker occurrences.

Reliability

- Effectiveness of modeling techniques for estimating life expectancy of interconnections of staked or underfilled over long-term operation has not been satisfactorily documented. These include the Solder Failure Models for Thermal Cycling, Vibration, and Mechanical Shock.

Sustainment

- There is a lack of diagnostic and prognostic processes to address Pb-free related failure modes, such as tin whisker shorts and solder joint opens, including intermittent failures.

5 Test Screen Development and Validation

Design

- Existing tests (design verification, product qualification) and screens used by the A&D community may not be valid for Pb-free product. Design verification (HALT / HAST), subsequent model development is difficult since fatigue constants, and stress states of board traces are different.
- Existing tests (design verification, product qualification) and screens used by the A&D community may not be valid for Pb-free product. Product qualification (MIL-STD-810, DO-160) may not be sufficient.
- Existing tests (design verification, product qualification) and screens used by the A&D community may not be valid for Pb-free product undergoing Environmental Stress Screening (ESS).
- There is no universally acceptable approach, which allows circuit designers to assess the risk and impact of tin whiskers, on circuit functionality during schematic design. This results in excessive program costs through potentially unnecessary material tracking and identification, expensive mitigation, and unpredictable and elevated field failure rates.
- Existing tests (for design verification or product qualification) used by the A&D community may not be valid for Pb-free products.

Manufacturing

- There is no proven durability and compatibility of adhesives/coatings/underfill materials with Pb-free soldering processes.

- The current component reprocessing procedures can result in component degradation
- The current ICT capability is not optimized for the processing of Pb-free assemblies.
- There is a lack of current industry standard component incoming screening procedures.

Test

- There are no standardized tests for simulated solder joints. There is little test data and no standardized specimen geometries and test methods, for evaluating the effects of Pb-free solder specimen size vis-à-vis microstructure on the mechanical and physical properties of the interconnections.

6 Tin Whisker Mitigation

Tin whiskers have been a known source of reliability issues for a number of years. A massive amount of effort has been initiated in predicting, preventing, or mitigating the growth of Tin whiskers. Due to the rapid transition of electronics to Pb-free solders and finishes, and the compaction of electronic circuitry to fit smaller and smaller devices, the likelihood of the occurrence of tin whiskers causing malfunctioning equipment in A&D related programs becomes greater. There is a great degree of knowledge on the various attributes of tin whiskers, but some of the fundamental science still needs to be explored, and a concerted effort to bridge the existing gaps in whisker mitigation techniques need to be addresses.

Design

- No single source exists for the A&D community to select tin whisker risk mitigation activities based on cost, availability, and degree of mitigation.
- No existing mitigation practice is universally implementable and definitively prevents the occurrence of tin whiskers.

Manufacturing

- The conformal coating processes lack objective evidence for tin whisker mitigation capability

7 Design Rules

- Ascribing the same characteristic behaviors on Pb-free materials as those stipulated for SnPb, would lead to misleading conclusions on the parameters that develop the heuristic conventions for many of the environmental tests used by designers to ensure a robust and well-tested product. Designers and Quality engineers need to feel confident that the test procedures meet the quality specifications. Using SnPb models that have been well researched and proven as sufficient predictors of field reliability, cannot be used for Pb-free materials, especially for A&D applications. Additional research needs to be undertaken to develop new sets of heuristic rules for the implementation of new Pb-free materials, and the subsequent environmental testing of assemblies constructed with them.

Design

- Existing heuristic rules for Metal Vapor Arcing used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product.
- Existing heuristic rules for Combined Environments used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product.
- Existing heuristic rules for vibration used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product.
- Existing heuristic rules for mechanical shock used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product.
- Existing heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free products using encapsulants, staking compounds, and underfill.
- Existing heuristic rules used for the selection of laminate material by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product.
- No current test method exists for determining whether a mechanical and electrical part is whicker prone over its lifetime. An industry standard test method is needed to identify tin whisker risk rapidly for mechanical and electrical parts.
- No existing mitigation practice is universally implementable and definitively prevents the occurrence of tin whiskers in high frequency RF circuits.
- There is insufficient information on how and when tin whiskers can impact circuit performance of high frequency RF circuits
- Existing electrical design heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product. Electrical design practice does not provide guidance regarding physical separation between critical devices (e.g., components from different critical functional elements) or redundancy to eliminate whisker risk.
- Existing heuristic rules on the solderability of finishes used by electrical and mechanical designers based on experience with SnPb programs, may be insufficient to ensure reliability of Pb-free product.
- Existing heuristic rules used conformal coating for tin whisker mitigation by electrical and mechanical designers based on experience with SnPb programs, may be insufficient to ensure reliability of Pb-free product.
- Existing heuristic rules used for PTH solder fill by electrical and mechanical designers based on experience with SnPb programs, may be insufficient to ensure reliability of Pb-free product. There are no established (thermal cycling, vibration, shock) correlations on the reliability of solder joints of PTHs that are 25 to 75% partially filled with Pb-free solder.
- There are no rules for mixed solders, "SnPb+Pb-free" joints or "Pb-free-Pb-free" alloys.
- There are no design rules for copper dissolution.
- In PCB Design, there is a risk that heritage SnPb solder geometries will need to change, or solder stencil designs will need to change to adjust the solder volume and geometry for Pb-free solders. Geometries are currently based on thermal cycle test results and neglect shock/vibration considerations.

Reliability

- Existing heuristic rules for creep rupture used by electrical and mechanical designers based on experience with SnPb programs, may be insufficient to ensure reliability of Pb-free product.

Test

- Existing heuristic rules used for tin pest by electrical and mechanical designers based on experience with SnPb programs, may be insufficient to ensure reliability of Pb-free product.
- There needs to be defined detection limits for Pb-free assemblies to prevent damage during handling, assembly, and test. Due to their stiffness, Pb-free alloys require additional precautions during handling and/or performing failure mode analysis.

8 Risk Assessment

The result of insufficient data to assess risk with the use of Pb-free materials is problematic in addressing the risks associated with changes in materials or processes. The same metrics used to asses risk on SnPb systems will not provide an accurate baseline in appraising the probability of introducing failure mechanisms commonly associated with the metallurgical joining processes such as soldering and plating deposition.

Design

- The current risk assessments for critical Pb-free failure mechanisms are insufficient in regards to timeliness and accuracy. There currently is no method to rapidly and accurately identify the risk of tin whiskering at the component level
- The current risk assessments for pad cratering and trace cracking on critical Pb-free failure mechanisms are insufficient in regards to timeliness and accuracy. There currently is no method to accurately identify the risk of pad cratering and trace cracking, quickly.
- There currently is little data on the risk of CAF formation within Pb-free laminates exposed to Pb-free processing temperatures.
- The current risk assessments for PTH fatigue failures on critical Pb-free failure mechanisms are insufficient in regards to timeliness and accuracy. There currently is no method to identify the risk of PTH fatigue failures, in an expedient and accurate manner.

Sustainment

- There is a lack of standards/requirements to address receiving inspection in sustainment situations for tin whisker identification.

9 Failure Identification

There is a need to refine the presently used tools and equipment to accommodate the modified appearance and the increased occurrences of failures in Pb-free assemblies

Design

- Introduction of Pb-free materials may increase the occurrence of intermittent failures during operation. Not enough is known about the nature or the cause of intermittent failures for Pb-free materials

Manufacturing

- Automated and manual inspection criteria are inadequate in assessing solder joint quality for A&D products.

10 Process Development

Design

- Rules of thumb for manufacturability and rework/repair must be re-examined for Pb-free solder to ensure that manufacturing process variation is minimized.

Manufacturing

- The process capability of manual solder tools, equipment, and periodic maintenance is not clearly defined.
- The current Industry Vapor Phase process chemistry and thermal load parameters are not robust for A&D.
- Industry rework equipment and processes are not capable of supporting Pb-free A&D product demands.
- Lead-free Laser soldering processes are undefined for A & D products.
- Based on using the current Pb-free soldering equipment, no requisites for defining thermal capability and producing profile parameters are specified to meet solder joint integrity requirements for A&D.
- The current cleaning technologies have no proven Pb-free soldering process flux residue removal performance for A&D.
- There is a lack of manufacturing protocols and procedures to mitigate solder defects resulting from Pb-free solder processes.
- There is a lack of manufacturing protocols and procedures to mitigate copper dissolution resulting from Pb-free solder processes.
- Inert Atmosphere parameter limits are not defined for Pb-free wave solder processes.
- Surface Mount assembly process placement accuracy and placement vision capability requires improved Gauge Repeatability & Reproducibility (R&R).
- Industry defined requirements for cross contamination limits for shared assembly processes do not exist for Pb-free assemblies.
- There is a lack of industry-defined requirements for equipment and component placement for Pb-free circuit card assembly singulation.

Gap Conclusions

- Pb-free electronics have made their way into A&D systems, and mitigation efforts need to be expedited rapidly
- Commercial electronics market has transitioned out of Pb-free and is phasing out SnPb
- Military electronics rely on commercial electronic parts and processes to reduce cost
- The A&D industry is finding it increasingly difficult to purchase COT components with Pb, or prevent the use Pb-free components causing cost growth
- Gaps have identified that the state of Pb-free electronics is currently in a risk accumulation scenario
- Pb-free finishes and assemblies are continuously being introduced into DOD assemblies
- The rate is increasing as SnPb becomes more costly.
- Pb-free COTS electronics are not suitable for most A&D applications that demand long life and operation in harsh environments due to reliability that is currently not quantifiable
- Pb-free electronics are fundamentally and drastically changing the way electronic products for A&D are designed, procured, manufactured, tested, and supported
- There is a need for a coordinated, proactive DoD wide Pb-free electronics Risk reduction program to deal with the gaps, and ensure that the highest quality and best products are available for the Warfighter
- The cultural issues for Pb-free electronics are as challenging as the technical issues, making it more difficult to obtain funding
- The Manhattan Project concept has been validated as a viable approach to deal with complex issues that demand a radical approach.

LEAD FREE ELECTRONICS MANHATTAN PROJECT PHASE 2 REPORT

APPENDIX B

GAPS TRANSFERRED TO PERM

A critical feature of the Pb-free Manhattan Project (LFEMP) is the generation of actionable deliverables, and their implement in the aerospace and defense (A&D) industries. Implementation may take many forms, such as (1) production of data, methods, and tools that can be used directly by A&D programs; (2) production of information that can be incorporated into A&D guidelines, standards or handbooks; or (3) requirements that can be used by customers to define and control program deliverables.

Figure 1 illustrates the flow of outputs from the LFEMP. These outputs come from two sources: (1) results of projects funded and conducted as part of Phase 3 of the Manhattan Project; and (2) industry needs that were identified in Phase 2 of the Manhattan Project, but are not addressed by Phase 3 projects. The outputs of the LFEMP will be transmitted either to the customers of specific LFEMP Phase 3 projects or to the Pb-free Electronics Risk Management (PERM) Consortium.

The outputs from the LFEMP are listed in the table below this section of the report. The outputs from Phase 3 projects in the five project areas:

A. Tin whiskers,

B. Assembly,

C. Solder Joints,

D. Components, and

E. Printed Circuit Boards.

These outputs result from gaps identified in Phase 2, but that are not specifically addressed by Phase 3 projects. PERM will evaluate all of the outputs that it receives from the LFEMP (either directly from Phase 2 or via project reports from Phase 3). PERM will decide upon the proper disposition of the inputs, and will either take action within its own structure, or refer the LFEMP output to another organization for action. The resulting actions may take various forms, such as (1) producing or revising industry standards, handbooks, or technical reports, (2) producing or revising program management requirements, or guidelines, (3) producing or revising industry policies, etc.,

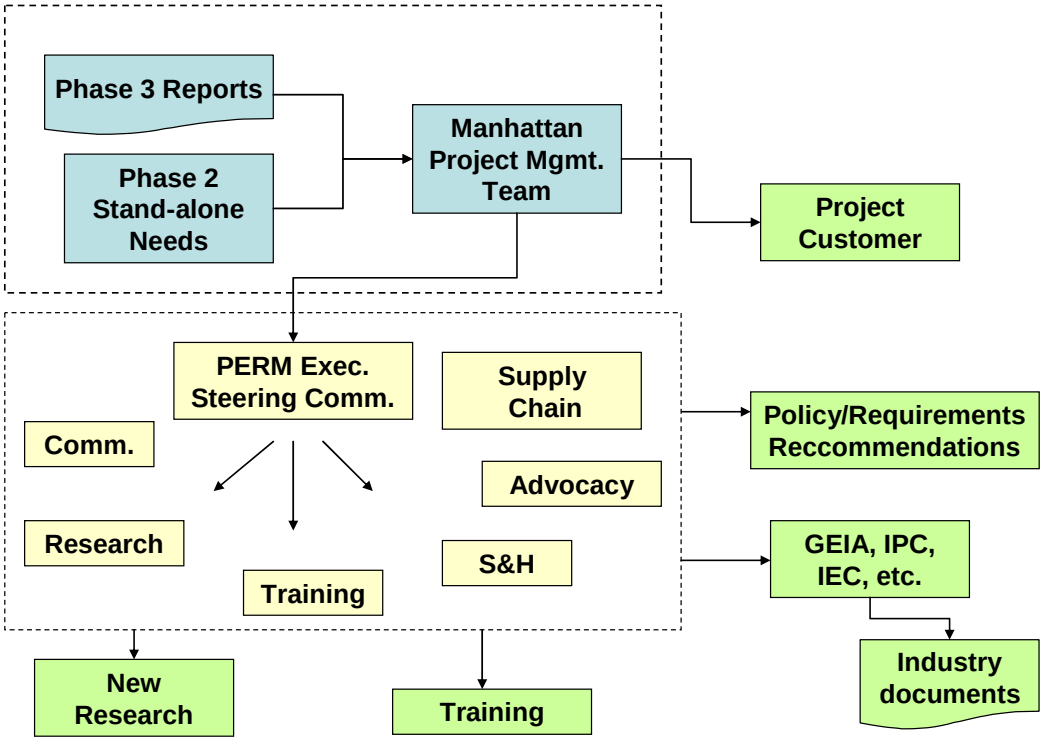


Figure 1. Flow chart of outputs from the Manhattan Project to the PERM consortium.

Table B-1

Phase 3 Deliverables to PERM

WBS	Phase 3 Task	Phase 3 Deliverable to PERM	PERM Task Team	Expected Action
ABE	WBS ABE. Review test methods for suitability to evaluate reliability of product (as mitigated) with whiskering. Develop and validate new methods for testing whiskering propensity at the product level.	New methods for testing whiskering propensity at the product level.	Standards and Handbooks (S&H)	Update GEIA-STD-0005-2.
ABC	Define design rules for CC selection for whisker mitigation based upon the efficacy of existing coatings, cost, other mitigations used in parallel, risk requirements, and whole-life cycle needs. If required, generate data by test or other means. (1) Design a standard test to quantify conformal coating coverage and thickness. (2) Compare effectiveness of conformal coating material(s) in use environment(s) with uncoated baseline.	(1) A standard test to determine conformal coating coverage and thickness for circuit card assemblies; (2) Design rules for use of conformal coating material(s) on Pb-free assemblies.	Standards and Handbooks (S&H)	Update GEIA-STD-0005-2.
ABF	Develop new tin whisker risk mitigations, quantify their effectiveness, and their interaction with other existing mitigations.	New tin whisker risk mitigations that are universally implementable and definitively prevent the occurrence of tin whiskers	Standards and Handbooks (S&H)	Update GEIA-STD-0005-2. Update GEIA-HB-0005-1.
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**
ABB	Define design rules for selection of whisker mitigation based upon a quantification of the efficacy of existing mitigations and their combinations, cost, risk requirements, and whole-life cycle needs. Where existing data is insufficient, generate data by test and other investigations.	Design rules for selection of whisker mitigation based upon a quantification of the efficacy of existing mitigations and their combinations, cost, risk requirements, and whole-life cycle needs.	Standards and Handbooks (S&H)	Update GEIA-STD-0005-2. Update GEIA-HB-0005-1.
ABA	Develop a method to automate critical physical part separation distance analysis during physical circuit layout to provide acceptable whisker risk mitigation.	Software to do critical physical part separation distance analysis during physical circuit layout to provide acceptable whisker risk mitigation.	Standards and Handbooks (S&H)	Update GEIA-STD-0005-2. Update GEIA-HB-0005-1.

ABD	Develop test method to rapidly and cheaply identify tin whisker risk at the part level for all classes of parts (mechanical & electrical).	A test method to rapidly and cheaply identify tin whisker risk at the part level for all classes of parts (mechanical & electrical).	Standards and Handbooks (S&H)	Update GEIA-STD-0005-2. Update GEIA-HB-0005-1. Update GEIA-HB-0005-4.
AAA	Characterize and quantify drivers for whisker-induced arcing (e.g. current, voltage, atmosphere, spacing) to provide risk reduction rules for designers.	Design rules that characterize and quantify drivers for whisker-induced arcing (e.g. current, voltage, atmosphere, spacing)	Standards and Handbooks (S&H)	Update GEIA-STD-0005-2. Update GEIA-HB-0005-1.
AAC	Define the effects of tin whisker growth on RF system performance. Survey existing knowledge then perform testing and analyses to provide additional knowledge as needed.	Test data on the effects of tin whisker growth on RF system performance.	Standards and Handbooks (S&H)	Update GEIA-STD-0005-2. Update GEIA-HB-0005-1.
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**
AAB	Define the V and I conditions for whisker-induced electrical shorting	Design rules to eliminate whisker shorting in circuit schematics	Standards and Handbooks (S&H)	Update GEIA-STD-0005-2. Update GEIA-HB-0005-1. Update GEIA-HB-0005-4.
AAD	Review existing field test data, test collection systems and procedures, and test methods for ability to identify intermittent faults anticipated from whiskers and interconnection failures (no fault found). Recommend and implement enhancements that will improve the identification and reporting of intermittent faults.	Improved standards for the identification and reporting of intermittent faults from whiskers and interconnection failures.	Standards and Handbooks (S&H)	Update GEIA-STD-0005-2. Update GEIA-HB-0005-1.
ACC	Develop whisker failure models to predict the performance of existing and future tin finishes.	A whisker failure model to predict the reliability of electronics containing tin finishes.	Standards and Handbooks (S&H)	Update GEIA-STD-0005-2. Update GEIA-HB-0005-1. Update GEIA-HB-0005-4.
ACB	Define dependency of electrical schematic structure and location upon whisker induced failure susceptibility.	Design rules to eliminate whisker shorting in circuit schematics	Standards and Handbooks (S&H)	Update GEIA-STD-0005-2. Update GEIA-HB-0005-1.

ACA	Develop tools and procedures to identify tin whiskers (and tin pest) at the depot level.	Tools and procedures to identify tin whiskers (and tin pest) at the depot level.	Standards and Handbooks (S&H)	Update GEIA-HB-0005-3
ACD	Perform research to gain fundamental understanding into tin whisker growth mechanisms, so that the extreme variations in whiskering propensity of deposits could be understood from first principles.	A model of the root causes of whisker formation and growth	Standards and Handbooks (S&H)	Update GEIA-STD-0005-2. Update GEIA-HB-0005-1. Update GEIA-HB-0005-4.
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**
BAAA	Investigate the applicability of current surface mount pad and plated thru holes design requirements for applicability for A&D product use environments. Test vehicles using selected typical component families shall be subjected to thermal cycle, vibration, and drop shock conditioning with verification of solder joint integrity	- A report documenting the test methodology, results, proposed Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and guidelines for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly - Recommendations for changes for IPC-AJ-820 (Pb-free critical solder process parameters), IPC-JSTD-001 (solder joint criteria), and IPC-A-610 (Pb-free specific solder defects)	Standards and Handbooks (S&H)	IPC and GEIA
BAAB	Define the minimum component placement boundary/accuracy requirements for acceptable A&D assembly yields. Test vehicles using a wide range of SMT component families (0201s, 0.4mm pitch area array, bottom terminated components, etc.) shall be utilized.	- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly	Standards and Handbooks (S&H)	IPC and GEIA

		- Recommendations for changes for IPC-AJ-820 (Pb-free critical solder process parameters), IPC-JSTD-001 (solder joint criteria), and IPC-A-610 (Pb-free specific solder defects)		
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**
BAAC	Define a process flow protocol allowing A&D product assemblers to utilize single process line flow. Minimum requirements shall be defined for cross contamination, workstation/equipment labeling, printed wiring assembly handling, process materials & tools organization, etc	- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly - A report recommending changes for IPC-AJ-820 (Pb-free critical solder process parameters), IPC-JSTD-001 (solder joint criteria), and IPC-A-610 (Pb-free specific solder defects)	Standards and Handbooks (S&H)	IPC and GEIA
BAAD	Define laser solder process critical parameters for A&D assemblies. Task includes equipment capabilities, material requirements, thermal profile/demand rules, solder joint workmanship criteria, rework/repair specifics and associated Pb-free specific root cause solder/infant mortality defects	- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly - A report recommending changes for IPC-AJ-820 (Pb-free critical solder process parameters), IPC-JSTD-001 (solder joint criteria), and IPC-A-610 (Pb-free specific solder defects)	Standards and Handbooks (S&H)	IPC and GEIA
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**

BAAE	Define wave/selective solder process critical parameters for A&D assemblies. Task includes equipment capabilities, specific solder alloy constraints, thermal profile/demand rules, thermal excursion degradation threshold limits, inert atmosphere minimum requirements, maximum solder bath contamination limits, solder joint workmanship criteria, and associated Pb-free specific root cause solder/infant mortality defects	- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly - A report recommending changes for IPC-AJ-820 (Pb-free critical solder process parameters), IPC-JSTD-001 (solder joint criteria), and IPC-A-610 (Pb-free specific solder defects)	Standards and Handbooks (S&H)	IPC and GEIA
BAAF	Define vapor phase solder process critical parameters for A&D assemblies. Task includes equipment capabilities, specific chemistry characteristics and constraints, thermal profile/demand rules, thermal excursion degradation threshold limits, solder joint workmanship criteria, and associated Pb-free specific root cause solder/infant mortality defects	- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly - A report recommending changes for IPC-AJ-820 (Pb-free critical solder process parameters), IPC-JSTD-001 (solder joint criteria), and IPC-A-610 (Pb-free specific solder defects)	Standards and Handbooks (S&H)	IPC and GEIA
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**

BAAG	Define reflow solder process critical parameters for A&D assemblies. Task shall include equipment capabilities, specific solder alloy constraints, thermal profile/demand rules, thermal excursion degradation threshold limits, inert atmosphere minimum requirements, solder joint workmanship criteria, and associated Pb-free specific root cause solder/infant mortality defects	- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly - A report recommending changes for IPC-AJ-820 (Pb-free critical solder process parameters), IPC-JSTD-001 (solder joint criteria), and IPC-A-610 (Pb-free specific solder defects)	Standards and Handbooks (S&H)	IPC and GEIA
BAAH	Define manual solder process critical parameters for A&D assemblies. Task includes equipment capabilities and durability's, thermal demand/temperature requirements, periodic maintenance rules, thermal excursion degradation threshold limits, solder joint workmanship criteria, and associated Pb-free specific root cause solder/infant mortality defects	- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly - A report recommending changes for IPC-AJ-820 (Pb-free critical solder process parameters), IPC-JSTD-001 (solder joint criteria), and IPC-A-610 (Pb-free specific solder defects)	Standards and Handbooks (S&H)	IPC and GEIA
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**

BAAI	Define cleaning process critical parameters for A&D assemblies. Task includes equipment capabilities, chemistry efficacy, material compatibility, impact of low stand component technologies, interaction with low residue flux process protocols and associated Pb-free specific root cause solder/infant mortality defects	- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly - A report recommending changes for IPC-AJ-820 (Pb-free critical solder process parameters), IPC-JSTD-001 (solder joint criteria), and IPC-A-610 (Pb-free specific solder defects)	Standards and Handbooks (S&H)	IPC and GEIA
BAAJ	Define conformal coating process critical parameters for A&D assemblies. Task includes minimum coverage requirements, coating process Gauge Repeatability & Reproducibility, compatibility with low residue/no clean process protocols and associated Pb-free specific root cause solder/infant mortality defects	- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly - A report recommending changes for IPC-AJ-820 (Pb-free critical solder process parameters), IPC-JSTD-001 (solder joint criteria), and IPC-A-610 (Pb-free specific solder defects)	Standards and Handbooks (S&H)	IPC and GEIA
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**

BAAK	Define depanelization/singulation process critical parameters for A&D assemblies. Task includes component location geometric rules/restrictions and maximum damage threshold limits and associated Pb-free specific root cause solder/infant mortality defects	- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly - A report recommending changes for IPC-AJ-820 (Pb-free critical solder process parameters), IPC-JSTD-001 (solder joint criteria), and IPC-A-610 (Pb-free specific solder defects)	Standards and Handbooks (S&H)	IPC and GEIA
BAAL	Define a relative cost comparison matrix for Pb-free solder processes using tin/lead as a baseline. The cost matrix will be formatted in categories of costs associated with each major assembly process element	A relative cost decision matrix comparing tin/lead solder versus Pb-free solder processes	Standards and Handbooks (S&H)	IPC and GEIA
	Project Management & Reporting: Task includes task scheduling, coordination of/collaboration between work packages areas and documentation completion			
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**
BABA	Define rework/repair solder process critical parameters for A&D assemblies. Task shall include equipment capabilities, specific solder alloy constraints, thermal profile/demand rules, thermal excursion degradation threshold limits, impact of long term storage, physical condition complications related to fielded assemblies and associated Pb-free specific	- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly	Standards and Handbooks (S&H)	IPC and GEIA

	root cause solder/infant mortality defects	- A report recommending changes for IPC-AJ-820 (Pb-free critical solder process parameters), IPC-JSTD-001 (solder joint criteria), and IPC-A-610 (Pb-free specific solder defects)		
BABB	Define rework/repair non - solder process (cleaning, conformal coating) critical parameters for A&D assemblies. Task shall include equipment capabilities, specific chemistry constraints, process induced degradation threshold limits, and associated Pb-free specific root cause solder/infant mortality defects	- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly - A report recommending changes for IPC-AJ-820 (Pb-free critical solder process parameters), IPC-JSTD-001 (solder joint criteria), and IPC-A-610 (Pb-free specific solder defects)	Standards and Handbooks (S&H)	IPC and GEIA
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**
BABC	Conduct a rework/repair solder process Gauge Reproducibility & Repeatability study to define process procedures/protocols for specific rework/repair methods	- A report documenting the rework/repair solder process Gauge Reproducibility & Repeatability study defining process procedures/protocols for specific rework/repair methodology - A report documenting suggested changes for IPC 7711/7722 specification (rework/repair critical process parameters)	Standards and Handbooks (S&H)	IPC and GEIA
BABD	Define a relative cost comparison matrix between a proposed Pb-free rework/repair process and a tin/lead solder baseline. The cost matrix will be formatted in categories of costs associated with each major assembly process element	A relative cost decision matrix comparing tin/lead solder versus Pb-free rework/repair processes	S&H, Communications	

BABE	Project Management & Reporting: Project Management & Reporting: Task includes task scheduling, coordination of/collaboration between work packages areas and documentation completion			
BBAA	Identify material failure modes that are responsible for electrical and mechanical failures in Pb-free products, including solder joint fatigue, pad cratering, conductor dissolution, or tin whiskers	A report that describes the qualification and acceptance test parameters for Pb-free products.	Research	
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**
BBAB	Analytical and computational models will be identified for predicting materials failure modes responsible for electrical signal failures and mechanical failures, including validation	A report that describes the qualification and acceptance test parameters for Pb-free products.	Research	
BBAC	The models are exercised to establish acceleration factors	A report that describes the qualification and acceptance test parameters for Pb-free products.	Research	
BBAD	Design will be established to define qualification and acceptance test parameters from the model predictions	A report that describes the qualification and acceptance test parameters for Pb-free products.	Research	
BBAE	Project Management and Reporting			
BBBA	Develop mechanics to acquire Pb-free, field functional failures (electrical and mechanical), including failure mode analyses. Particular attention will be paid to product subjected to repair-and-rework activities.	A report describing qualification and acceptance test parameters for Pb-free assemblies with additional validation from field failure data.	Research	
BBBB	Similarity assumption of failure modes will be confirmed between field failures and those underlying the qualification and acceptance tests. Failure modes will be documented that are unique to the field	A report describing qualification and acceptance test parameters for Pb-free assemblies with additional validation from field failure data.	Research	
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**
BBBC	Assuming similarity of failure modes between test and field,	A report describing qualification and acceptance	Research	

	the materials failure rates observed under the qualification and acceptance test conditions will be compared to the materials failure rates in the field to validate the acceleration factor of the models. The predicted rates of functional failures (electrical and mechanical) under qualification and acceptance test conditions will be compared to the observed rates of functional failures in the field data to validate the acceleration factor associated with the functional test parameters	test parameters for Pb-free assemblies with additional validation from field failure data.		
BBBD	Failure mode discrepancies will be reconciled between those documented in qualification and acceptance testing and those recorded from field failures, including the potential need to revise the underlying analytical or computational models	A report describing qualification and acceptance test parameters for Pb-free assemblies with additional validation from field failure data.	Research	
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**
BBBE	Functional failure rate discrepancies will be reconciled between those predicted by supporting qualification and acceptance testing versus field failure rates, including the potential need to revise the underlying analytical or computational models	A report describing qualification and acceptance test parameters for Pb-free assemblies with additional validation from field failure data.	Research	
BBBF	Project Management and Reporting			
BCXX	Still working on tasks	A demonstration facility that the A& D industry can utilize to validate design rules, exercise manufacturing procedures and exercise critical process parameters, explore sustainment protocols to enable greater success for systems to manage Pb-free issues, including those involving incorporating Pb-free materials and those limiting materials changes.		

WBS	Phase 3 Task	Phase 3 Deliverable to PERM	PERM Task Team	Expected Action
CA	Solder Joint Reliability Models			
CAA	Test Vehicle Design and Fabrication	Common test vehicles	Stds. & Hbks.	Document
CAB	Validation Data Collection and Assessment	Common data set for model validation	Stds. & Hbks.	Document
CAC	Materials Properties & Constitutive Relations	Common material database for design modeling and evaluation	Stds. & Hbks.	Document
CAD	Thermal Expansion Mismatch Induced Fatigue	Validation Test Data for Model Development	Stds. & Hbks.	Document
CAE	Vibration	Validation Test Data for Model Development	Stds. & Hbks.	Document
CAF	Combined Loading	Validation Test Data for Model Development	Stds. & Hbks.	Document
CAG	Shock and Drop	Validation Test Data for Model Development	Stds. & Hbks.	Document
CAH	Creep Rupture	Validation Test Data for Model Development	Stds. & Hbks.	Document
CAI	An Optimized Test Approach for Further Alloy	Test methodology for acceptance of new solders	Stds. & Hbks.	Document
CAJ	Reliability Modeling	Acceleration models for TC, Vib, Combined Environments including aging and geometry	Stds. & Hbks.	Document
CB	Solder Joint Reliability Effects			
CBA	Electromigration Effects	Test method, data, maximum operation current level for current Pb-free and mixed solder interconnects.	Stds. & Hbks.	Document
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**
CBB	Corrosion Effects	Test method for corrosion impact on solder interconnects	Stds. & Hbks.	Document
CBC	Reflow/Repair and Board Laminate/Finish Effects	Test method and data for board laminate and finish effect	Stds. & Hbks.	Document
CBD	Contamination Effects (Wave)		Stds. & Hbks.	Document
CBE	Solder Paste Effects	Evaluation of acceptable contamination levels	Stds. & Hbks.	Document
CBF	Tin Pest Formation Factors	Evaluation of impact of vendor solder pastes	Stds. & Hbks.	Document
CD	New Solders and Compatibility for A&D	Determination of factors that produce tin pest	Stds. & Hbks.	Document

CDA	Compatibility Process Study of SnPb Solder Pastes and New Component Materials		Stds. & Hbks.	Document
CDB	Compatibility Process Study of Existing Solder Pastes and New Component Materials	Method for testing solder compatibility with main Pb-free (SAC305, SN100C) solder assembly process	Stds. & Hbks.	Document
CDC	New Solders Gate Evaluation For A&D Products	Minimum requirements of solder for consideration for A&D	Stds. & Hbks.	Document
CDD	A&D Compatibility with Low Melt Solder Rework	Determination if low temperature solder rework meets A&D performance	Stds. & Hbks.	Document
CC	Underfill, Staking, and Coating		.	
CCA	Underfill Life Testing	Test method and common test data for evaluation of underfill on solder interconnect failure	Stds. & Hbks.	Document
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**
CCB	Staking and Coating Life Testing	Test method and common test vehicle for evaluation of stacking and coating on solder interconnect failure	Stds. & Hbks.	Document
CCC	Properties and Property Degradation	Material parameters, test methods, and set of material properties needed for modeling underfill, stacking, and coating materials.	Stds. & Hbks.	Document
CCD	Solder Joint Life Models for Underfilled, Staked, and Coated Surface Mount Parts	Models for assessing solder interconnect life of underfilled, staked, and coated surface mount components	Stds. & Hbks.	Document
CE	Insertion Mount (PTH)			
CEA	Reliability of PTH solder joints depending on the Cu thickness remained after assembly and rework	Design guide for copper thickness specification for PTHs	Stds. & Hbks.	Document
		Test method and common test vehicle for evaluation of stacking and coating on solder interconnect failure	Stds. & Hbks.	Document
CFA	Handling and ICT Testing	Test methods and data for evaluating handlings induced failures	Stds. & Hbks.	Document
CFB	Handling Model and Guide	Guidelines and models for assessing handling induced failures	Stds. & Hbks.	Document
WBS	**Phase 3 Task**	**Phase 3 Deliverable to**	**PERM Task**	**Expected Action**

		PERM	Team	
DAAA	Temperature exposure limits	Maximum Pb-free reflow cycles Temperature sensitive test standard	Standards and Handbooks (S&H)	Incorporate in Standard
DAAB	Receiving/incoming inspection requirements	Receiving/incoming inspection protocols	Standards and Handbooks (S&H)	Incorporate in Standard
DAAC	Storage requirements for unassembled components	Storage requirements for unassembled components	Standards and Handbooks (S&H)	Incorporate in Standard
DAAD	Component properties database	Component properties for failure models	Standards and Handbooks (S&H)	Incorporate into Tech Hdbk
DAAE	Fluxes/cleaning process compatibility with components	Identify compatibility properties of components with fluxes	Standards and Handbooks (S&H)	Incorporate into Tech Hdbk
DABA	Component Refinishing/Reprocessing	Cost/schedule impacts for GEIA-STD-0006 update	Standards and Handbooks (S&H)	Incorporate in GEIA-STD-0006
DACA	Temperature Sensitivity Capability Improvement	J-STD-075 update	Standards and Handbooks (S&H)	Incorporate in J-STD-075
DADA	Finish Solder Joint Effect	Finish impact on reliability	Standards and Handbooks (S&H)	Incorporate into Tech Hdbk
DADB	Solderability	Solderability test method	Standards and Handbooks (S&H)	Update JEDEC/IPC Std
DAEA	Corrosion Acceleration Factors	Cleanliness requirements	Standards and Handbooks (S&H)	Incorporate into Tech Hdbk
DAEB	Corrosion Mitigation	Design mitigations	Standards and Handbooks (S&H)	Incorporate into Tech Hdbk
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**
EAA	Perform copper pad design/ stencil design assessment and confirmation of reliability	Pad design/ stencil design assessment and confirmation of design rule reliability	Standards and Handbooks (S&H)	Update GEIA-HB-0005-2
EAB	Evaluate copper requirements and copper dissolution	Copper requirements and copper dissolution design rules	Standards and Handbooks (S&H)	Update GEIA-HB-0005-2, Relevant IPC document
EAC	Develop acceptance test methods for void formation associated with aging of solder/copper plated structures	Acceptance test methods for void formation associated with aging of solder/copper plated structures	Standards and Handbooks (S&H)	Update GEIA-HB-0005-2, Relevant IPC document
EBA	Evaluate thermal robustness of laminate material	Provide guidance on the selection of laminate materials with respect to thermal robustness	Standards and Handbooks (S&H)	Update GEIA-HB-0005-2, Relevant IPC document

EBB	Evaluate pad cratering	Provide guidance on the selection of laminate materials with respect to pad cratering	Standards and Handbooks (S&H)	Update GEIA-HB-0005-2, Relevant IPC document
EBC	Evaluate conductive anodic filament (CAF) formation	Provide guidance on the selection of laminate materials with respect to conductive anodic filament (CAF)	Standards and Handbooks (S&H)	Update GEIA-HB-0005-2, Relevant IPC document
EBD	Support development of new Pb-free laminate materials for A&D applications	Provide new Pb-free laminate materials for A&D applications	Standards and Handbooks (S&H)	Update GEIA-HB-0005-2, Relevant IPC document
ECA	Evaluate new Pb-free surface finishes for A&D applications	Provide guidance on Pb-free surface finish selection	Standards and Handbooks (S&H)	Update GEIA-HB-0005-2, Relevant IPC document
ECB	Develop Pb-free surface finish test methods	Provide guidance on Pb-free surface finish testing	Standards and Handbooks (S&H)	Update GEIA-HB-0005-2, Relevant IPC document
WBS	**Phase 3 Task**	**Phase 3 Deliverable to PERM**	**PERM Task Team**	**Expected Action**
ECC	Support development of New PCB surface finish plating materials for A&D applications	Provide new Pb-free surface finish plating materials for A&D applications	Standards and Handbooks (S&H)	Update GEIA-HB-0005-2, Relevant IPC document
ECD	Evaluate sporadic brittle failure of Pb-free solder due to nickel plating	Provide design guidance to avoid sporadic brittle failure of Pb-free solder due to nickel plating	Standards and Handbooks (S&H)	Update GEIA-HB-0005-2, Relevant IPC document
ED	Develop a database of PCB test data and design Rules	The culmination of the Pb-free printed circuit board materials and design activities will be captured in a database for A&D designers and manufacturers use	Standards and Handbooks (S&H)	Update GEIA-HB-0005-2, Relevant IPC document

Table B-2
Phase 1 Issues and Tasks to PERM

WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task Team**	**Expected Action**
N/A	Pb-free impact on spares provisioning is not defined	Define spares provisioning requirements	Supply Chain, Advocacy	Spares provisioning guidelines in GEIA-HB-0005-1
N/A	Repair facilities need to limit repair alloys allowed		Supply Chain, Advocacy	GEIA-STD-0005-1 and GEIA-HB-0005-3 Repair facility guidelines, DO-

				254
N/A	Qualification requirements have not been developed for impact of Pb-free	Develop qualification methods, tests, and guidelines	Supply Chain, Training, S&H, Advocacy	Revise GEIA-HB-0005-2 and GEIA-STD-0005-3 System engineering guidelines
N/A	Qualification test results may become "out of date" as new Pb-free information becomes available	Re-evaluate qualification prior to execution to include up-to-date Pb-free knowledge	Supply Chain, Training, S&H, Advocacy	Revise GEIA-HB-0005-2 and GEIA-STD-0005-3 System engineering guidelines
N/A	Test methods may be impacted by the Pb-free alloy, but this information is typically not coordinated between the customer, systems engineering, hardware design, manufacturing, and sustainment.	The solder alloy, model parameters, and test methods must be agreed upon by the customer, systems engineers, hardware designers, manufacturers, and sustainment engineers.	Supply Chain, Advocacy	GEIA-HB-0005-2, GEIA-STD-0005-3, GEIA-STD-0005-1 System engineering guidelines, DO-254
N/A		Document that the design and construction meets the life cycle application, environmental, and operating profiles.	Supply Chain, S&H, Advocacy	GEIA-STD-0005-1 Require LFCP, DO-254
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task Team**	**Expected Action**
N/A	There needs to be a way to adjust qualification requirements, and potentially the contract, based on the most recent Pb-free reliability and failure mode information.	Develop provisions for adjusting the qualification test requirements, and possibly the contract, to consider the most recent Pb-free test, modeling, and failure modes data.	Supply Chain, S&H, Advocacy	GEIA-STD-0005-3, GEIA-HB-0005-4, GEIA-HB-0005-1 Program guidelines, DO-254
N/A	Impact of repair on reliability is not known.	Provide qualification requirements for spares procurement and repairs	S&H, Advocacy	GEIA-STD-0005-3, GEIA-HB-0005-4, GEIA-STD-0005-1, GEIA-HB-0005-1 Program guidelines
N/A	Safety requirements, design reviews and the system safety analysis process may need updates for Pb-free considerations	It is a technical imperative that safety systems add GEIA-STD-0005-1 to the appropriate standards that are used to assure A&D systems safety.	S&H, Advocacy	GEIA-STD-0005-3, GEIA-HB-0005-4, GEIA-STD-0005-1

				Require LFCP, DO-254
N/A	Tin whisker risk is not incorporated as part of electronics reliability modeling.	Tin whisker risk needs to be incorporated as part of electronics reliability modeling.	S&H, Advocacy	GEIA-STD-0005-1, GEIA-STD-0005-2, GEIA-HB-0005-4 Require LFCP, DO-254
N/A	MIL-HB-217 does not address Pb-free issues.	Require GEIA-STD-0005-1 and update MIL-HBK-217	S&H, Advocacy	GEIA-STD-0005-1, GEIA-STD-0005-2, GEIA-HB-0005-4 DO-254, MIL-HBK-217
N/A	GEIA-STD-0009 may provide an improved, updated approach to reliability prediction.	Evaluate GEIA-STD-0009	S&H	Evaluate GEIA-STD-0009
N/A	Solder dipping and BGA reballing increases risks that must be managed.	Certain finishes and certain Pb-free solder alloys should be banned. Processes must produce reliable products	S&H, Training	Evaluate GEIA-STD-0006
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task Team**	**Expected Action**
N/A	Until Pb-free qualification requirements are worked out, heritage SnPb based test methods will continue to be used at risk.		S&H, Supply Chain, Advocacy	Update necessary documents Program guidelines
N/A	Existing GEIA standards are based on incomplete technical knowledge		S&H, Advocacy	Update necessary documents Program guidelines
N/A	There is no efficient process to verify compliance to GEIA-STDs.		S&H, Advocacy	Develop certification requirements
N/A		Recommend review and/or update of MIL-STD-882 and other related systems safety standards for consistency.	S&H, Advocacy	Recommend action to DoD
N/A	J-STD-001 allows for multiple Pb-free alloys under certain conditions, which may not give sufficient guidance for sustainability.	Update J-STD-0001	S&H	Advise IPC
N/A	Differentiation in part marking/identification for Pb-free is required.	Develop part marking requirements	S&H	Update GEIA-STD-0005-1

N/A	There has been little involvement of VME manufacturers in industry Pb-free activities. This is identified as a serious gap.	Update A&D program requirements to require VME manufacturers to have LFCP compliant to GEIA-STD-0005-1. VME manufacturers should participate in PERM and other industry Pb-free activities.	S&H, Advocacy	Recommend action to DoD, FAA, NASA to require LFCP for VME cards Involve VITA
N/A	GEIA-STD-0005-3 has not been verified as accurate.	Solicit feedback from users of GEIA-STD-0005-3 to assess strengths and weaknesses of its approach.	S&H	Update GEIA-STD-0005-3
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task Team**	**Expected Action**
N/A	Inadequacies in current industry standards (J-STD-609, J-STD-020, JESD201A)	Additional categories must be added to the PPL database to capture all issues identified by the reliability, manufacturing, and sustainment teams	S&H, Advocacy	Evaluate J-STD-609, J-STD-020, JESD201A
N/A	GEIA-HB-0005-2 Section 9 needs to be updated (BGA reballing)		S&H, Advocacy	Update GEIA-STD-0005-2 Develop design guidelines
N/A	There are no standard rules for converting existing SnPb designs to Pb-free solder.		S&H, Advocacy	Document rules
N/A	Rigorous HAST and HALT testing methodologies are needed to determine the overall design limits of Pb-free solder joints, for specific applications.	Test adequate sample sizes	S&H	Update GEIA-STD-0005-3
N/A	Very little information about COTS assemblies or processes is available regarding Pb-free solder. Changes are made with little or no notification or visibility.		S&H, Advocacy	Update EIA-933, DO-254, and relevant IEC documents
N/A	COTS becomes a concern since the designer cannot control the components or materials used in the item.		S&H, Advocacy	· Revise GEIA-HB-0005-2 and GEIA-STD-0005-3 System engineering guidelines
N/A	J-STD-001 allows for multiple Pb-free alloys under certain conditions, which may not give sufficient guidance for sustainability considerations.		S&H, Advocacy	Advise IPC
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task**	**Expected Action**

			Team	
N/A	The current versions of IPC-A-610 and J-STD-001 may not be adequate to address all Pb-free issues.		S&H, Advocacy	Advise IPC
N/A	Assembly soldering in accordance with J-STD-001 allows Pb-free solder alloys to be used if they meet the "objective evidence of reliability" requirement, but could result in sustainment challenges through the introduction of Pb-free alloys or alloys incompatible with the repair solder alloy (e.g. SnPb, SAC, SnCuNi).		S&H, Advocacy	Evaluate J-STD-001
N/A	To date, equipment produced with any of the currently available Pb-free alloys has not demonstrated the ability to conform to all performance requirements.	Obtain concurrence on the final use environments rather than relying on traditional testing. This is a technical imperative. Consider controlled storage of released equipment and/or development of an aggressive preventive maintenance schedule.	S&H, Advocacy	Develop storage and use condition guidelines and requirements Require LFCP
N/A	In cases where the environmental conditions are not defined, assumptions are often applied than can either result in significant added cost due to over design or incorrect computation of solder joint life in actual service. Pb-free alloy material properties can change dramatically with extended aging that reduces subsequent thermal cycling reliability.	A methodology or protocol should be established in which the customer/stakeholder and supplier collaboratively work to carefully select appropriate and accurate operating, transportation, and storage requirements.	S&H, Advocacy	Develop guidelines Require LFCP
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task Team**	**Expected Action**
N/A	Supply chain, integrated logistics support, and repair processes are executed per program-specific (which may include military or federal standards) requirements. To date, none of these practices has undergone standard modifications or adaptations for Pb-free.	Formulate a supply chain strategy with focus on control of Pb-free components.	Supply Chain, S&H	Develop and modify standards System engineering requirements

N/A	The incorporation of Pb-free introduces the potential use of a wide variety of materials and processes that have significant effects on logistics requirements, particularly repair practices and spares materials procurement. Construction and layout of assemblies impact maintainability and reparability. The interface between Logistics disciplines and the Design authority should address particular Pb-free issues.		S&H, Advocacy	Develop logistics requirements System engineering requirements
N/A		Consider adding a section on quality assurance testing in a revision to GEIA-STD-0005-3.	S&H	Revise GEIA-STD-0005-3
N/A	Production Readiness Reviews, in general, do not include specific flags to address risk and/or challenges of Pb-free implementation. As a result, manufacturing technical data packages could be deficient.	Develop the content for Production Readiness Reviews	S&H Advocacy	Update GEIA-HB-0005-1 Production readiness review guidelines
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task Team**	**Expected Action**
N/A	Documentation must be assessed for Pb-free impacts to assure sufficient information to assure successful spares procurement and repair action.	Identify part finishes and solder alloys used on assemblies per J-STD-609, and specify repair solder alloys and processes that assure sufficient reliability.	S&H, Advocacy	Update GEIA-HB-0005-1 DO-254
N/A	Laminate properties have been known to vary from published data. Variation may be between manufacturing sites (especially offshore), or even from lot to lot. Users may consider auditing to IPC-1730 and IPC-1731.		Supply Chain, S&H. Advocacy	Revise GEIA-HBK-0005-1 and -2 Update IPC standards
N/A	Material supplier claims that a PCB material is Pb-free compatible are insufficient and the material must be evaluated in the application to determine suitability [Smetana 2009].		Supply Chain	Revise GEIA-HBK-0005-2 Update IPC standards

N/A	Manufacturers of COTS chasses, enclosures, and parts could change surface finish materials without communication to the end customer.		Supply chain, Advocacy	Update EIA-933 and other GEIA and IEC documents
N/A	Heritage finishes called out on custom mechanical parts are becoming more difficult to obtain (increased cost and lead-time).		Supply chain	Update GEIA-HB-0005-1
N/A	Non-CCA electrical assembly manufacturers could change surface finish materials and solder without communication to the end customer.		Supply Chain	Update GEIA-0005-1 and EIA-933
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task Team**	**Expected Action**
N/A	No change in part numbers with change in surface finish		Supply chain, Advocacy	Require LFCP
N/A	Customer requirements and systems engineering management plans often do not include sufficient detail for Pb-free risk management, such as definition of GEIA-STD-0005-2 level requirements, COTs requirements, and sustainment requirements.	The customer requirements and the systems engineering management plan (SEMP) need to capture the specific Pb-free risk mitigation requirements a. Tin whisker risk: Regardless as to whether the assembly uses SnPb or Pb-free solder, the Pb-free risk from components should be acknowledged and the appropriate GEIA-STD-0005-2 tin whisker mitigation level should be defined. b. Sustainment requirements: The sustainment and repair requirements such as compatible repair solder alloys should be defined where appropriate.	Training, advocacy	Provide policy recommendations to customers DO-254 System engineering requirements
N/A	Restricted/prohibited materials lists have grown due to regulations. Customers and programs specify materials “boiler plate” language from other equipment. For example, electronic assemblies use Ni as a barrier layer, and there no replacement. Lack of knowledge of to the risk of material restrictions to A&D systems	Systems engineering management plan requirements should mandate that solder alloy material be part of the design documentation, part of COTS requirements, and the sustainment package.	S&H	System engineering requirements Program guidelines
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task**	**Expected Action**

			Team	
N/A	Currently, Pb-free failure modes are not part of the table of failure modes which may challenge fault tolerance assumptions and assumptions of one failure at a time		S&H	Revise GEIA-HB-0005-4 MIL-HBK-217 DO-254
N/A	Designers in the military / aerospace community will typically use heuristic rules that may be dramatically incorrect for Pb-free.	Review parts on products which may already have extensive experience with some of these high risk finishes. An example of heritage tin use on a mechanical part is the tin finish specified on military wire lug terminals under compressive screw loading (e.g. MS20659 or MS25036).	S&H, Advocacy	Revise documents as required DO-254
N/A	The electrical design community has not been made aware of specific design constraints/considerations needed for Pb-free solder use in A&D applications.	Establish a research test and analysis plan to identify and characterize specific design constraints/considerations needed for Pb-free solder use in A&D applications such as: • Tin whiskers impact on high frequency RF circuits. • Current density rules established to avoid electromigration in Pb-free solder assembly. • Designing for metal vapor arcing initiated from whisker shorts.	S&H	Develop design guidelines requirements (or reference existing ones). May be included in GEIA-STD-0005-1 and -2.
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task Team**	**Expected Action**
N/A	Lack of Pb-free awareness regarding manufacturing hand-off (Transition to Production)	Implement an awareness/communications campaign to emphasize Pb-free risk assessment and mitigation plans in product development systems at the company level. 2. Implement an awareness/communications campaign to emphasize Pb-free part identification should be supplied by engineering in the Manufacturing Technical Data Packages, for applications where Pb-free finish tracking is necessary.	S&H, Communications, Training	DO-254

N/A		3. Document Pb-free part sensitivities to temperature and moisture, and confirm compatibility with assembly/repair processes.	S&H	Update GEIA-HB-0005-1 and -3
N/A	The link between tin finish and Pb-free solder use on a particular function circuit element occurs at various stages of the design but is often not captured sufficiently in a searchable database.		S&H	Define database
N/A	The output of failure mode and effects analysis (FMEA) and failure mode, effects, and criticality analysis (FMECA) may change if the functional block or component is lead-free.		Training	Update GEIA-HB-0005-4 DO-254
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task Team**	**Expected Action**
N/A	Design practices and review checklists not mature with regard to Pb-free, while complete Pb-free designs are being done today.	Update design review checklist items to include Pb-free considerations pertaining to Fault tree, FMEA and FMECA Analysis.	S&H, Training	Update GEIA-HB-0005-2 and -4 DO-254
N/A	COTS defined designs before 2006 may have changed from SnPb to Pb-free solder without notice and may impact fault analysis.	Re-evaluate Pb-free COTS risks in the fault tree with particular attention on Pb-free COTS power supplies.	S&H, Training	State COTS assembly requirements Update EIA-933 and IEC documents
N/A	Design reviews are not necessarily stopgaps for all issues. Preparation is required to assure that all key concerns are addressed concurrently with the completed design rules.	Exploit a set of Pb-free design rules as part of the disciplined product development process, and document compliance.	S&H	Develop design guidelines requirements (or reference existing ones). May be included in GEIA-STD-0005-1 and -2.
N/A	`Checklists and heritage knowledge by the review board members do not include Pb-free design considerations.	Document part finishes, solder materials, fluxes, verification methods and data used to confirm compatibility with assembly processes and life cycle requirements.	S&H, Advocacy	Develop design guidelines requirements (or reference existing ones). May be included in GEIA-STD-0005-1 and -2.

N/A	Managing restricted and prohibited materials lists is a challenge because electronic assemblies include thousands of parts from hundreds of suppliers. Evaluating the extensive lists of restricted materials should be accounted for during project planning and contracting.	It may be advantageous to accumulate the materials data for electronic parts in a database.	Research Coordination, S&H	Develop database requirements
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task Team**	**Expected Action**
N/A	There has been little involvement of VME manufacturers in industry Pb-free activities. This is identified as a serious gap.	Update A&D program requirements to require VME assembly manufacturers to have LFCP compliant to GEIA-STD-0005-1. VME manufacturers should participate in PERM and other industry Pb-free activities.	S&H, Advocacy	Recommend action to DoD, FAA, NASA Involve VITA
N/A	When multiple solders are used in assembly, certain combinations of solders could be a risk due to a narrow process window and max component temps.	Finalize Cross-Compatibility Matrix	Advocacy	Include in GEIA-HB-0005-1 and -2
N/A	Rules of thumb for manufacturability and rework/repair must be re-examined for Pb-free solder to ensure that manufacturing process variation is minimized.		S&H	Include in GEIA-HB-0005-1 and -2
N/A	Reparability verification requires assessment of reliability after repair, with consideration for degradation mechanisms that affect Pb-free assemblies in the field.	Provide inputs to repair procedures and manuals to assure reliability of repaired equipment.	S&H	Include in GEIA-HB-0005-1 and -2. Revise GEIA-HB-0005-4
N/A	Using SnPb solder stress design levels for Pb-free designs will not necessarily result in satisfactory life in high stress environments.	Development of new heuristic rules for stress levels in the preliminary design phase to ensure subsequent detailed stresses are computed, to minimize future design changes.	S&H	Include in GEIA-HB-0005-1 and -2. Revise GEIA-HB-0005-4 and GEIA-STD-0005-3
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task Team**	**Expected Action**
N/A	These improved shock resistant alloys are not part of J-STD-006.		S&H	Revise J-STD-006

N/A	Lack of training and certification protocols for Pb-free solder personnel	(1) Develop/implement a Pb-free solder training and certification plan	Training	Update training
N/A	Lack of configuration control to address material compatibility issues	Develop and identify marking standards; solder mask colors; RFID use; identification of critical configuration characteristics	S&H, Advocacy	Revise GEIA-STD-0005-1 Require LFCP
N/A	Lack of consistent definition for form, fit, function considerations for Pb-free applications/experiences	Address pure tin and Pb-free solder introduction; verification/qualification methods definition; define item requirements that meet system requirements to evaluate material set changes	S&H, Advocacy	Revise GEIA-STD-0005-1 Require LFCP
N/A	Lack of receiving inspection requirements to address Pb-free issues in sustainment (understanding finishes/solders/materials)	Develop standards and req'ts	S&H	Revise and/or update relevant documents
N/A	Field Service data feedback requirements, process and content definition are not adequate	Improve and expand existing standards and req'ts	Research Coordination	Develop database requirements
N/A	Lack of diagnostic and prognostic processes to address Pb-free related failure modes, such as tin whisker shorts and solder joint opens, including intermittent failures.	Identify methods to identify failure modes; determine Pb-free impact on FMECA output (Design topic covers?)	Stds & Hbks	Revise GEIA-HB-0005-4
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task Team**	**Expected Action**
N/A	Lack of maximum reflow cycles control and requirements (part/component limitations on repair/rework cycles)	temperature degradation, PWB delamination, CAF, Cu dissolution, pad cratering, reflow cycles monitor technology	S&H	Capture LFEMP project output in appropriate PERM documents
N/A	Shipping and handling procedures do not address Pb-free factors	Develop procedures	S&H	Capture LFEMP project output in appropriate PERM documents
N/A	Lack of consistent sustainment methodology for COTS assemblies and components	Insight into materials and construction to support product assurance; throw-away vs. repair analysis (LORA); periodic reassessment approach	S&H	Capture LFEMP project output in appropriate PERM documents (GEIA-HB-0005-3?)
N/A	Lack of standard requirements that address Pb-free issues in spares contracts	Develop standards and req'ts	S&H	Revise GEIA-HB-0005-3

N/A	Lack of Pb-free Control Plans (in accordance with GEIA-STD-0005-1) across the A&D industry, and throughout supply chain, and logistics organizations.	Hammer	Advocacy	Require LFCP
N/A	Lack of consistent customer requirements for logistics to manage the impacts of Pb-free parts, materials, and processes.	Develop standards and req'ts	Advocacy	Require LFCP
WBS	**Issue/Task**	**Deliverable to PERM**	**PERM Task Team**	**Expected Action**
N/A	Lack of standards and requirements for testing repaired items; lack of qualification on repaired items	Develop standards and req'ts	S&H, Advocacy	Revise GEIA-HB-0005-3
N/A	Repair facility work instructions do not adequately address Pb-free materials	Develop standard repair procedures	S&H, Advocacy	Revise GEIA-HB-0005-3
N/A	Lack of operator training for Pb-free repair	Develop training requirements	Training, advocacy	Update and require training

LEAD FREE ELECTRONICS MANHATTAN PROJECT PHASE 2 REPORT

APPENDIX C

DETAILED TECHNICAL APPROACH

A Tin Whiskers

Description: The greatest reliability risks associated with Pb-free electronics are the formation of tin whiskers, vibration and mechanical shock solder joint failures, and the lack of validated models required to design tests and predict field lifetimes for these failure modes. A lack of these validated test procedures are exacerbated by the harsh environments of Aerospace & Defense (A&D) applications and by the impact of failure on critical A&D systems.

The formation of Sn whiskers threatens the reliability of A&D systems that use Pb-free surface finishes and solders. Current tin whisker testing methods cannot predict whether a finish or solder will grow tin whiskers nor can they identify what additional whisker mitigation strategies are needed for a particular part or assembly. Existing whisker mitigation strategies are only partially effective, leaving a significant gap with respect to protecting the most vulnerable circuits. A comprehensive approach to design rules for tin whisker mitigation is needed that includes mitigation strategies from circuit analysis and design and component placement to characteristics of the tin plating, the component mitigations used, and board-level mitigation, such as coatings applied directly to assemblies. Reliable whisker test methods for parts and assemblies, mitigation strategies and a lifetime prediction model need to be developed, based upon a fundamental knowledge of the relationships between whisker formation and the parameters that are under the control of the A&D industry. A direct linkage between field failure root cause analysis, lifetime prediction models, test methods, and design rules will be essential to assess the validity of such tests and models. The expected result of the R&D program area described here is a significant reduction in risk of tin whisker-induced failure in A&D applications.

Gaps Addressed:

- D22: The lack of appropriate and validated failure models prevents accurate failure prediction, test development, and creation of heuristic rules for tin whiskers.
- D30: No single source exists for the A&D community to select tin whisker risk mitigation activities based on cost, availability, and degree of mitigation.
- D31: Existing heuristic rules for Metal Vapor Arcing used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free electronic products.
- D37: The current risk assessments for critical Pb-free failure mechanisms are insufficient in regards to timeliness and accuracy. There currently is no method to rapidly and accurately identify the risk of tin whiskering at the component level.
- D41: No current test method exists for determining whether a mechanical and electrical part is whisker prone over its lifetime. An industry standard test method is needed to rapidly identify tin whisker risk for mechanical and electrical parts.
- D42: No existing mitigation practice is universally implementable and definitively prevents the occurrence of tin whiskers in high frequency RF circuits.
- D43: There is insufficient information on how and when tin whiskers can impact circuit performance of high frequency RF circuits
- D45: Existing electrical design heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free products. Electrical design practice does not provide guidance regarding physical separation between critical devices (e.g., components from different critical functional elements) or redundancy to eliminate whisker risk.
- D46: Existing tests (for design verification or product qualification) used by the A&D community may not be valid for Pb-free products.
- D48: No existing mitigation practice is universally implementable and definitively prevents the occurrence of tin whiskers.
- D49: Existing heuristic rules used conformal coating for tin whisker mitigation by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free products.
- M03: The conformal coating processes lack objective evidence for tin whisker mitigation capability.

- S12: There is a lack of standards/requirements to address receiving inspection in sustainment situations for tin whisker identification
- S15: The field service data feedback requirements, process and content definition are not adequate to capture the most prevalent issues around Pb-free assemblies in the field.
- R01: There is a lack of understanding of fundamental whisker growth mechanisms.

Expected Results: A set of greatly enhanced tools for management of tin-whisker risks will be developed. This will decrease costs through more efficient targeted application of costly mitigations, while providing greater assurance of long-term system reliability.

Deliverables:

- Quantitative definitions of how tin whiskers cause electrical faults, and how to properly identify these faults.
- New cost effective risk mitigations.
- Implementable design rules that will assure quantifiable performance through the employment of cost-effective risk mitigations.
- Validated test methods to accelerate tin whisker growth in a quantifiable manner.
- Validated life prediction tools that permit quantified prediction of tin whisker induced unreliability.

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $18.5M

AA Tin Whisker Failure Modes

Description: Quantify the conditions under which the presence of tin whiskers can result in the functional failure of electrical circuits, and define procedures to provide for enhanced detectability of these failure modes.

Gaps Addressed:

- Tin whisker induced shorts can result in metal vapor arcing events. SnPb design rules used by electrical and mechanical designers may be insufficient to ensure reliability of Pb-free product. (See Exhibit A, Gap D31)
- Defining the voltage and current conditions for whisker-induced electrical shorting (See Exhibit A, Gap DAAB - D43c)
- No existing mitigation practice is universally implementable and definitively prevents the occurrence of tin whiskers. Insufficient information on how and when tin whiskers can influence circuit performance of high frequency RF circuits. (See Exhibit A, Gap D42)
- Field Service data feedback requirements, process and content definition are not adequate. (See Exhibit A, Gap S15)

Expected Results: This project will define specific conditions under which the presence of tin whiskers will create a quantifiable probability of the occurrence of different types of electrical failure modes. These conditions will be defined in terms of algorithms, when this is deemed most appropriate. This task will also provide standardized procedures for detection of intermittent anomalies such as those caused by tin whiskers in assemblies.

Deliverables:

- Final reports from each of the four subsidiary tasks describing the project, results, conclusions, and recommendations. – Month 36
- Algorithms to facilitate communication of the results across the A&D community. – Month 36

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $ 1,840K

AAA Metal Vapor Arcing

Description: Characterize the conditions under which tin whisker induced shorts can result in metal vapor arcing events. As a minimum, investigate conditions with respect to applied current and voltages (DC and AC), atmosphere, temperature and humidity, and conductor spacing.

AAAA: A literature survey shall be performed so that the extensive bodies of previous work on metal vapor arcing in general and tin whisker physical properties can be fully leveraged.

AAAB: Experimentation shall be formulated and set up. Testing shall be selected to validate previous results with insufficient replication. Additional experimentation shall be selected as necessary to expand the envelope of understanding to cover combinations of conditions of importance to the A&D community.

AAAC: Execute the experimental plan.

AAAD: Developing detailed definitions for arcing conditions.
The probability of the occurrence of metal vapor arcing because of the presence of the tin whisker shall be defined as a function of critical parameters to include as a minimum: conductor spacing, voltage and current conditions, and atmospheric conditions. If the function is best described as an algorithm, formulation of an algorithm is acceptable.

AAAE: Work project management including planning, reporting, and collaboration.

Gaps Addressed: Tin whisker induced shorts can result in metal vapor arcing events. SnPb design rules used by electrical and mechanical designers may be insufficient to ensure reliability of Pb-free product. (See Exhibit A, Gap D31)

Expected Results: The definition of the probability of the occurrence of a tin whisker induced metal vapor arcing event as a function of a clearly defined set of conditions of interest to the A & D community.

Deliverables:

- Final report describing the project, results, conclusions, and recommendations. – Month 12
- An algorithm to facilitate communication of the results across the A&D community. – Month 12

Interdependencies:

Needs: None

Collaborate: ACC, Tin Whisker Life Prediction Final = Provide report and algorithm.

Feeds:

- ABA, Design Rules for Circuit Layout = Provide report and algorithm.
- DACB, Automated Tool for Circuit Layout for Tin Whisker Risk Mitigation = Provide report and algorithm.

Schedule:

- Start Month: 1
- Expected Duration: 12 Months

ROM Cost: $221K

AAB Define the Voltage and Current Conditions for Whisker-induced Electrical Shorting

Description: Define the conditions under which whiskers can induce electrical shorts by bridging two conductors and define circuit model elements that cover all possible voltage and current conditions resulting in a tin whisker that becomes an active circuit device.

AABA: During the planning phase, a literature survey shall be performed so that the extensive body of previous work on tin whisker short circuit properties can be fully leveraged.

AABB: Experimentation shall be performed to validate previous results with insufficient replication. Additional experimentation shall be performed as necessary to expand the envelope of understanding to cover combinations of conditions of importance to the A&D community.

AABC: A detailed report covering all phases of the project including all conclusions and recommendations shall be provided. If the results can best be communicated in the form of an algorithm or simple software tool, this is acceptable and shall be provided together with the report.

AABD: Work project management including planning, reporting, coordination and collaboration.

Gaps Addressed: Define the voltage and current conditions for whisker-induced electrical shorting. (See Exhibit A, Gap D43c, DAAB)

Expected Results: This task will result in the definition of the probability of the occurrence of a tin whisker induced short circuit event as a function of a clearly defined set of conditions of interest to the A & D community. NOTE: This presumes the existence of a tin whisker between two conductors but adds the set of conditions that result in an actual electrical short.

Deliverables:

- Final report describing the project, results conclusions, and recommendations. – Month 15
- Report providing project results for use by the projects covered in ACB, ABA, and ACC. – Month 15

Interdependencies:

Needs: None

Collaborate:

- ACC, Tin Whisker Life Prediction = Conditions for whisker-induced electrical shorting.
- BBA, Assembly Test Protocol = Conditions for whisker-induced electrical shorting.
- BBB, Field Life Data for Validating Qualification and Acceptance Predictions = Conditions for whisker-induced electrical shorting.

Feeds:

- ABA, Automate Spacing Design Rules for Circuit Layout = Conditions for whisker-induced electrical shorting.
- DACB, Circuit analysis = Conditions for whisker-induced electrical shorting.

Schedule:

- Start Month: 1

- Expected Duration: 15 Months

ROM Cost: $539K

AAC RF Effects of Tin Whiskers

Description: Determine the effects of tin whisker growth on the RF performance of devices, packages, assemblies, and systems. Communicate results and form that can be used in subsequent circuit and system risk analysis.

AACA: A literature survey shall be performed so that the previous relevant work on RF effects of tin whiskers can be fully leveraged.

AACB: Experimentation shall be formulated and set up. Testing shall be selected to validate previous results with insufficient replication. Additional experimentation shall be selected as necessary to expand the envelope of understanding to cover combinations of conditions of importance to the A&D community.

AACC: Execute the experimental plan.

AACD: Developing detailed descriptions of the RF effects of tin whiskers. Develop descriptions of the RF effects of tin whiskers on components, assemblies, and systems. The effects should be quantified in terms of frequency, bandwidth, power levels, and geometries. If the results can best be communicated in the form of an algorithm, this is acceptable and shall be provided together with the report.

AACE: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: No existing mitigation practice is universally implementable and definitively prevents the occurrence of tin whiskers. Insufficient information exists on how and when tin whiskers can affect circuit performance of high frequency RF circuits. (See Exhibit A, Gap D42)

Expected Results: A quantitative description of the effects that the growth of tin whiskers will have on the RF performance of components, assemblies, and systems.

Deliverables: Final report describing the project, results, conclusions, and recommendations. – Month 12

Interdependencies:
Needs: None

Collaboration: ACC, Tin Whisker Life Prediction, = Whisker impact circuit performance of high frequency RF circuits.

Feeds:

- ABA, Automate Spacing Design Rules for Circuit Layout = Whisker impact circuit performance of high frequency RF circuits.
- ACB, Automated Tool for Circuit Layout for Tin Whisker Risk Mitigation = Whisker impact circuit performance of high frequency RF circuits.

Schedule:

- Start Month: 1
- Expected Duration: 12 Months

ROM Cost: $249K

AAD Detection of Intermittent Tin Whisker Field Failures

Description: The ability of current field return systems to detect intermittent faults resulting from tin whiskers will be analyzed and modifications to current processes, protocols, and equipment will be recommended to improve detection of intermittent faults due to tin whiskers.

AADA: Review existing field test data, test collection systems and procedures, and test methods for ability to identify intermittent faults anticipated from whiskers and interconnection failures (no fault found).
Benchmark against high reliability non-A&D electronics industry to determine their processes for identifying the root causes of intermittent failure.

AADB: Review JEDEC inspection methods for tin whiskers and other existing methods used for identifying failure location, root cause, and determine the best practices for visual inspection of assemblies.

AADC: Recommend and demonstrate enhancements that will improve the identification and reporting of intermittent faults. With respect to tin whiskers, the repaired hardware database will now contain information regarding the VI operating conditions and identify board locations/lead spacing at greatest risk for whisker-induced shorting that might be used by field repair personnel

AADD: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: Field Service data feedback requirements, process and content definition are not adequate. (See Exhibit A, Gap S15)

Expected Results: Inspection methods for intermittent field failures should be able to identify root causes and therefore provide valuable input to improve design rules and lifetime prediction models since the current field return systems are able to detect faults for only half of returned systems. In order to improve reliability and sustainment, intermittent faults caused by tin whiskers will be associated with their specific root cause.

Deliverables:

- Report on the review of existing field test data, test collection systems and procedures, and test methods for their ability to identify intermittent faults. This report defines the process used in all phases of the analysis, including literature search, data types, criteria for data evaluation, and recommendations of modifications to existing test methods, and test collection systems and procedures that should better meet the needs of the A&D community – Month 24
- Report on the review of JEDEC inspection methods and other methods for tin whiskers for their applicability at the field return level. This report defines the process used in all phases of the analysis, including literature search, data types, criteria for data evaluation, and recommendations of modifications to existing test methods, and test collection systems and procedures that should better meet the needs of the A&D community. – Month 24
- Demonstration of the efficacy of recommended modifications to existing test methods to model intermittent failures on product test coupons. – Month 33

Interdependencies:

Needs: None

Collaborate:

- AAB, Voltage and Current Design Rules = Tin whisker field failures.
- ABA, Automate Spacing Design Rules for Circuit Layout = Tin whisker field failures.
- ACB, Circuit Analysis = Tin whisker field failures.

- ACA, Standards to Address Tin Whisker Inspection of Field Return hardware = Tin whisker field failures.
- BAB, Rework and Repair Critical Process Parameters = Tin whisker field failures.

Feeds: None

Schedule:

- Start Month: 18
- Expected Duration 15 Months

ROM Cost: $832K

AB Tin Whisker Risk Mitigation

Description: This project will significantly enhance the ability of the A&D community to mitigate tin whisker risk effectively and efficiently. This will be accomplished in three main areas: development of new mitigation techniques, development of new test methods, and by the definition of integrated design rules.

Gaps Addressed:

- No existing mitigation practice is universally implementable and definitively prevents the occurrence of tin whiskers. No single source for the A&D community to select tin whisker risk mitigation activities based on cost, availability, and degree of mitigation. (See Exhibit A, Gap D30)
- No current test method exists for determining whether a mechanical and electrical part is whisker prone over its lifetime. Need industry standard test method to identify tin whisker risk for mechanical and electrical parts quickly. (See Exhibit A, Gap D41)
- SnPb design rules used by electrical and mechanical designers may be insufficient to ensure reliability of Pb-free product. Electrical design practice does not provide guidance regarding physical separation between critical devices (e.g., components from different critical functional elements) or redundancy to eliminate whisker risk. (See Exhibit A, Gap D45)
- Existing tests (design verification, product qualification) and screens used by the A&D community may not be valid for Pb-free product. (See Exhibit A, Gap D46)
- No existing mitigation practice is universally implementable and definitively prevents the occurrence of tin whiskers. No existing mitigation practice is universally implementable and definitively prevents the occurrence of tin whiskers. (See Exhibit A, Gap D48)
- Conformal coating processes lack objective evidence for tin whisker mitigation capability. (See Exhibit A, Gap M3)

Expected Results: New cost-effective and implementable tin whisker risk mitigation techniques will be provided. Newly developed and validated test methods usable on components and on systems will be defined. An implementable set of design rules for tin whisker risk mitigation that will permit tin whisker risk to be controlled to quantifiable levels in a cost-effective manner will be provided. Specific modifications to existing standard design tools will be defined.

Deliverables:

- New, technically feasible and cost effective tin whisker risk mitigation techniques will be developed and documented. – Month 36
- New test validated methods that will be capable of accelerating tin whisker growth on components and methods capable of accelerating tin whisker growth at the system level will be developed and documented. – Month 36
- A set of design rules that can be readily implemented across the A&D community to manage the risk of tin whisker induced failures in a cost-effective manner. This can take the form of a written report,

algorithms, software tools, and other mathematical or automated products that are most appropriate to facilitate implementation of the design rules across the A&D community. – Month 36

- A report that clearly defines the process and data to be added to one or more existing design tools relating design risk analysis to hardware design practices. – Month 36

Expected Duration: 36 Months

ROM Cost: $9,152K

ABA Automate Spacing

Description: Develop a critical design process for implementing spacing at the circuit/CCA level to mitigate whisker risk. Circuit design and reliability analysis needs to determine the acceptable risk, generally related to hazard level or mission criticality requirements, for whisker shorts from component lead-to-lead spacing and inter component CCA spacing. New rules for part selection based on lead-to-lead spacing and the CCA layout rules for separation will be defined. This work should be incorporated into the board design section of existing tin whisker standards.

ABAA: Develop, document and then create a lead-to-lead package spacing component part list as an input to design rules. It should include dependencies for the combined possible use of multiple mitigations. This information will assure cost effective mitigation for component design.

ABAB: Add spacing resolution to the circuit card design layout process. Develop and document a script element or software add-on to an existing CCA layout used by CAD design tools. This added capability will enable spacing mitigation at the earliest possible design level.

ABAC: A detailed report covering all phases of the project including all conclusions and recommendations shall be provided. If the results can best be communicated in the form of an algorithm, script or simple software tool add on, this is acceptable and shall be provided together with the report.

ABAD: Work project management including planning, reporting, coordination and collaboration.

Gaps Addressed: SnPb design rules used by electrical and mechanical designers may be insufficient to ensure reliability of Pb-free product. Electrical design practice does not provide guidance regarding physical separation between critical devices (e.g., components from different critical functional elements) or redundancy to eliminate whisker risk. (See Exhibit A, Gap D45)

Expected Results: This task should result in design rules and tools that use spacing as a Sn whisker mitigation strategy in the formalized design process.

Deliverables:

- Final report describing the project, results conclusions, and recommendations. – Month 18
- Report providing project results for use by the project covered in ABB. – Month 18

Interdependencies:

Needs: None

Collaborate:

- AAA, Tin Whisker Metal Vapor Arching = Inter-part spacing to mitigate whisker risk.
- AAB, Voltage and Current Design Rules = Inter-part spacing to mitigate whisker risk.
- ABB, Develop Design Rules = Inter-part spacing to mitigate whisker risk.
- ACB, Circuit Analysis = Inter-part spacing to mitigate whisker risk.

Feeds: None

Schedule:

- Start Month: 1
- Expected Duration: 18 Months

ROM Cost: $681K

ABB Design Rules for Tin Whisker Risk Mitigation

SOW Description: Develop a set of design rules that can be implemented across the A&D industry that will provide adequate control of the risk of tin whisker induced failures in a cost-effective manner. Since restricting the use of tin always involves some additional cost, the goal is to identify the widest range of conditions under which the use of tin can be reliably proven consistent with system-level performance requirements. These design rules must be based upon the full set of quantitative and qualitative information currently available, or which will become available during the course of the project as a result of other related projects that will be providing formal input or happen to be performed independently elsewhere in the world.

Design rules must include considerations of all levels of product integration (plating level, component level, assembly level, module level, through system-level). These design rules should take into account all relevant environments (manufacturing environment, storage environments, transportation environments, and field service environments) as applicable. These design rules should provide for assured compliance with specified maximum quantified probability of failures as a function of time and environmental exposures.

Design rules shall be formulated both in the written form and embodied in an algorithm or other suitable software tool.

ABBA: Survey and evaluation of existing design rules. Search literature and use other contacts to identify existing design rules in use. Evaluate for validity, utility, and lessons learned to guide development of new rules. Issue an interim report on the findings of the search.

ABBB: Defining plating level issues and effects. Define the effects on whisker risk specific to the tin finish properties including such data as can reasonably be assumed available to designers. Such properties include as a minimum: use of under plating, composition of substrate, deposition process for tin, the use of any post-plating heat treatments, and the presence of any intentional alloy additions to the plating.

ABBC: Defining component level issues and effects. Define the effects of component geometry and manufacture on whisker risk. Such effects include as a minimum: the application of coatings at the component level, the effect of lead forming and trimming, intra-lead spacing, number of leads, and the positioning of leads.

ABBD: Defining assembly level issues and effects. Define the effects of assembly level processes and geometry on whisker risk. Such effects include as a minimum: the effect of contact pressure and sliding during connector mating, effects of lead deformation during socket insertion, spacing to adjacent conductors not on the same component, and the application of coatings at the assembly level.

ABBE: Defining system-level issues and effects. Define the effects of system-level issues on the risk of tin whisker induced failures. Such effects include as a minimum: the sensitivity of various circuit locations to propagate local tin whisker induced anomalies to higher-level anomalies, the effect of system-level environmental conditions, and the effect of system-level life and lifecycle considerations including rework.

ABBF: Integrate effects from all levels. Integrate all of the effects identified in tasks ABBA - ABBE above considerations into a single interdependent set of effects.

ABBG. Formulating design rules. Formulate an integrated set of design rules based upon the integrated effects defined task ABBF above together with cost.

ABBH: Developing algorithms. Develop algorithms or software tools that embody the design rules formulated in task ABBG above. These algorithms and tools should be in a format that can be readily assimilated by the A&D community.

ABBI: Project Management and reporting. Work project management including planning, reporting, and collaboration.

Gaps Addressed: No existing mitigation practice is universally implementable and definitively prevents the occurrence of tin whiskers. No single source for the A&D community to select tin whisker risk mitigation activities based on cost, availability, and degree of mitigation. (See Exhibit A, Gap D30)

Expected Results: A set of design rules that can be readily implemented across the A&D community so that the risk of tin whisker induced failures can be managed in a cost-effective manner.

Deliverables:

- A set of design rules that can be readily implemented across the A&D community. – Month 18
- Algorithms, or software tools, to facilitate implementation of the design rules across the A&D community. – Month 18
- Interim report providing preliminary set of design rules for rapid implementation. – Month 9
- Final report describing the project, results, conclusions, and recommendations. – Month 18

Interdependencies:

Needs: None

Collaborate:

- ABA, Automate Spacing = final software package with documentation
- ABC, Conformal Coating Whisker Mitigation = final report
- ABF, New Mitigations = final report
- ACB, Circuit Analysis Tin Whisker Risk Assessment = final report
- ACC, Tin Whisker Life Prediction = final report and any tools and algorithms developed

Feeds: None

Schedule:

- Start Month: 19
- Expected Duration: 18 Months

ROM Cost: $1,281K

ABC Conformal Coating Whisker Mitigation

Description: Enable reduction of tin whisker failures by application of specified types and thicknesses of conformal coatings to circuit card assemblies (CCA).

ABCA: Research and tabulate performance parameters of existing and proposed tin whisker mitigating conformal coatings. This will include masking, initial coating cost, reworkability, and its expected tin whisker mitigation potential. Document all advantages and disadvantages of each conformal coating process and material, including costs for masking material and labor in initial assembly process, and rework labor.

ABCB: Determine, collect and document environmental requirements of whisker mitigating conformal coatings. This will include mechanical, chemical, hermeticity, outgassing, thickness, voltage breakdown, SIR (Surface Insulation Resistance), and all other requirements of coatings acceptable for use on key DoD weapons systems.

ABCC: Build demonstration CCAs (IPC B52 Conformal Coating Evaluation Coupon) with coatings that can potentially be used as dual-purpose conformal coatings and tin whisker mitigations. Evaluate each conformal coating per IPC-830-B specification as well as tin whisker mitigation potential per Seattle coupon and Immersion Tin coupon analysis.

ABCD: Tabulate conformal coating results as input to D30 gap (Design Rules for Tin Whisker Mitigation).

ABCE: Work project management including planning, reporting, coordination, and collaboration

Gaps Addressed: Conformal coating processes lack objective evidence for tin whisker mitigation capability. (See Exhibit A, Gap M3)

Expected Results: Verify and tabulate tin whisker mitigation effectiveness of selected conformal coatings to enable valid design rule development for gap D30.

Deliverables:

- Preliminary report of test results. – Month 6
- Final Report tabulating tin whisker mitigation effectiveness of selected conformal coatings input to design rules. – Month 24

Interdependencies:

Needs: None

Collaborate:

- ABB, Design Rules for Tin Whisker Risk Mitigation (i.e. design rules for CC) = mitigation
- ABD, Test method for tin whisker risk at the part level = part level test method
- ABE, Test methods for tin whisker risk at the product level = product level test method

Feeds: None

Schedule:

- Start Month: 1
- Expected Duration: 24 Months

ROM Cost: $1,079K

ABD Test Method for Tin Whisker Risk at the Part Level for A&D Electronics

Description: Develop a test method to rapidly identify tin whisker risk at the part level for all classes of parts (mechanical and electrical, including printed circuit board). This test method will determine the propensity of whisker growth for mechanical and electrical parts in less than six months.

ABDA: Survey and document existing test standards for current accelerated test conditions.

ABDB: Obtain representative mechanical & electrical parts with representative Sn and Sn alloy finishes.

ABDC: Evaluate current methods and develop new test methods to determine the propensity of whisker growth in less than six months. The test environments can include but are not limited to temperature, humidity, temperature cycling, and stress.

ABDD: Determine quantitatively which test method indentifies whisker propensity in the shortest time.

ABDE: Determine an acceleration factor that relates test results to whisker growth in field environments.

ABDF: Standard test method or amendment to a current test method standard to rapidly identify tin whisker risk for mechanical and electrical parts.

ABDG: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: No current test method exists for determining whether a mechanical and electrical part is whisker prone over its lifetime. Need industry standard test method to identify tin whisker risk for mechanical and electrical parts rapidly. (See Exhibit A, Gap D41)

Expected Results: Test methods that reduce the time required to evaluate electroplated tin surface finishes for whisker growth.

Deliverables: Standard test method or amendment to a current test method standard to rapidly identify tin whisker risk of mechanical and electrical parts. – Month 36

Interdependencies:
Needs: None

Collaborate:

- ABC, Design rules for conformal coating = indentify whisker propensity
- ABF, New mitigations = indentify whisker propensity
- ACD, Fundamental research = indentify whisker propensity
- ECA, Surface finish evaluation = indentify whisker propensity
- ECB, Surface finish test methods = indentify whisker propensity
- ECC, New finishes = indentify whisker propensity

Feeds: None

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $ 4,131K

ABE Test Method for Tin Whisker Risk at the Product Level for A&D Electronics

Description: The project will identify and validate test methods for accurately determining if an electronic product will form whiskers during its service lifetime.

ABEA: Evaluate test methods for determining if Class 3 A&D electronic products will form whiskers during their service lifetimes. The development of new and novel test methods that reduce the time required to obtain the test results is encouraged. Test parameters evaluated might include (but are not limited to) humidity, temperature, temperature cycling, vibration, and combinations thereof. Successful completion of the task will require the ability to assemble test vehicles representative of Class 3 electronic products. Test vehicles with and without whisker mitigations shall be used during evaluation of the test methods.

Qualitative and quantitative evaluations of whisker density and length using optical and scanning electron microscopy will be required for this task.

ABEB: Determine the relationship between the results from these test methods and whisker formation in a field environment (i.e., acceleration factors).

ABEC: Produce a final report detailing test method evaluation.

ABED: Project management including planning, reporting, coordination and collaboration.

Gaps Addressed:

- Existing tests (for design verification or product qualification) used by the A&D community may not be valid for Pb-free products. (See Exhibit A, Gap D46)
- Test methods based on JESD22-A121A and JESD201 for determining if an A&D electronic product will form whiskers during its service lifetime may not be appropriate. The relationship between the results from these tests and whisker formation and growth in a field environment has not been demonstrated. The use of inappropriate test methods can indicate a whiskering problem where none exists or, conversely, can allow the release of unreliable product into the field.
- JEDEC standard JESD22-A121A, "Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes," is not a qualification standard. Its purpose is only to recommend whisker growth test conditions so that data collected industry wide can be compared and used to improve the understanding of whisker growth. Both JESD22-A121A and its companion document JESD201, "Environmental Acceptance Requirements for Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes," are for consumer electronics only and explicitly state they are not applicable to A&D applications.

Expected Results: The project will identify and validate test methods for accurately determining if an electronic product will form whiskers during its service lifetime. These validated test methods will also allow meaningful evaluation of mitigation strategies for preventing whiskering on A&D products.

Deliverables: Validated test methods for determining if an electronic product (with or without mitigations) will form whiskers during its service lifetime. – Month 36

Interdependencies:

Needs: None

Collaborate: ACD, Fundamental Research = Define fundamental drivers behind whisker formation and growth.

Feeds: None

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $ 917K

ABF New Mitigations

Description: The project will identify and quantify the effectiveness of new mitigation technologies for preventing whisker formation and growth on A&D products

ABFA: Evaluate new tin whisker mitigation technologies for Class 3 A&D electronic products and quantify their effectiveness. Mitigation strategies for both tin platings and tin-based solders should be addressed.

The mitigation technologies shall be easy to implement and cost effective. Candidate mitigation technologies might include (but are not limited to) electroplating parameters, underplatings, plating and solder dopants, and surface treatments. The test coupons used for evaluating the mitigation technologies shall be representative of configurations actually found in A&D electronics (e.g., matte tin over copper). Control coupons that do not incorporate the mitigation strategy shall also be used for comparison. Use of test conditions designed to accelerate whisker growth is acceptable but an attempt should be made to understand the acceleration factor between the test condition and the use condition of the product. Qualitative and quantitative evaluations of whisker density and length using optical and scanning electron microscopy will be required in order to demonstrate the effectiveness of each mitigation technology. The interaction of the new mitigation technologies with existing mitigation strategies (such as conformal coatings) shall also be addressed.

ABFB: Produce a final report detailing the evaluation of the whisker mitigation technologies.

ABFC: Project management including planning, reporting, coordination and collaboration.

Gaps Addressed: No existing whisker mitigation practice is universally implementable and definitively prevents the occurrence of whiskers. (See Exhibit A, Gap D48)

Expected Results: The project will identify and quantify the effectiveness of mitigation technologies for preventing whisker formation and growth on A&D products. Validated mitigation strategies will reduce field failures and the costs associated with identifying and tracking whisker-prone materials.

Deliverables:

- New whisker mitigation technologies that are universally implementable and definitively prevent the formation and growth of whiskers on platings and solders. – Month 36

Interdependencies:

Needs: None

Collaborate: ACD, Fundamental Research = Define fundamental drivers behind whisker formation and growth.

Feeds: None

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $1,063K

AC Tin Whisker Risk Assessment

Description: This project will provide the A&D community with the ability to predict the reliability and lifetime of electronic products for both parts and assemblies based on tin whisker failure modes. Algorithm development, automated circuit analysis, new whisker inspection techniques, and fundamental whisker research will result in more reliable tin whisker risk assessment.

Gaps Addressed:

- Lack of standards to address receiving inspection in sustainment situation for tin whisker identification (See Exhibit A, Gap S12)
- There is no universally acceptable approach that allows circuit designers to assess the risk and impact of tin whiskers. This pertains to on circuit functionality during schematic design. This results in

excessive programs costs through potentially unnecessary material tracking and identification, expensive mitigation, and unpredictable and elevated field failure rates. (See Exhibit A, Gap D43)

- Lack of appropriate and validated failure models prevents accurate failure prediction, test development, and creation of design rules. (See Exhibit A, Gap D22)
- Lack of understanding of fundamental whisker growth mechanisms. (See Exhibit A, Gap R01)

Expected Results:

- ACA - Standards to address receiving inspection at the depot level for tin whisker identification.
- ACB - An automated tool that will allow the circuit designer to identify tin whisker risks based on the failure modes initiated by electrical connections between various nodes and other aspects of the system design.
- ACC - There are software modules to be developed that will allow the A&D community the ability to predict the reliability and lifetime based on tin whisker failure modes and perform tradeoff analysis for various whisker mitigations.
- ACD - This should result in higher fidelity test methods for tin whisker formation and provide required algorithms for development of design rules and of life prediction models for tin whisker risk mitigation.

Deliverables:

- ACA - Techniques and procedures to identify tin whiskers at the depot level. – Month 9
- ACA - Standards to address receiving inspection at the depot level for tin whisker identification. – Month 9
- ACB - A report detailing the approach. – Month 12
- ACB - An automated tool for circuit designers. – Month 12
- ACC - Report on the algorithms developed and validation data. – Month 24
- ACC - Software modules for reliability engineers and systems designers. – Month 24
- ACD – A report on a critical analysis of existing tin whisker research on fundamental mechanisms and their relationship to test methods for model systems, simulated, and commercial parts (electrical and mechanical) including gathering detailed information on the characteristics of materials, model system and part fabrication processes, assembly processes, and use conditions for parts. A best practices guide for gathering data, measuring physical, chemical, and microstructural parameters, and characterizing the kinetics of tin whisker formation for tin whisker research. – Month 36
- ACD - Report on a critical analysis of tin whisker test methods for assemblies, including test coupons and test vehicles for evaluating mitigation methods, that defines the process used in all phases of the analysis. This includes literature search, data types, criteria for data evaluation, and recommendations of modifications to existing test methods based on fundamental mechanisms of whisker growth and/or alternative approaches to test method that should better meet the needs of the A&D community. – Month 36
- ACD - Research report, database of evaluated tin whisker data based on fundamental physical, chemical, and microstructural measurements and their relationship to whisker formation and mechanisms, and an algorithm quantifying the relationships between tin whisker formation as measured by existing and proposed test methods, and materials and processes that are known to affect whiskers. – Month 36

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $ 7,531K

ACA Develop techniques and procedures to identify tin whiskers on field returned hardware

Description: Lack of standards/requirements to address receiving inspection in sustainment situation for tin whisker identification.

ACAA: Develop inspection technique to identify tin whiskers on returned assemblies.

ACAB: Create standard for inspection technique to identify tin whiskers on returned assemblies.

ACAC: Work project management included planning, reporting, coordination, and collaboration.

Gaps Addressed: Lack of standards to address receiving inspection in sustainment situation for tin whisker identification. (See Exhibit A, Gap S12)

Expected Results: Standards to address receiving inspection at the depot level for tin whisker identification.

Deliverables:

- Techniques and procedures to identify tin whiskers at the depot level. – Month 9
- Standards to address receiving inspection at the depot level for tin whisker identification. – Month 9

Interdependencies:

Needs: None

Collaborate: AAD, Detection of Intermittent Tin Whiskers Field Failures = Whisker inspection methods

Feeds: None

Schedule:

- Start Month: 1
- Expected Duration: 9 Months

ROM Cost: $ 606K

ACB Circuit Analysis Tin Whisker Risk Assessment

Description: Incorporate results from tin whisker failure mode activity into an open source software tool that will allow the circuit designer to identify tin whisker risks based on the failure modes initiated by electrical connections between various nodes and other aspects of the system design

ACBA: Perform a survey to define software requirements by gathering existing industry best practices and identifying needs, expectations, and limitations of the circuit analysis tin whisker risk assessment tool.

ACBB: Define design inputs. Must include the standard file inputs, such as net list and bill of materials. The tool must also allow the user to provide inputs or guidance to the analysis. These would include component-level (plating structure, lead spacing, component-level mitigation), circuit-level (voltages, currents, criticality, design rules), and system-level (environment, desired reliability, expected lifetime, criticality).

ACBC: Define design outputs. The outputs will consist of identifying connections of concern and providing quantifiable risk numbers. The output this tool can then be used to perform accurate FMECAs, initiate appropriate mitigations, such as component spacing (D45) and other design rules (D30), through quantitative tradeoff analysis, and identify and narrow the focus of intermittent detection (S15).

ACBD: Develop a user interface that meets customer requirements in regards to selection of analysis, modification of analysis (expert mode) and review of inputs and outputs

ACBE: Develop the analytical engines. Within this structure, the tool will use design rules and algorithms developed by prior investigations AAA (Metal Vapor Arcing), AAB (RF Failure Modes), AAC (Whisker Shorting Voltages and Currents), and ACC (Tin Whisker Life Prediction Model) to assess the intra-component and inter-component risk of tin whisker induced failure modes.

ACBF: Develop a user interface that meets customer requirements in regards to selection of analysis, modification of analysis (expert mode) and review of inputs and outputs.

ACBG: Identify appropriate users for initial assessment of alpha version of software. Implement user feedback in regards to capability with various file formats, compatibility with various operating systems.

ACBH: Provide beta version of the automated tool for broader assessment and verification of compatibility with a range of inputs. After final validation, release tool and source code to A&D community.

ACBI: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: There is no universally acceptable approach that allows circuit designers to assess the risk and impact of tin whisker on circuit functionality during schematic design. This results in excessive programs costs through potentially unnecessary material tracking and identification, expensive mitigation, and unpredictable and elevated field failure rates. (See Exhibit A, Gap DACB)

Expected Results: An open source software tool that will allow the circuit designer to identify tin whisker risks based on the failure modes initiated by electrical connections between various nodes and other aspects of the system design.

Deliverables:

- A preliminary report detailing the analytical approach, which will include key findings and recommendations from AAA (Metal Vapor Arcing), AAB (RF Failure Modes), AAC (Whisker Shorting Voltages and Currents), and ACC (Tin Whisker Life Prediction Model) – Month 6
- Alpha version of open software for circuit designers. – Month 9
- An open source software tool for circuit designers. – Month 12
- Project results that will be used by ABA (Automated Spacing Tool), ABB (Design Rules for Tin Whisker Mitigations), and AAD (Intermittent Detection). – Month 12

Interdependencies:

Needs: None

Collaborate: Circuit analysis methods, AAA, AAB, AAC, AAD, ABA, ABB, ACC

- AAA, Metal Vapor Arcing = Likelihood of metal vapor arcing as a function of V/I/frequency
- AAB, Whisker Shorting Voltages and Currents = Likelihood of a tin whisker short and intermittent behavior as a function of V/I/frequency.
- AAC, RF Failure Modes = Likelihood of EMI due to a tin whisker as a function of V/I/frequency
- AAD, Intermittent Detection = Identification of portions of the circuit that may be susceptible to intermittent failure behavior due to tin whiskers.
- ABA, Automated Spacing Tool = Identification of critical components that may require spacing mitigation.
- ABB, Design Rules for Tin Whisker Mitigation = A tool that can be used to implement design rules.
- ACC, Tin Whisker Life Prediction = Likelihood of tin whisker event regardless of spacing as a function of time, environment, and part level and board-level mitigations.

Feeds: None

Schedule:

- Start Month: 18
- Expected Duration: 12 Months

ROM Cost: $1,010K

ACC Tin Whisker Life Prediction

Description: Develop methodologies and tools that will predict the likelihood of tin whisker induced failures.

ACCA: Identify relevant failure modes relevant for life prediction. Will incorporate the results from AAA (Metal Vapor Arcing), AAB (Whisker Shorting Voltages and Currents), AAC (RF Failure Modes), and ACD (Fundamental Tin Whisker Research).

ACCB: Identify existing algorithms for the relevant tin whisker failure modes.

ACCC: Determine if existing algorithms are sufficiently validated.

ACCD: Develop new or modified algorithms where appropriate with inputs from AAA, AAB, AAC and R1 as necessary

ACCE: Perform testing to validate existing algorithms where insufficient data exists and new or modified algorithms

ACCF: Modify algorithms based on results of validation testing, if necessary

ACCG: Depending on the algorithm, the software module can be formatted within existing defined formats (Excel, Access, etc.) or developed using traditional software tools (Java, C++, etc.)

ACCH: Work project management including planning, reporting, coordination, and collaboration

Gaps Addressed: Lack of appropriate and validated failure models prevents accurate failure prediction, test development, and creation of heuristic rules. (See Exhibit A, Gap DACC)

Expected Results: Software modules that will allow the A&D community the ability to predict the reliability and lifetime based on tin whisker failure modes and perform tradeoff analysis for various whisker mitigations.

Deliverables:

- Preliminary report on tin whisker life prediction algorithms and gaps in regards to applicability and validation. – Month 3
- Initial software modules based on existing and validated algorithms. – Month 6
- Preliminary report on new or modified algorithms. – Month 6
- Preliminary report on test results. – Month 15
- Final report on test results. – Month 21
- Software modules for the prediction of tin whisker induced failures. – Month 24

Interdependencies:

Needs: None

Collaborate:

- AAA, Metal Vapor Arcing = Tin whisker failure model
- AAB, Whisker Shorting Voltages and Currents = Tin whisker failure model
- AAC, RF Failure Modes = Tin whisker failure model
- ACD, Fundamental Tin Whisker Research = Tin whisker failure model
- ABB, Design Rules for Tin Whisker Mitigations = Tin whisker failure model

Feeds: None

Schedule:

- Start Month: 6
- Expected Duration: 24 Months

ROM Cost: $1,189K

ACD Fundamental Research for Tin Whisker Risk Assessment

Description: Perform research to gain fundamental understanding of tin whisker growth mechanisms, so that the extreme variations in whiskering propensity of tin film deposits can be understood from first principles. This fundamental understanding will be linked to development of test methods for parts and assemblies, to development of life prediction models, to design of new mitigation strategies and materials with lower propensities for whisker formation, and to processes and materials that minimize tin whisker formation after rework and repair.

ACDA: Perform critical analysis of existing tin whisker research on fundamental mechanisms and their relationship to test methods for model systems, simulated, and commercial parts (electrical and mechanical) including gathering detailed information on the characteristics of materials, model system and part fabrication processes, assembly processes, and use conditions for parts. This task focuses on measuring whisker growth formation, kinetics, and specific characteristics that affect whisker formation and growth and their relationship to the physical, chemical, and microstructural characteristics that affect whiskering propensity. Develop a best practices guide for gathering data, measuring physical, chemical, and microstructural parameters, and characterizing the kinetics of tin whisker formation for tin whisker research.

ACDB: Perform critical analysis of existing tin whisker research on fundamental mechanisms and their relationship to test methods for test coupons, model assemblies, and production assemblies, including but not limited to corrosion, assembly processes, and effects of mitigation methods in relationship to the fundamental mechanisms that may be operating. Compare the physical, chemical, and microstructural parameters, between the materials, components, assembly processes, mitigation applied, and subsequent storage and/or use conditions, including corrosion and rework, for which tin whiskers have been observed on assemblies. This task focuses on the characteristics of whiskers that form on assemblies (growth rate, length, densities, distributions, etc.) and not on the V-I characteristics of the assemblies in operation.

ACDC: Quantify the relationships between whisker propensities, the physical, chemical, and microstructural characteristics of a comprehensive suite of representative plated parts or model parts, and their use conditions using a disciplined design-of-experiments research approach designed based on scientific fundamentals. The physical, chemical, and microstructural characteristics will include measurements, for example, of tin film stresses, local and crystallographic texture of the tin films and substrates, film, intermetallic, and substrate compositions and microstructures. The final output for this task will be a model or an algorithm for tin whisker formation kinetics.

ACDD: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: Lack of understanding of fundamental whisker growth mechanisms. (See Exhibit A, Gap R01)

Expected Results: The knowledge of the fundamental mechanisms will be critical input to create valid test methods for screening parts and assemblies for whisker risk. This will determine which assemblies require additional tin whisker risk mitigation and at what levels, and to identify the windows of materials, part manufacturing processes, and assembly, rework and repair conditions that create different levels of risk for Pb-free parts and assemblies. This work will result in higher fidelity test methods for tin whisker formation, provide required models and algorithms for development of design rules and of life- prediction models and a precision risk reduction approach for tin whisker risk mitigation.

Deliverables:

- Reports on a critical analysis of existing tin whisker research on fundamental mechanisms and their relationship to test methods for model systems, simulated, and commercial parts (electrical and mechanical) including gathering detailed information on the characteristics of materials, model system and part fabrication processes, assembly processes, and use conditions for parts. A best practices guide for gathering data, measuring physical, chemical, and microstructural parameters, and characterizing the kinetics of tin whisker formation for tin whisker research. – Months 6, 12, 18, 24, 30 (interim reports), 36 (final report)
- Reports on a critical analysis of tin whisker test methods for assemblies, including test coupons and test vehicles for evaluating mitigation methods, that define the process used in all phases of the analysis. This includes literature search, data types, criteria for data evaluation, and recommendations for modification of existing test methods based on fundamental mechanisms of whisker growth and/or alternative approaches. The resulting test methods should better meet the needs of the A&D community. – Months 6, 12, 18, 24, 30 (interim reports), Month 36 (final report)
- Research report, database of evaluated tin whisker data based on fundamental physical, chemical, and microstructural measurements and their relationship to whisker formation mechanisms, and an algorithm quantifying the relationships between the fundamental mechanisms for tin whisker formation, the use and test conditions, and the parameters that can be controlled. This also provides an independent validation of materials, test methods, lifetime prediction models, and rework and repair processes proposed by ABD, ABE, ACC, ECB and BAB. – Months 18 (interim report), Month 36 (final Report)

Interdependencies:

Needs: None

Collaborate:

- ABD, Tin Whisker Test Methods for Parts = Development of more robust, faster, and cheaper test methods for parts (electrical and mechanical)
- ABE, Tin Whisker Test Methods for Products = Development of tin whisker test methods for assemblies and products, including effectiveness of mitigation strategies
- ACC, Life Prediction Models = Development of algorithms for life prediction models that include materials, processing, mitigation, assembly, repair, and rework contributions
- BAB, Rework and Repair Critical Process Parameters = Report on effects of repair and rework processes on whisker propensity
- CBB, Corrosion = Data sharing on effect of corrosion on whisker formation on assemblies.
- ECB, Surface Finish Test Methods = Development of surface finish test methods for tin surface finishes that include tin whisker propensity

Feeds: None

Schedule:

- Start Month: 1

- Expected Duration: 36 Months

ROM Cost: $ 4,726K

B ASSEMBLY

Description: This project area focuses on the manufacturing and repair issues for circuit card assemblies (CCAs) using Pb-free solders and finishes. The project area includes the development and validation of qualification and acceptance tests for Pb-Free electronics products. As an option to be separately funded, a 10-year Reliability Assessment is defined for a Pb-free pathfinder equipment field assessment. The ROM costs for this pathfinder option are for the first three years of the reliability assessment, and are not included in the roll-up of costs for the basic Pb-free Electronics Risk Reduction Program.

Gaps Addressed:

- Need specific critical Pb-free electronics process parameters for A&D electronics products (e.g., inert atmosphere quality, removal of Pb-free flux, solder pad design influence on solder joint quality).
- Need rework/repair process guidelines base-lining the critical Pb-free electronics process parameters and Pb-free specific root cause defects for use by A&D product manufacturing.
- Reliability assessment tests performed during assembly (qualification and acceptance tests) have not had their parameters identified, which capture the materials failures pertinent to Pb-free products, including solder fatigue, pad cratering, and tin whiskers, in particular, those leading to intermittent failures.

Expected Results:

- Defined set of Pb-free process guidelines for A&D manufacturing.
- Guidelines for rework/repair of A&D assemblies.
- Recommendations on possible non-solder attachment technologies and alternative printed circuit assembly attachment technologies.
- Cost decision matrix comparing relative cost of a current tin/lead solder process versus a proposed Pb-free solder process.
- Qualification and acceptance test parameters based on field life data.
- Field performance data for Pb-free assembly (Separately funded Option).

Deliverables:

- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing.
- A relative cost decision matrix comparing tin/lead solder versus Pb-free solder processes.
- A report documenting suggested changes for IPC-AJ-820 handbook (Pb-free critical solder process parameters), IPC-JSTD-001 specification (solder joint criteria), and IPC-A-610 specification (Pb-free specific solder defects).
- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for the rework/repair process element, and the guideline rationale for A&D product manufacturing.
- A report documenting the rework/repair solder process “Gauge Reproducibility & Repeatability” study, defining process procedures/protocols for specific rework/repair methodology.
- A relative cost decision matrix comparing tin/lead solders versus Pb-free rework/repair processes.
- A report documenting suggested changes for IPC 7711/7722 specification (rework/repair critical process parameters) and IPC-A-610 specification (Pb-free specific solder defects).
- A report that describes the qualification and acceptance test parameters for Pb-free products.
- A report describing qualification and acceptance test parameters for Pb-free assemblies that are validated by field failure data.

Expected Duration: 36 Months

ROM Cost: $8.3M

BA A&D Manufacturing Processes

Description: The A&D Manufacturing Process Project is comprised of three work packages:

(1) The critical Pb-free process parameters for each of the major process elements producing a defined set of Pb-free process guidelines for A&D manufacturing sector use. This includes a cost decision matrix comparing relative cost of a current tin/lead solder process, versus a proposed Pb-free solder process

(2) The evaluation of the rework/repair of A&D assemblies in terms of critical Pb-free process parameters; maximum degradation threshold limits; rework/repair process gauge, repeatability/reproducibility; and a cost decision matrix comparing relative cost of a current tin/lead versus Pb-free rework/repair solder process.

(3) Conduct a "State of the Art" technology assessment for non-solder attachment technologies resulting in a list of proposed alternative printed circuit assembly attachment technologies.

Gaps Addressed: A&D products have unique manufacturing process parameters resulting from the program critical and safety critical nature of the product use environments. A&D products are comprised of printed wiring assemblies with unique geometric/highly complex construction attributes that do not exist in the industrial electronic product base. The construction attributes result in a need for specific critical Pb-free process parameters for the A&D electronics product segment. A&D products can also be characterized as having significantly long product life cycles and sustainment cost value in comparison to the industrial electronic product segment. The rework/repair manufacturing processes have a major impact in terms of potential latent field defects and product degradation

Expected Results:

- A Pb-free process guidelines document base-lining the critical process parameters and Pb-free specific root cause solder defects for each major assembly process element for A&D product manufacturing.
- A cost decision matrix comparing relative cost of a current tin/lead solder process versus a proposed Pb-free solder process assessing each major element of the solder processes. The cost matrix will be formatted in categories of costs associated with each major assembly process element
- A rework/repair process guideline base-lining the critical Pb-free process parameters and Pb-free specific root cause defects for use by A&D product manufacturing.
- A cost decision matrix-comparing relative cost of a current tin/lead versus Pb-free, assessing each major element of the rework/repair solder process. The cost matrix will be formatted in categories of costs associated with each major assembly process element
- An information data set of specific critical process parameters applicable to IPC High Performance Class 3 products that can be used to revise/supplement current IPC specifications and standards.

Deliverables:

- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly. – Months 6, 9, 18, 24 and 36
- A relative cost decision matrix comparing tin/lead solder versus Pb-free solder processes – Month 6

- A report documenting suggested changes for IPC-AJ-820 handbook (Pb-free critical solder process parameters), IPC-JSTD-001 specification (solder joint criteria), and IPC-A-610 specification (Pb-free specific solder defects) – Month 36
- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for the rework/repair process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free rework/repair process baseline for A&D product assembly. – Month 12 and 24
- A report documenting the rework/repair solders process "Gauge Reproducibility & Repeatability" study, defining process procedures/protocols for specific rework/repair methodology. – Month 33
- A relative cost decision matrix comparing tin/lead solder versus Pb-free rework/repair processes – Month 6
- A report documenting suggested changes for IPC 7711/7722 specification (rework/repair critical process parameters) and IPC-A-610 specification (Pb-free specific solder defects) – Month 36

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $5,418K

BAA Critical Process Parameter Development

Description: The objective of this work package is to define the critical Pb-free process parameters for each of the major process elements. This activity will require characterization and assessment of the Pb-free solder process for A&D assemblies resulting in a defined set of Pb-free process guidelines for A&D manufacturing sector use. A test vehicle comprised of the necessary internal structures, thermal capacity, and component technologies will be used to investigate four Pb-free solder alloys. A cost decision matrix comparing relative cost of a current tin/lead solder process versus a proposed Pb-free solder process assessing each major element of the solder processes shall be produced.

BAAA: Investigate the applicability of current surface mount pad, plated thru holes design and internal PCB structure requirements for applicability for A&D product use environments. A test vehicle using selected typical component families and a representative set of pads/plated thru holes/PCB structures shall be subjected to thermal cycle, vibration, and drop shock conditioning with verification of solder joint integrity.

BAAB: Define the minimum component placement boundary/accuracy requirements for acceptable A&D assembly yields. A test vehicle using a wide range of SMT component families (0201s, 0.4mm pitch area array, bottom terminated components, etc.) shall be utilized.

BAAC: Define a process flow protocol allowing A&D product assemblers to utilize single process line flow. Minimum requirements shall be defined for cross contamination, workstation/equipment labeling, printed wiring assembly handling, and process materials & tools organization.

BAAD: Define laser solder process critical parameters for A&D assemblies. Task shall include equipment capabilities, material requirements, thermal profile/demand rules, solder joint workmanship criteria, rework/repair specifics and associated Pb-free specific root cause solder/infant mortality defects.

BAAE: Define wave/selective solder process critical parameters for A&D assemblies. Task shall include equipment capabilities, specific solder alloy constraints, thermal profile/demand rules, thermal excursion degradation threshold limits, inert atmosphere minimum requirements, maximum solder bath

contamination limits, solder joint workmanship criteria, and associated Pb-free specific root cause solder/infant mortality defects.

BAAF: Define vapor phase solder process critical parameters for A&D assemblies. Task shall include equipment capabilities, specific chemistry characteristics and constraints, thermal profile/demand rules, thermal excursion degradation threshold limits, solder joint workmanship criteria, and associated Pb-free specific root cause solder/infant mortality defects.

BAAG: Define reflow solder process critical parameters for A&D assemblies. Task shall include equipment capabilities, specific solder alloy constraints, thermal profile/demand rules, thermal excursion degradation threshold limits, inert atmosphere minimum requirements, solder joint workmanship criteria, and associated Pb-free specific root cause solder/infant mortality defects.

BAAH: Define manual solder process critical parameters for A&D assemblies. Task shall include equipment capabilities and durability, thermal demand/temperature requirements, periodic maintenance rules, thermal excursion degradation threshold limits, solder joint workmanship criteria, and associated Pb-free specific root cause solder/infant mortality defects.

BAAI: Define cleaning process critical parameters for A&D assemblies. Task shall include equipment capabilities, chemistry efficacy, material compatibility, impact of low stand component technologies, interaction with low residue flux process protocols and associated Pb-free specific root cause solder/infant mortality defects.

BAAJ: Define conformal coating process critical parameters for A&D assemblies. Task shall include minimum coverage requirements, a coating process "Gauge Repeatability & Reproducibility (R&R)" study, compatibility with low residue/no clean process protocols, and associated Pb-free specific root cause solder/infant mortality defects.

BAAK: Define de-panelization/singulation process critical parameters for A&D assemblies. Task shall include component location geometric rules/restrictions and maximum damage threshold limits and associated Pb-free specific root cause solder/infant mortality defects.

BAAL: Define a relative cost comparison matrix for A&D assemblies using current tin/lead solder process as the baseline and a proposed Pb-free solder process. The cost matrix shall be formatted in categories of costs associated with each major assembly process element.

BAAM: Work project management including planning, reporting, coordination, and collaboration

Gaps Addressed: A&D products have unique manufacturing process parameters resulting from the program critical and safety critical nature of the product use environments. A&D products are comprised of printed wiring assemblies with unique geometric/highly complex construction attributes that do not exist in the industrial electronic product base. The construction attributes result in a need for specific critical Pb-free process parameters for the A&D electronics product segment. Process characteristics such as inert atmosphere quality, cross contamination of a shared solder process line, thermal capacity challenges of thick PCBs, removal of Pb-free flux and solder pad design influence on solder joint quality (See Exhibit A, Gap M01, M2, M4, M05, M07, M08, M09, M10, M12, M13, M18, D09, D58).

Expected Results:

- A Pb-free process guidelines document base-lining the critical process parameters and Pb-free specific root cause solder defects for each major assembly process element for A&D product manufacturing.
- A cost decision matrix comparing relative cost of a current tin/lead solder process versus a proposed Pb-free solder process assessing each major element of the solder processes.
- An information data set of specific critical process parameters applicable to IPC High Performance Class 3 products that can be used to revise/supplement current IPC specifications and standards.

Deliverables:

- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for each major assembly process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free solder process baseline for A&D product assembly. – Months 6, 9, 18, 24 and 36
- A relative cost decision matrix comparing tin/lead solder versus Pb-free solder processes. – Month 6
- A report documenting suggested changes for IPC-AJ-820 handbook (Pb-free critical solder process parameters), IPC-JSTD-001 specification (solder joint criteria), IPC-A-610 specification (Pb-free specific solder defects), GEIA-STD-0005-1(solder processes input), GEIA-STD-0005-1 (tin whisker mitigation input), GEIA-HB-0005-2 (solder processes input), and GEIA-HB-0005-3 (rework/repair process input). – Month 36

Interdependencies:

Needs: EBA Thermal Robustness of Laminate Materials – laminate properties

Collaborations:

- ED PCB Design and Database – pad design rules
- EC PCB Finishes – surface finish process applicability limits
- EAA Pad Design/ Stencil Design Assessment and Confirmation – pad design configurations
- DA Component Characterization – component process applicability limits
- DC Temperature Sensitivity Capability Improvement - component process applicability limits
- DD Component Finish - component process applicability limits
- EAB Copper Requirements and Copper Dissolution – rework/repair damage threshold limits
- CAA Test Vehicle Design & Fabrication – applicability of test vehicle results for modeling tasks
- CDD Low Temperature Rework Alloy – solder alloy process applicability
- CB Solder Joint Reliability Effects – processed assembly influence for modeling tasks
- CD Mixed Solder Joints – maximum wave/selective bath contamination limits

Feeds: None

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $3,852K

BAB Rework & Repair Critical Process Parameter Development

Description: The objective of this Work Package is to evaluate and assess the rework/repair of A&D assemblies in terms of critical Pb-free process parameters, maximum degradation threshold limits, rework/repair process repeatability/reproducibility, and associated Pb-free specific root cause solder defects. A test vehicle comprised of the necessary internal structures, thermal capacity, and component technologies will be used to investigate four Pb-free solder alloys. A cost decision matrix comparing relative cost of a current tin/lead versus Pb-free assessing each major element of the rework/repair solder process and a rework/repair Gauge R&R study shall be produced.

BABA: Define rework/repair solder process critical parameters for A&D assemblies. Task shall include equipment capabilities, specific solder alloy constraints, thermal profile/demand rules, thermal excursion degradation threshold limits, impact of long term storage, physical condition complications related to fielded assemblies and associated Pb-free specific root cause solder/infant mortality defects.

BABB: Define the rework/repair non -solder process (cleaning, conformal coating) critical parameters for A&D assemblies. Task shall include equipment capabilities, specific chemistry constraints, process

induced degradation threshold limits, and associated Pb-free specific root cause solder/infant mortality defects.

BABC: Conduct a rework/repair solder process "Gauge Reproducibility & Repeatability" study to define process procedures/protocols for specific rework/repair methods.

BABD: Define a relative cost comparison matrix for A&D assemblies using current tin/lead solder rework/repair process as the baseline and a proposed Pb-free solder rework/repair process. The cost matrix will be formatted in categories of costs associated with each major assembly process element.

BABE: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: A&D products are characterized as having significantly long product life cycles and sustainment cost value in comparison to the industrial electronic product segment. The rework/repair manufacturing process task has a major impact in terms of potential latent field defects and product degradation. Process characteristics such as maximum thermal excursions, impact on components/PCBs due to more aggressive flux formulations and effects of solder alloy on solder joint quality (See Exhibit A, Gap M2, M4, M11, M18, S1, S05, S06, D10, D56).

Expected Results:

- Produce a rework/repair process document base lining the critical Pb-free process parameters and Pb-free specific root cause defects used by A&D product manufacturing.
- Provide a cost decision matrix comparing relative cost of a current tin/lead versus Pb-free assessing each major element of the rework/repair solder process.
- An information data set of specific critical process parameters applicable to IPC High Performance Class 3 products that can be used to revise/supplement current IPC specifications and standards.

Deliverables:

- A report documenting the test methodology, investigation results, a proposed set of Pb-free critical process parameters, Pb-free specific root cause solder defects for the rework/repair process element, and the guideline rationale for A&D product manufacturing. The report will serve as the Pb-free rework/repair process baseline for A&D product assembly. – Month 12 and 24
- A report documenting the rework/repair solder process Gauge Reproducibility & Repeatability study defining process procedures/protocols for specific rework/repair methodology. – Month 33
- A relative cost decision matrix comparing tin/lead solders versus Pb-free rework/repair processes. – Month 6
- A report documenting suggested changes for IPC 7711/7722 specification (rework/repair critical process parameters), IPC-A-610 specification (Pb-free specific solder defects), GEIA-STD-0005-1(solder processes input), GEIA-STD-0005-1 (tin whisker mitigation input), GEIA-HB-0005-2 (solder processes input), and GEIA-HB-0005-3 (rework/repair process input). – Month 36

Interdependencies:

Needs: EBA Thermal Robustness of Laminate Materials– laminate properties

Collaborations:

- AAD Tin Whisker Intermittent Detection – effectiveness of tin whisker detection method
- ED PCB Design and Database – pad design rules
- EC PCB Finishes – surface finish process applicability limits
- EAA Pad Design/ Stencil Design Assessment and Confirmation – pad design configurations
- DA Component Characterization – component process applicability limits
- DC Temperature Sensitivity Capability Improvement - component process applicability limits
- DD Component Finish - component process applicability limits
- CAA Test Vehicle Design & Fabrication – applicability of test vehicle results for modeling tasks
- CB Solder Joint Reliability Effects – processed assembly influence for modeling tasks
- CD Mixed Solder Joints – maximum wave/selective bath contamination limits

Feeds: None

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $1,354K

BAC State of the Art Assessment of Non-solder Attachment Technologies

Description: The objective of this Work Package is to conduct an industry assessment of the "State of the Art" for non-solder attachment technologies. Academia, Industry consortia, Department of Defense, Department of Energy, Department of Commerce, Federal Aviation Administration, NASA, industry publications, and private industry will be surveyed for applicable technologies that could replace soldering as the primary printed circuit assembly attachment methodology.

BACA: Create a "State of the Art" technology assessment survey package covering the topic of non-solder printed circuit assembly attachment technology.

BACB: Create a list of point of contacts for survey participation from the following group listing: Academia, Industry consortia, Department of Defense, Department of Energy, Department of Commerce, Federal Aviation Administration, NASA, industry publications, and private industry.

BACC: Conduct "State of the Art" technology assessment survey.

BACD: Compile, analyze, and summarize "State of the Art" technology assessment survey results.

BACE: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: A&D products have traditionally utilized soldering as a printed circuit assembly attachment technology. However, the use of soldering as a printed circuit assembly attachment process has several material and process limitations. A review of non-solder printed circuit assembly attachment technologies should be conducted as part of an "out of the box" thought process in addressing the topic of Pb-free soldering technology impact on A&D products.

Expected Results: A "State of the Art" technology assessment for non-solder attachment technologies and a list of proposed alternative printed circuit assembly attachment technologies.

Deliverables: A report documenting the "State of the Art" technology assessment survey responses and results including a proposed list of non-solder attachment technologies that should be further investigated. – Month 12

Interdependencies:

Needs: None

Collaborate: None

Feeds: None

Schedule:

- Start Month: 1
- Expected Duration: 8 Months

ROM Cost: $211K

BB Development, Validation, Qualification & Acceptance Tests for Pb-Free Products

Description: This project establishes qualification and acceptance test parameters to determine the reliability of Pb-free products at the time of assembly, capturing all relevant failure modes. Field failure data will be acquired, including functional failures (electrical and mechanical) as well as associated failure modes, to validate the analytical and computational models to optimize their prediction fidelity for determining the qualification and acceptance test parameters for Pb-free product.

Gaps Addressed: The reliability assessment tests performed during assembly – that is, qualification and acceptance tests – have not had their parameters identified, which capture the materials failures pertinent to Pb-free products, including solder fatigue, pad cratering, and tin whiskers, in particular, those leading to intermittent failures. In addition, there is a lack of field failure data, including functional failure rates and failure modes, to optimize validation of the underlying analytical and computational predictive models.

Expected Results:

- Identification of analytical and computational models that predict materials failure modes that is responsible for electrical and mechanical failures in Pb-free products.
- A protocol for determining qualification and acceptance test parameters for Pb-free products.
- Confirmation of the similarity assumption of failure modes present during qualification and acceptance tests and those of field failures.
- Acceleration factor that correlates the rates of functional failures (electrical and mechanical) measured during qualification and acceptance tests to those in the field, with special attention paid to repaired-and-reworked units.

Deliverables:

- A report that describes the qualification and acceptance test parameters for Pb-free products. – Month 36
- A report describing qualification and acceptance test parameters for Pb-free assemblies that are validated by field failure data. – Month 36

Schedule:

- Start Month: 1
- Duration: 36 months

ROM Cost: $2,874K

BBA Method for Determining Qualification and Acceptance Test Parameters

Description: Establish qualification and acceptance test parameters to determine the reliability of Pb-free products at the time of assembly, capturing all relevant failure modes.

BBAA: The materials failure modes will be identified that are responsible for the electrical failures and mechanical failures in Pb-free products, including solder joint fatigue (homogeneous and mixed solder compositions), pad cratering, conductor dissolution, or tin whiskers.

BBAB: Analytical and computational models will be identified for predicting materials failure modes responsible for electrical signal failures and mechanical failures, including validation.

BBAC: The models are exercised to establish acceleration factors.

BBAD: Determine qualification and acceptance test parameters from the model predictions.

BBAE: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: The existing tests for design verification, product qualification, and product acceptance are not valid for Pb-free product to be used in the A & D community. (See Exhibit A, Gaps D05, D27, D28, and D29.)

Expected Results:

1. List of materials failure modes that are responsible for the electrical signal and mechanical failures of Pb-free assemblies.
2. Analytical or computational models are identified, which reflect the pertinent materials failure modes.
3. Protocol for determining qualification and acceptance test parameters for Pb-free products from the model predictions and computed acceleration factors.

Deliverables: A report that describes the qualification and acceptance test parameters for Pb-free products. – Month 36

Interdependencies:

Needs:

- CAE, Reliability Modeling – analytical or computational thermal mechanical fatigue model
- CAG, Vibrations – analytical or computational vibration fatigue model
- CAH, Combined Loading – analytical or computational model of combined environments

Collaborations:

- AAB, Define voltage and current conditions for whisker induced electrical shorting – there will be an increased understanding of intermittent failures caused by whiskers
- CEA, Reliability of PTH Solder Joints Depend on Cu Thickness Remaining After Assembly and Rework – copper dissolution is an assembly failure mode addressed by qualification and acceptance at the time of assembly
- EBC, Conductive Anodic Filaments (CAF) – this intermittent failure mode can occur in service and, thus, should be addressed at qualification and acceptance testing.
- EBB, Materials Verification – an intermittent failure mode is the result of pad cratering.

Feeds: CAB, Validation Data Collection and Assessment – these data can be used to validate the intermittent failure mode of tin whiskers

Schedule:

- Start Month: 1
- Duration: 36 months

ROM Cost: $1,243K

BBB Field Life Data for Validating Qualification and Acceptance Test Predictions

Description: Establish the logistics needed to acquire field failure data, including functional failures (electrical and mechanical) and associated failure modes, to validate the analytical and computational models that will establish qualification and acceptance test parameters.

BBBA: The mechanics will be developed to acquire field functional failures (electrical and mechanical), including failure mode analyses, for SnPb and Pb-free alloys. Particular attention will be paid to products subjected to repair-and-rework activities.

BBBB: The similarity assumption of failure modes will be confirmed between field failures and those underlying the qualification and acceptance tests. Failure modes will be documented that are unique to the field.

BBBC: Assuming similarity of failure modes between test and field, the materials failure rates observed under the qualification and acceptance test conditions will be compared to the materials failure rates in the field to validate the acceleration factor of the models. The predicted rates of functional failures (electrical and mechanical) under qualification and acceptance test conditions will be compared to the observed rates of functional failures in the field. The acceleration factor associated with the functional failure test parameters will be validated.

BBBD: Failure mode discrepancies will be reconciled between those documented in qualification and acceptance testing and those recorded from field failures, including the potential need to revise the underlying analytical or computational models.

BBBE: Functional failure rate discrepancies will be reconciled between those predicted by supporting qualification and acceptance testing versus field failure rates, including the potential need to revise the underlying analytical or computational models.

BBBF: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: There is an absence of reliability data pertaining to the field performance of Pb-free products, including failure rates, and failure modes that can be used to establish acceleration factors for qualification and acceptance testing. (See Exhibit A, Gaps S02, S07, S15, D04, and D59.)

Expected Results:

- Failure modes and functional failure rates (electrical and mechanical) will be documented for fielded Pb-free products, with special attention paid to repaired-and-reworked units.
- Confirmation will be made that the failure mode, which underlies the analytical or computational model, is similar to that active in the field failures, thereby validating the acceleration factor.
- Confirmation will be made that the predicted, functional failure rates (electrical and mechanical) correlate to field functional failure rates; the correlation is defined by the acceleration factor.
- A recommendation will be made to determine the need to revise analytical and computational models in order to establish similarity of failure mode and/or and a consistent acceleration factor between functional failures (electrical and mechanical) under qualification and acceptance testing parameters versus those in the field.

Deliverables:

- A report describing qualification and acceptance test parameters for Pb-free assemblies with additional validation from field failure data. – Month 36

Interdependencies:

Needs:

- CAB, Validation Data Collection and Assessment – these data can be used to validate the intermittent failure mode of tin whiskers
- CAE, Reliability Modeling – analytical or computational thermal mechanical fatigue model
- CAG, Vibrations – analytical or computational vibration fatigue model
- CAH, Combined Loading – analytical or computational model of combined environments

Collaborations:

- AAB, Define voltage and current conditions for whisker induced electrical shorting – there will be an increased understanding of intermittents caused by whiskers

- CEA, Reliability of PTH Solder Joints Depend on Cu Thickness Remaining After Assembly and Rework – copper dissolution is an assembly failure mode addressed by qualification and acceptance at the time of assembly
- EBC, Conductive Anodic Filaments (CAF) – this intermittent failure mode can occur in service and, thus, should be addressed at qualification and acceptance testing.
- EBB, Materials Verification – an intermittent failure mode is the result of pad cratering.

Feeds: CAB, Validation Data Collection and Assessment – these data can be used to validate the intermittent failure mode of tin whiskers

Schedule:

- Start Month: 1
- Duration: 36 months

ROM Cost: $1,631K

BC Pb-Free Pathfinder (OPTION: 10-YEAR RELIABILITY ASSESSMENT NOT INCLUDED IN BASIC PROGRAM)

Description: This project will perform a prototype assembly build of an actual aerospace and defense (A&D) product using a Pb-free solder. The entire manufacturing procedure will be exercised at a predetermined manufacturing facility. The hardware will be fielded and, where necessary, returned to the depot to record the failure and failure mode as well as effect repairs and replacement of the unit in order to place it back into the field

Gaps Addressed: There have been very few studies made public which document challenges of the assembly of an actual A and D product with Pb-free solders. There is presently no experience with the sustainment stage of a Pb-free product lifecycle, including the number of field failures in *as-manufactured* Pb-free product, failure mode documentation, repair, and the service life of *repaired* hardware.

Expected Results:

- Acquisition logistics, assembly process definition determined by design of experiments (DoE), and determination of qualification and acceptance test parameters defined by computation models to field ten units and have two spares.
- Field failure data of *as-manufactured* Pb-free product.
- A method to perform failure mode analysis on hardware efficiently, which will return to service.
- Field failure data of a *repaired* Pb-free product.

Deliverables:

- A quantity of ten prototype units will be fabricated for fielding and two spare units, which also includes a determination of qualification and acceptance test parameters by computational models, and detailed report that describes lessons-learned from the *assembly* process. – Month 12
- *As-manufactured failures*: Assessment of fielded Pb-free assemblies that reports upon field failures, including use conditions and failure mode analysis, that occurred after 66 months or, after a duration so that greater than, or equal to, 25% of the fielded units had repairable failures. – Month 72
- *Repaired failures*: Report of field failures, including use conditions and failure mode analysis for a period of 114 months or, if possible, no less 75% of the total time required to obtain 25% total failures of the as-manufactured units. – Month 120

Schedule:

- Start Month: 1
- Expected duration: 120 months

ROM Cost: $889K **(Cost for first three years of Optional 10-Year Reliability Assessment, not included in Basic Program Cost Roll-up)**

BCA Fabrication of ten prototype units and two spare units (OPTION: 10-YEAR RELIABILITY ASSESSMENT NOT INCLUDED IN BASIC PROGRAM)

Description: The test vehicle will be down-selected from candidate hardware for fabrication. Materials, components, printed circuit boards, and structural members will be procured. This effort will include surface finish alteration, if necessary. (It will be assumed that relevant vendors have already been identified.)

BCAA: Down selection will be made of a suitable product vehicle from candidate hardware. This task includes a rendering of the complete set of materials and assembly drawing, parts lists, as well as process travelers associated with manufacturing the hardware. Test documents are also required, including those pertaining to incoming hardware qualification and acceptance tests as well as qualification and acceptance testing of the finished product. It is important to list personnel expertise, whether employed or retired, from the source company.

BCAB: Procure the components as stated on the bill of material (BOM). This task will include all qualification and acceptance testing as well as additional efforts such as altering the surface finishes, where necessary.

BCAC: Procure the printed circuit boards necessary to build the hardware. This task will include all qualification and acceptance testing.

BCAD: Procure solder paste, solder wire, or solder pot materials as well as stencils, fluxes, and cleaning materials for the respective assembly processes. This task will include all qualification and acceptance testing.

BCAE: Assemble the Pb-free product per best practices.

BCAF: Perform qualification and acceptance testing on the hardware to ready for placing in the field. Write a report.

Gaps Addressed: A lack of experience with the assembly of Pb-free solder electronics. (See Exhibit A, Gap S19)

Expected Results:

- Lessons-learned from the Pb-free product assembly process development.
- Baseline data on the yield and failure modes of post-assembled, Pb-free product.
- Use of computational models to develop the qualification and acceptance test parameters.
- Qualification and acceptance test data for the Pb-free product.

Deliverables:

- Report describing the details of the assembly process, inspection protocols, process yields, as well as qualification and acceptance test methods. – Month 12
- Ten Pb-free assemblies for placing in the field and two spare units. – Month 12

Interdependencies:

Needs: None

Collaborate:

- AA, Tin Whisker Failure Modes – The failure modes must be understood as they may occur during the field.
- AB, Tin Whisker Mitigation – These procedures may be required or purposely *not* implemented for the components surface finishes.
- AC, Tin Whisker Risk Assessment – Understand the risk of not pursuing mitigation strategies.
- BA, A&D Manufacturing Process – The process parameters can be obtained to bracket the assembly processes to direct the hardware manufacturing effort.
- BB, Development and Validation of Qualification and Acceptance Tests for Pb-Free Products – This process will assist with the development of these two tests; but the methods to and test parameters will be determined, independently, in this project.
- DA, Component Assembly Processing and Life – understanding the survivability of components exposed to Pb-free process.
- EB, Laminates – understanding the survivability of components exposed to Pb-free process

Feeds:

- CA, Solder Joint Reliability Model – the solder reliability models will benefit from a validation by failures that occur in the field, including failure rate as well as failure mode.
- CB, Solder Joint Reliability Effects – correlate the effects of service conditions on the reliability of the solder joints

Schedule:

- Start Month: 1
- Expected duration: 12 months

ROM Cost: $338K **(Cost for first three years of Optional 10-Year Reliability Assessment, not included in Basic Program Cost Roll-up)**

BCB Assessment of Fielded Pb-free Products (OPTION: 10-YEAR RELIABILITY ASSESSMENT NOT INCLUDED IN BASIC PROGRAM)

Description: This project will assess the performance of as-manufactured, Pb-free product in the field, including a full documentation of failure rates and failure modes. Methodologies will be proven with which to document repair activities as well as performing failure mode analysis on hardware that will be returned to service. An assessment will also include the field performance of *repaired* Pb-free product.

BCBA: Develop the methodology and procedures to assess the failure rates of the Pb-free product that is in the field. This methodology includes the tracking of failures by site and duration of service as well as a detailed documentation of the performance drop leading to a failure. This task shall be supported for a period no less than that required to obtain repairable failure greater than, or equal to, 25% of the units.

BCBB: Construct a methodology to perform failure analysis on hardware. This step includes the retention of damage parts for root-cause analysis. It will also require that the limits be designated as to the level of failure mode analysis performed on the hardware to be repaired and then returned to the field.

BCBC: Assess the performance of fielded Pb-free units that have undergone repair activity. This task shall be supported for a period of no less 75% of the total time required to obtain 25% total failures of the as-manufactured units.

Gaps Addressed: A Lack of experience with Pb-free solder electronics, including failure rates and failure modes. (See Exhibit A, Gap S19)

Expected Results:

- Field failure data will be obtained for *as-manufactured* Pb-free product.
- Methods will be developed to perform failure mode analysis on hardware that will return to service.
- Field failure data will be obtained for a *repaired* Pb-free product.

Deliverables:

- Assessment of as-fabricated, fielded Pb-free assemblies that reports upon field failures, including use conditions and failure mode analysis, that occurred over a duration of 66 months or, if possible, a duration so that greater than, or equal to, 25% of the fielded units had repairable failures. – Month 72
- *Repaired*: Assessment of field failures on repaired Pb-free hardware that includes use conditions and failure mode analysis for a period of 114 months or, if possible, no less 75% of the total time that was required to obtain 25% total failures in as-manufactured units. – Month 120

Interdependencies:

Needs: None

Collaborate:

- BA, A&D Manufacturing Process – The process parameters can be obtained to bracket the assembly processes to direct the hardware manufacturing effort.
- BB, Development and Validation of Qualification and Acceptance Tests for Pb-Free Products – This process will assist with the development of these two tests; but the methods to and test parameters will be determined, independently, in this project.
- DA, Component Assembly Processing and Life – understanding the survivability of components exposed to Pb-free process.

Feeds:

- AA, Tin Whisker Failure Modes – The failure modes must be understood if they occur during the field.
- AB, Tin Whisker Mitigation – The success of these procedures will be assessed.
- AC, Tin Whisker Risk Assessment – Understand the likelihood of a failure due to the observation of whiskers, if any, in these units.
- CA, Solder Joint Reliability Model – the solder reliability models will benefit from a validation by field data, including failure rate as well as failure mode.
- CB, Solder Joint Reliability Effects – obtain actual data that documents the effects of service conditions on the reliability of the solder joints

Schedule:

- Start Month: 1
- Expected Duration: 120 months

ROM Cost: $607K **(Cost for first three years of Optional 10-Year Reliability Assessment, not included in Basic Program Cost Roll-up)**

C Solder Joints

Description: This major project area was formulated in terms of a set of strongly interdependent tasks to develop the capabilities to assess and predict the reliability of lead free solder joints in service. A few alloys and mixtures of alloys shall be selected based on common usage and availability. Acceleration factors and actual reliability models shall be validated, emphasizing long term service applications, by establishing a quantitative understanding of the underlying mechanisms.

A set of representative, generic service scenarios shall be identified and the capabilities to assess life under these shall be developed. Available data shall be collected and carefully assessed for use in model validation. Suitable test vehicles shall be designed and assembled for use in thermal cycling, vibration, shock and drop testing, ensuring comparability across tasks. Accelerated testing will be conducted for a carefully selected range of test parameters and results used to develop convenient expressions for the acceleration factors to service.

Modeling and extrapolations are greatly complicated by the sensitivity to design and process parameters and the continuous variation of solder properties during loading and long term aging. Each of these factors is taken into account through the development of dynamically adaptive constitutive relations based on correlations between microstructure and properties quantified during testing.

The ultimate goal is the development of a comprehensive solder reliability model accounting for failure due to thermal fatigue, vibration, drop, shock, creep rupture and combinations of these. The effects of combinations are the subject of a separate task.

Gaps Addressed:

- Existing ESS tests may not be valid for Pb-free solders.
- Lack appropriate computational models for solder joints that address thermo-mechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration.
- The absence of credible predictive models for the failure of solder joints in shock and drop (including pyrotechnic shock) is largely due to insufficient assembly test data, including effects of low temperatures and/or preconditioning (storage).
- Need systematic data on distributions of failure under a range of thermal and mechanical cycling conditions, including effects of aging.
- Need simpler acceleration factor models and heuristic rules of Pb-free solders.
- There is a clear need for rules for mixed solder applications.
- Pb-free material corrosion rates in A&D service environments are not well understood and increase reliability risk.
- Lack knowledge on the effect of contamination on the properties of Pb-free solders.
- Standardized test vehicles are needed to quantify interactions and conduct comparisons of effects.

Expected Results:

- Qualified set of materials for use in A&D applications.
- Models for assessing life and reduction in life due to exposure to environmental stress screens.
- Solder qualification requirements.
- A consistent set of models and data for assessing life expectancy of qualified set of solder materials.
- Order of magnitude ranking for influences of
    - Electro-migration
    - Corrosion
    - Board Finish/Multiple reflows
    - Tin pest
- Solder acceptance screening requirements.
- Insertion mount fill requirements and rework limits.
- Soldered assembly handling guidelines.

Deliverables:

- Validated models for the prediction of life in service.
- Modulus and CTE of realistic solder bumps correlated with microstructure.
- Preliminary predictions of effects of different combinations of loading on solder properties.
- Dynamically adaptive constitutive relations for realistic solder joints.
- Preliminary accelerated test protocols and ‘best guess’ acceleration factors to life in service.
- Preliminary failure distribution data for reliability model development.

- Preliminary data on microstructure evolution for constitutive relations study.
- Reference failure data for combined loading studies.
- Systematic data for reliability model development.
- Comprehensive data base on reliability and associated damage and microstructure evolution.
- Guidelines to ensure the same failure mechanism in accelerated test and service.
- Final accelerated test protocols and acceleration factors to long-term service.
- Protocols for the prediction of early failures.
- Solder joint design rules.
- Reports on impact of current, corrosive environments, rework/repair, board material, board pad finish, solder paste on solder joint reliability.
- Report on factors that promote formation of tin pest.
- Report on degree of mixing of lead-free BGAs including SAC405, SAC305, and SAC105 solder balls with SnPb solder depending on reflow parameters.
- Report describing Harsh Environment reliability results, conclusions and recommendations on process parameters for reliable mixed SnPb solder/ SAC solders components including SAC405, SAC305, and SAC105 solder balls.
- Report on BGA with additives to the lead-free solder ball materials, selection for performance in Harsh A&D environment, and recommendations on SnPb and SAC305 assembly parameters.
- Report describing results, conclusions and recommendations on high performance lead-free solder for A&D.
- Report describing results, conclusions and recommendations on Low Melt Solder rework solution for A&D.
- Report providing recommendations on test methods for evaluation of new solder materials.
- Report describing the results and conclusions on PTH hole fill needed to ensure reliable system assembly.
- Report describing the results and conclusions on minimum remaining copper plating thickness after assembly and rework using different solder alloys that insure reliability for the A&D applications.
- Report documenting recommendations for acceptable PCB strain, strain rate and deflection in handling for design roles in the A&D industry with identification of conditions and combinations that warrant further study.

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $42.4M

CA Solder Joint Reliability Models

Description: This project was formulated in terms of a set of interdependent tasks to develop the capabilities to assess and predict the reliability of lead free solder joints in service. A few alloys and mixtures of alloys shall be selected based on common usage and availability. Acceleration factors and actual reliability models shall be validated, emphasizing long-term service applications, by establishing a quantitative understanding of the underlying mechanisms.

A set of representative, generic service scenarios shall be identified and the capabilities to assess life under these developed. Available data shall be collected and carefully assessed for use in model validation. Suitable test vehicles shall be designed and assembled for use in thermal cycling, vibration, shock and drop testing, ensuring comparability across tasks. Accelerated testing will be conducted for a carefully selected range of test parameters and results used to develop convenient expressions for the acceleration factors to service.

Modeling and extrapolations are greatly complicated by the sensitivity to design and process parameters and the continuous variation of solder properties during loading and long-term aging. Each of these factors is taken into account through the development of dynamically adaptive constitutive relations based on correlations between microstructure and properties quantified during testing.

The ultimate goal is the development of a comprehensive solder reliability model accounting for failure due to thermal fatigue, vibration, drop, shock, creep rupture and combinations of these. The effects of combinations are the subject of a separate task.

Gaps Addressed: Nobody currently has the capability to predict the reliability of lead free solder joints under realistic long-term service conditions with the necessary degree of fidelity, nor even to decide which among a set of materials, design, or process alternatives will perform best in service.

Expected Results: The industry will have the tools required to optimize and assess the reliability of lead free solder based electronics products in service.

Deliverables: Validated models for the prediction of life in service.

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $22,406K

CAA Test Vehicle Design and Fabrication

Description: This task will serve as a shared support for a number of other tasks. Common test vehicles shall be employed in these other tasks to the extent possible.

CAAA: Daisy-chained model components shall be designed to simulate BGAs, CSPs, flip chips and LGAs and passives, effectively spanning the relevant range of solder microstructures and resulting properties. The BGA, CSP and flip chip designs will be produced with solder balls of SAC305, SnAg, SAC105, and SnPb.

CAAB: A representative range of commercial (daisy-chained) components shall be procured for cross checking and calibration of results achieved with the model components. These shall include components known to have particularly limited life such as passives and TSOPs.

CAAC: A range of different PCB designs shall be developed in collaboration with the other tasks to accommodate thermal cycling, cyclic bending, drop and vibration testing. The pad designs shall normally be optimized to favor solder failure, as opposed to pad cratering or intermetallic bond failure. A special, solder mask defined, design shall be developed to allow the study of intermetallic bond failures.

CAAD: Components and PCBs shall all be thoroughly characterized in terms of effective modulus and CTE vs. temperature, above and below T_g, as well as warpage vs. temperature during reflow and thermal cycling.

CAAE: Test vehicles shall be assembled with two different reflow profiles and both SAC305 solder paste and two different volumes of SnPb solder paste each. In addition, passives shall also be assembled with SN100C paste to simulate wave-soldered assemblies.

Gaps Addressed: A large number of projects addressing critical gaps all need similar test vehicles. Standardization will help quantify interactions and relations, as well as saving money.

Expected Results: Standardized test vehicles will be available for different tests and comparisons of effects.

Deliverables: Test vehicles for other tasks – Month 12

Interdependencies:
Needs: None

Collaborate:
- CAC, Materials Properties & Constitutive Relations = PCB design input
- CAD, Thermal Expansion Mismatch Induced Fatigue = PCB design input
- CAE, Vibration = PCB design input
- CAF, Combined Loading = PCB design input
- CAG, Shock and Drop = PCB design input
- CAC, Materials Properties & Constitutive Relations = Test Vehicles
- CAD, Thermal Expansion Mismatch Induced Fatigue = Test Vehicles
- CAE, Vibration = Test Vehicles
- CAF, Combined Loading = Test Vehicles
- CAG, Shock and Drop = Test Vehicles
- CBA, Electromigration = Test Vehicles
- CBB, Corrosion Effects = Test Vehicles
- CBC, Reflow Effects = Test Vehicles
- CCC, Life Testing = Test Vehicles
- CD, New Solders and Compatibility with A&D = Test Vehicles

Feeds: None

Schedule:
- Start Month: 1
- Expected Duration: 12 Months

ROM Cost: $708K

CAB Validation Data Collection and Assessment

Description: Available solder joint reliability test data shall be collected, together with all possible experimental details, component and PWB properties, etc. The credibility and completeness of the available information shall be carefully assessed and uncertainties assigned to the data. Contact shall be made with the original experimenters and/or owners of the data for verifications and further details.

A survey of the industry and users (the military) shall be conducted to complement currently available representative examples of challenging service conditions for which the military has a particular need to assess long-term life.

Gaps Addressed: The paucity of appropriately documented assembly test data poses a major obstacle to the formulation and validation of predictive failure models. (See Exhibit A, D03; D14)

Expected Results: All available data will be accounted for in critical model validation. Anticipated systematic trends will be identified for further quantification. Reliability assessment approaches and models will consider all possible service conditions when extrapolating accelerated test results.

Deliverables: Reliability data from different sources for use in reliability model validation. A complete range of possible 'service scenarios' for which models must apply. – Month 6

Interdependencies:

Needs: None

Collaborate:

- CAC, Materials Properties & Constitutive Relations = Test Vehicles
- CAD, Thermal Expansion Mismatch Induced Fatigue = Anticipated trends
- CAE, Vibration = Anticipated trends
- CAF, Combined Loading = Anticipated trends
- CAG, Shock and Drop = Anticipated trends

Feeds:

- CAJ, Reliability Modeling = Anticipated trends and data for validation
- PERM Consortium – Research findings

Schedule:

- Start Month: 1
- Expected Duration: 6 Months

ROM Cost: $128K

CAC Materials Properties & Constitutive Relations

Description: Constitutive relations shall be developed that describe the evolution of deformation and damage propagation (damage resistance) properties as a function of time, temperature and loading history. Credibility of extrapolations shall be established through a quantitative relationship between the solder properties and fundamental materials features and mechanisms. All data generated under other tasks shall be incorporated to minimize the current task. Mixing lead free joints with SnPb solder will change the properties to a degree that varies strongly with the specific Pb concentration, i.e., general constitutive relations will not be meaningful, but two examples will be considered.

CACA: A detailed test matrix shall be developed and submitted for approval based on the general requirements outlined below. Details shall be modified to reflect the latest knowledge and understanding, in collaboration with task CAJ, but the overall workload shall remain the same. The matrix shall be structured so that the overwhelming majority of data becomes available after 30 months or less.

CACB: Special test structures shall be defined to allow the standardized testing of solder microstructures typical of realistic assemblies. Such structures shall be produced with the solder alloy combinations defined under task CAA. Creep properties for five different loads shall be measured on these structures at each of five different temperatures ranging from -25°C to 150°C. Isothermal strain controlled fatigue life shall be measured for three different peak strains at the same temperatures.

CACC: Each fatigue life test shall be interrupted at selected stages of the fatigue life and samples removed for microstructure analysis to quantify precipitate distributions and sizes, dendritic dimensions, Sn grain sizes and numbers, as well as the individual Sn grain orientations. Microstructure analysis shall also quantify the onset and progression of recrystallization and crack growth.

CACD: Depending on component and substrate properties real solder joint loading conditions in cycling range somewhere between constant stress and constant strain conditions. Realistic solder bumps on both Cu (OSP) and Ni/Au coated solder pads shall therefore also be tested to quantify and compare the number of cycles to failure in both stress-controlled and strain-controlled cycling. For each of three different temperatures, testing shall employ three different peak stresses and three different peak

strains selected to give a range of characteristic failure life values ranging from a few cycles to 50,000. An effective average test time to failure should not exceed one hour. At least 12 replicates shall be tested for each combination of test parameters, alloys and solder volume. The combination of two solder volumes and two solder alloys defined under task CAA shall be included in the matrix, as shall one volume of the SN100C. Also included shall be SAC305 balls soldered with five different, carefully quantified, SnPb volumes.

CACE: These samples shall all be subjected to microstructure analysis after testing to quantify precipitate distributions and sizes, dendritic dimensions, Sn grain sizes and numbers, and the degree of recrystallization if any. Each of the 10 combinations of solder alloy and volume shall also be analyzed like this before testing. It is anticipated that each of the 190 variations shall require one day of high quality SEM analysis as well as careful image analysis.

CACF: Following microstructure analysis the 10 different solder joint configurations shall also be tested for creep response at three different loads at each of three different temperatures, both before and after testing under a single selected cycling condition, using either nano-indentation or an impression creep test. Separate bumps shall be characterized in terms of modulus and CTE.

CACG: Specially designed test vehicles shall allow the simultaneous cycling and individual monitoring of a significant number of solder joints subject to essentially identical loading along two opposite rows of the assembly in cyclic bending. Each test shall proceed until at least 16 failures have been recorded. BGA, CSP, flip chip, and LGA joints with the solder alloy combinations defined under task CAA shall be cycled with three different amplitudes each at three different temperatures as above. Amplitudes shall be selected to provide a wide range of life times with an effective average one week per test. Results shall be correlated with the above results for stress and strain controlled cycling.

CACH: All failed joints shall be analyzed to quantify Sn grain sizes and numbers, voids and other defects, and the degree of recrystallization if any. In addition, solder microstructures shall be quantified to the necessary statistical degree in terms of secondary precipitate distributions and sizes, as well as associated dendritic dimensions, before and after cycling.

CACI: Following microstructure analysis samples from each of the 72 bending tests shall be tested for quantification of the creep response at four combinations of load and temperature using either nano-indentation or an impression creep test. Creep response before cycling shall be quantified as well. The results shall be correlated with Sn grain orientations measured by EBSD on the same samples.

CACJ: Separately, the same range of assemblies (CACG) shall be aged for four different lengths of time at three different temperatures. For each case solder microstructures shall be quantified to the necessary statistical degree in terms of secondary precipitate distributions and sizes, as well as associated dendritic dimensions. In this experiment, samples shall be cross-sectioned and microstructures quantified before aging, strongly reducing statistical scatter by measuring on the same joints before and after aging.

CACK: Another set of the same range of assemblies shall be aged for as long as is practical at each of the same three temperatures. Microstructures of the 120 samples (to be tested under the five creep conditions) shall be quantified, Sn grain orientations shall be measured by EBSD, and the creep properties measured before aging. The microstructure and creep properties of each shall be quantified, measuring on the same sample, after aging and the results correlated with the microstructure.

CACL: The above results and data obtained from tasks CAD, CAE, CAF, and CAG shall be analyzed and constitutive relations shall be established to account for effects of solder composition, volume, process, and thermomechanical history through quantitative relationships between properties and microstructure. Different relations shall predict the evolution of deformation properties, recrystallization, and crack growth properties.

CACM: Both sets of SAC305 assemblies (two different solder volumes) shall also be analyzed by EBSD to determine the Sn grain orientations, after failure in each of the nine tests in CACG, and correlated with the 16 values for measured life. Correlations between life and microstructure shall be analyzed and a mathematical approach developed to predict the functional shape of the statistical failure distribution for use in extrapolations to very early failures.

CACN: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: Insufficient information on solder materials prevents the formulation and validation of predictive models of solder joint fatigue, as well as the creation of simpler acceleration factor models and heuristic rules. (See Exhibit A, Gaps DO1, D14, D24, D25, D32, R04, S07, T05, D53, R06)

Expected Results: The ability to predict the evolution of realistic solder joint properties through any combination of temperature, time, and loading. Consistent use of the same constitutive relations across the A&D industry.

Deliverables:

- Preliminary predictions of effects of thermal aging on solder joint properties. – Month 18
- Modulus and CTE of realistic solder bumps correlated with microstructure. – Month 12
- Preliminary predictions of effects of different combinations of loading on solder properties. – Month 24
- Dynamically adaptive constitutive relations for realistic solder joints. – Month 33

Interdependencies:

Needs: None

Collaborate:

- CAA, Test Vehicle Design and Fabrication = Test vehicles
- CAD, Thermal Expansion Mismatch Induced Fatigue = creep data for joints after cyclic loading
- CAE, Vibration = creep data for joints after cyclic loading
- CAF, Combined Loading = creep data for joints after cycling, for validation
- CAG, Shock and Drop = creep data for joints after cyclic loading
- CAA, Test Vehicle Design and Fabrication = Design of Test vehicles
- CAD, Thermal Expansion Mismatch Induced Fatigue = creep measurements
- CAE, Vibration = creep measurements
- CAF, Combined Loading = creep measurements
- CAG, Shock and Drop = creep measurements
- CAJ, Reliability Modeling = Interpretation of results
- CAD, Thermal Expansion Mismatch Induced Fatigue = Definition of aging conditions
- CAE, Vibration = Definition of aging conditions
- CAF, Combined Loading = Definition of aging conditions
- CAG, Shock and Drop = Definition of aging conditions
- CAJ, Reliability Modeling = Constitutive relations

Feeds: PERM Handbooks

Schedule:

- Start Month: 1
- Expected Duration: 33 Months

ROM Cost: $3,423K

C**AD** **Thermal Cycling Induced Fatigue**

Description: A database of systematic and comprehensive accelerated thermal cycling results shall be established which can serve as the basis for validation of solder joint fatigue models and determination of acceleration factors in thermal cycling induced fatigue failure. This database shall include the statistical distributions of solder failure, failure mode, the associated evolution of solder microstructure and creep properties as a function of stress and time, and the physical and mechanical properties of the components and the circuit boards required as critical input into solder joint fatigue models. Accelerated test protocols and acceleration factors applicable to long-term service under representative conditions shall be developed based on this database. This shall include guidelines to ensure that the solder failure mechanism is the same in service and test (that both are equally affected by recrystallization).

CADA: Thermal cycling tests shall be designed to reveal and quantify interactive dependencies of life on maximum and minimum temperatures, dwell times at either of these temperatures, ramp rates and ΔT's. Test vehicle design and selection shall ensure the validation of predicted dependencies on stress, strain rates and effects of component warpage. Designs and test procedures shall ensure that individual components are removed as soon as they fail. Fifteen different sets of thermal cycling test parameters shall be employed, tests to failure lasting an estimated ***average*** of one year each. The selection of test parameters shall be subject to modification at any time when learning progresses. Each test shall include assemblies aged for two different lengths of time at 125°C. A detailed test matrix shall be developed and submitted for approval based on the preceding and subsequent general requirements outlined. Details shall be modified to reflect the latest knowledge and understanding, in collaboration with task CAJ, but the overall workload shall remain the same. The matrix shall be structured so that the overwhelming majority of data becomes available after 30 months or less.

CADB: Input shall be provided to task CAA for the design of test vehicles allowing for testing to failure within periods of 6-30 months.

CADC: Each test shall be interrupted after cycles corresponding to 0%, 25%, 50%, and 75% of the anticipated life. During each interruption, representative assemblies shall be removed for analysis: One model BGA, one flip chip, one LGA and one passive component, as well 4 commercial components (see CAA). BGAs with two sizes each of SAC305 and SAC105 balls, respectively, assembled with both SAC305 and SnPb paste (providing for two different Pb concentrations) shall be considered, as shall flip chips with one alloy. LGAs and passives, each assembled with both SAC305 and SnPb paste shall also be included. Furthermore, three of these combinations, each aged for two lengths of time at 125°C before cycling, shall be analyzed. Together with the four commercial components, this provides for a minimum of 23 different combinations of alloys, components and preconditioning.

The analysis shall include cross sectioning of two samples of each of the 23 different combinations to quantify Sn grain sizes and numbers, voids and other defects, and the degree of recrystallization if any. It shall also include dye-and-pry of five samples of each to quantify crack areas. Cross sections shall be tested for micro hardness.

CADD: 16 replicates of each combination shall be tested to failure, to the extent allowed by the 36-month schedule. All failures shall be cross-sectioned and analyzed as above. In addition, solder microstructures shall be quantified for the un-aged model components in terms of secondary precipitate distributions and sizes, as well as associated dendrite dimensions. Comparisons of measurements from before and after cycling will be used to establish kinetics of microstructure evolution, and statistical scatter shall be minimized and quantified. It is anticipated that each measurement shall require one day of high quality SEM analysis as well as detailed image analysis. In addition, creep properties shall be quantified before and after cycling for each case, using the same creep testing technique as employed for solder joints under task CAC, Materials Properties and Constitutive Relations.

CADE: Any dependence of the correlation between recrystallization and crack growth (see CADC) on cycling parameters shall be noted and used to propose guidelines to ensure that the solder failure mechanism is the same in service and test.

CADG: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: Insufficient, fully characterized assembly test data covering necessary parameter ranges prevents the formulation and validation of predictive models of solder joint fatigue, as well as of acceleration factors and heuristic rules. There is a clear need for rules for mixed solders. (See Exhibit A, Gaps D03, D14, D24, D53, R06)

Expected Results: Systematic data on distributions of failure under a range of thermal cycling conditions, including effects of aging, will serve as a comprehensive base for the development of reliability models. Correlations of failure with solder microstructure and its evolution in cycling, together with the characterization of damage evolution, will provide unique data for the formulation of mechanistically justified constitutive relations. Resulting failure models will account for systematic effects of design, materials, and process parameters.

Deliverables:

- Preliminary accelerated test protocols and 'best guess' acceleration factors to life in service. – Month 18
- Preliminary failure distribution data for reliability model development. – Month 18
- Preliminary data on microstructure evolution for constitutive relations study. – Month 18
- Reference failure data for combined loading studies. – Month 18
- Systematic data for reliability model development. – Month 30
- Comprehensive data base on reliability and associated damage and microstructure evolution. – Month 36
- Guidelines to ensure the same failure mechanism in accelerated test and service. – Month 36
- Final accelerated test protocols and acceleration factors to long-term service. – Month 36
- Protocols for the prediction of early failures. – Month 36
- Solder joint design rules. – Month 36

Interdependencies:

Needs: None

Collaborate:

- CAA, Test Vehicle Design and Fabrication = Test vehicles
- CAB, Validation Data Collection and Assessment = Credible observed trends for ongoing planning of cycling parameters. Definition of representative service conditions of interest.
- CAC, Materials Properties and Constitutive Relations = Predictions of aging effects for selection of preconditioning parameters, Data for constitutive relations development
- CAF, Combined Loading = Reference data for studies of effects
- CAJ, Reliability Modeling = Design of experiments and interpretation of results, data for model development
- CCD, Underfilling, Staking, and Coating Selection = Reference data for studies of effects.

Feeds: PERM Handbook

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $4,031K

CAE Vibration

Description: A systematic database of the statistical distributions of solder failure in accelerated vibration testing shall be established. These shall be correlated with solder microstructure and

creep properties for use in reliability model development. Accelerated test protocols and acceleration factors applicable to long-term service under representative conditions shall be developed. This shall include guidelines to ensure that the solder failure mechanism is the same in service and test.

CAEA: A detailed test matrix shall be developed and submitted for approval based on the requirements outlined below.

CAEB: Input shall be provided to task CAA for the design of test vehicles.

CAEC: Carefully designed narrowly banded vibration tests with different inputs shall be conducted at three different temperatures (high, medium, and low) chosen based on task CAB. It is currently anticipated that each test will need to be designed to ensure the same (known) total energy input to the solder joints no matter what the assembly resonance frequency (within a narrow range), but this requirement will be subject to revision. Three appropriately spaced input levels shall be chosen to cause failures after a wide range of test times. A carefully selected subset of assemblies shall be tested with levels that lead to failure after more than three months. Two different frequency ranges shall be tested to verify predictions of combined effects reached under task CAF, Combined Loading. Each test shall include assemblies aged for two different lengths of time at 125°C, providing for 23 different combinations of alloys and preconditioning (aging). The specifics of these requirements shall be subject to revision depending on results and ongoing learning. However, it is expected that a total of 25 or more assemblies will be undergoing vibration testing at any given time and that approximately 2500 assemblies will be tested and analyzed.

CAED: Each test shall be interrupted after cycles corresponding to 0%, 50%, and 75% of the anticipated life for one sample each of 23 different combinations of alloys and preconditioning (aging). That sample shall be cross-sectioned for microstructure analysis. The analysis shall quantify Sn grain sizes and numbers, voids and other defects, and the degree of recrystallization if any.

CAEE: A minimum of 10 replicates of each combination shall be tested to failure, to the extent allowed by the 36-month schedule. All failures shall be cross-sectioned and analyzed as above. In addition, solder microstructures shall be quantified for the un-aged model components in terms of secondary precipitate distributions and sizes, as well as associated dendritic dimensions. Comparisons of numbers from before and after cycling will be used to establish kinetics, and statistical scatter shall be minimized and quantified. It is anticipated that each number shall require one day of high quality SEM analysis as well as careful image analysis. In addition, creep properties shall be quantified before and after cycling for each case, using the same creep testing technique as employed for solder joints under task CAC, Materials Properties and Constitutive Relations.

CAEF: Any dependence of the correlation between recrystallization and crack growth on cycling parameters shall be noted and used to propose guidelines to ensure that the solder failure mechanism is the same in service and test.

CAEG: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: The absence of credible predictive models for the fatigue of solder joints in vibration is largely due to insufficient assembly test data, including effects of preconditioning (storage). There is also a clear need for improved, simple acceleration factor models and heuristic rules. Special rules are needed to ensure the reliability of mixed solders. (See Exhibit A, Gap D03, D14, D15, D24, D53, R06, D33, R04)

Expected Results: Systematic data on distributions of failure under a range of vibration conditions, including effects of aging, will serve as a comprehensive base for the development of reliability models. Correlations of failure with solder microstructure and its evolution in cycling, together with the characterization of damage evolution, will provide unique data for the formulation

of mechanistically justified constitutive relations. Resulting failure models will account for systematic effects of design, materials, and process parameters.

Deliverables:

- Preliminary accelerated test protocols and 'best guess' acceleration factors to life in service. – Month 18
- Preliminary failure distribution data for reliability model development. – Month 18
- Preliminary data on microstructure evolution for constitutive relations study. – Month 18
- Reference failure data for combined loading studies. – Month 18
- Systematic data for reliability model development. – Month 30
- Comprehensive data base on reliability and associated damage and microstructure evolution. – Month 36
- Final accelerated test protocols and acceleration factors to long-term service. – Month 36
- Protocols for the prediction of early failures. – Month 36
- Solder joint design rules. – Month 36

Interdependencies:

Needs: None

Collaborate:

- CAA, Test Vehicle Design and Fabrication = Test vehicles
- CAB, Validation Data Collection and Assessment = Definition of representative service temperatures and other conditions of interest.
- CAC, Materials Properties and Constitutive Relations = Predictions of aging effects for selection of preconditioning parameters.
- CAF, Combined Loading = Predictions of effects of frequency range.
- CAJ, Reliability Modeling = Design of experiments and interpretation of results
- CCD, Underfilling, Staking, and Coating Selection = Reference data for studies of effects.

Feeds: PERM Research/Handbook

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $3,550K

CAF Combined Loading

Description: A systematic database of the statistical distributions of solder failure under various combinations of loading shall be established. These shall be correlated with solder microstructure and creep properties for use in reliability model development. Accelerated test protocols and guidelines for the assessment of damage accumulation shall be developed. This shall include guidelines to ensure that the solder failure mechanism is the same in service and test.

CAFA: Input shall be provided to task CAA for the design of test vehicles allowing for testing to failure within periods of 6-30 months.

CAFB: Existing linear and non-linear damage accumulation models shall be critically reviewed in terms of potential for adaptation to sequential loading and accounting for observed trends. Combined loading experiments shall be designed and conducted to test the applicability of combinations of these models and constitutive relations developed under task CAC. These experiments shall include sequential combinations of vibration with vibration, thermal cycling with thermal cycling (including effects of mini-cycles), and vibration with thermal cycling, shock (incl. single shock) with vibration, and shock with thermal cycling.

CAFC: Applicable models, if any, shall be critically reviewed and tested in terms of applicability to simultaneous loading. These experiments shall include random vibration, as well as simultaneous vibration and thermal cycling. The latter shall include at least four combinations of vibration levels and thermal cycling profiles.

CAFD: The concept of simultaneous damage evolution and evolution of solder properties shall be analyzed theoretically and an approach to extract effective values for the damage function as a function of solder properties, using the constitutive relations for deformation established under task CAC, shall be developed. Experiments shall be designed to validate this approach and extract values for the solder alloys and alloys combination defined under task CAA.

CAFE: A systematic database of statistical distributions of failure under different combinations of loading (see above) shall be established. These shall include testing of assemblies aged for two different lengths of time at different stages of the loading histories. Each test shall be interrupted after various numbers of cycles. During each interruption, representative assemblies shall be removed for analysis. Analysis shall include cross sectioning for microstructure analysis and creep testing. Microstructure analysis shall quantify precipitate distributions and sizes, dendritic dimensions, Sn grain sizes and numbers, voiding and other defects. Microstructure analysis shall also quantify the onset and progression of recrystallization and crack growth. The creep testing technique shall be the same as employed for solder joints under task CAC, Materials Properties and Constitutive Relations.

CAFF: Cycling shall continue to failure of at least 85% of the samples in each test. All failures shall be carefully analyzed, quantifying the microstructures of the failed joints as above as well as measuring the individual Sn grain orientations. Other joints exhibiting larger cracks than anticipated based on their location shall be similarly analyzed.

CAFG: Any dependence of the correlation between recrystallization and crack growth on cycling parameters shall be noted and used to propose guidelines to ensure that the solder failure mechanism is the same in service and test.

CAFH: A systematic study shall be conducted to assess the effects of common ESS procedures on life under various long-term service conditions.

CAFG: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: Existing ESS tests may not be valid for lead free solders. The absence of credible predictive models for the fatigue of solder joints is largely due to insufficient assembly test data, including effects of preconditioning (storage). This is particularly critical for conditions where more than one level or type of load is applied, sequentially or simultaneously. There is also a clear need for improved, simple acceleration factor models and heuristic rules. Design guidelines may change and special rules are needed to ensure the reliability of mixed solders. (See Exhibit A, Gap D03, D14, D24, D29, D53, R06, D18, D32)

Expected Results: The data and mechanistic understanding of damage accumulation required to account for the combinations of different loads, sequential and simultaneous, typical of long-term service conditions in the reliability model to be developed under task CAJ.

Deliverables:

- Preliminary accelerated test protocols and guidelines for assessment of life under combined loads. – Month 18
- Preliminary failure distribution data for reliability model development. – Month 18
- Systematic data on creep and microstructure evolution for development and validation of constitutive relations. – Month 36
- Theoretical understanding of damage accumulation. – Month 36
- Systematic data for reliability model development. – Month 36

- Guidelines to ensure the same failure mechanism in accelerated test and service. – Month 36
- Final accelerated test protocols and guidelines for the assessment of damage functions. – Month 36
- Solder joint design rules. – Month 36

Interdependencies:
Needs: None

Collaborate:
- CAA, Test Vehicle Design and Fabrication = Test vehicles
- CAB, Validation Data Collection and Assessment = Definition of representative service conditions of interest.
- CAC, Materials Properties and Constitutive Relations = Constitutive relations accounting for effects of cycling on solder properties., Data for constitutive relations development
- CAD, Thermal Expansion Mismatch Induced Fatigue = Data on life under individual cycling conditions
- CAE, Vibration = Data on life under individual cycling conditions
- CAG, Shock and Drop = Data on life under individual cycling conditions
- CAJ, Reliability Modeling = Design of experiments and interpretation of results. Development of understanding of damage accumulation, Data for reliability model development.

Feeds: PERM research/handbooks

Schedule:
- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $6,010K

CAG Shock and Drop

Description: A systematic database of the statistical distributions of solder failure in selected shock and drop tests shall be established. These shall be correlated with solder microstructure and creep properties for use in reliability model development. Test protocols together with guidelines for the generalization of test results to all the variations of conditions encountered under typical service conditions shall be recommended.

CAGA: A detailed test matrix shall be developed and submitted for approval based on the requirements outlined below.

CAGB: Input shall be provided to task CAA for the design of test vehicles.

CAGC: A carefully selected range of shock and drop tests shall be conducted to quantify systematic dependencies on strain rates, stress, and temperature. A combination of test vehicle instrumentation and simple mechanics modeling shall be used to determine these primary parameters for the solder joints that fail. The range of peak loads and loading rates shall be selected to induce failure after a number of cycles ranging from one to several hundred. Pyrotechnic shock conditions shall be systematically investigated. Tests shall be conducted at five different temperatures selected to include the lowest and highest temperatures ever encountered in service according to task CAB. Each test shall include assemblies aged for four different lengths of time at three different elevated temperatures. The specifics of these requirements shall be subject to revision depending on results and ongoing learning. A minimum of 16 samples shall be tested for each condition.

CAGD: Each test shall be interrupted after cycles corresponding to 0%, 20%, 40%, 60%, and 80% of the anticipated life for 12 samples each. Four of these samples shall be cross-sectioned for

microstructure analysis and creep testing. The other eight shall be tested in dye-and-pry to quantify crack areas followed by microstructure analysis. Microstructure analysis shall quantify precipitate distributions and sizes, dendritic dimensions, Sn grain sizes and numbers, voiding and other defects. The creep testing technique shall be the same as employed for solder joints under task CAC, Materials Properties and Constitutive Relations.

CAGE: All failures shall be carefully analyzed, quantifying the microstructures of the failed joints as above as well as measuring the individual Sn grain orientations.

CAGF: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: The absence of credible predictive models for the failure of solder joints in shock and drop (including pyrotechnic shock) is largely due to insufficient assembly test data, including effects of low temperatures and/or preconditioning (storage). There is also a clear need for improved, simple acceleration factor models and heuristic rules. Design guidelines may change and special rules are needed to ensure the reliability of mixed solders. (See Exhibit A, Gap ID D03, D16, D17, D24, D34, D53, D58, R06, R04)

Expected Results: Systematic data on distributions of failure under a range of shock and drop conditions, including pyrotechnic shock, will serve as a comprehensive base for the development of reliability models. Data will include effects of aging time and temperature. Correlations of failure with solder microstructure and its evolution, together with the characterization of damage evolution, will provide unique data for the formulation of mechanistically justified failure models to account for systematic effects of design, materials, and process parameters.

Test protocols together with guidelines for the generalization of test results to all the variations of conditions encountered under typical service conditions shall be recommended.

Deliverables:

- Preliminary failure distribution data for reliability model development. – Month 12
- Reference failure data for combined loading studies. – Month 12
- Systematic data for reliability model development. – Month 24
- Test protocols and guidelines for the generalization of test results. – Month 24
- Protocols for the prediction of early failures. – Month 24
- Solder joint design rules, including for pyrotechnic shock conditions. – Month 24

Interdependencies:

Needs: None

Collaborate:

- CAA, Test Vehicle Design and Fabrication = Test vehicles
- CAB, Validation Data Collection and Assessment = Definition of representative service temperatures and other conditions of interest.
- CAC, Materials Properties and Constitutive Relations = Predictions of aging effects for selection of preconditioning parameters.
- CAF, Combined Loading = Reference data for studies of effects
- CAA, Test Vehicle Design and Fabrication = Design of Test vehicles
- CAJ, Reliability Modeling = Design of experiments and interpretation of results, Data for model development
- CCD, Underfilling, Staking, and Coating Selection = Reference data for studies of effects.

Feeds: PERM Research/Handbook

Schedule:

- Start Month: 1

- Expected Duration: 24 Months

ROM Cost: $862K

CAH Creep Rupture

Description: Guidelines shall be developed for the rapid prediction of time to creep rupture failure under various conditions of load, temperature and thermomechanical history and relevant materials data quantified.

Solder joints representative of the attachment of a wire to a terminal shall be tested under constant load creep, simulating a gravitational load, at three different loads each at three different temperatures. Samples shall include some preconditioned for two different lengths of time at each of three different aging temperatures. Steady state creep rates shall be established and strain or time to failure measured when possible. The solder microstructure shall be quantified before and after testing and compared to predictions based on the constitutive relations established under task CAC. SAC305 and SN100C solders shall be considered.

Gaps Addressed: The lack of validated failure models prevents accurate failure prediction, test development and creation of heuristic rules. (See Exhibit A, Gap D01, D24, R05)

Expected Results: Design tools will prevent creep rupture.

Deliverables: Guidelines for the prediction of time to creep rupture. – Month 36

Interdependencies:
Needs: None

Collaborate:
- CAC, Materials Properties & Constitutive Relations = Data or predictions of microstructure evolution.
- CAJ, Reliability Modeling = Prediction of time to failure

Feeds: PERM Research/Standards

Schedule:
- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $160K

CAI An Optimized Test Approach for Additional Alloys

Description: The available results and conclusions from the other solder joint testing tasks shall be carefully reviewed. A new, reduced test plan sufficient for testing of additional solder alloys shall be defined based on this.

Gaps Addressed: Current lead free solder alloys may be inappropriate for some A&D products, and the consumer electronics industry continues its search for better materials as well. There is a clear need for an affordable approach to the assessment and characterization of additional, including future, alloys (See Exhibit A, Gaps D01, D03, D13, D14, D17, D23, R06)

Expected Results: Additional alloys may be characterized and compared in a manner consistent with the present work but at an expense that may be affordable and justifiable to industry.

Deliverables: A comprehensive test plan for the complete characterization of a solder alloy in terms of reliability. – Month 31

Interdependencies:
Needs: None

Collaborate:
- CAC, Materials Properties & Constitutive Relations = Functional shapes of relations, so that only constants need to be measured
- CAJ, Reliability Modeling = General model
- CAD, Thermal Expansion Mismatch Induced Fatigue = Experiences
- CAE, Vibration = Experiences
- CAF, Combined Loading = Experiences
- CAG, Shock and Drop = Experiences
- CAH, Creep Rupture = Experiences

Feeds: PERM Research/Handbook

Schedule:
- Start Month: 25
- Expected Duration: 6 Months

ROM Cost: $95K

CAJ Reliability Modeling

Description: Individual life prediction models for different failure modes shall be developed and combined into a comprehensive computational model predicting failure rates and life under conditions of thermal fatigue, vibration, shock and drop, creep rupture and combinations of these.

CAJA: The available validation data shall be used for critical evaluation of existing, publicly available models and apparent trends used for input to reliability testing tasks and preliminary structuring of an improved model.

CAJB: Constitutive relations shall be adapted into existing models, where possible, as well as the improved model.

CAJC: Data on solder failure distributions from thermal fatigue, vibration, shock and drop, creep rupture and combined loading testing shall be analyzed, together with the associated microstructure evolution and solder properties, and the preliminary model updated to account for these. The model shall be validated against available data. The underlying philosophy behind this is that life times depend on the initial solder microstructure and its evolution during cycling. The former must be calibrated by comparison of predictions to an accelerated test result, while the latter is determined by the constitutive relations developed under task CAC. Validation shall therefore focus on cases where test vehicles assembled under the same process conditions have been tested in two different cycles.

CAJD: The cratering lifetime model developed under another task shall be incorporated in the final reliability model. The model shall be validated against available data.

CAJE: A model shall be developed for predicting the distribution of intermetallic failures under conditions of vibration, shock and drop, and combinations of different loading modes.

1. Different volumes of the solder alloys selected under task CAA shall be soldered to different size pads with Cu (OSP), ENIG, and electrolytic Ni/Au finishes using a representative range of reflow profiles.
2. Intermetallic microstructures shall be characterized for different combinations of solder alloy, pad finishes, and processes. Effects of aging for three different times at three different elevated temperatures shall be assessed and a quantitative understanding established.
3. A systematic database shall be established of the ultimate strengths and fatigue resistances of these structures as a function of peak load and strain rate. The data shall be correlated with the associated microstructures and thus with materials and processes. Effects of aging temperatures and times shall be quantified and correlated with the microstructure evolution.
4. A mechanics based model shall be developed based on this.
5. Predictions shall be validated against vibration, shock and drop test results for assemblies.
6. Pad design guidelines shall be developed to balance risks of pad cratering, intermetallic failure and trace cracking under service conditions.

CAJF: The intermetallic bond lifetime model shall be incorporated in the final reliability model.

CAJG: A critical set of validation experiments shall be defined, based on the final model, and conducted.

CAJH: Predicted life times shall be used to check and possibly improve the simpler, but probably more practical, acceleration factors expressions and the design rules developed as parts of the individual tasks on thermal fatigue, vibration, shock and drop, creep rupture and combinations of loading.

CAJI: 'What if' studies shall be conducted to test the assumptions underlying the accelerated test protocols proposed for thermal cycling, vibration, shock and drop, creep rupture and combinations of loading.

CAJJ: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: An absence of validated, predictive failure models prevents accurate life prediction, test development and the creation of heuristic rules (See Exhibit A, Gaps D14, D15, D16, D17, D18, D20, D21, D24, D25)

Expected Results: A comprehensive computational life prediction model, accounting for the competing effect of pad cratering as well as the failure of intermetallic bonds and solder, will be available to the A&D community. The model will extrapolate accelerated test results to failure, accounting for systematic effects of design, materials, and process parameters. Mechanistically justified and validated against an exceptionally broad range of data this model will offer a unique level of confidence in predictions of long-term life in service.

Deliverables:

- Final design guidelines for reliability optimization. – Month 24
- A comprehensive reliability prediction model that can be implemented across the A&D community. – Month 36
- Final improvements to test protocols, acceleration factors and design rules. – Month 36

Interdependencies:

Needs: CAB, Validation Data Collection and Assessment = Representative service conditions and validation data

Collaborate:

- CAC, Materials Properties and Constitutive Relations = Input for the model
- CAD, Thermal Expansion Mismatch Induced Fatigue = Data, Design of experiments and interpretation of results, Improvements to test protocols, acceleration factors, and design rules

- CAE, Vibration = Data, Design of experiments and interpretation of results
- CAF, Combined Loading = Data, Design of experiments and interpretation of results
- CAG, Shock and Drop = Data, Design of experiments and interpretation of results
- CAH, Creep Rupture = Data, Design of experiments and interpretation of results
- CCD, Underfilling, Staking, and Coating Selection = Integration of solder fatigue into model for underfilled systems
- CAI: Improved test protocols

Feeds: PERM: Improved test protocols, acceleration factors, models to predict test and field performance

Schedule:

- Start Month: 6
- Expected Duration: 36 Months

ROM Cost: $3,440K

CB Solder Joint Reliability Effects

Description: A number of conditions play a role in solder joint reliability. Work package CA addresses the primary recognized and tested conditions and provides a detailed research plan to provide data and models to allow for reliable production in A&D application. This work package is designed to complement the CA and examine other detrimental factors to solder joint reliability that are not characterized and that may be detrimental to solder joint reliability. With close examination of phenomenon identified in this work package, unexpected and unpredicted earlier failures may occur in A&D applications. Areas of concern include:

- Role of electrical current
- Role of elevated corrosive environments
- Role of rework/repair
- Role of board material and finish
- Role of solder paste
- Determine factors influencing the formation of tin pest

Gaps Addressed:

- Predictive models of the solder joint electromigration phenomenon under high current density conditions are not well understood for Pb-free alloys. This is a lack of understanding on how the correlation between the solder alloy and test condition will affect the results.
- The Pb-free material corrosion rates and how they correlate to service environments is not fully understood, resulting in increased reliability risk. This includes corrosive interactions with solder, PCB finishes, and component finishes, under powered and off storage conditions within A&D environments.
- There is a lack of understanding on what the additional stresses of rework/repair will do to Pb-free assemblies.
- There is no defined specification for the maximum amount of reflow cycles and limitation requirements for each part/component that undergoes repair/rework cycles.
- There is a lack of appropriate and validated failure models, which prevents accurate failure prediction, test development, and creation of heuristic rules on assemblies which have been influenced by prior events, such as environmental stress and field conditions.
- There is a lack of standards/requirements to address receiving inspection in sustainment situations for tin whisker identification.
- The current Pb-free materials are insufficient to test for tin pest on A&D products.
- The variation in solder joint reliability can arise from a variety of sources. Presently there is no reliable method of assigning cause to the large variation in reliability for Pb-free solders.

Expected Results:

- Order of magnitude ranking for influences of
  - Electromigration
  - Corrosion
  - Board Finish/Multiple reflows
  - Tin pest
  - Wave Solder Contamination

Deliverables: Reports on impact of current, corrosive environments, rework/repair, board material, board pad finish, solder paste on solder joint reliability. Report on factors that promote formation of tin pest. – Month 36

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $7,092K

CBA Current Density Effects (Electromigration)

Description: This project addresses the knowledge gaps regarding current density effects on solder life with the following objectives:

CBAA: Summarize literature on current density and electromigration on solder joint life expectancy.

CBAB: Define test plan to determine time and current level influence on electro migration for SAC305, SnAg, SAC105, and SnPb solder spheres attached with SAC305 and SnPb solder paste, with bare copper and nickel over copper lands. Solder spheres < 350 micron and > 600 microns will be used. Plan shall include period microstructural evaluation.

CBAC: Obtain test plan approval for electromigration onset tests.

CBAD: Execute electromigration onset tests.

CBAE: Correlate microstructural changes with on set of electromigration and define model to assess electromigration over range of test materials.

CBAF: Define test plan to assess influence of elevated current density (AC and DC) on solder joint failure due to temperature cycling and mechanical cycling. Test plan shall include schedule for assessing “in-situ” and preconditioned DC and AC current density effect on two solder volumes (< 350 micron, > 600 micron) for the 8 program selected solder joints compositions subject to two levels of mechanical cycling and two levels of temperature cycling. Obtain plan approval.

CBAG: Execute test plan. Conduct failure analysis sufficient to identify failure location. Conduct statistical analysis and report test findings.

CBAH: Provide project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: D19: Absence of predictive models of solder joint electromigration (high current density). Absence of a complete understanding of the phenomenon as a function of solder alloy and test condition. (All Surface Mount Technology).

Expected Results:

- Electromigration current density levels for eight critical program solder joint compositions.
- Impact of elevated current density on mechanical cycling induced solder joint life of eight critical program solder joint compositions.
- Impact of elevated current density on temperature cycling induced solder joint life of eight critical program solder joint compositions

Deliverables:

- Report of known current density effects. – Month 6
- Electromigration on Set Test Plan. – Month 2
- Report on electromigration on set. Test vehicle and measurement plan. – Month 9
- Interim Reports. – Every 6 months
- Report on elevated current density on solder interconnects failure under mechanical cycling. – Month 24

Interdependencies:

Needs: None

Collaborate: CAA, Test Vehicle Design and Fabrication, = Test Vehicles

Feeds: PERM: Design Guide on Electromigration with solder alloy and life impact

Schedule:

- Start Month: 1
- Expected Duration: 24 Months

ROM Cost: $1,739K

CBB Corrosion

Description: This project addresses the knowledge gaps regarding the effects of corrosion on solder joint life with the following objectives:

CBBA: Review existing literature on corrosion impact on solder joint life under relevant field conditions including temperature cycling, vibration, and shock.

CBBB: Develop test plan for assessing impact of corrosive environments and contamination on solder joint reliability. Common test vehicles appropriate for required loading conditions and a common surface mount part shall be used for all tests. Three solders (SAC305, SN100C, and SnPb) will be evaluated. Examine initial exposure, mid-point exposure on changing life expectancy. Examine two levels of corrosion of current and two load levels to test type to determine impact on life. Corrosion exposure shall include mixed flowing gas exposure and un-reacted diluted flux exposure. Tests shall include two levels temperature cycling, two levels mechanical cycling. A continuous exposure test shall be conducted documenting formation of surface corrosion products

CBBC: Obtain test plan approval

CBBD: Execute test plan and provide period status reports.

CBBE: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: D52: Pb-free material corrosion rates with respect to service environments being not well understood increases reliability risk. Solder, PCB finishes, Component finishes, and powered on assembly conditions in A&D environments and powered off storage conditions.

Expected Results: Definitive assessments of effect of corrosive environment on solder joint fatigue of lead-free solders

Deliverables:

- Report on current corrosion of lead-free solder and finishes. – Month 6
- Report on observed surface corrosion correlated with corrosion exposures. – Month 12
- Report on corrosive environment exposure impact on solder joint life. – Month 24

Interdependencies:

Needs: None

Collaborates: CAA, Test Vehicle Design and Fabrication

Feeds: None

Schedule:

- Start Month: 1
- Expected Duration: 24 Months

ROM Cost: $1,551K

CBC Reflows and Repair and Board/Finish Impact

Description: This project addresses the knowledge gaps regarding the effects of reflows and repairs on solder joint life with the following objectives:

CBCA: Review existing literature on reflow/repair impact on solder joint life under relevant field conditions including temperature cycling and repetitive shock.

CBCB: Develop test plan to evaluate impact of rework/repair process on solder joint reliability subject to repetitive shock and temperature cycling. Select a single surface mount package format for evaluation. Select three solders (SAC305, SN100C, and SnPb), three laminate materials, and three finishes critical to A&D applications. Plan should include immediate rework and repair of a set of test assemblies subject to extensive temperature cycling. Second test assembly should include area array packages. Second test assembly will be subjected to additional post reflows. Plan should include failure monitoring and failure identification. Obtain test plan approval.

CBCC: Execute test plan, conducting tests, collecting test data, processing failure statistics, and conducting failure analysis sufficient to identify failure location.

CBCD: Provide project management including report generation.

Gaps Addressed:

- S05: Lack of maximum reflow cycles control and requirements (part/component limitations on repair/rework cycles).
- S1: Lack of understanding repair/rework stresses.

Expected Results:

- Determination of effect of multiple reflows on lead free solders relevant to A &D applications.
- Determine impact of repair on failure statistics based on laminate selection relevant to A &D applications.

Deliverables:

- Report on rework/repair process and process parameters. – Month 3
- Report on life impact of BGA solder joint reliability subject to multiple reflows. – Month 12
- Report on life impact of repaired SMT solder joint. – Month 12

Interdependencies:
Needs: None

Collaborate: CAA, Test Vehicle Design and Fabrication, = Test Vehicles

Feeds: None

Schedule:
Start Month: 1
Expected Duration: 12 Months

ROM Cost: $1,573K

CBD Wave Solder Contamination Effects

Description: This project addresses the knowledge gaps regarding the effects of wave solder contamination on solder joint life with the following objectives:

CBDA: Collaborate with BAAE for wave-soldered attachment, conduct effects study to determine reliability impact on attachments made above the contamination limits identified in BAAE.

CBDB: Use common wave solder test specimens developed under CAA to conduct life impact evaluation.

CBDC: Conduct two level reliability tests for temperature cycling and shock.

Gaps Addressed: 25a: Lack of knowledge on the effect of contamination on the properties of the Pb-free solder. Absence of materials properties effect by contamination. Absence of the predictive models. Absence of validation data and failure mode effects. (All Joints).

Expected Results: Acceptability of solder joint reliability (TC, Shock, and Vibration) on joints formed from baths outside of critical bath limits.

Deliverables: Report on impact of solder joint life with joints produced outside the critical bath limits. – Month 36

Interdependencies:
Needs: None

Collaborate:
- BAAE, Contamination = Fabricate test specimens
- CAA, Test Vehicle Design and Fabrication, = Test Vehicles

Feeds: PERM: Reliability Guide for wave solder formed joints above defined contamination limits.

Schedule:
Start Month: 25
Expected Duration: 12 Months

ROM Cost: $532K

CBE Solder Paste Effects

Description: This project addresses the knowledge gaps regarding the effects of solder paste coatings on solder joint life with the following objectives:

CBEA: Define test vehicle and test plan for evaluating variation due to solder paste. Plan shall include evaluation of a least four clean and no-clean solder pastes suppliers. Surface mount parts shall consider two BGA packages (<300 micron and >600 micron solder spheres) and four solder sphere compositions, a leadless SMT, and a leaded SMT. Assemblies will include temperature cycling and shock test boards. Test assemblies shall be common test specimens defined by CAA Test Vehicle Design and Fabrication. Tests shall characterize solder pastes including solder spread, wetting, slump, and contamination.

CBEB: Obtain test plan approval.

CBED: Execute test plan.

CBEE: Conduct failure analysis sufficient to identify failure location.

CBEF: Analysis test results determine correlation to solder parameters and solder joint life.

CBEG: Work project management including planning, reporting coordination, and collaboration.

Gaps Addressed:

- Variation in solder joint reliability can arise from a variety of sources.
- To assess solder joint reliability accurately, variably must be defined.

Expected Results: Determine variation in solder joint reliability due to solder paste in Month 24

Deliverables:

- Interim Reports. – Every 6 months
- Test report on time to failure data for all tests. – As available, complete Month 24
- Report on variation in solder joint life due to solder paste selection. – Month 24

Interdependencies:

Needs: None

Collaborate:

- CAA, Test Vehicle Design and Fabrication, = Test Vehicles
- CAB, Materials Properties & Constitutive Relations = Solder Pastes
- CAM Reliability Modeling = Solder Selection Variability

Feeds: PERM: Reliability of wave solder formed joints above defined contamination limits.

Schedule:

- Start Month: 13
- Expected Duration: 24 Months

ROM Cost: $1,112K

CBF Tin Pest

Description: This project addresses the knowledge gaps regarding the effects of tin pest on solder joint life with the following objectives:

CBFA: Collect and review of existing tin pest research.

CBFB: Develop protocol for visually indentifying tin pest and a method for confirming tin pest.

CBFC: Develop test plan for identifying tin pest formation factors. Plan shall indentify existing tin pest research to create a list of possible factors that may promote tin pest. Plan shall define surface mount assembly test specimens including surface finishes, mechanical parts, solder ingots, and soldered assemblies.

CBFD: Conduct designed experiment with the purpose of producing tin test on solder assembled test specimen based on identified factors to determine if tin pest.

CBFE: Provide project management including planning, reporting, coordination, and collaboration.

Gaps Addressed:

- S12: Lack of standards/requirements to address receiving inspection in sustainment situation for tin whisker (and tin pest) identification.
- T02: Current Pb-free materials are insufficient for A&D products. Tin pest.

Expected Results:

- Factors, if any, that will produce create tin pest in lead-free soldered assemblies.
- Inspection criteria for identifying tin pest.

Deliverables:

- Report on visual characteristics of tin pest and methods for accurate verification. – Month 3
- Report providing current knowledge on tin pest. – Month 6
- Report identifying potential tin pest generating factors and finding from design experiment. – Month 36

Interdependencies:

Needs: None

Collaborate: CAA, Test Vehicle Design and Fabrication = Coordinate test materials and structures.

Feeds: PERM: Update lead-free handbook.

Schedule:

Start Month: 1
Expected Duration: 36 Months

ROM Cost: $584K

CC Underfill, Staking, and Coating Effects

Description: This project addresses the knowledge gaps regarding the effects of underfill, staking, and coatings on solder joint life with the following objectives:

- Document life impact of underfill on solder joint life of Pb-free assembled area array packages relevant to A&D environments.
- Document life impact of staking on solder joint life of Pb-free assembled surface mount parts to A&D environments.

- Document life impact of conformal coating on solder joint life of Pb-free assembled surface mount parts to A&D environments.
- Document material behavioral properties of underfill, staking, and coating components relevant to development of models to assess solder joint life expectancy.
- Detailed modeling approach suitable for commercial finite element analysis software for predicting life expectancy of underfilled, staked, and conformally coated lead-free assembled surface mount parts.
- Analytic modeling approach suitable for spreadsheet implantation for predicting life expectancy of underfilled, staked, and conformal-coated Pb-free assembled surface mount parts.

Gaps Addressed:

- D14: Absence of predictive models of solder joint fatigue. Insufficient materials properties data for model input. Lack of appropriate computational models to address thermomechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration. Lack of validation test vehicles and data. Other factors: Insufficient information on the effects of underfill, staking methods, preconditioning environments, stress screening environments, and field conditions. (All Joint Technologies).
- D35: Existing heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product. Encapsulants, staking compounds, and underfill.
- M17: Unproven durability and compatibility of adhesives/coatings/underfill materials with lead-free soldering processes.
- R02: Life test data is not readily available for interconnect life of staked and underfilled components. Life test data is not readily available for interconnect life of staked and underfilled components.
- R03: Effectiveness of modeling techniques for estimating life expectancy of interconnections of staked or underfilled over long-term operation has not been satisfactorily documented. Solder Failure Models (Thermal Cycling, Vibration, Mechanical Shock).
- S20: Limited understanding of Underfill reparability degradation in storage.

Expected Results:

- Proven solder joint life improvement of lead-free surface mount packages archived through used of underfill, staking and coating materials.
- Qualification of impact of solder composition, precondition, and solder flux type (clean and no-clean) on solder joint interconnect life of underfilled, staked and coated surface mount parts.

Deliverables:

- Material properties and measurement techniques for solder joint life models of underfilled, staked, and conformally coated surface mount parts. – Month 30
- Report on detailed modeling approaches for solder joint life of underfilled, staked, and coated surface mount parts sufficient for wide spread implementation with correlations with generated test data. – Month 36
- Report on analytic models for solder joint life assessment of underfilled, staked, and coated surface mount parts with correlation to generated test data. – Month 36

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $2,605K

CCA Underfill Life Testing

Description: Summarize underfill research related to solder joint reliability. Create test plan including test specimen design and failure criteria. At a minimum, the test specimens shall include six candidate underfills (two reworkable, four non-reworkable). Parts will include two area array

packages (<350 and > 600 micron solder spheres) with four solder sphere alloys and one surface mount perimeter leaded package. Parts will be assembled with either SnPb or SAC305 solder paste. Both clean and no-clean pastes will be used. A board for temperature cycling and mechanical cycling will be defined. Test board designs will be created in collaboration with test vehicle design and fabrication activity. Environmental tests will include two temperature cycles, two vibration conditions, and two drop shock. Precondition will include ambient storage, elevated temperature and humidity storage, and elevated temperature storage. Test specimen count will be sufficient to determine the effect of precondition, underfill, and solder volume. Pilot tests will be conducted to assure significant relevant failure within test scope. Provide pilot test results and obtain approval for test plan. Execute test plan. Conduct failure analysis sufficient to identify failure location. Conduct statistical assessment of test results.

Gaps Addressed: R02: Life test data is not readily available for interconnect life of staked and underfilled components. Life test data is not readily available for interconnect life of staked and underfilled components.

Expected Results:

- Defined impacts of underfill on solder joint life of lead-free surface mount packages under A&D relevant loading conditions.
- Qualification of impact of solder composition, precondition, and solder flux type (clean and no-clean) on solder joint interconnect life of staked and coated surface mount parts.

Deliverables:

- Report on existing knowledge related to impact of underfill on solder joint life. – Month 2
- Test vehicle and measurement plan. – Month 2
- Interim reports on test status and findings. – Every 6 month
- Time to failure data for underfill test matrix. – Month 18
- Test report summarizing the finding from underfill test matrix. – Month 24

Interdependencies:

Needs: None

Collaborate: CAA: Define and create appropriate test vehicle

Feeds:

- PERM – Test data for handbook
- CCD – Underfill, Staking, and Coating Solder Joint Life Model – Test data for model development

Schedule:

- Start Month: 1
- Expected Duration: 24 Months

ROM Cost: $752K

CCB Staking and Coating Life Testing

Description: Summarize staking and coating research related to solder joint reliability. Create test plan including test specimen design and failure criteria. At a minimum, the test specimens shall include 4 candidate staking and 4 coating materials, parts will include two area array packages (<350 and > 600 micron solder spheres), one leadless part and one leaded part, BGAs will include 4 program solder sphere composition, assemblies sets will be created with tin-lead and SAC305 solder pastes. BGA staking will include corner and edge. Environmental testing will be conducted on sets per unique combination of bonding (staking or coating), solder joint material.

Three preconditions including ambient storage, elevated temperature and humidity storage, and elevated temperature storage will be defined. Test specimen count will be sufficient determine effect of precondition, bond type, and solder. Pilot tests will be conducted to assure significant relevant failure within test scope. Provide pilot test results and obtain approval for test plan. Execute test plan. Conduct failure analysis sufficient to identify failure location. Conduct statistical assessment of test results.

Gaps Addressed:

- D14: Absence of predictive models of solder joint fatigue. Insufficient materials properties data for model input. Lack of appropriate computational models to address thermomechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration. Lack of validation test vehicles and data. Other factors: Insufficient information on the effects of underfill, staking methods, preconditioning environments, stress screening environments, and field conditions. (All Joint Technologies).
- D35: Existing heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product. Encapsulants, staking compounds, and underfill.
- M17: Unproven durability and compatibility of adhesives/coatings/underfill materials with lead-free soldering processes.
- R02: Life test data is not readily available for interconnect life of staked and underfilled components. Life test data is not readily available for interconnect life of staked and underfilled components.
- R03: Effectiveness of modeling techniques for estimating life expectancy of interconnections of staked or underfilled over long-term operation has not been satisfactorily documented. Solder Failure Models (Thermal Cycling, Vibration, Mechanical Shock).

Expected Results:

- Defined impact of staking and coating materials on solder joint life of lead-free surface mount packages under A&D relevant loading conditions.
- Qualification of impact of solder composition, precondition, and solder flux type (clean and no-clean) on solder joint interconnect life of staked and coated surface mount parts.

Deliverables:

- Report on existing knowledge related to impact of staking and coating on solder joint life. – Month 2
- Test vehicle and measurement plan. – Month 2
- Interim reports on test status and findings. – Every 6 months
- Time to failure data for staked and coating test matrix. – Month 18
- Test report summarizing the finding from staking and coating tests. – Month 24

Interdependencies:

Needs: None

Collaborate: CAA , Test Vehicle Design and Fabrication = Define test vehicle designs

Feeds:

- CCD, Solder Joint Life Model for Underfilled, Staked, and Coated Surface Mount Parts
- PERM, Report on staking and coating impact on life expectancy of surface mount parts

Schedule:

- Start Month: 1
- Expected Duration: 24 Months

ROM Cost: $901K

CCC Properties and Property Degradation

Description: Obtain list of underfill, staking, and coating compounds. In collaboration with modeling activity, identify material properties to be measured and characterized. Envisioned properties will include glass transition temperature, elastic modulus, Prony series, Poisson's ratio, shrinkage, and adhesion properties. Property measurements will be made for "as cured" and under aging conditions coordinated with testing groups. For adhesion properties, tests will be conducted on six areas, and apply to two relevant solder mask materials over solder mask only, over defined land pattern with tin-lead solder, and over defined land pattern with lead-free solder. Defined land patterns should be processed with both no-clean solder paste and cleaned solder paste. Provide measurement plan and schedule. Obtain plan approval. Conduct material measurements and provide measurement results. Work project management including planning, reporting, and coordination.

Gaps Addressed:

- D14: Absence of predictive models of solder joint fatigue. Insufficient materials properties data for model input. Lack of appropriate computational models to address thermomechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration. Lack of validation test vehicles and data. Other factors: Insufficient information on the effects of underfill, staking methods, preconditioning environments, stress screening environments, and field conditions. (All Joint Technologies).
- D35: Existing heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product. Encapsulants, staking compounds, and underfill.
- M17: Unproven durability and compatibility of adhesives/coatings/underfill materials with lead-free soldering processes.
- R02: Life test data is not readily available for interconnect life of staked and underfilled components. Life test data is not readily available for interconnect life of staked and underfilled components.
- R03: Effectiveness of modeling techniques for estimating life expectancy of interconnections of staked or underfilled over long-term operation has not been satisfactorily documented. Solder Failure Models (Thermal Cycling, Vibration, Mechanical Shock).
- S20: Limited understanding of Underfill reparability degradation in storage.

Expected Results:

- Material properties suitable for input in the solder interconnect life models subject to underfill, staking, and coating.
- Measurement needs for assessing new underfill, staking, and coating materials

Deliverables:

- Quarter reports defining progress. – Every 4 months
- Guidelines for measuring underfill, staking, and coating compounds necessary for solder joint life prediction. – Month 3
- Data for selected materials from defined measurement methods. – Month 24
- Report providing material properties for selected underfill, staking, and coating compounds. – Month 24

Interdependencies:

Needs:

- CCA = Underfill materials, solder material and flux, board assembly
- CCB = Staking and coating materials, solder materials, test board

Collaborate: CCD Solder Joint Life Model For Underfilled, Staked, and Coated Parts = Material properties

Feeds: PERM Consortium – Underfill, staking, and coating material properties and characterization methods

Schedule:

- Start Month: 3
- Expected Duration: 24 Months

ROM Cost: $752K

CCD Solder Joint Life Models for Underfilled, Staked, and Coated Surface Mount Parts

Description: Summarize existing modeling approaches to underfill, staking, and coating. Develop detailed modeling approaches for assessing the impact of underfill, staking, and coating on solder interconnect life of Pb-free solders under temperature cycling, vibration, and drop shock. Model will be developed based on constitutive properties from CAC and compound properties from CCC. Develop an analysis models to predict life expectancy of underfilled, staked, and coated surface mount parts suitable to spreadsheet implementation. Analytic model must also use constitutive models and material properties derived from CAC and CCC activities. Correlate analytical models with detailed model and test data generated from CCA and CCD. Work project management including planning, reporting, and coordination.

Gaps Addressed:

- D14: Absence of predictive models of solder joint fatigue. Insufficient materials properties data for model input. Lack of appropriate computational models to address thermomechanical fatigue, combined environments, vibration, mechanical shock, as well as low temperature shock and vibration. Lack of validation test vehicles and data. Other factors: Insufficient information on the effects of underfill, staking methods, preconditioning environments, stress screening environments, and field conditions. (All Joint Technologies).
- D35: Existing heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product. Encapsulants, staking compounds, and underfill.
- M17: Unproven durability and compatibility of adhesives/coatings/underfill materials with lead-free soldering processes.
- R02: Life test data is not readily available for interconnect life of staked and underfilled components. Life test data is not readily available for interconnect life of staked and underfilled components.
- R03: Effectiveness of modeling techniques for estimating life expectancy of interconnections of staked or underfilled over long-term operation has not been satisfactorily documented. Solder Failure Models (Thermal Cycling, Vibration, Mechanical Shock).

Expected Results: Appropriate modeling approaches and supporting data for assessing underfilled, staked, and coated surface mount parts.

Deliverables:

- Quarter report on progress. – Every 4 Months
- Report on detailed modeling approach for solder joint life prediction of underfilled surface mount parts sufficient for wide spread implementation with correlations with generated test data. – Month 12
- Report on detailed modeling approaches for solder joint life of staked surface mount parts sufficient for wide spread implementation with correlations with generated test data. – Month 12
- Report on detailed modeling approaches for solder joint life coated surface mount parts. – Month 12
- Report on analytic models for solder joint life assessment of underfilled, staked, and coated surface mount parts with correlation to generated test data. – Month 24

Interdependencies:

Needs: None

Collaborate:

- CAC Materials Properties & Constitutive Relations - material properties from detailed modeling
- CAJ Reliability Modeling - Integration of solder fatigue model for underfill systems

Feeds: PERM Consortium – Report on modeling approaches for assessing life expectancy of solder joints of underfilled, staked, and coated surface mount parts.

Schedule:

- Start Month: 12
- Expected Duration: 24 Months

ROM Cost: $202K

CD New Solders and Compatibility for A&D

Description: This project will be evaluating manufacturability and reliability in harsh environment of standard SnPb and Sn-Ag-Cu lead-free solders (SAC) with lead-free BGA ball materials. The BGA ball materials will include the widely used SAC405, SAC305, SAC105 and Low Ag solders with additives such as Ni, Mn, and rare earth elements that were introduced by component manufacturers to improve the mechanical performance. The process parameters that provide high reliability in harsh environment will be defined.

The project also will be evaluating the reliability of some of the new lead-free solders in harsh environments. Several compositions with Bi, In, or combinations of Bi, Ni, and Sb additives are proposed, which may provide long term reliability performance for both high mechanical and high thermal stress conditions. The project will deliver data on the new solders' compatibility with existing and new lead-free components using different assembly parameters. The performance in harsh environment mechanical and thermo mechanical conditions will be tested, and the results delivered. The best performer/performers will be recommended for further qualification in the A&D industry.

In this project the new rework solution using Low Melt solder, which demonstrated good electrical properties and higher reliability than pure SnPb joints in computer/networking operating environments, will be evaluated for performance in the harsher A&D operating conditions.

Gaps Addressed:

- DO1: Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. Insufficient information on solder material properties of existing and future Pb-free alloys to formulate failure models (solder, pad cratering, trace cracking).
- D03: Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. Insufficient information on assembly test data to validate failure models (solder, pad cratering, and trace cracking).
- D11: Current Pb-free materials are insufficient for A&D products. There is no known part plating finish that meets or exceeds SnPb assembly and reliability performance.
- D13: Current Pb-free materials are insufficient for A&D products. There is no known Pb-free alloy that meets or exceeds SnPb assembly and reliability performance.
- M14: Industry lacks knowledge about the relationship between solder alloys and solder processes/equipment to produce an acceptable solder joint microstructure.
- M19: There is a lack of manufacturing protocols and procedures to mitigate solder defects resulting from lead-free solder processes.
- D53: Need rules for mixed solders, "SnPb+Pb-free" joints or "Pb-free-Pb-free" alloys.
- D55: When multiple solders are used in assembly, certain combinations of solders are incompatible or have a narrow process window.

- ID D44: Current Pb-free materials are insufficient for A&D products. Current PCB laminate materials formulated for Pb-free assembly have significant risk in regards to assembly and reliability.

Expected Results:

- Microstructure of joints formed from SnPb solder and SAC balled components
- Process parameters for uniform fully mixed joint formation
- Solder joint strength
- Microstructure of joints formed from SnPb solder and components balled with new lead-free solders
- Microstructure of joints formed from SAC 305 solder and components balled with new lead-free solders
- Microstructure of joints formed from new solders and components balled with SAC
- -55C to 125C thermal cycling performance
- Vibration performance
- Drop test performance
- Comparison of microstructures of solder joints reworked with low melting solder to industry baseline work from the computing/network operating environment.
- Harsh environment results of reliability impact of alloys with additives combined with manufacturing processes and identification of combinations that warrant further study.

Deliverables:

- Preliminary report on degree of mixing of lead-free BGAs including SAC405, SAC305, and SAC105 solder balls with SnPb solder depending on reflow parameters. – Month 9
- Final report on assembly. – Month 36
- Final report describing Harsh Environment reliability results, conclusions and recommendations on process parameters for reliable mixed SnPb solder/ SAC solders components including SAC405, SAC305, and SAC105 solder balls. – Month 24
- Final report on BGA with additives to the lead-free solder ball materials, selection for performance in Harsh A&D environment, and recommendations on SnPb and SAC305 assembly parameters. – Month 36
- Final report describing results, conclusions and recommendations on high performance lead-free solder for A&D. – Month 36
- Final report describing results, conclusions and recommendations on Low Melt Solder rework solution for A&D. – Month 18
- Report providing recommendations on test methods for evaluation of new solder materials. – Month 36

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $6,527K

CDA Compatibility Study of SnPb Solder Pastes and Lead-Free Component Materials

Description: This project will be evaluating the manufacturability and reliability of SnPb solders with Pb-free BGA ball materials. Incorporating Pb-free BGAs in tin-lead solder using conventional process may or may not allow full mixing; a resulting microstructure may not be uniform and could cause a reduction in reliability. The solder joint quality, microstructure, manufacturing parameters, and long-term reliability in harsh environments will be systematically studied for different mixture levels of SnPb solder with lead-free components including SAC105 and its modifications.

CDAA: Select Components and Design Test Vehicle.

CDAB: Procure components and Test Vehicles.

CDAC: Phase One Test vehicle Assembly to Determine Full Mixing Conditions.

CDAD: Microstructural Analysis, including SEM Analysis.

CDAE: Report on Conditions Required for Full Mixing.

CDAF: Phase Two Test Vehicle Assembly for Reliability Testing.

CDAG: Vibration Testing.

CDAH: Shock Testing.

CDAI: ATC Testing.

CDAJ: Failure Analysis.

CDAK: Reliability Testing Report.

CDAL: Work project management including planning, reporting coordination, and collaboration.

Gaps Addressed:

- D53: Need rules for mixed solders, "SnPb+Pb-free" joints or "Pb-free-Pb-free" alloys.
- M14: Industry lacks knowledge about the relationship between solder alloys and solder processes/equipment to produce acceptable solder joint microstructure.
- DO1: Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. Insufficient information on solder material properties of existing and future Pb-free alloys to formulate failure models (solder, pad cratering, and trace cracking).
- D03: Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. Insufficient information on assembly test data to validate failure models (solder, pad cratering, and trace cracking).

Expected Results:

- Microstructure of joints formed from SnPb solder and SAC balled components
- Process parameters for uniform fully mixed joint formation
- Solder joint strength
- -55C to 125C thermal cycling performance
- Vibration performance
- Drop test performance

Deliverables:

- Preliminary report on degree of mixing of lead-free BGAs with SnPb solder depending on reflow parameters. – Month 9
- Final report describing results, conclusions and recommendations on process parameters for reliable mixed SnPb solder/ SAC solders components including SAC405, SAC305, and SAC105 solder balls. – Month 24

Interdependencies:

Needs: None

Collaborates:

- CDB, Compatibility Study of Existing Solder Pastes and New Component Materials
- CDC, New Solders Qualification – Test vehicle

Feeds: None

Schedule:

- Start Month: 1
- Expected Duration: 24 Months

ROM Cost: $1,508K

CDB Compatibility Study of Existing Solder Pastes and New Component Materials

Description: This project will evaluate the manufacturability and reliability of industry accepted SAC305 and SnPb solders with new Pb-free BGA ball materials. Low Ag solders with additives such as Ni, Mn, and rare earth elements were introduced by component manufacturers to improve the mechanical performance of consumer electronics. The melting temperature of these new solders are higher than SAC305. The solder joint quality, microstructure, manufacturing parameters, and long-term reliability in harsh environments are unknown.

CDBA: Select Components and Design Test Vehicle.

CDBB: Procure components and Test Vehicles.

CDBC: Reballing of Components (If Necessary).

CDBD: Phase One Test vehicle Assembly to Determine Full Mixing Conditions.

CDBE: Microstructural Analysis, including SEM Analysis.

CDBF: Pull Testing.

CDBG: Report on Conditions Required for Full Mixing.

CDBH: Phase Two Test Vehicle Assembly – for Reliability Testing.

CDBI: Vibration Testing.

CDBJ: Shock Testing.

CDBK: ATC Testing.

CDBL: Failure Analysis.

CDBM: Reliability Testing Report.

CDBN: Work project management including planning, reporting coordination, and collaboration.

Gaps Addressed:

- D11: Current Pb-free materials are insufficient for A&D products. There is no known part plating finish that meets or exceeds SnPb assembly and reliability performance.
- DO1: Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. Insufficient information on solder material properties of existing and future Pb-free alloys to formulate failure models (solder, pad cratering, and trace cracking).
- D03: Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. Insufficient information on assembly test data to validate failure models (solder, pad cratering, and trace cracking).

- D55: When multiple solders are used in assembly, certain combinations of solders are incompatible or have a narrow process window.
- D53: Need rules for mixed solders, "SnPb + Pb-free" joints or "Pb-free - Pb-free" alloys.
- M14: Industry lacks knowledge about the relationship between solder alloy and solder processes/equipment to produce acceptable solder joint microstructure.
- M19: Lack of manufacturing protocols and procedures to mitigate solder defects resulting from lead-free solder processes

Expected Results:

- Microstructure of joints formed from SnPb solder and components balled with new lead-free alloys
- Process parameters for uniform fully mixed joint formation
- -55C to 125C thermal cycling performance
- Vibration performance
- Drop test performance

Deliverables:

- Final report on assembly. – Month 16
- Final report on BGA with new lead-free solder ball materials selection for A&D and recommendations on SnPb and SAC305 assembly parameters. – Month 36
- Report providing recommendations on test methods for evaluation of new solder materials. – Month 36

Interdependencies:

Needs: None

Collaborates:

- CDA, Compatibility Study of SnPb Solder Pastes and Lead-Free Component Materials - Test vehicle
- CDC, New Solders Qualification, report providing recommendations on test methods for evaluation of new solder materials

Feeds: None

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $2,027K

CDC New Solders Qualification

Description: This project will be an evaluation of new Pb-free solders with high reliability in harsh environments. Several compositions with Bi, In, or combinations of Bi, Ni, and Sb additives were proposed for these new Pb-free solders, which may provide long term reliability in high mechanical and thermal stress conditions. The data on solder compatibility with existing and new lead-free components, assembly parameters, and thermo mechanical performance are needed.

CDCA: Select Components and Design Test Vehicle.

CDCB: Procure components and Test Vehicles.

CDCC: Phase One Test vehicle Assembly to Determine Full Mixing Conditions.

CDCD: Microstructural Analysis, Including SEM Analysis.

CDCE: Pull Testing.

CDCF: Report on Conditions Required for Full Mixing.

CDCG: Phase Two Test Vehicle Assembly – for Reliability Testing.

CDCH: Vibration Testing.

CDCI: Shock Testing.

CDCJ: ATC Testing.

CDCK: Failure Analysis.

CDCL: Reliability Testing Report.

CDCM: Work project management including planning, reporting coordination, and collaboration.

Gaps Addressed:

- D13: Current Pb-free materials are insufficient for A&D products. There is no known Pb-free alloy that meets or exceeds SnPb assembly and reliability performance.
- DO1: Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. Insufficient information on solder material properties of existing and future Pb-free alloys to formulate failure models (solder, pad cratering, and trace cracking).
- D03: Insufficient information on existing and future Pb-free materials prevents the formulation and validation of appropriate failure models. Insufficient information on assembly test data to validate failure models (solder, pad cratering, and trace cracking).
- D55: When multiple solders are used in assembly, certain combinations of solders are incompatible or have a narrow process window.

Expected Results:

- Microstructure of joints formed from new solders and components balled with SAC
- Process parameters for uniform fully mixed joint formation
- -55C to 125C thermal cycling performance
- Vibration performance
- Drop test performance

Deliverables:

- Final report on assembly. – Month 18
- Final report describing results, conclusions and recommendations on high performance lead-free solder for A&D. – Month 36

Interdependencies:

Needs: None

Collaborate: CDA, Compatibility Study of SnPb Solder Pastes and Lead-Free Component Materials - Test vehicle

Feeds: None

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $2,077K

CDD Low Melt Solder Rework

Description: A new solder and rework process with a peak reflow temperature not higher than 217 + 2°C is proposed. The reduced process temperature avoids component overheating, reduces board warpage and cratering, and protects neighboring components from thermal damage. The new rework solution demonstrated good electrical properties and higher reliability than pure SnPb joints in 0°C to 100°C cycling. This project will be evaluating -55°C to 125°C thermal cycling, vibration and drop/shock performance of reworked solder joints using this new solder.

CDDA: Select Components and Design Test Vehicle.

CDDB: Procure components and Test Vehicles.

CDDC: Test vehicle Assembly.

CDDD: Test Vehicle Rework.

CDDE: Microstructural Analysis, Including SEM Analysis.

CDDF: Report on Assembly/Rework/Time Zero Microstructure.

CDDG: Vibration Testing.

CDDH: Shock Testing.

CDDI: ATC Testing.

CDDJ: Failure Analysis.

CDDK: Reliability Testing Report.

CDDL: Work project management including planning, reporting coordination, and collaboration.

Gaps Addressed:

- D13: Current Pb-free materials are insufficient for A&D products. There is no known Pb-free alloy that meets or exceeds SnPb assembly and reliability performance
- D44: Current Pb-free materials are insufficient for A&D products. Current PCB laminate materials formulated for Pb-free assembly have significant risk in regards to assembly and reliability.

Expected Results:

- Microstructure of reworked joints
- -55C to 125C thermal cycling performance
- Vibration performance
- Drop test performance

Deliverables:

- Final report on rework. – Month 9
- Final report describing results, conclusions and recommendations on Low Melt Solder rework solution for A&D. – Month 24

Interdependencies:

Needs: None

Collaborate: CDA, Compatibility Study of SnPb Solder Pastes and Lead-Free Component Materials - Test vehicle

Feeds: None

Schedule:

- Start Month: 13
- Expected Duration: 24 Months

ROM Cost: $915K

CE Insertion Mount (PTH)

Description: Current IPC-610 barrel fill specifications were originally established in the 1970's considering a 0.062" thick board and SnPb alloy, and the requirements have not been updated to suit today's thicker boards and use of lead free alloys. The specification requirements, especially considering the size (>0.120" thick), complexity and multiple ground connections of some of today's high complexity products, can be unnecessarily challenging. Recent literature within the industry has shown that barrel fill requirements should be based on the wetted pin length, as opposed to a percentage fill. It states that a board up to a thickness of 0.130" only needs to obtain up to 36% barrel fill to establish a suitably strong joint to survive both thermal and mechanical environments.

This project addresses two main concerns with respect to pin-through-hole (PTH) devices. The first objective is to assess the reliability performance of pin-through-hole SAC 305 solder joints in a harsh environment when hole fill levels do not reach current IPC-610 Class 3 specification levels on a printed circuit board equal to or greater than 120 mil in thickness. The second objective is to assess the impact of high levels of copper dissolution on the thermal reliability, and shock and vibration robustness of PTH connections. In addition to these two main objectives, the project will also characterize the impact which contamination levels of the solder bath have on the final barrel fill and copper dissolution rates. The project will also evaluate the effect of certain wave solder process parameters (e.g. preheat/pot temperatures and flux chemistries) and evaluate the impact that certain key board design features have on obtaining barrel fill (i.e., pin to hole aspect ratio, thermal connection and relief designs).

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Gaps Addressed:

- D20: Lack of appropriate and validated failure models prevents accurate failure prediction, test development, and creation of heuristic rules. PCB Failure Models (PTH)
- D50: Existing heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product. Un-established (thermal cycling, vibration, shock) reliability of SAC 305 solder joints of PTHs that are 25 to 75% partially filled with Pb-free solder.

Expected Results:

- Harsh Environment ATC thermal fatigue cycles to failure (Wiebull plots at various hole fill levels)
- Shock/Vibration/Combination (Static & Dynamic) mechanical failure distributions at various hole fill levels and Cu thicknesses.
- Performance comparisons of various lead-free alloy systems (Define which alloys/connector lead finish combinations will be tested).
- Impact of process parameters, board features and material/chemicals on barrel fill.

- Potential for updated Aerospace hole fill requirements applicable to industry specifications (adoption required) based on accelerated testing in Harsh environments.
- Establish a remaining copper plating thickness that provides a reasonable level of plating to resist barrel cracking, under thermal fatigue and mechanical loads in accelerated Harsh Environment testing.

Deliverables:

- Final report describing the results and conclusions on PTH hole fill needed to ensure reliable system assembly, regardless of how bad the solder joints may look during visual and X-ray inspections as per IPC-610 Class 3 requirements. – Month 36
- Design rules for PTH that can be implemented across the A&D community. – Month 36

Schedule:

- Start Month: 13
- Expected Duration: 24 Months

ROM Cost: $1,699K

CEA Reliability of PTH Solder Joints - Cu Plating Thickness after Assembly

Description: The process issues relating to high copper dissolution rates have been well documented within the industry. The copper dissolution rates of SAC305/405 plus many of the leading alternative lead-free wave alloys has been characterized and pin through-hole rework process windows assessed. One remaining gap within the A&D industry is the understanding of how copper dissolution or thinning of the through-hole barrel wall/knee locations affects the thermal, under harsh environment and mechanical reliability of a pin through-hole joint. This project will provide attempts to assess the impact of high levels of copper dissolution on the thermal reliability and Shock and Vibration Robustness of PTH connectors.

CEAA: Select components and design test vehicle.

CEAB: Procure components and test vehicles.

CEAC: Test vehicle assembly & rework.

CEAD: Microstructural analysis, including cross-sections and measure remaining Cu thickness, comparing different solders after assembly and simulated rework.

CEAE: ATC testing.

CEAF: Combined (Static and Dynamic) Mechanical Testing.

CEAG: Report on initial findings.

CEAH: Statistical analysis.

CEAI: Work project management including planning, reporting coordination, and collaboration.

CEAJ: Failure analysis.

CEAK: Reliability testing report.

CEAL: Work project management including planning, reporting coordination, and collaboration.

Gaps Addressed: D20: Lack of appropriate and validated failure models prevents accurate failure prediction, test development, and creation of heuristic rules. PCB Failure Models (PTH)

Expected Results:

- ATC thermal fatigue cycles to failure, Wiebull plots at various Cu thicknesses.
- Shock/Vibration/Combination (Static & Dynamic) mechanical failure distributions at various Cu thicknesses.
- Performance comparisons of various lead-free alloy systems.
- Establish a remaining copper plating thickness that provides a reasonable level of plating to resist barrel cracking, under thermal fatigue and mechanical loads.
- Develop non-destructive 3D x-ray techniques which can be used to measure copper dissolution on a product.

Deliverables

- Final report describing the results and conclusions on minimum remaining copper plating thickness after assembly and rework using different solder alloys that insure reliability for the A&D applications. – Month 30
- Design rules for PTH that can be implemented across the A&D community. – Month 30

Interdependencies:

Needs: None

Collaborate: BAB, Rework & Repair Critical Process Parameter Development

Feeds: None

Schedule:

- Start Month: 13
- Expected Duration: 18 Months

ROM Cost: $ 805K

CEB Shock and Vibration Robustness of Partially Filled Pb-free PTH Connector Barrels

Description: The majority of work conducted to date on lead-free PTH thermal-mechanical reliability assessment has focused on maximizing hole fill on ground and signal leads. Assembly materials and processes have been optimized to achieve 100% barrel fill with subsequent reliability assessment.

This project will assess the reliability performance of PTH solder joints in harsh environments when optimized hole fill is NOT achieved on thicker PCB cross sections. The goal is to understand the thermal-mechanical reliability performance of partially filled PTH barrels, better. Target scope would be: 25-75% hole fill as per IPC-610, on a nominal PCB cross section range of 0.120 - 0.135".

CEAA: Select components and design test vehicle.

CEAB: Procure components and test vehicles.

CEAC: Test vehicle assembly and rework.

CEAD: 5DX x-ray analysis.

CEAE: ATC testing.

CEAF: Statistical analysis.

CEAG: Report on findings .

CEAH: Work project management including planning, reporting coordination, and collaboration.

CEAI: Combined (static and dynamic) mechanical testing.

CEAJ: Failure analysis.

CEAK: Reliability testing report.

CEAL: Work project management including planning, reporting coordination, and collaboration.

Gaps Addressed: D50: Existing heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product. Un-established (thermal cycling, vibration, shock) reliability of SAC 305 solder joints of PTHs that are 25 to 75% partially filled with Pb-free solder.

Expected Results:

- ATC thermal fatigue cycles to failure, Wiebull plots at various hole fill levels.
- Shock/Vibration/Combination (Static & Dynamic) mechanical failure distributions at various hole fill levels.
- Performance comparisons of various lead-free alloy systems.
- Updated hole fill requirements applicable to industry specifications (adoption required).

Deliverables:

- Final report describing the results and conclusions on minimum PTH hole fill needed to ensure reliable system assembly, regardless of how bad the solder joints may look during visual and x-ray inspections as per IPC-610 requirements. – Month 30
- Design rules for PTH that can be implemented across the A&D community. – Month 30

Interdependencies:

Needs: None

Collaborate: EBB, Pad Cratering

Feeds: None

Schedule:

- Start Month: 13
- Expected Duration: 24 Months

ROM Cost: $895K

CF Handling

Description: The goal of this project is the establishment of rules for the maximum PCB deflection allowed once or relatively few times in handling, ICT, etc. Conservative estimates will be based on how much lead free solder joints, integral pads and their attachment to laminates can be loaded a given number of times without having a significant effect on subsequent assembly reliability.

Assembly and individual solder joint testing will be employed to quantify the acceptable loads, subjecting assemblies to thermal cycling, vibration, shock, drop and flexural loading to quantify subsequent life. Results will be compared to the life obtained without preconditioning. Specific test parameters will be selected based on available mechanistic understanding to be as sensitive as possible to projected differences in service life.

Limits will first be quantified in terms of loads and strains on the solder joints. Simple mechanical analysis will then be employed to convert these into practical limits on PCB deflection, surface strain and strain rate for various critical component types with the intent of generating strain rate dependent process limits for surface strain. Modeling and calculations will be based on the constitutive relations developed under another task.

Gaps Addressed:

- M24: Current ICT capability is not optimized for the processing of lead-free assemblies
- D57: Using SnPb solder stress design levels for Pb-free designs will not necessarily result in satisfactory life in high stress environments.
- T07: Existing heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product. Define detection limits for Pb-free assemblies to prevent damage during handling, assembly, and test. (Due to their stiffness, Pb-free alloys require additional precautions during handling and/or performing failure mode analysis.)
- S17: Shipping and handling procedures do not address Pb-free factors
- Pb free solders have substantially different material properties than eutectic SnPb solder. Additionally, Processing of Pb-free solder alloys require more thermally robust laminates. These laminates also have significantly different mechanical properties compared to materials common to SnPb processing. Proliferation of alloy and laminate solutions for Pb-free processing makes negative interactions in material sets not only possible but also probable. A variety of failure modes may occur and new failure modes may dominate or become the limiting criteria for deflection during manufacturing processes. Higher processing temperatures also produce increased residual strains in finished assemblies, reducing margins for externally applied stains in both primary assembly and repair operations.

Expected Results:

- The Selection of critical materials and components for flexural test matrix tests
- Safe working strain levels across the range of strain rates that occur in assembly and packaging processes.
- Failure modes, failure distribution and process limits for monotonic flexural failure at selected strain rates.
- Failure modes, failure distributions and process limits for low cycle and medium cycle flexural strains at selected strain rates.
- The effects of process strains on vibration performance to establish equivalent service life.
- The effect of process strains on harsh environment service life. ATC (-55C to 125C) performance after stain cycle preconditioning to establish equivalent service life.

Deliverables:

- A preliminary report on material selection, component types, assembly processes and test methods. – Month 9
- Report on test methods, failure modes, failure distributions and limiting process strains for selected critical components based on single event flexural strains. – Month 12
- Report on test methods, failure modes, failure distributions and limiting process strains for selected components based on low cycle and mid cycle flexural strains. – Month 15
- Report on vibration performance of preconditioned lots. – Month 21
- Report on ATC performance of preconditioned lots. – Month 24
- Report documenting recommendations for acceptable PCB strain, strain rate and deflection in handling for design roles in the A&D industry with identification of conditions and combinations that warrant further study. – Month 24

Schedule:

- Start Month: 13
- Expected Duration: 36 Months

ROM Cost: $2,052K

CFA Handling and ICT Testing

Description: The goal is the establishment of rules for the maximum PCB deflection allowed once or relatively few times in handling, ICT, etc. Conservative estimates will be based on how much lead free solder joints can be loaded a given number of times without having a significant effect on subsequent joint reliability.

Assembly and individual solder joint testing shall be employed to quantify the acceptable loads, subjecting assemblies to thermal cycling, vibration, shock, drop and combined loading to quantify subsequent life. Results shall be compared to the life obtained without preconditioning. Specific test parameters shall be selected based on available mechanistic understanding to be as sensitive as possible to projected differences in service life.

Limits shall first be quantified in terms of loads and strains on the solder joints. Simple mechanical analysis shall then be employed to convert these into practical limits on PCB deflection, etc. Modeling and calculations shall be based on the constitutive relations developed under another task.

CFAA: Test Vehicle Design & Optimized using Spherical Bend Test Method.

CFAB: Document handling stresses in A&D assembly process, transport, storage, and installation. Identify critical handling failures sites and modes.

CFAC: Define test plan for assessing handling failures and execute test. Test assembly shall include variations of board laminate materials, board finish, and part finish sufficient to cover relevant A&D products, as well as monitoring approach and failure identification.

CFAD: Perform Destructive analysis.

CFAE: Establish pad cratering distributions.

CFAF: Vibration testing to establish service life equivalency.

CFAG: ATC testing (-55C to 125C) establish service life equivalency.

CFAH: Work project management including planning, reporting coordination, and collaboration.

Gaps Addressed:

- M24: Current ICT capability is not optimized for the processing of lead-free assemblies.
- D57: Using SnPb solder stress design levels for Pb-free designs will not necessarily result in satisfactory life in high stress environments.
- T07: Existing heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product. Define detection limits for Pb-free assemblies to prevent damage during handling, assembly, and test. (Due to their stiffness, Pb-free alloys require additional precautions during handling and/or performing failure mode analysis.)
- S17: Shipping and handling procedures do not address Pb-free factors.

Expected Results:

- A Selection of critical materials and components for flexural test matrix.
- Safe working strain levels across the range of strain rates that occur in assembly and packaging processes.
- Failure modes, failure distribution and process limits for monotonic flexural failure at selected strain rates.
- Failure modes, failure distributions and process limits for low cycle and medium cycle flexural strains at selected strain rates.
- Effects of process strains on vibration performance to establish equivalent service life.
- Effect of process strains on harsh environment service life. ATC (-55C to 125C) performance after stain cycle preconditioning to establish equivalent service life.

Deliverables:

- Preliminary Report on material selection, component types, assembly processes and test methods. – Month 9
- Report on test methods, failure modes, failure distributions and limiting process strains for selected critical components based on single event flexural strains. – Month 12 month
- Report on test methods, failure modes, failure distributions and limiting process strains for selected components based on low cycle and mid cycle flexural strains. – Month 15
- Report on vibration performance of preconditioned lots. – Month 21
- Report on ATC performance of preconditioned lots. – Month 24
- Report on recommendations for acceptable PCB strain, strain rate and deflection in handling for design roles in the A&D industry with identification of conditions and combinations that warrant further study. – Month 24

Interdependencies:

Needs: None

Collaborates:

- Input from task CAD, Materials Properties and Constitutive Relations
- Input from task CAH, Combined Loading

Feeds: None

Schedule:

- Start Month: 13
- Expected Duration: 24 Months

ROM Cost: $1,638K

CFB Handling Assessment Models and Guide

Description: This project consists of the following tasks to develop handling assessment models and a guide:

CFBA: Summarize critical handling inducted failures and input conditions, structures, models, and material properties necessary for assessing identified failures.

CFBB: Develop, demonstrate, and document detailed modeling approach to assess handing stress.

CFBC: Develop, demonstrate, and document first principle models providing validation against test data and detailed models.

CFBD: Work project management including planning, reporting, and coordination.

Gaps Addressed:

- M24: Current ICT capability is not optimized for the processing of lead-free assemblies
- D57: Using SnPb solder stress design levels for Pb-free designs will not necessarily result in satisfactory life in high stress environments.
- T07: Existing heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product. Define detection limits for Pb-free assemblies to prevent damage during handling, assembly, and test. (Due to their stiffness, Pb-free alloys require additional precautions during handling and/or performing failure mode analysis.)
- S17: Shipping and handling procedures do not address Pb-free factors

Expected Results: Ability to use appropriate modeling approaches and supporting data for assessing overstress and structural damage due to handling and in circuit testing.

Deliverables:

- Quarter report on progress – Every 4 Months
- Report on detailed modeling approaches for critical handling induced failures. – Month 12
- Report on first principles models and correlation to test and detailed models for critical handling induced failures. – Month 24
- Provide guide for assessing handling environment and impact on assembly reliability. – Month 24

Interdependencies:

Needs: None

Collaborate:

- CAC Materials Properties & Constitutive Relations - material properties from detailed modeling
- CFA Handling and ICT Testing – Validate models
- EBB Pad Crating - Assesses pad crating model

Feeds: PERM Consortium – Report on modeling approaches for assessing life expectancy of solder joints of underfilled, staked, and coated surface mount parts.

Schedule:

- Start Month: 25
- Expected Duration: 24 Months

ROM Cost: $414K

D Components

Description: The objective of this major project area is to characterize component properties relevant to Pb-free assembly processes and requirements. Tasks include:

- Design and conduct experiments, interpret results, and recommend program requirements to assure that components meet system requirements through storage, use, and possible repair actions.
- Determine impact of refinished components on cost and schedule.
- Evaluate new materials, design, and construction for components to improve temperature sensitivity.
- Develop approach to evaluate the performance of component finishes for A&D applications.
- Establish approaches to test for whether part finishes meet A&D requirements for assembly robustness, gold embrittlement, copper-nickel-tin failures, Kirkendall voiding, and new problems. The degradation mechanisms must account for assembly stresses (e.g., multiple reflows), and environmental and operating stresses.
- Develop approach to evaluate the solderability performance of component finishes for A&D applications.
- Characterize corrosion rates for Pb-free assembly materials and develop mitigation techniques.

Gaps Addressed:

- Currently available components do not consistently provide the robustness to support higher Pb-free processing temperatures.
- Capability of components to survive multiple Pb-free solder reflow cycles is not sufficiently characterized.
- Lack understanding of component and process compatibility issues that cause reliability degradation & latent defects from Pb-free soldering.
- Lack industry standard procedures for storing components before assembly to assure solderability and capability to survive Pb-free soldering processes.
- Insufficient information on existing and future Pb-free components structural properties prevents formulation and validation of appropriate failure models.

Expected Results:

- Receiving inspection guidelines and incoming requirements for components
- Component properties database for assembly requirements and reliability modeling
- Temperature sensitivity
  - Characterization of sensitivity to support reliable assembly
  - Improvement for some components types
- Characterization /models of component finish effects on solderability and solder joint reliability
- Methods to assess cost/schedule impact of component refinishing
- Flux and cleaning characteristics
  - Determination of flux compatibility with components
  - Circuit card assembly cleaning requirements and corrosion/degradation impacts
- Storage requirements for unassembled components

Deliverables:

- Component temperature reflow cycle limits.
- Receiving inspection protocol and requirements.
- Storage requirements for unassembled components in Pb-free applications.
- Component properties database.
- Flux compatibility and cleaning requirements for components.
- Test methods and requirements to evaluate component finishes for Pb-free solder applications.
- Corrosion rate models for Pb-free materials and assemblies.

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $5.4M

DA Component Characterization

Description: Characterize component properties relevant to Pb-free assembly processes and requirements. Design and conduct experiments, interpret results, and recommend program requirements to assure that components meet system requirements through storage, use, and possible repair actions.

Gaps Addressed:

- Currently available components do not consistently provide the robustness to support higher Pb-free processing temperatures, and the capability to survive multiple reflow cycles is not sufficiently characterized.

- Lack of current industry standard incoming screening procedures for components to assure proper finishes.
- Lack of current industry standard procedures for storing components before assembly to assure solderability and capability to survive Pb-free soldering processes.
- Insufficient information on existing and future Pb-free components structural properties prevents the formulation and validation of appropriate failure models.
- Lack of understanding of component and process compatibility issues that cause reliability degradation and latent defects from Pb-free soldering processes. (See Exhibit A, Gap D02A, D11, M16, M24, M25, S05, S06, S07, S17, T7)

Expected Results: Component requirements to assure compatibility with assembly processes to reduce defects and field failure rate

Deliverables:

- Component temperature reflow cycle limits. – Month 24
- Receiving inspection protocol and requirements. – Month 6
- Storage requirements for unassembled components in Pb-free applications. – Month 24
- Component properties database. – Month 24
- Flux compatibility and cleaning requirements for components. – Month 18

Schedule:

- Start Month: 1
- Expected Duration: 24 Months

ROM Cost: $1,894 K

DAA Temperature Exposure Limits

Description: Investigate thermal durability/survivability of current component families to establish A&D Pb-free assembly process margins and practices. This effort will characterize components capability to survive soldering process temperature excursions to determine maximum number of permissible exposures to solder process reflow cycles. The characterization will consider degradation and introduction of latent defects due to assembly rework, field storage and use, and rework, and include refinished components.

DAAA: Develop test and component selection plan to determine temperature exposure limits for Pb-free applications. Prioritize selection of components to assess for temperature sensitivity based on anticipated factors that affect thermal degradation. Include refinished/reprocessed components (e.g., SnPb dipped leads, reballing) in the assessment. Utilize J-STD-075 for guidance.

DAAB: Execute the stress exposure test plan to include consideration for aging (humidity and temperature), assembly, rework and repair stresses (including soldering temperature profile with possible multiple passes), and field storage and use environmental stresses. Approach shall include testing to represent lifetime stresses on typical component families of functional devices after exposure to maximum expected reflow cycles.

DAAC: Characterize the component damage using techniques such as acoustic microscopy, warpage measurement (such as, Moiré or digital image correlation), and x-ray, as well as functional testing. Determine limits on repair level and repair process stresses, accounting for degradation of assembly during storage and use. Establish lifetime maximum reflow cycles for components.

DAAD: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: Currently available components do not consistently provide the robustness to support higher Pb-free processing temperatures, and the capability to survive multiple reflow cycles is not sufficiently characterized. (See Exhibit A, Gap M16, S05, S07)

Expected Results: There is a need to develop a set of thermal degradation requirements for components to assure compatibility with assembly processes and reduce defects and field failure rate in A&D applications.

Deliverables: Component temperature reflow cycle limits. – Month 24

Interdependencies:

Needs: BAA, Critical Process Parameter Development – Process temperature profiles

Collaborates: CAB, Validation Data Collection - required component properties data

Feeds:

- DAC, Temperature Sensitivity improvement - Component temperature sensitivity data
- DAE, Component Properties Database - Component temperature limits
- PERM Consortium - Industry handbooks and standards, J-STD-075
- CAJ, Reliability models

Schedule:

- Start Month: 1
- Expected Duration: 24 Months

ROM Cost: $680K

DAB Receiving/Incoming Inspection Requirements

Description: Establish incoming inspection approaches to assure that components finishes correspond to the design requirements.

DABA: Develop incoming component test and identification screening protocol for A&D products, based on potential for introduction of improper materials. Define inspection equipment capabilities to provide adequate performance in identifying finish properties (e.g., elements, thickness). Consider issues related to source of supply (integrity of supplier, and component history within supply chain), cost of inspection (sampling approaches provide cost effective information), and prevalence of unwanted finishes for particular components.

DABB: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: Lack of current industry standard incoming screening procedures for components to assure proper finishes. (See Exhibit A, Gap M25)

Expected Results: Incoming inspection requirements and methods to assure correct component configuration and quality.

Deliverables: Incoming inspection protocols suitable for inclusion in standards (Month 6)

Interdependencies:

Needs: None

Collaborates: None

Feeds:

- PERM Consortium - Industry handbooks and standards

Schedule:

- Start Month: 1
- Expected Duration: 6 Months

ROM Cost: $167K

DAC Storage Requirements for Unassembled Components

Description: Develop environmental condition requirements for storage of components before assembly.

DACA: Accumulate current data on storage effects and develop test plan to augment available data to aid development of long-term storage environment requirements to maintain component solderability and structural integrity prior to assembly. Provide this information in an interim report.

DACB: Execute plan to determine long-term storage environment requirements to maintain component solderability and structural integrity prior to assembly. Perform validation testing and evaluation of published literature to confirm long-term storage effects on Pb-free finish solderability, and that established requirements (time limits, and environment levels) control component degradation. Develop storage requirements that address factors such as humidity and temperature, and gases that can affect Solderable finish integrity. Provide report with best practices for storage environment and test methods to assure storage life suitable for incorporation in industry standards.

DACC: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: Lack of current industry standard procedures for storing components before assembly to assure solderability and capability to survive Pb-free soldering processes. (See Exhibit A, Gap M16)

Expected Results: Develop component storage requirements to assure compatibility with assembly processes to reduce defects and field failure rate.

Deliverables: Component storage requirements to support successful assembly. – Month 24

Interdependencies:

Needs: None

Collaborates: DDB, Solderability, solderability requirements for Pb-free applications

Feeds: PERM Consortium - Industry handbooks and standards, IPC, JEDEC

Schedule:

- Start Month: 12
- Expected Duration: 12 Months

ROM Cost: $299K

DAD Component Properties Database

Description: Characterize component properties relevant to Pb-free assembly processes and requirements. Design and conduct experiments, interpret results, and recommend program requirements to assure that components meet system requirements through storage, use, and possible repair actions. Components may be exposed to multiple reflow cycles that can degrade reliability.

DADA: Collaborate with Solder Joint Project Area (CAB and CAJ) to identify component properties to characterize. Prepare plan that identifies selected components, test methods for properties characterization, and environmental conditioning approaches to represent assembly, rework, and repair stresses, and life cycle environmental and use stresses.

DADB: Execute the plan to generate data to support failure model development, including coefficient of thermal expansion and flexural modulus (component body and leads), and other information as indicated by the collaboration effort. Characterize the change in component characteristics after exposure to assembly/repair processes. Create a database of component properties based on this effort, and provide in final report suitable for incorporation in industry handbooks.

DADC: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: Insufficient information on existing and future Pb-free components structural properties prevents the formulation and validation of appropriate failure models. (See Exhibit A, Gap D02)

Expected Results: Component characteristics to support failure model development and reliability prediction

Deliverables: Component properties database. – Month 24

Interdependencies:

Needs: None

Collaborates:

- CAB, Validation Data Collection and Assessment, measured component characteristics
- CAJ, Reliability Modeling, needed component characteristics

Feeds: PERM Consortium - Industry handbooks and standards – component properties database

Schedule:

- Start Month: 1
- Expected Duration: 24 Months

ROM Cost: $595K

DAE Fluxes/Cleaning Process Compatibility with Components

Description: Determine component compatibility with Pb-free fluxes and cleaning processes to meet A&D life cycle requirements.

DAEA: Prepare plan to evaluate flux and cleaning process compatibility with components. Include consideration for different flux types, cleaning processes, finishes and solders. Coordinate test vehicle and selected components with DAA and DAC. Address maximum reflow cycles exposure of components and life cycle environmental exposure of assemblies that could contribute to component degradation.

DAEB: Execute plan to evaluate component flux and cleaning process compatibility. Provide report defining component compatibility with fluxes and cleaning processes suitable for incorporation into industry handbooks.

DAEC: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: Lack of understanding of component and process compatibility issues that cause reliability degradation and latent defects from Pb-free soldering processes. (See Exhibit A, Gap M16, S06, S07)

Expected Results: Characterization of components compatibility with Pb-free fluxes/cleaning materials and processes.

Deliverables: Component flux/cleaning compatibility report. – Month 18

Interdependencies:
Needs: BAA, Critical Process Parameter Development - Flux/cleaning processes used for Pb-free assembly

Collaborates:

- DAA, Temperature Exposure Limits, coordination of test vehicles
- DAC, Storage Requirements, coordination of test vehicles

Feeds: PERM Consortium - Industry handbooks and standards

Schedule:

- Start Month: 6
- Expected Duration: 12 Months

ROM Cost: $153K

DB Component Refinishing/Reprocessing

Description: Determine impact of refinished components on cost and schedule.

Gaps Addressed: Current component reprocessing procedures can result in component degradation. (See Exhibit A, Gap M23)

Expected Results: A methodology to aid decision on refinishing/reprocessing components to balance risk of whiskers (pure tin finishes) and unreliable solder joints (ball replacement).

Deliverables: Metrics and tools to aid decision on refinishing components – Month 24

Schedule:

- Start Month: 12
- Expected Duration: 12 Months

ROM Cost: $250K

DBA Component Refinishing/Reprocessing

Description: Determine impact of refinished components on cost and schedule.

DBAA: Develop a methodology to assess cost and schedule impact of damaged components and/or latent field failures induced by component refinishing, leveraging existing research, which utilizes Monte Carlo methods to support decision-making processes that include impact of repair, rework, and replacement. Address risk for ball grid array solder ball reprocessing to replace Pb-free balls with SnPb balls. Also, assess cost and schedule impact for components that pass the GEIA-STD-0006 requirements. Submit report with suitable information for incorporation into industry standards and handbooks.

DBAB: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: Current component reprocessing procedures can result in component degradation. (See Exhibit A, Gap M23)

Expected Results: A methodology to aid decision on refinishing/reprocessing components to balance risk of whiskers (pure tin finishes) and unreliable solder joints (ball replacement) with cost and schedule impact.

Deliverables: Metrics and tools to aid decision on selecting and refinishing components. – Month 24

Interdependencies:
Needs: None

Collaborations: None

Feeds:
- PERM Consortium - Design rules for component selection
- PERM Consortium - Handbook and Standards updates, such as GEIA-STD-0006
- AC, Tin Whisker Risk Assessment – refinishing/reprocessing cost/schedule impacts

Schedule:
- Start Month: 12
- Expected Duration: 12 Months

ROM Cost: $250K

DC Temperature Sensitivity Capability Improvement

Description: Evaluate new materials, design, and construction for components to improve temperature sensitivity.

Gaps Addressed: The high temperature exposure sensitivity of components (especially passives, and particularly capacitors) subjected to Pb-free solder process temperatures results in reliability reductions and premature failures. (See Exhibit A, Gap D51)

Expected Results: A components technology that reduces degradation of component performance due to thermal exposure to Pb-free assembly processes.

Deliverables: Materials, and design and construction techniques to reduce thermal degradation of components. – Month 36

Schedule:
- Start Month: 12

- Expected Duration: 24 Months

ROM Cost: $1,005K

DCA Temperature Sensitivity Capability Improvement

Description: Evaluate new materials, design, and construction for components to improve temperature sensitivity.

DCAA: Prepare plan to develop materials changes and component redesigns to improve thermal degradation sensitivity. Assess current published data, information from DAA, and survey industry for indications of component families most sensitive to Pb-free process reflow high temperatures to determine component types to target for improvement. Collaborate with components manufacturers, as allowed. Determine functional degradation kinetics as a function of process temperature exposure to assess degradation that will affect A&D application reliability. Apply J-STD-075 methodology, and note any required improvements. Evaluate performance of proposed changes with life cycle stress testing that includes assembly, repair/rework, and life cycle environmental and use stresses.

DCAB: Execute the plan to evaluate proposed materials and construction changes to assess improvement. Provide a report on the proposed improvements and evaluation results.

DCAC: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: The high temperature exposure sensitivity of components (especially passives, and particularly capacitors) subjected to Pb-free solder process temperatures results in reliability reductions and premature failures. (See Exhibit A, Gap D51)

Expected Results: Components technology that reduces degradation of component performance due to thermal exposure of Pb-free assembly processes.

Deliverables: Materials, and design and construction techniques to reduce thermal degradation of components. – Month 36

Interdependencies:
Needs: DAA, Temperature Exposure Limits, Temperature degradation data

Collaborates: None

Feeds:
- PERM Consortium - Standards requirements input, update for J-STD-075
- PERM Consortium - Design practices for improve temperature sensitivity

Schedule:
- Start Month: 12
- Expected Duration: 24 Months

ROM Cost: $1,005K

DD Component Finish

Description: Develop approach to evaluate the performance of component finishes for A&D applications. Establish approaches to test for whether part finishes meet A&D requirements for assembly robustness, gold embrittlement, copper-nickel-tin failures, Kirkendall voiding, and new

problems. The degradation mechanisms must account for assembly stresses (e.g., multiple reflows), and environmental and operating stresses. Develop approach to evaluate the solderability performance of component finishes for A&D applications.

Gaps Addressed: Insufficient data exists to characterize solder joint reliability dependence on component finishes to assure acceptable performance in A&D applications. The existing methods for finish solderability verification are not validated for Pb-free assemblies. (See Exhibit A, Gap D11, D47, M16)

Expected Results: This project will provide the methodology to evaluate existing and new component finishes, and provide characterization data of existing finishes, along with requirements to specify solderability requirements for Pb-free applications.

Deliverables:

- Test Methods and requirements to evaluate component finishes for Pb-free solder applications. – Month 36
- Characterization data for current finishes and interaction with key solders. – Month 36
- Solderability evaluation test method and requirements. – Month 18
- Solderability characterization data for various finishes and solders. – Month 18

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $1,442K

DDA Finish Solder Joint Effect

Description: Develop approach to evaluate the performance of component finishes for A&D applications. Establish approaches to test for whether part finishes meet A&D requirements for assembly robustness, gold embrittlement, copper-nickel-tin failures, Kirkendall voiding, and new problems. The degradation mechanisms must account for assembly stresses (e.g., multiple reflows), and environmental and operating stresses. Develop approach to evaluate the solderability performance of component finishes for A&D applications.

DDAA: Prepare plan to characterize performance of Pb-free finishes (e.g., Sn, SnBi, SnAg, SnCu, SAC dip, Au) in A&D applications, including contribution to solder joint integrity. Develop approach and test methods to characterize life cycle (primarily, temperature cycle, vibration, and shock effects) performance of Pb-free finishes with key solder alloys to address failure mechanisms related to finish.

DDAB: Execute the plan to evaluate finish performance in Pb-free solder applications. Validate effectiveness of test methods. Identify new failure mechanisms related to finish.

DDAC: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: Insufficient data exists to characterize solder joint reliability dependence on component finishes to assure acceptable performance in A&D applications. (See Exhibit A, Gap D11, M16)

Expected Results: This project will provide the methodology to evaluate existing and new component finishes, and provide characterization data of existing finishes as well as requirements to specify solderability requirements for Pb-free applications.

Deliverables:

- Test Methods and requirements to evaluate component finishes for Pb-free solder applications – Month 36
- Characterization data for current finishes and interaction with key solders – Month 36

Interdependencies:

Needs: None

Collaboration:

- CAA, Test Vehicle Design and Fabrication
- CAD, Solder Joint Temperature Cycle
- CAE, Solder Vibration
- CAG, Solder Shock

Feeds:

- CAJ, Reliability model
- PERM Consortium - design handbooks, IPC and JEDEC standards; test methods

Schedule:

- Start Month: 6
- Expected Duration: 30 Months

ROM Cost: $1,012K

DDB Solderability

SOW Description: Develop approach to evaluate the solderability performance of component finishes for A&D applications.

DDBA: Prepare plan to establish approaches to test for whether part finishes meet A&D requirements for solderability. Determine design characteristics that affect solderability performance, and establish finish requirements to meet different performance levels (including solder joint integrity). Evaluate suitability of existing solderability test requirements for A&D applications. Coordinate DDA finish testing for solder joint integrity to evaluate relationship between solderability and solder joint integrity.

DDBB: Execute the plan to evaluate solderability performance of the various component finishes in Pb-free solder applications.

DDBC: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: The existing methods for finish solderability verification are not validated for Pb-free assemblies. (See Exhibit A, Gap D47)

Expected Results: This project will provide the methodology to evaluate existing and new component finishes, and provide characterization data of existing finishes as well as requirements to specify solderability requirements for Pb-free applications.

Deliverables:

- Solderability evaluation test method and requirements. – Month 18
- Solderability characterization data for various finishes and solders. – Month 18

Interdependencies:

Needs: None

Collaboration: DDA, Finish Solder Joint Effect, coordinate test vehicles

Feeds:

- PERM Consortium -Component finish characteristics and performance database
- PERM Consortium - IPC and JEDEC standards

Schedule:

- Start Month: 1
- Expected Duration: 18 Months

ROM Cost: $430K

DE Component Corrosion

Description: Characterize corrosion rates for Pb-free assembly materials and develop mitigation techniques.

Gaps Addressed: Lack of data to characterize Pb-free material corrosion rates and lack of validated Pb-free assembly corrosion mitigation methods in A&D service environments increases reliability risk. (See Exhibit A, Gap D52)

Expected Results: A capability to characterize corrosion susceptibility and design mitigation practices.

Deliverables:

- Corrosion rate models for Pb-free materials and assemblies. – Month 36
- Corrosion mitigation techniques. – Month 36

Schedule:

- Start Month: 12
- Expected Duration: 24 Months

ROM Cost: $823K

DEA Corrosion Acceleration Factors

Description: Characterize corrosion rates for Pb-free assembly materials and develop mitigation techniques.

DEAA: Prepare plan to conduct research to establish corrosion (such as electrochemical, dendritic, galvanic) acceleration factors, for common Pb-free finishes (e.g., Sn, SnBi, SnCu, SnAg, SAC dip) on component leads in A&D application environments and life cycles. Address effects of flux and other ionic residues, Pb-free process reflow profiles, and atmospheric corrosion contributors, such as moisture, sulfur dioxide, and halides.

DEAB: Execute the plan to determine corrosion models and acceleration factors for Pb-free component finishes.

DEAC: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: Lack of data to characterize Pb-free material corrosion rates in A&D service environments increases reliability risk. (See Exhibit A, Gap D52)

Expected Results: A capability to characterize corrosion susceptibility and design mitigation practices.

Deliverables: Corrosion rate models for Pb-free materials and assemblies. – Month 36

Interdependencies:
Needs: BAA, Critical Process Parameter Development – Process temperature profiles, fluxes, and cleaning

Collaborates: EC, Surface Finish – corrosion studies

Feeds: PERM Consortium - Design practices inputs

Schedule:

- Start Month: 12
- Expected Duration: 24 Months

ROM Cost: $401K

DEB Corrosion Mitigation

Description: Define and demonstrate design practice mitigation techniques, such as conformal coating and cleaning, to preclude corrosion effects.

DEBA: Prepare plan to develop and demonstrate design practice mitigation techniques, such as conformal coating and cleaning, to preclude corrosion effects. Assess life cycle environmental effects on the mitigation technique. Compare to non-mitigated conditions in DEA.

DEBB: Execute the plan to evaluate the proposed corrosion mitigation techniques and establish improvement relative to unmitigated conditions. Provide a report with information suitable for inclusion in industry handbooks.

DEBC: Work project management, including planning, reporting, coordination, and collaboration.

Gaps Addressed: Lack of validated corrosion mitigation methods for Pb-free assemblies in A&D service environments increases reliability risk. (See Exhibit A, Gap D52)

Expected Results: Capability to characterize corrosion susceptibility and design mitigation practices.

Deliverables: Corrosion mitigation techniques. – Month 36

Interdependencies:
Needs: DEA, Corrosion Acceleration Factors, to establish mitigation corrosion reduction

Collaborates: EC, Surface Finish – finish corrosion studies/test environment/vehicles coordination

Feeds: PERM Consortium - Handbook design practices

Schedule:

- Start Month: 18
- Expected Duration: 18 Months

ROM Cost: $422K

E Printed Circuit Board (PCB)

Description: There are significant reliability and sustainment issues associated with the Pb-free impacts to the printed circuit board copper materials and structures, laminate material integrity, surface finishes and design rules. The following is a summary of the tasks to be completed:

- EA Copper: The printed circuit board copper structures and material must be evaluated when using Pb-free in A&D applications. Plated-through-hole design and copper dissolution for Pb-free assemblies must be understood to ensure reliable repair.

- EB Laminate: The performance of laminates claimed to be Pb-free compatible varies widely and little evaluation has been performed with these materials in complex board constructions typical of A&D applications. There is a need to encourage development of new laminate materials that will provide enhanced thermal robustness and improved performance.

- EC Finishes: A&D needs printed circuit finishes with a long shelf life to support high mix, low volume manufacturing and repair. An assessment of the surface finishes and development of test methods for A&D applications is needed.

- ED Database and Design Rules: The culmination of the Pb-free printed circuit board materials and design activities will be captured in a database for A&D designers and manufacturers use.

Gaps Addressed:

- In PCB design, there is a risk that heritage SnPb solder geometries will need to change, or solder stencil designs will need to change, to adjust the solder volume and geometry for Pb-free solder that are currently based on thermal cycle test results and neglect shock/vibration considerations.
- Current A&D printed wiring board materials are not capable of surviving Pb-free soldering processes.
- Existing heuristic design rules, laminate materials, and assembly processes may be insufficient to ensure the manufacturability and reliability of PCB in a Pb-free manufacturing environment.

Expected Results:

- Validated surface mount pad geometries and stencil designs for IPC High Performance Class 3 products.
- Improvement in copper circuit board structures that can withstand Pb-free assembly, rework, and repair processes, resulting in more consistent and higher durability in Pb-free solder assemblies subjected to handling stresses, thermal cycling, vibration, shock, and thermal shock is expected.
- Improvement in copper circuit board structures that are more consistent and have higher durability for Pb-free solder assemblies subjected to handling stresses, thermal cycling, vibration, shock, and thermal shock is expected.
- A process for identifying the propensity of a PCB assembly to experience thermally-induced cracking or delamination after exposure to a Pb-free manufacturing environment.
- A process for evaluating the propensity of a PCB assembly to experience pad cratering during manufacturing, design testing, service and repair.
- A new laminate material able to meet assembly, reliability, and cost expectations of the A&D community

Deliverables:

- A report documenting validated surface mount pad geometry and stencil design with suggested changes for IPC-7525 Guidelines (stencil design) and IPC-SM-782 specification (surface mount pad patterns). – Month 12
- A report on a critical analysis of test methods for assessing void formation at copper/solder interfaces that defines the process used in all phases of the analysis and recommendation of test methods and/or alternative approaches to test methods. – Month 18
- A report on solder process parameter requirements for reflow, wave, and rework technologies to control copper dissolution and to maintain durability and integrity of copper structures for circuit board assemblies, and recommendations of modifications to existing test methods and/or alternative approaches to test methods. – Month 24
- Test protocol, laminate selection process, and design rules to avoid thermal degradation based on laminate material properties, PCB geometry, Pb-free manufacturing parameters (peak temperatures, number of exposures, etc.) and Pb-free manufacturing processes (reflow, solder iron, etc.). – Month 15
- Design rules for avoiding pad cratering due to single flexure events, mechanistic fracture model for pad cratering, test protocol for pad cratering and life model/accelerated test protocols for pad cratering driven by cyclic events. – Month 18
- Design rules for reducing or eliminating Conductive Anodic Filaments (CAF) in Pb-free electronic designs, data to help formulate PCB failure models, and recommendations to the IPC Working Group handling CAF issues. – Month 28
- Test protocol for thermally induced degradation in printed circuit boards. – Month 12
- A laminate selection process based on PCB geometry, PCB design features, Pb-free manufacturing parameters (peak temperatures, number of exposures, etc.) and Pb-free manufacturing processes (reflow, solder iron, etc.). – Month 15
- Design rules to avoid thermal degradation based on laminate material properties, PCB geometry, Pb-free manufacturing parameters (peak temperatures, number of exposures, etc.) and Pb-free manufacturing processes (reflow, solder iron, etc.). – Month 18
- Design rules for reducing or eliminating CAF in Pb-free electronic designs. – Month 28
- Data to help formulate PCB failure models. – Month 28
- A new laminate material able to meet assembly, reliability, and cost expectations of the A&D community. – Month 36

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $11.5M

EA Copper

Description: The printed circuit board copper structures and material must be evaluated when using Pb-free in A&D applications. Currently there are few A&D applications, starting at inception, that have been designed to be Pb-free. As a result, the copper PCB design rules have not yet been proven, especially with respect to vibration, shock and rework. Furthermore, plated-through-hole design and copper dissolution for Pb-free assemblies must be understood to ensure reliable repair. In addition, the interaction between Pb-free solder and copper plated structures has made a voiding condition worst that can adversely affect mechanical reliability. The tasks identified to resolve these issues are:

- EAA: Pad Design/ Stencil Design Assessment and Confirmation
- EAB: Copper Requirements and Copper Dissolution
- EAC: Acceptance Test Methods for Void Formation associated with Aging of Solder/Copper Plated Structures

Gaps Addressed:

- In PCB Design, there is a risk that heritage SnPb solder geometries will need to change, or solder stencil designs will need to change to adjust the solder volume and geometry for Pb-free solder that are currently based on thermal cycle test results and neglect shock/vibration considerations. (See Exhibit A, Gap # D58)
- Increased copper dissolution and plated-through-hole stresses during Pb-free soldering results in reduced interconnect reliability. (See Exhibit A, Gap T04, M15, D54, D15, D03.)
- The sporadic formation of voids near the interface between copper and the intermetallic bond continues to be underestimated across the industry. (See Exhibit A, D20)

Expected Results:

- Validated surface mount pad geometries and stencil designs for IPC High Performance Class 3 products
- Improvement in copper circuit board structures that can withstand Pb-free assembly, rework, and repair processes, resulting in more consistent and higher durability in Pb-free solder assemblies subjected to handling stresses, thermal cycling, vibration, shock, and thermal shock is expected.
- Improvement in copper circuit board structures that are more consistent and have higher durability for Pb-free solder assemblies subjected to handling stresses, thermal cycling, vibration, shock, and thermal shock is expected.

Deliverables:

- A report documenting validated surface mount pad geometry and stencil design with suggested changes for IPC-7525 Guidelines (stencil design) and IPC-SM-782 specification (surface mount pad patterns). – Month 12
- Report on a critical analysis of test methods for assessing copper dissolution that defines the process used in all phases of the analysis, including literature search, data types, criteria for data evaluation, experimental procedures, results and recommendation of test methods and/or alternative approaches to test method to meet the needs of the A&D community. – Month 18
- Report on solder process parameter requirements for reflow, wave, and rework technologies to control copper dissolution and to maintain durability and integrity of copper structures for circuit board assemblies. – Month 24
- Database/report of evaluated copper integrity and durability data needed to establish test method as standard. – Month 30
- Report on a critical analysis of test methods for assessing void formation at copper/solder interfaces. – Month 20
- Database/report of evaluated copper plating property data and interim standard test results needed to establish test method and coupon as standard, along with a compilation of additional processing or properties of the copper plating as a design rule or specification. – Month 20

Schedule:

- Start Month: 1
- Expected Duration: 30 Months

ROM Cost: $1,328K

EAA Pad Design/ Stencil Design Assessment and Confirmation

Description: Review failure modes in conjunction with IPC pad design rules for A&D products, and validate pad and stencil design rules using "Design of Experiment." The factors include solder alloys and flux to demonstrate solder joint quality/ strength using pad and stencil design rules. An A&D Pb-free test vehicle can be utilized for thermal cycle, vibration and shock environments.

EAAA: Analyze and review currently published Pb-free surface mount pad and stencil design rules.

EAAB: Generate and select surface mount pad geometry sets and stencil design protocols using spread test method with OSP, Immersion silver, Immersion tin, and ENIG PCB surface finishes in an assessment/down-select methodology.

EAAC: Perform, detailed inspection, cross section analysis for integrity, metallurgy and morphology. Evaluate axial pull / shear testing, thermal cycling, vibration and shock of selected parts (particularly area array devices).

EAAD: Formalize validated surface mount pad geometry and stencil design rules for Pb-free assembly.

EAAE: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: In PCB Design, there is a risk that heritage SnPb solder geometries will need to change, or solder stencil designs will need to change to adjust the solder volume and geometry for Pb-free solder that are currently based on thermal cycle test results and neglect shock/vibration considerations. (See Exhibit A, Gap # D58)

Expected Results: Validated surface mount pad geometries and stencil designs for IPC High Performance Class 3 products.

Deliverables: A report documenting validated surface mount pad geometry and stencil design with suggested changes for IPC-7525 Guidelines (stencil design) and IPC-SM-782 specification (surface mount pad patterns). – Month 12

Interdependencies:

Needs: None

Collaborate:

- BAA Critical Process Parameter Development = collaborate on pad designs during testing
- CAA Test Vehicle Design & Fabrication = collaborate on pad designs during test vehicle development

Feeds: ED, Database and Design Rules = feed test results to database and determine design rules

Schedule:

- Start Month: 1
- Expected Duration: 12 months

ROM Cost: $454K

EAB Copper Requirements and Copper Dissolution

SOW Description: To provide the A&D community with design rules, test methods, and Pb-free solder process parameters to improve the durability and integrity of printed circuit board copper structures after assembly and rework and to mitigate problems caused by copper dissolution and plated through hole copper cracking during service and/or repair.

EABA: Develop test method to capture risk of lot-to-lot variations of copper platings for printed circuit boards with respect to copper dissolution and copper PTH specifications. (1) Perform critical analysis of existing data on copper dissolution effects and PTH life. (2) Based on best practices test, develop test coupon as an interim standard, (3) Run DOE necessary to establish test data on dissolution and repair stresses. (4) Gather other physical property and geometry data on structures.

EABB: Determine the Pb-free solder process parameter requirements needed for reflow, wave, and rework technologies to maintain the durability and integrity of printed circuit card copper structures for A&D products.

EABC: Create database and body of knowledge required to establish test method as a standard and, if possible, processing or properties of the copper plating as a design rule or specification.

EABD: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: Increased copper dissolution and plated-through-hole stresses during Pb-free soldering results in reduced interconnect reliability. Several mainstream Pb-free solders cause extensive dissolution of the PCB copper metallization during wave and select fountain soldering creating issues in reliability and limiting repair. The dissolution with Pb-free solder is worse than heritage SnPb solder because of the higher processing temperatures associated with Pb-free solder and greater solubility limits of copper in Pb-free solder. Further complicating the problems of both copper dissolution and PTH reliability is that the large thermal mass typical of A&D assemblies requires long exposure to the molten solder to achieve a properly formed solder joint during both initial assembly and repair. The heritage SnPb design rules for surface copper and plated through holes are insufficient for Pb-free use in A&D products that must be capable of long-term service, rework and repair. (See Exhibit A, Gap T04, M15, D54, D15, D03.)

Expected Results: Improvement in copper circuit board structures that can withstand Pb-free assembly, rework, and repair processes, resulting in more consistent and higher durability in Pb-free solder assemblies subjected to handling stresses, thermal cycling, vibration, shock, and thermal shock is expected.

Deliverables:

- Report on a critical analysis of test methods for assessing copper dissolution that defines the process used in all phases of the analysis, including literature search, data types, criteria for data evaluation, experimental procedures, results and recommendation of test methods and/or alternative approaches to test method to meet the needs of the A&D community. – Month 18
- Report on solder process parameter requirements for reflow, wave, and rework technologies to control copper dissolution and to maintain durability and integrity of copper structures for circuit board assemblies. The report should include test coupons and test vehicles for evaluating test methods, that defines the process used in all phases of the analysis, including literature search, data types, and criteria for data evaluation. A set of recommendations of modifications to existing test methods and/or alternative approaches to test method to meet the needs of the A&D community, should be developed. – Month 24
- Database/report of evaluated copper integrity and durability data needed to establish test method as standard. – Month 30

Interdependencies:

Needs: None

Collaborate:

- BAA, Critical Process Parameter Development = Report on solder process parameters for reflow, wave, and rework technologies to control copper dissolution and to maintain durability and integrity of copper structures for circuit board assemblies
- BAB, Repair and Rework Critical Process Parameters = Report on solder process parameters for reflow, wave, and rework technologies to control copper dissolution and to maintain durability and integrity of copper structures for circuit board assemblies

  Feeds: ED, PCB Design Rules and Databases = Final Report

Schedule:

- Start Month: 13

- Expected Duration: 18 Months

ROM Cost: $580K

EAC Acceptance Test Methods for Void Formation - Aging of Solder/Copper Plated Structures

Description: To provide the A&D community with a standard test method to screen copper platings and copper board structures for void formation during aging of solder/copper structures to improve the durability and integrity of printed circuit board solder joints. It is well known that the copper plating process introduces impurities into the copper that can lead to void formation during aging. At a minimum, an acceptance test shall be developed for the copper plating on printed circuit boards with respect to this degradation mode.

EACA: Develop acceptance test method to capture risk of lot-to-lot variations of copper platings for void formation during aging of copper/solder interfaces. (1) Determine baseline best practices test from existing data; (2) Based on best practices test, develop test coupon as an interim standard test coupon that captures the effects of pad size, edges, and corners on local plating conditions, (3) Run DOE necessary to establish test parameter effects on void formation.

EACB: Perform validation test of test method.

EACC: Create database and body of knowledge required to establish test method as a standard and, if possible, processing or properties of the copper plating as a design rule or specification.

EACD: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: The sporadic formation of voids near the interface between copper and the intermetallic bond continues to be underestimated across the industry. The problem is caused by the incorporation of impurities into the copper. Lead-free solder with less ductility can exacerbate the problem. A quantitative understanding of the problematic mechanism, along with how the phenomena is accelerated, has generated some established practical remedies that still need to be implemented in a production environment (Exhibit A, D20)

Expected Results: Improvement in copper circuit board structures that are more consistent and have higher durability for Pb-free solder assemblies subjected to handling stresses, thermal cycling, vibration, shock, and thermal shock is expected.

Deliverables:

- Report on a critical analysis of test methods for assessing void formation at copper/solder interfaces. This will define the process used in all phases of the analysis, including literature search, data types, criteria for data evaluation, experimental procedures, results, including validation experiments, and recommendation of test methods and/or alternative approaches to test methods to meet the needs of the A&D community. – Month 20
- Database/report of evaluated copper plating property data and interim standard test results needed to establish test method and coupon as standard, along with a compilation of additional processing or properties of the copper plating as a design rule or specification. – Month 20

Interdependencies:
Needs: None

Collaborate: None

Feeds: EAB, Copper Requirements and Copper Dissolution – requirements for copper voiding.

Schedule:

- Start Month: 13
- Expected Duration: 8 Months

ROM Cost: $294K

EB Laminate

Description: The printed circuit laminates used in industry have changed to accommodate Pb-free processing. The performance of laminates claimed to be Pb-free compatible varies widely and little evaluation has been performed with these materials in complex board constructions typical of A&D applications. Some of these laminates are more brittle than the heritage material making them more susceptible to fracturing under the pads, a phenomenon called "pad cratering." In addition, the Pb-free processing makes traditional A&D failures modes such as conductive anodic filament growth worse. There is a need to encourage development of new laminate materials that will provide enhanced thermal robustness and improved performance. The tasks identified to resolve these issues are:

- EBA Thermal Robustness of Laminate Material
- EBB Pad Cratering
- EBC Conductive Anodic Filament (CAF)
- EBD Development of New Laminate Material

Gaps Addressed:

- Existing heuristic design rules, laminate materials, and assembly processes may be insufficient to ensure the manufacturability and reliability of PCB in a Pb-free manufacturing environment (see Exhibit A, Gap #D36, D44, M15, D02, and S5).
- Existing heuristic design rules, laminate materials, assembly and repair processes, and tests and screens may be insufficient to ensure the reliability of PCBA when exposed to handling, temperature cycling, mechanical shock, and vibration environments (see Exhibit A, Gap #D36, D44, D02, S5, D15, D16, D17, D18, D21, D27, D38, R04, S07, S11)
- Conductive anodic filament (CAF) formation is a degradation mechanism that results in short circuit failures from PCB plated through holes to adjacent conductors. The elevated PCB processing temperatures in combination with the service environments in A&D applications exacerbates this failure mode and result in reduced reliability. There currently is little data on the risk of CAF formation within lead-free laminates exposed to lead-free processing temperatures. (See Exhibit A, D39, D02)
- Existing laminate material is insufficient in regards to assembly and reliability expectations of the A&D community when assembled with Pb-free solder (see Exhibit A, Gap D02, D36, D44, and M15)

Expected Results:

- A process for identifying the propensity of a PCB assembly to experience thermally-induced cracking or delamination after exposure to a Pb-free manufacturing environment.
- A process for evaluating the propensity of a PCB assembly to experience pad cratering during manufacturing, design testing, service and repair.
- The test results should provide a better understanding of the CAF resistance of Pb-free laminates exposed to Pb-free processing conditions.
- A new laminate material able to meet assembly, reliability, and cost expectations of the A&D community

Deliverables:

- Test protocol for thermally induced degradation in printed circuit boards. – Month 12

- A laminate selection process based on PCB geometry, PCB design features, Pb-free manufacturing parameters (peak temperatures, number of exposures, etc.) and Pb-free manufacturing processes (reflow, solder iron, etc.). – Month 15
- Design rules to avoid thermal degradation based on laminate material properties, PCB geometry, Pb-free manufacturing parameters (peak temperatures, number of exposures, etc.) and Pb-free manufacturing processes (reflow, solder iron, etc.). – Month 18
- Design rules for reducing or eliminating CAF in Pb-free electronic designs. – Month 28
- Data to help formulate PCB failure models. – Month 28
- Deliver test data to the IPC Working Group handling CAF issues. Month 28
- Validated new laminate material. – Month 36

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $5,260K

EBA Thermal Robustness of Laminate Material

SOW Description: Develop test protocols for evaluating laminate materials for acceptability to meet thermal conditions expected in Pb free A&D manufacturing environments

EBAA: Develop a fundamental understanding of the degradation that initiates when laminate material is exposed to manufacturing temperatures. Focus should be on both cohesive and interfacial mechanisms and the influence of materials (silane chemistry, material formulation, filler type and resin volume), laminate design (glass weave, resin content), and PCB processing (lamination profile).

EBAB: Capture the influence of PCB geometry (size, thickness, number of layers) and PCB design features (copper thickness, functional pads, etc.).

EBAC: Capture the influence of long-term aging and moisture absorption on the robustness of laminate material when exposed to manufacturing temperatures.

EBAD: Capture the influence of type of manufacturing process (reflow, solder iron, hot air, and laser) on the robustness of laminate material.

EBAE: Develop test protocols to assess thermal robustness of laminate material.

EBAF: Identify laminate material relevant to the A&D community and initiate testing on representative samples using develop test protocols.

EBAG: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: Existing heuristic design rules, laminate materials, and assembly processes may be insufficient to ensure the manufacturability and reliability of PCB in a Pb-free manufacturing environment (see Exhibit A, Gap #D36, D44, M15, D02, and S5).

Expected Results: Develop a process for identifying the propensity of a PCB assembly to experience thermally-induced cracking or delamination after exposure to a Pb-free manufacturing environment

Deliverables:

- Test protocol for thermally induced degradation in printed circuit boards. – Month 12

- A laminate selection process based on PCB geometry, PCB design features, Pb-free manufacturing parameters (peak temperatures, number of exposures, etc.) and Pb-free manufacturing processes (reflow, solder iron, etc.). – Month 15
- Design rules to avoid thermal degradation based on laminate material properties, PCB geometry, Pb-free manufacturing parameters (peak temperatures, number of exposures, etc.) and Pb-free manufacturing processes (reflow, solder iron, etc.). – Month 18

Interdependencies:

Needs: None

Collaborate:

- BAA, Critical Process Parameter Development = Process parameters
- BAB, Rework and Repair Critical Process Parameter Development = Process parameters
- EBB, Pad Cratering = Pad cratering is a failure mode influenced by the thermal robustness of laminate materials
- EBC, CAF = CAF is a failure mode influenced by the thermal robustness of laminate materials

Feeds:

- EBD, New Laminates = Material drivers for thermal degradation
- ED, Databases and Design Rules = Material and design drivers for thermal degradation

Schedule:

- Start Month: Month 1
- Expected Duration: 18 Months

ROM Cost: $1,013K

EBB Pad Cratering

Description: Develop test protocols and models for evaluating and predicting the propensity of pad cratering during flexure events.

EBBA: Capture existing capabilities of the electronic industry supply chain to characterize laminate material parameters and handling and storage limits and loading magnitudes.

EBBB: Develop a fundamental understanding of pad cratering that occurs during a single flexure event. Focus should be on both cohesive and interfacial fracture mechanisms and the influence of materials (silane chemistry, resin formulation, filler type and resin volume), laminate design (glass weave, resin content, etc.), and PCB design features (pad size, pad definition, copper thickness). Activities may include characterization of the fracture and fatigue strength of glass/resin composites and stress analysis to capture crack initiation events. Assist in development of a coupon level test that could facilitate ranking of laminate for pad cratering and possibly scaling of laminate cratering performance with factors such as force magnitude, force rate, pad size, etc.

EBBC: Develop and validate a mechanistic fracture model predicting the onset of single event pad cratering as a function of laminate properties, loading rates, PCB design features, solder material, and component package.

EBBD: Assess effect of exposure to Pb-free manufacturing environments and conditions (reflow parameters, number of reflows, etc.), ambient temperatures and long-term aging on single event pad cratering.

EBBE: Correlate the coupon test to service conditions. Assess effect of multiple flexure events on the onset of pad cratering. Include drivers such as ambient conditions, sequence of prior loading (aging,

moisture absorption, thermal cycling, vibration, etc.) and actual loading conditions (strain, strain rate, etc.). Laminate materials relevant to the A&D community should be selected to this activity. Characterization of the laminate material in correlation with Task EBBB should be performed.

EBBF: Develop test protocol to assess the potential for single event and multi-event pad cratering on laminate material Testing at both the PCB fabricator and the assembly manufacturer should be part of protocol.

EBBG: Develop a life model for this pad cratering due to multiple flexure events.

EBBH: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: Existing heuristic design rules, laminate materials, assembly and repair processes, and tests and screens may be insufficient to ensure the reliability of PCBA when exposed to handling, temperature cycling, mechanical shock, and vibration environments (see Exhibit A, Gap #D36, D44, D02, S5, D15, D16, D17, D18, D21, D27, D38, R04, S07, S11)

Expected Results: A process for evaluating the propensity of a PCB assembly to experience pad cratering during manufacturing, design testing, service and repair.

Deliverables:

- Initial design rules for avoiding pad cratering due to single flexure events. – Month 6
- Initial mechanistic fracture model for pad cratering. – Month 9
- Final mechanistic fracture model for pad cratering. – Month 18
- Test protocol for pad cratering (primary focus on accept/reject criteria for laminate material). – Month 18
- Life model for pad cratering driven by cyclic events. – Month 24
- Accelerated test protocols and representative acceleration factors (may involve modification of existing dynamic test standards). – Month 24

Interdependencies:

Needs:

- None

Collaborate:

- BAA, Critical Process Parameter Development = Process parameters
- BAB, Rework and Repair Critical Process Parameter Development = Process parameters
- EBA, Thermal Robustness of Laminate Materials = Pad cratering is a failure mode influenced by the thermal robustness of laminate materials
- CEB, Shock and Vibration Robustness of Partially Filled Lead-Free PTH Connector Barrels for A&D

Feeds:

- CFB, Handling = Loading drivers for pad cratering
- EBD, New Laminates = Material drivers for pad cratering
- ED, Databases and Design Rules = Material and design drivers for pad cratering

Schedule:

- Start Month: Month 6
- Expected Duration: 24 Months

ROM Cost: $2,500K

EBC Conductive Anodic Filament (CAF)

Description: Conduct testing to provide a better understanding of the CAF resistance of Pb-free laminates exposed to Pb-free processing conditions.

EBCA: Determine if the current IPC test methods and coupons are suitable for evaluating CAF formation using Pb-free processing conditions and Pb-free laminates. If the IPC test methods are found to be inappropriate, modify the test methods.

EBCB: Assess the risk of CAF formation associated with the use of Pb-free processing conditions and Pb-free laminates. Conduct a test program using test coupons fabricated from a variety of Pb-free laminates. These coupons shall contain PTH nets fabricated using a range of drill sizes and PTH wall-to-wall spacing which are representative of A&D electronic designs. The same vendor using Class 3 processes shall make all test coupons. All PTH's shall be drilled on the same drill machine and the run-out on each spindle of the drill machine shall be measured. Each coupon will then be exposed to five Pb-free reflow profiles or SnPb control profiles using a reflow oven suitable for A&D electronics assembly. The coupons will then be tested using IPC-TM-650, Method 2.6.25 or other appropriate method. Traditionally, 100 VDC bias is applied to each PTH net in a 65 ºC and 87% relative humidity environment. A decade drop in the test circuit resistance shall indicate CAF failure. Aging of test coupons in a combined vibration/shock/temperature cycle environment representative of actual field conditions may also be conducted and the results compared to the traditional CAF test data. After testing, an attempt shall be made to verify CAF failures using micro sections. Visual inspections of the test coupon surfaces shall be conducted to rule out any non-CAF failure mechanisms. It is recommended that a vendor familiar with CAF testing conduct the test. The results of the testing shall be fully documented in a test report.

EBCC: Task EBCB should be repeated several times to capture CAF risk lot-to-lot.

EBCD: Develop design rules for reducing or eliminating CAF in new designs based upon the results of the CAF testing.

EBCE: Project management including planning, reporting, coordination and collaboration.

Gaps Addressed: Conductive anodic filament (CAF) formation is a degradation mechanism that results in short circuit failures from PCB plated through holes to adjacent conductors. The elevated PCB processing temperatures in combination with the service environments in A&D applications exacerbates this failure mode and result in reduced reliability. There currently is little data on the risk of CAF formation within lead-free laminates exposed to lead-free processing temperatures. (See Exhibit A, D39, D02)

Expected Results:
The test results should provide a better understanding of the CAF resistance of Pb-free laminates exposed to Pb-free processing conditions.

Deliverables:

- Design rules for reducing or eliminating CAF in Pb-free electronic designs. – Month 28
- Data to help formulate PCB failure models. – Month 28
- Deliver test data to the IPC Working Group handling CAF issues. – Month 28

Interdependencies:

Needs: None

Collaborate:

- BBB, Field Life Data for Validating Qualification and Acceptance Predictions = Data to feed models
- BBA, Method for Determining Qualification and Acceptance Test Parameters = Data to feed models
- EBA, Thermal Robustness of Laminate Material = Effects of thermal environments on laminates

Feeds:

- EBD, New Laminates = Data on new laminates
- ED, PWB Design Rules and Databases = Yields new design rules

Schedule:

- Start Month: 13
- Expected Duration: 15 Months

ROM Cost: $447K

EBD Development of New Laminate Material

Description: Development of new laminate material that meets the assembly, reliability, and cost expectations of the A&D community.

EBDA: Capture current laminate capabilities, limitations, and costing. Identify major limitations within the laminate industry and attempt to correlate laminate capabilities and limitations with polymer formulation, glass treatments, glass weave, fillers, and post treatments. Rely on results from Thermal Robustness of Laminate Materials (EBA), EBB (Pad Cratering), and Conductive Anodic Filament (EBC)

EBDB: Investigate opportunities to improve laminate performance specific to the major limitations identified in Task 1

EBDC: Obtain preliminary cost information to narrow potential solution approaches.

EBDD: Initiate prototype build of new laminate material(s) and perform qualification testing.

EBDE: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: Existing laminate material introduce is insufficient in regards to assembly and reliability expectations of the A&D community when assembled with Pb-free solder (see Exhibit A, Gap D02, D36, D44, and M15)

Expected Results: A new laminate material able to meet assembly, reliability, and cost expectations of the A&D community.

Deliverables:

- Initial proposal for new laminate material – Month 30
- New laminate material – Month 36
- Validation data for new laminate material – Month 36

Interdependencies:

Needs:

- EBA, Thermal Robustness of Laminate Materials = Material drivers for thermal degradation
- EBB, Pad Cratering = Material drivers for pad cratering
- EBC, CAF = Material drivers for CAF

Collaborate: None

Feeds: ED, Database and Design Rules

Schedule:

- Start Month: Month 18
- Expected Duration: 18 Months

ROM Cost: $1,300K

EC Finishes

Description: The Pb-free printed circuit finishes being used by the consumer industry do not have the same system level performance as heritage tin-lead solder finishes. In particular, A&D needs finishes with a long shelf life to support high mix low volume manufacturing and repair. Many of the finishes that have been developed for consumer electronics may be acceptable as long as they are fully covered with solder during assembly. Unfortunately, there are many instances where the original printed circuit board finish will not be soldered during assembly (e.g. press fit connectors, test points, etc.). There are also failure mechanisms that are exacerbated with the increased rigidity of the Pb-free solder and the intermetallic compounds that can form with some of the Pb-free alloys being considered. In addition, an assessment of the surface finishes and development of test methods for A&D applications is needed. The tasks identified to resolve these issues are:

- ECA Surface Finish Evaluation
- ECB Surface Finish Test Methods
- ECC Development of New PCB Plating Material
- ECD Sporadic Brittle Failure of Pb-Free Solder Due to Nickel Plating

Gaps Addressed:

- Current Pb-free materials are insufficient for A&D products. There is no known optimal PCB plating finish that meets or exceeds SnPb assembly and reliability performance. (See Exhibit A, Gap D12, D47 D52)
- Current Pb-free materials are insufficient for A&D products. There is no known part plating finish that meets or exceeds SnPb assembly and reliability performance. Pb-free surface finish performance with respect to service environments being not well understood increases reliability risk during long-term storage and in long-term service with electric power applied. The test methods used as a basis for PCB design rules currently utilize heritage SnPb methods that may be insufficient to ensure solderability and corrosion resistance of Pb-free finishes in A&D applications. In addition, new methods must be developed to improve PCB finish verification to ensure that the qualified configuration is maintained during initial manufacture and repair. Furthermore, tin whisker propensity of purchased PCBs is needed to ensure reliability of A&D Pb-free product. (See Exhibit A, D12, D47, D52)
- Current plating materials and heuristic rules may be insufficient to ensure reliability of Pb-free A&D product (see Exhibit A, Gap D12 and D47)
- There is no known part plating finish that meets or exceeds SnPb assembly and reliability performance. Currently nickel plating is used extensively as a barrier layer over the copper to prevent excessive dissolution during soldering. It has been observed that current nickel plating on parts soldered with Pb-free solder is susceptible to sporadic occurrences of brittle fracture between the solder and the nickel region in or adjacent to the intermetallic creating issues during the initial manufacture assemblies. Furthermore, with the use of stiffer and stronger Pb-free solder alloys in harsh A&D environments this failure mode is expected to increase. (Exhibit A, D12, D47, D52)
- There is no known part plating finish that meets or exceeds SnPb assembly and reliability performance. Currently nickel plating is used extensively as a barrier layer over the copper to prevent excessive dissolution during soldering. It has been observed that current nickel plating on parts soldered with Pb-free solder is susceptible to sporadic occurrences of brittle fracture between the solder and the nickel region in or adjacent to the intermetallic creating issues during the initial manufacture assemblies. Furthermore, with the use of stiffer and stronger Pb-free solder alloys in harsh A&D environments this failure mode is expected to increase. (Exhibit A, D12, D47, D52)

Expected Results:

- The project will quantify the following lead-free finish attributes after assembly: their robustness in harsh environments; their solderability after aging; their corrosion resistance, and their resistance to forming tin whiskers.

- Test methods for solderability, corrosion, finish verification and tin whiskers for PCB finishes.
- A process for preventing brittle failures of solder joints on ENIG or electrolytic Ni pads.
- A new plating material able to meet assembly, reliability, and cost expectations of the A&D community

Deliverables:

- Report of the test results to PERM and IPC 45XX Committees. – Months 16 & 36
- Solderability preconditioning assessment report. – Month 6
- Corrosion test method report. – Month 6
- Finish verification method report. – Month 9
- Final report providing project results for use by PERM and or IPC committee 3-11C, and those maintaining J-STD-003, IPC-45XX. – Month 12
- Validation data for new plating material. – Month 36

Schedule:

- Start Month: 18
- Expected Duration: 18 Months

ROM Cost: $4,662K

ECA Surface Finish Evaluation

Description: This project will quantify the following lead-free finish attributes after assembly: their robustness in harsh environments; their solderability after aging; their corrosion resistance; and their resistance to forming tin whiskers.

ECAA: Assembly Robustness of Surface Finishes

- ECAAA: Literature Survey – Perform a literature survey to determine the current knowledge base concerning environmental testing of assemblies in harsh environments.
- ECAAB: Experimental Formulation – A partial factorial experimental matrix shall be formulated that shall evaluate: five solder finishes (e.g. SnPb, ENIPEG, HASL SAC, HASL SN100C, OSP Copper) and three solders (e.g. SnPb, SAC305, SN100C) combined with one storage condition, three soldering conditions (e.g. FCR, wave, manual), three environmental conditions (e.g. thermal cycling, vibration and shock), and one flux (cleanable). The experimental design shall be peer reviewed (e.g. reviewed with IPC 45XX Task Groups).
- ECAAC: Execute experiments, perform analyses and reduce results for joint reliability, compatibility with various solder alloys, and intermetallic strength.
- ECAAD: Establish preconditioning methods that shall be done prior to performing solderability testing.
- ECAAE: A work project management report including, planning, reporting, coordination and collaboration.

ECAB: Solderability Assessment of Surface Finishes

- ECABA: Literature Survey – Perform a literature survey to determine the current knowledge base concerning solderability testing for harsh environments.
- ECABB: Experimental Design – A partial factorial experimental matrix shall be designed that shall evaluate: five solder finishes (e.g. SnPb, ENIPEG, HASL SAC, HASL SN100C, OSP Copper) and three solders (e.g. SnPb, SAC305, SN100C) combined with two storage conditions, four reflow conditions (e.g. STD SMT, 6X SMT. Wave, Manual), and one flux (cleanable). The experimental design shall be peer reviewed (e.g. reviewed with IPC 45XX Task Groups).
- ECABC: Execute experiments, perform analyses and reduce results.
- ECABD: Establish preconditioning methods that shall be done prior to performing solderability testing.

- ECABE: Work project management including, planning, reporting, coordination and collaboration.

ECAC: Corrosion Assessment of Surface Finishes

- The purpose is to characterize the effects of the following on finish corrosion
  - Alloying additions.
  - Electric power application
  - Environmental atmosphere
  - Multiple reflows and flux types
- ECACA: Literature Survey – Perform a literature survey to determine the current knowledge base concerning corrosion testing of finishes for harsh environments. The following items shall be evaluated: non-solder coated pads, solder coated pads and the boundary between non-solder coated and solder coated regions on the same pad.
- ECACB: Experimental Design – A partial factorial experimental matrix shall be formulated that shall evaluate: five solder finishes (e.g. SnPb, ENIPEG, HASL SAC, HASL SN100C, OSP Copper) and three solders (e.g. SnPb, SAC305, SN100C), combined with four reflow conditions (e.g. 3X SMT, 6X SMT, 1X Wave, 3X Wave) two environmental conditions (humidity, mixed flowing gasses), and one flux (cleanable). In addition, two electrical stress levels shall be evaluated. The experimental design shall be peer reviewed (e.g. reviewed with IPC 45XX Task Groups).
- ECACC: Execute experiments, perform analyses and reduce results.
- ECACD: Establish preconditioning methods that shall be done prior to performing solderability testing.
- ECACE: Work project management including, planning, reporting, coordination and collaboration.

ECAD: Tin Whisker Assessment of PCB Surface Finishes

- ECADA: Literature Survey – Perform a literature survey to determine the current knowledge base concerning tin whisker testing of finishes for harsh environments. The following items shall be evaluated: non-solder coated pads, solder coated pads and the boundary between non-solder coated and solder coated regions on the same pad.
- ECADB: Experimental Design – A partial factorial experimental matrix shall be designed that shall evaluate: three solder finishes (e.g. SnPb, HASL SAC, HASL SN100C) and three solders (e.g. SnPb, SAC305, SN100C), subjected to four reflow conditions (e.g. STD SMT, 6X SMT), and three environmental conditions (humidity, mixed flowing gasses and thermal cycling).
- ECADC: Execute experiments, perform analyses and reduce results.
- ECADD: Establish preconditioning methods that shall be done prior to performing solderability testing.
- ECADE: Work project management including, planning, reporting, coordination and collaboration.

ECAF: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: Current Pb-free materials are insufficient for A&D products. There is no known optimal PCB plating finish that meets or exceeds SnPb assembly and reliability performance. Of particular concern are Pb-free solders, PCB finishes, and component finishes, subjected to long storage and/or powered on service conditions in harsh A&D environments. Current Pb-free finishes with the best shelf life characteristics such as ENIG or Ni/Au, can form a detrimental brittle SnNiCu intermetallic when soldered with Pb-free SAC solder. In addition, Pb-free material corrosion rates with respect to service environments being not well understood increases reliability risk. Immersion Silver and copper organic solderability preservatives form better intermetallic joints with the Pb-free solder than ENIG, but must be used with care in corrosive salt or sulfur environments since they may need additional coating or sealing to prevent dendrites. Furthermore, Pb-free alloy additions such as zinc or indium may also exhibit unsatisfactory corrosion resistance in harsh A&D applications. Immersion tin has the best corrosion resistance, but is susceptible to tin whisker formation and has a limited shelf life. Existing heuristic rules used by mechanical designers based

on experience with SnPb programs may be insufficient to ensure solderability and reliability of Pb-free products. (See Exhibit A, Gap D12, D47 D52)

Expected Results: The project will quantify the following lead-free finish attributes after assembly: their robustness in harsh environments; their solderability after aging; their corrosion resistance, and their resistance to forming tin whiskers.

Deliverables:

- Preliminary report of the test results to PERM and IPC 45XX Committees. – Month 16
- Final report of the test results to PERM and IPC 45XX Committees. – Month 36

Interdependencies:

Needs: None

Collaborate:

- ABD, New Test Methods (Part-Level) = Develop new tin whisker test methods
- ABE, New Test Methods (Product-Level) = New tin whisker test methods
- BAA, Critical Process Parameter Development = Assembly process guidelines
- BAB, Rework and Repair Critical Process Parameter Development = Rework guidelines
- ECB, Surface Finish Test Methods = Develop new surface finish tests
- ECC, Develop New Finishes = Develop new PWB finishes
- ED, Data Base = Design rules for PCBs

Feeds: ED, PCB Design Rules and Databases = Final Report

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $1,586K

ECB Surface Finish Test Methods

Description: The performance of Pb-free PCB finishes is ensured through design, PCB lot testing and procurement requirements. The existing solderability and corrosion practices (e.g. JEDEC/IPC) shall be reviewed in the context of Pb-free. Standards in A&D harsh and long service environments for their applicability to 1 to 3-year shelf life and long-term corrosion resistance. In addition, methods shall be evaluated for the verification of PCB finishes during initial receipt and repair to ensure that the qualified configuration is maintained. Furthermore, tin whisker test methods shall be established to assess the whisker propensity of Pb-free tin rich finishes on PCBs. A database of the information and design rules shall be compiled periodically and in conclusion of the project.

ECBA Solderability Preconditioning/Testing Assessment – The J-STD-003 has recently been updated to included solderability testing of Pb-free finishes, however, the sample preconditioning requirements prior to testing need to be developed to ensure applicability to A&D product. In the present task, solderability preconditioning and testing methods shall be evaluated for various Pb-free assembly alloys with SnPb as a reference. The test methods shall be tested over various storage and service conditions with samples subjected to typical solder processes used in initial manufacture and rework over typical A&D storage and service conditions.

- ECBAA: Literature Survey – Perform literature survey to determine state of the art for solderability testing considering harsh long storage and fielded environments.
- ECBAB: Experimental Formulation – The project shall establish the key factors influencing solderability in order to define preconditioning and test methods for A&D circuit boards. A

partial factorial experimental matrix shall be formulated to support the development of the preconditioning/test method combination to evaluate the sensitivity of Pb-free solder finish composition and finish type (plated or fused) with several classes of solder and types of soldering processes and fluxes. Service environment considerations including electrical bias shall be considered in the preconditioning/method development. The board sample or coupon for the test shall consider the following items: non-solder coated pads, solder coated pads and pads with a boundary between non-solder coated and solder coated regions. The preconditioning and test method shall be peer reviewed (e.g. IPC J-STD-003 committee).

- ECBAC: Execute Experiment, perform analysis and reduce results
- ECBAD: Establish preconditioning methods:
  Preconditioning methods that will be performed prior to solderability testing or modifications to existing solderability processes shall be established. In necessary, PCB procurement requirements shall be established to ensure long-term solderability for manufacture.
- ECBAE: Work project management including, planning, reporting, coordination and collaboration.

ECBB Corrosion Test Method Assessment – The corrosion performance shall be evaluated for various Pb-free finishes, under conditions of electrical bias and non-bias, various storage conditions, and conditions simulating various service environmental atmospheric conditions. The effect of multiple reflows and flux types shall be included in the evaluation. The test method shall include evaluation of non-soldered regions and non-soldered/soldered pad boundary regions on the PCB for long-term corrosion over various storage and fielded environments.

- ECBBA: Literature Survey – Perform literature survey to determine state of the art of corrosion testing for harsh long storage and fielded environments.
- ECBBB: Experimental Formulation – Develop experiments to determine the key factors driving corrosion for Pb-free finishes over long-term harsh A&D service conditions. Test plan shall be peer reviewed (e.g. reviewed by IPC Corrosion task group 3-11G).
- ECBBC: Execute Experiment, perform analysis and reduce results.
- ECBBD: Establish preconditioning methods that shall be done prior to performing solderability testing.
- ECBBE: Work project management including, planning, reporting, coordination and collaboration.

ECBC Finish verification method – Evaluate surface finish verification methodologies (cross sectioning, EDX, XRF, coupon form factor, method for R&R verification, etc…) to ensure reliable assembly and maintenance of the qualified configuration.

- ECBCA: Literature Survey – Perform literature survey to determine state of the art of finish verification of PCBs that would be suitable for use at initial manufacture, incoming inspection and during repair.
- ECBCB: Experimental Formulation – Verify the effectiveness of the finish verification methods during initial manufacturing and repair, particular in the case where the PCB pads have been solder coated.
- ECBCC: Execute Experiment, perform analysis and reduce results.
- ECBCD: Document method to verify finish of PCBs.
- ECBCE: Work project management including, planning, reporting, coordination and collaboration.

ECBD Tin whisker test method – Adopt the tin whisker test method established in the tin whisker Technical Approach to PCB whisker growth.

- ECBDA: Literature Survey – Perform literature survey to determine state of the art for tin whisker testing of PCBs.
- ECBDB: Experimental Formulation – Develop a coupon for board level tin whisker assessment to implement the component tin whisker test developed by the tin whisker group. Perform a

pilot assessment of the tin whisker test coupon for various finishes, reflows and environments considering the fundamental tin whisker growth knowledge at the time.

- ECBDC: Execute Experiment, perform analysis and reduce results.
- ECBDD: Establish preconditioning methods that shall be done prior to performing solderability testing.
- ECBDE: Work project management including, planning, reporting, coordination and collaboration.

Gaps Addressed: Current Pb-free materials are insufficient for A&D products. There is no known part plating finish that meets or exceeds SnPb assembly and reliability performance. Pb-free surface finish performance with respect to service environments being not well understood increases reliability risk during long-term storage and in long-term service with electric power applied. The test methods used as a basis for PCB design rules currently utilize heritage SnPb methods that may be insufficient to ensure solderability and corrosion resistance of Pb-free finishes in A&D applications. In addition, new methods must be developed to improve PCB finish verification to ensure that the qualified configuration is maintained during initial manufacture and repair. Furthermore, tin whisker propensity of purchased PCBs is needed to ensure reliability of A&D Pb-free product. (See Exhibit A, D12, D47, D52)

Expected Results: Test methods for solderability, corrosion, finish verification and tin whiskers for PCB finishes.
Current Pb-free materials are insufficient for A&D products. There is no known part plating finish that meets or exceeds SnPb assembly and reliability performance. Pb-free surface finish performance with respect to service environments being not well understood increases reliability risk during long-term storage and in long-term service with electric power applied. The test methods used as a basis for PCB design rules currently utilize heritage SnPb methods that may be insufficient to ensure solderability and corrosion resistance of Pb-free finishes in A&D applications. In addition, new methods must be developed to improve PCB finish verification to ensure that the qualified configuration is maintained during initial manufacture and repair. Furthermore, tin whisker propensity of purchased PCBs is needed to ensure reliability of A&D Pb-free product. (See Exhibit A, D12, D47, D52)

Deliverables:

- Solderability preconditioning assessment - Preliminary report. – Month 6
- Corrosion test method - Preliminary report. – Month 6
- Finish verification method – Final report – Month 9
- Tin whisker test coupon – Final report – Month 9
- Final report providing project results for use by PERM and or IPC committee 3-11C, and those maintaining J-STD-003, IPC-45XX. – Month 12

Interdependencies:

Needs: None

Collaborate:

- ECA Surface Finish Evaluation – Use feedback from testing to modify test methods
- ABD Test Method for Tin Whisker Risk at the Part Level – Tin whisker test for components
- ABE Validated Test Methods (Product) – Tin whisker test for product

Feeds:

- ECC Development of New PCB Plating Material – Results of testing methodology feeds requirements for new platings
- ED Database and Design Rules – Results of project will feed into a database and design rules

Schedule:

- Start Month: 1

- Expected Duration: 12 Months

ROM Cost: $939K

ECC Development of New PCB Plating Material

Description: Development of new plating material that meets the assembly, reliability, and cost expectations of the A&D community.

ECCA: Assess current PCB plating materials compatible with Pb-free solder. Identify capabilities and limitations in regards to the needs of the A&D community. Rely on results from Board Laminate and Finish Effects (CDE), Copper Dissolution (EAB), Surface Finish Evaluation (ECA), Surface Finish Test Methods (ECB), and Sporadic Nickel Plating (ECD).

ECCB: Investigate opportunities to improve the performance of PCB plating materials compatible with Pb-free solder specific to the major limitations identified in Task 1

ECCC: Obtain preliminary cost information to narrow potential solution approaches.

ECCD: Perform plating material research and development.

ECCE: Initiate prototype build of substrates with new plating material and perform qualification testing. Qualification testing will be based on industry standard practice (solderability, long-term storage, etc.) and additional test protocols identified in other activities (tin whisker, corrosion, etc.).

ECCF: Work project management including planning, reporting, coordination, and collaboration.

Gaps Addressed: Current plating materials and heuristic rules may be insufficient to ensure reliability of Pb-free A&D product (see Exhibit A, Gap D12 and D47)

Expected Results: A new plating material able to meet assembly, reliability, and cost expectations of the A&D community

Deliverables:

- Initial proposal for new plating material. – Month 30
- New plating material. – Month 36
- Validation data for new plating material. – Month 36

Interdependencies:

Needs:

- CDE, Board Laminate and Finish Effects
- EAB, Copper Dissolution
- ECB, Surface Finish Test Methods
- ECD, Sporadic Nickel Plating

Collaborate: ECA, Surface Finish Evaluation

Feeds: ED, Database and Design Rules

Schedule:

- Start Month: Month 18
- Expected Duration: 18 Months

ROM Cost: $1,093K

ECD Sporadic Brittle Failure of Pb-Free Solder Due to Nickel Plating

Description: Major intermetallic bond failures in Pb-free solder can be traced to sporadic problems with the plated nickel (Ni) surface finishes. An effective screening procedure will be identified. Guidelines for electroplating to prevent the problem will be developed.

ECDA: Electroless nickel / immersion gold (ENIG) and electrolytic nickel (Ni) / electroless gold (Au) coated copper (Cu) pads shall be sampled from suppliers and users and problematic pads exhibiting extremely weak intermetallic bonds shall be identified by soldering and mechanical testing. Intermetallic microstructures shall be characterized in terms of thicknesses, morphologies and composition.

ECDB: Substrates with and without problematic pads shall have solder balls attached and they shall all be subjected to a range of mechanical tests. Test procedures shall include shear strength, pull strength in different directions, cyclic loading in shear and pull, and cyclic impact testing. For each procedure, the distributions of strength or number of cycles to failure shall be compared. The test procedure leading to the greatest differences between failure distributions from one substrate to another shall be identified. The occurrences of extremely weak intermetallic bonds shall be correlated with the corresponding failure distributions on the same substrates.

ECDC: A practical screening protocol shall be developed based on testing a limited number of pads with the procedure identified.

ECDD: Systematic electroplating experiments shall be conducted under controlled conditions. Simpler chemistries may be employed to establish a quantitative understanding of the electrochemistry of nickel plating, but proposed composition and process shall be verified with commercial chemistries. This effort shall be supported by soldering and testing to establish correlations between impurity incorporation or other surface features and brittle failure.

ECDE: Establish guidelines for electroplating of nickel to prevent the problem.

ECDF: Work project management including planning, reporting, and coordination.

Gaps Addressed: There is no known part plating finish that meets or exceeds SnPb assembly and reliability performance. Currently nickel plating is used extensively as a barrier layer over the copper to prevent excessive dissolution during soldering. It has been observed that current nickel plating on parts soldered with Pb-free solder is susceptible to sporadic occurrences of brittle fracture between the solder and the nickel region in or adjacent to the intermetallic creating issues during the initial manufacture assemblies. Furthermore, with the use of stiffer and stronger Pb-free solder alloys in harsh A&D environments this failure mode is expected to increase. (Exhibit A, D12, D47, D52)

Expected Results: A process for preventing brittle failures of solder joints on ENIG or electrolytic Ni pads

Deliverables:

- A practical screening procedure for ENIG and electrolytic Ni/Au pad finishes. – Month 24
- Nickel electroplating guidelines for prevention of brittle Pb-free solder failure. – Month 36

Interdependencies:

Needs: None

Collaborate: ECB, Surface Finish Test Methods = Test methods to assess new nickel electroplating guidelines

Feeds: ED, Database and Design Rules

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $1,043K

ED Database and Design Rules

Description: Collect all data from project area E Printed Circuit Board and create a database. Develop PCB design rules for Pb-free assembly of A&D products.

Gaps Addressed: Current Pb-free materials are insufficient for A&D products. There is no known PCB plating finish that meets or exceeds SnPb assembly and reliability performance. Heuristic rules used by electrical and mechanical designers based on experience with SnPb programs may be insufficient to ensure reliability of Pb-free product. Pb-free material PCB corrosion rates with respect to service environments being not well-understood increases reliability risk. Current A&D printed wiring board materials are not capable of surviving Pb-free soldering processes. Lack of maximum reflow cycles control and requirements and lack of understanding of materials and process compatibility issues that affect repair.

Expected Results: This project will provide a database of new and future materials attributes and compatibilities resulting in design rules for PCBs used in Pb-free assembly of A&D products.

Deliverables:

- Preliminary Database/design rules. – Month 9
- Interim Database/design rules. – Month 21
- Final Database/design rules. – Month 36
- Report to PERM Consortium and IPC on design rules for Pb-free for A&D – Months 9, 21, 36

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $207K

F Program Management and Systems Engineering

Description: This project area contains the Program management and administration for the overall execution of the Pb-free Electronics Risk Reduction Program as described in the Technical Approaches A through F. Technical Approach FA includes the management and administration of subcontracts required to execute the R&D tasks described (and funded) in Technical Approaches A through F.

Technical Approach FB contains the Systems Engineering effort required to manage the technical interdependencies between and within Technical Approaches A through E, including the allocation and closure of identified R&D gaps. Technical Approach FB includes the development and maintenance of a Systems Engineering Management Plan in contractor format and the conduct of overall Technical Opportunity and Risk Management.

Gaps Addressed: This task manages the overall program activities to deal with all identified Pb-free electronics technical Research and Development (R&D) gaps addressed by Technical Approaches A through E.

Expected Results:

- Effective management of R&D activities including cost and schedule performance.
- Timely dissemination of R&D progress and results to the government customer.
- Coordinated hand-off of R&D findings to the PERM Consortium for follow-on dissemination and implementation activities.
- On-going assessments of technical progress and closure of identified R&D gaps
- Sound, integrated technical approach for the R&D tasks

Deliverables:

- Quarterly Program Review Meetings – Every 3 Months beginning in Month 4
- Monthly Technical Progress Reports – Monthly Beginning in Month 2
- Monthly Cost Expenditure Reports – Monthly Beginning in Month 2
- Systems Engineering Management Plan in contractor format – Month 4
- Technical Opportunity and Risk Management Reports – Month 4, Updated Quarterly
- Final Report – Month 36

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $8.6M

FA Program Management

Description: The full-time Program Management team shall consist of a Program Manager, Chief Engineer, Subcontract Manager, and Administrative Assistant. The PM team is responsible for effective communication and coordination with the Government Program Office. Interface with the customer shall include:

- Communication of program activities, progress, and issues and their resolution
- The conduct of Quarterly Program Review Meetings
- The submittal of Monthly Technical Progress Reports and Cost Expenditure Reports
- The preparation and submittal of a Final Report.

The PM team is also responsible for interfacing with the Pb-free Electronics Risk Management (PERM) Consortium's Executive Steering Committee to coordinate an effective hand-off of R&D results to the appropriate PERM Consortium Task Teams. This interface activity includes participation in quarterly PERM Consortium meetings and periodic teleconferences. The Chief Engineer will participate in the PERM Consortium's Research Coordination Task Team meetings and teleconferences.

The PM team will interface with other government, industry and academia groups as warranted to promote collaboration in the R&D required to deal with Pb-free electronics issues impacting the aerospace and defense community.

Gaps Addressed: This task manages the overall program activities to deal with all identified Pb-free electronics technical Research and Development (R&D) gaps addressed by Technical Approaches A through E.

Expected Results:

- Effective management of R&D activities including cost and schedule performance.
- Timely dissemination of R&D progress and results to the government customer.
- Coordinated hand-off of R&D findings to the PERM Consortium for follow-on dissemination and implementation activities.

Deliverables:

- Quarterly Program Review Meetings – Every 3 Months beginning in Month 4
- Monthly Technical Progress Reports – Monthly beginning in Month 2
- Monthly Cost Expenditure Reports – Monthly beginning in Month 2
- Final Report – Month 36

Interdependencies:

Needs: Technical execution of Technical Approaches A through E and FB (Systems Engineering)

Collaborates: All tasks

Feeds:

- Provides overall Program Management and administration for Technical Approaches A through E and FB
- Provides overall technical oversight for Technical Approaches A through E and FB
- Provides overall Subcontract Management and administration for Technical Approaches A through E and FB

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $5,528K

FB Systems Engineering

Description: The Systems Engineering team shall consist of sixteen Pb-free electronics R&D subject matter experts led by the Chief Engineer. Participation in Phase 1 and 2 of the Pb-free Electronics R&D Manhattan Project is not a prerequisite, but is highly encouraged for continuity.

The Systems Engineering team shall participate in the Quarterly Program Review Meetings (Ref: Technical Approach FA) and conduct monthly teleconferences to review and assess the technical progress and closure of identified R&D gaps. Members of the Systems Engineering team may also be engaged in the conduct of the R&D activities contained in Technical Approach A through E.

Gaps Addressed: This Technical Approach manages the R&D Systems Engineering activities to deal with all identified Pb-free electronics technical gaps addressed by Technical Approach A through E.

Expected Results:

- On-going assessments of technical progress and closure of identified R&D gaps
- Sound, integrated technical approach for the R&D tasks

Deliverables:

- Systems Engineering Management Plan in contractor format – Month 4
- Technical Opportunity and Risk Management Report – Month 4, Updated Quarterly

Interdependencies:

Needs:

- Chief Engineer and PM support contained in Technical Approach FA
- Technical execution of Technical Approaches A through E

Collaborates: All tasks

Feeds:

- Provides overall systems engineering oversight for Technical Approaches A through E
- Provides integrated Technical Opportunity and Risk Management for Technical Approaches A through E

Schedule:

- Start Month: 1
- Expected Duration: 36 Months

ROM Cost: $3,114K

LEAD FREE ELECTRONICS MANHATTAN PROJECT PHASE 2 REPORT

APPENDIX D

Gap Key

Gap Area	ID	Technical Area
DATABASE & TESTING	D01	SOLDER
DATABASE & TESTING	D02	LAMINATE
DATABASE & TESTING	D03	TEST DATA
DATABASE & TESTING	D04	LONG TERM RELAIBILITY
FAILURE IDENTIFICATION	D05	INTERMITTENT FAILURES
PB FREE COST MODELS	D06	SUSTAINMENT
PB FREE COST MODELS	D07	NRE
PB FREE COST MODELS	D10	HIGH STRESS ENVIRONMENTS
MATERIALS RESEARCH	D11	MANUFACTURING
MATERIALS RESEARCH	D12	COMPONENT PLATING
MATERIALS RESEARCH	D13	PCB PLATING
FAILURE MODE DEVELOPMENT	D14	MUTIPLE SOLDERS
FAILURE MODE DEVELOPMENT	D15	SOLDER JOINT
FAILURE MODE DEVELOPMENT	D16	VIBRATION
FAILURE MODE DEVELOPMENT	D17	MECHANICAL SHOCK
FAILURE MODE DEVELOPMENT	D18	HIGH G
FAILURE MODE DEVELOPMENT	D19	COMBINED ENVIRONMENTAL
FAILURE MODE DEVELOPMENT	D20	ELECTROMIGRATION
FAILURE MODE DEVELOPMENT	D21	PTH
FAILURE MODE DEVELOPMENT	D22	PAD CRATERING & TRACE CRACKING
FAILURE MODE DEVELOPMENT	D23	TIN WHISKERS
FAILURE MODE DEVELOPMENT	D24	PROCESS VARIATIONS
FAILURE MODE DEVELOPMENT	D25	PRECONDITIONING
FAILURE MODE DEVELOPMENT	D25A	PRIOR EVENTS
FAILURE MODE DEVELOPMENT	D26	CONTAMINATION
TEST SCREEN DEVELOPMENT & VALIDATION	D27	DIAGNOSTIC PROCESSES
TEST SCREEN DEVELOPMENT & VALIDATION	D29	DESIGN VERIFICATION
TIN WHISKER RISK MITIGATION	D30	DESIGN VERIFICATION OR PRODUCT QUALIFICATION
DESIGN RULES	D31	TIN WHISKER PREVENTION
DESIGN RULES	D32	METAL VAPOR ARCING
DESIGN RULES	D33	COMBINED ENVIRONMENTAL
DESIGN RULES	D34	VIBRATION
DESIGN RULES	D35	MECHANICAL SHOCK
DESIGN RULES	D36	ENCAPSULANTS & UNDERFILL
RISK ASSESSMENT	D37	COMPONENT WHISKERING
RISK ASSESSMENT	D38	PAD CRATERING & TRACE CRACKING
RISK ASSESSMENT	D39	CAF
RISK ASSESSMENT	D40	PTH FATIGUE FAILURES
DESIGN RULES	D41	LAMINATE
DESIGN RULES	D42	WHISKER PRONE
DESIGN RULES	D43	RF CIRCUITS

TEST SCREEN DEVELOPMENT & VALIDATION	D43	PRODUCT QUALIFICATION
MATERIALS RESEARCH	D44	PB FREE ALLOY
DESIGN RULES	D45	ELECTRICAL DESIGN
TEST SCREEN DEVELOPMENT & VALIDATION	D46	TIN WHISKER IMPACT
DESIGN RULES	D47	SOLDERABILITY OF FINISHES
TIN WHISKER RISK MITIGATION	D48	TIN WHISKER RISK COST MITIGATION
DESIGN RULES	D49	CONFORMAL COATING
DESIGN RULES	D50	PTH SOLDER FILL
DATABASE & TESTING	D51	PREMATURE FAILURES
DESIGN RULES	D53	MIXED SOLDERS
DESIGN RULES	D54	COPPER DISSOLUTION
MATERIALS RESEARCH	D55	PCB LAMINATE
PROCESS DEVELOPMENT	D56	REWORK-REPAIR
DATABASE & TESTING	D57	STORAGE CONDITIONS
DESIGN RULES	D58	SOLDER GEOMETRIES
FAILURE MODE DEVELOPMENT	D59	PI FACTORS
PROCESS DEVELOPMENT	M01	PROCESS CAPABILITY
MATERIALS RESEARCH	M02	CLEANING PROCESS
TIN WHISKER RISK MITIGATION	M03	TIN WHISKER MITIGATION
MATERIALS RESEARCH	M04	CONFORMAL COATING
PROCESS DEVELOPMENT	M05	INERT ATMOSPHERE
MATERIALS RESEARCH	M06	CONTAMINATION
PROCESS DEVELOPMENT	M07	REPEATABILITY & REPRODUCIBILITY
PROCESS DEVELOPMENT	M08	CROSS CONTAMINATION
PROCESS DEVELOPMENT	M09	SINGUALTION
PROCESS DEVELOPMENT	M10	VAPOR PHASE
PROCESS DEVELOPMENT	M11	REWORK EQUIPMENT
PROCESS DEVELOPMENT	M12	LASER SODLERING
PROCESS DEVELOPMENT	M13	SOLDERING EQUIPMENT
MATERIALS RESEARCH	M14	JOINT MICROSTRUCTURE
MATERIALS RESEARCH	M15	PWB MATERIALS
MATERIALS RESEARCH	M16	COMPONENTS
TEST SCREEN DEVELOPMENT & VALIDATION	M17	DURABILITY
PROCESS DEVELOPMENT	M18	FLUX RESIDUE
PROCESS DEVELOPMENT	M19	SOLDER DEFECTS
FAILURE IDENTIFICATION	M21	INSPECTION
TEST SCREEN DEVELOPMENT & VALIDATION	M24	ICT
TEST SCREEN DEVELOPMENT & VALIDATION	M25	SCREENING PROCEDURES
TEST SCREEN DEVELOPMENT & VALIDATION	M28	REPROCESSING
PROCESS DEVELOPMENT	M29	COPPER DISSOLUTION

MATERIALS RESEARCH	R01	WHISKER GROWTH MECHANISMS
DATABASE & TESTING	R02	LIFE TEST DATA UNDERFILLED COMPONENTS
FAILURE MODE DEVELOPMENT	R03	MODELING TECHNIQUES
DATABASE & TESTING	R04	LOW TEMPERATURE BEHAVIOUR
DESIGN RULES	R05	CREEP RUPTURE
MATERIALS RESEARCH	R06	PB-FREE MATERIAL INFORMATION
MATERIALS RESEARCH	S01	REWORK/REPAIR STRESSES
CONFIGURATION MANAGEMENT	S02	MATERIAL COMPATIBILIITY IN CONFIGURATION CONTROL
MATERIALS RESEARCH	S05	REFLOW CYCLES
MATERIALS RESEARCH	S06	MATERIAL COMPATIBILIITY IN REPAIR
MATERIALS RESEARCH	S07	RELIABILITY DEGRADATION FROM REPAIR
FAILURE MODE DEVELOPMENT	S11	DIAGNOSTIC PROCESSES FOR TIN WHISKERS
RISK ASSESSMENT	S12	INCOMING INSPECTION STANDARDS FOR TIN WHISKERS
DATABASE & TESTING	S15	FIELD SERVICE DATA
MATERIALS RESEARCH	S17	SHIPPING AND HANDLING PROCEDURES
MULTIPLE CATEGORIES	S19	NO SUSTAINMENT EXPERIENCE FOR PB FREE
MATERIALS RESEARCH	S20	UNDERFILL REPAIRABILITY AND DEGRADATION IN STORAGE
DESIGN RULES	T01	TIN PEST DESIGN RULES
MATERIALS RESEARCH	T02	TIN PEST TESTING
MATERIALS RESEARCH	T04	COPPER DISSOLUTION TESTING
TEST SCREEN DEVELOPMENT & VALIDATION	T05	STANDARDIZED TESTS FOR SIMULATED SOLDER JOINTS
DESIGN RULES	T07	DEFINED LIMITS ON HANDLING FOR Pb-free ASSEMBLIES

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