Lead Free Electronic Manhattan Project
Best Practices and Benchmarking Center of Excellence

Carmine Meola
R&D Projects Manager
ACI Technologies
cmeola@aciusa.org

Forward: The document is a complied extraction of the various passages from the fully referenced Lead Free Manhattan Project – Phase [1] book to be published on Dec 3rd, 2009 by the *Benchmarking and Best Practice Center of Excellence.* The effort to address the various aspects of Pb-free, which affects the Aerospace and Defense industry has been a collaborative one, and continues as of this writing. The members and efforts of this team should be duly noted and recognized for their efforts.

Abstract: The dissemination of the best Pb-free mitigation practices was established through the Pb-free Manhattan Project Phase 1 to mitigate the effects of the worldwide movement to Pb-free electronics. DoD Mission Critical programs are the most susceptible in the worldwide movement to adapt Pb-free processes and materials as the standard in the manufacturing of electronic assemblies. The recommendations made from Phase I have been developed for the purpose of consolidating data and information to assure a minimum risk associated with the use of manufacturing processes which have required modification due to the introduction of Pb-free materials.

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. Using the corporate knowledge collected from The Pb-Free Electronics Manhattan Project, a research and development roadmap for future projects was established in each specific area of focus (Design, Materials, Manufacturing, Sustainment, Test, and Reliability) to address the tangible deficiencies.

Finally, the model for the conduct of the Pb-Free Electronics Manhattan project has proven to be a successful method for integrating a diverse body of subject matter experts and creating an environment of synthesized information exchange and capture. It is recommended that this process be identified as a best practice and applied to other pervasive issues.

1. Introduction

The worldwide electronics supply industry is adopting lead (Pb) 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 them, reject them, 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.

4th International Workshop on Reliable Engineering Computing (REC 2010)
Edited by Michael Beer, Rafi L. Muhanna and Robert L. Mullen

ISBN: 978-981-08-5118-7. *Published by* Research Publishing Services.
doi:10.3850/978-981-08-5118-7_068

Although the European Union (EU) legislation was the initial reason for suppliers to transition to Pb-free electronics, many have been transitioning for a myriad of other reasons such as establishing a competitive advantage in the marketplace.

Aerospace and Defense OEMs are at risk because they are unable to control the global electronics supply chain because their collective demand is low compared to that of commercial manufacturers. Establishing control over this supply chain by high-reliability users such as the Department of Defense (DoD) and the commercial airline industry is futile. Over 50% of the electronics manufacturing today is conducted off-shore to the USA, and the collective demand by all of the military electronics users represents less than 1% of the total world-wide market. Consequently, it is inevitable that they will unknowingly receive Pb-free components in place of SnPb-based electronics, regardless of what was ordered.

Factors which exacerbate this risk are:

1) A lack of standardization as to what type of data and the level of data that should be provided by the suppliers when they deliver materials or parts.

2) A lack of material characterization data required to establish confidence in part usage and uncertainty regarding the test protocols currently established to yield confidence data. The current test standards and protocols (i.e., temperature cycling and dwell times, mechanical shock and vibration tests, etc.) have evolved and are interpreted based upon 50 plus years of experience using eutectic Pb-based solder alloys, and may not provide the appropriate stress test conditions for Pb-free based solder alloys. Hence, currently there is no standard test protocol available to qualify Pb-free electronic products, other than the fallback position of using existing standards which are based on Pb.

3) A lack of standardized manufacturing, assembly, rework and repair processes due to a dearth of information and standards on how to sustain Pb-free products.

All of these factors contribute to an A&D OEM dilemma where there is little to no contractual guidance to help steer the use of Pb-free electronics materials and processes. Yet the supply chain that OEMs depend upon continues to transition and propagate Pb-free usage.

Consequently, A&D OEMs are ultimately being forced to use Pb-free electronics or implement costly processes to ensure their denial. 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. Sustainment of these platforms necessitates greater attention to manage and control electronics inventories, while preparing for the use of specialized rework and repair processes to maintain a "Pb-only" baseline, as well as a Pb-based and Pb-free component mix.

2. Overview

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 form Electrical and Electronic Equipment (WEEE))* and Pacific-Rim geographical regions (circa 2006). Many non-US countries have followed suit in order to restrict the disposal of electronic 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 the manufacturing and disposal of electronic equipment. To date, Aerospace and Defense OEMs are exempt form this legislation.

The general definition of Pb-free is depicted in Europe and in the US as packages that contain solder and other materials that have a maximum of 0.1% Pb (percent 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 transition or shift in the supplier baseline has undermined the fundamental process of how electronics assemblies are built 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, while understanding its impact upon their product performance, and establishing risk mitigation processes for its use; Thus creating a pervasive issue. Exacerbating this issue is the fact that a single "drop-in" replacement for the legacy SnPb baseline does not exist. 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 electronics 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 of A&D products built using this technology in typical "harsh environments" and long product lives, is un-quantified. Pb-free 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 typical commercial product life, which is measured over a few years. These factors contribute to the risk associated with Pb-free electronics, and the uncertainty of how to adequately address them within current required 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*.

The customer base has a general awareness of Pb-free electronics use, bu reliance upon performance-based procurements has shifted the burden of awareness and product risk mitigation to the A&D OEMs. Unfortunately, without a uniform approach and existing standards to guide the OEMs, a current state exists where A&D OEMs can deliver an assortment of mixed SnPb and Pb-free, and/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 to some extent contain product pedigrees that are unknown and whose build of materials vary widely. This situation greatly impacts product sustainability and leads to a high total ownership cost (TOC) and a logistical quagmire. Extrapolation of this situation leads to a state of unrestrained cost growth.

3. Technical Issues

The major risks confronting products 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 the defined environmental applications outlined in its contractual service life. The primary product reliability risks related to Pb-free electronics is the premature failure of the solder joint interface 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
Build of Material:	**Build of Material:**
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	

Table 2–1 Pb-free Electronics Risk Factors. Use of Pb-free electronics poses risk to product reliability and sustainability and shown are those risk factors which must be addressed in the life cycle.

The product development cycle as outlined in Figure 3-1, shows that the inclusion and ramifications of Pb-free materials, begins at the platform requirements phase, and propagates through to product sustainment. While eutectic and near-eutectic SnPb alloys have long been the benchmark for electronic assembly, Pb-free solder and Pb-free surface finishes present challenges in design and qualification test development for aerospace and defense (A&D) equipment. Under some accelerated thermal cycling conditions, consumer Pb-free assemblies have been reported to have good reliability with respect to SnPb assemblies. However, Pb-free consumer hand held devices have been found to have lower reliability in drop-shock testing than the SnPb counterparts. Unfortunately, little testing has been done for the full spectrum of aerospace and defense environments such as extended storage, thermal cycling, vibration, shock, humidity, and corrosion, or some combination of these tests. As is outlined in Table 3-1[2] , Pb-free is not as consistently reliable as SnPb, and can introduce additional failure modes not normally assocaited with SnPb assemblies. As a result of not having a drop-in-replacement for SnPb, the design details at every level need to be evaluated. While high-volume design and manufacturing of Pb-free assemblies have been developed over the last 10 years, aerospace and defense (A&D) designs that utilize Pb-free solder in severe or complex operating environments, are only beginning to be done. It is well known that the increased processing temperatures of Pb-free solders, have caused the manufacturing process windows to tighten significantly. As a result of this change, designs for consumer products have adapted to meet the demands of high volume manufacturing, while A&D designs will have had to settle for lower yields, in an a manufacturing enviroment where a high mix of products at low volumes is typical. Addtionaly, A&D designs must also accommodate long term relaibility and sustainability requirements that are not usually mandatory for consumer products.

4. Design

The product development cycle as outlined in Figure 3-1, shows that the inclusion and ramifications of Pb-free materials, begins at the platform requirements phase, and propagates through to product sustainment. While eutectic and near-eutectic SnPb alloys have long been the benchmark for electronic assembly, Pb-free solder and Pb-free surface finishes present challenges in design and qualification test development for aerospace and defense (A&D) equipment. Under some accelerated thermal cycling conditions, consumer Pb-free assemblies have been reported to have good reliability with respect to SnPb assemblies. However, Pb-free consumer hand held devices have been found to have lower reliability in drop-shock testing than the SnPb counterparts. Unfortunately, little testing has been done for the full spectrum of aerospace and defense environments such as extended storage, thermal cycling, vibration, shock, humidity, and corrosion, or some combination of these tests. As is outlined in Table 3-1, Pb-free is not as consistently reliable as SnPb, and can introduce additional failure modes not normally assocaited with SnPb assemblies. As a result of not having a drop-in-replacement for SnPb, the design details at every level need to be evaluated. While high-volume design and manufacturing of Pb-free assemblies have been developed over the last 10 years, aerospace and defense (A&D) designs that utilize Pb-free solder in severe or complex operating environments, are only beginning to be done. It is well known that the increased processing temperatures of Pb-free solders, have caused the manufacturing process windows to tighten significantly. As a result of this change, designs for consumer products have adapted to meet the demands of high volume manufacturing, while A&D designs will have had to settle for lower yields, in an a manufacturing enviroment where a high mix of products at low volumes is typical. Addtionaly, A&D designs must also accommodate long term relaibility and sustainability requirements that are not usually mandatory for consumer products.

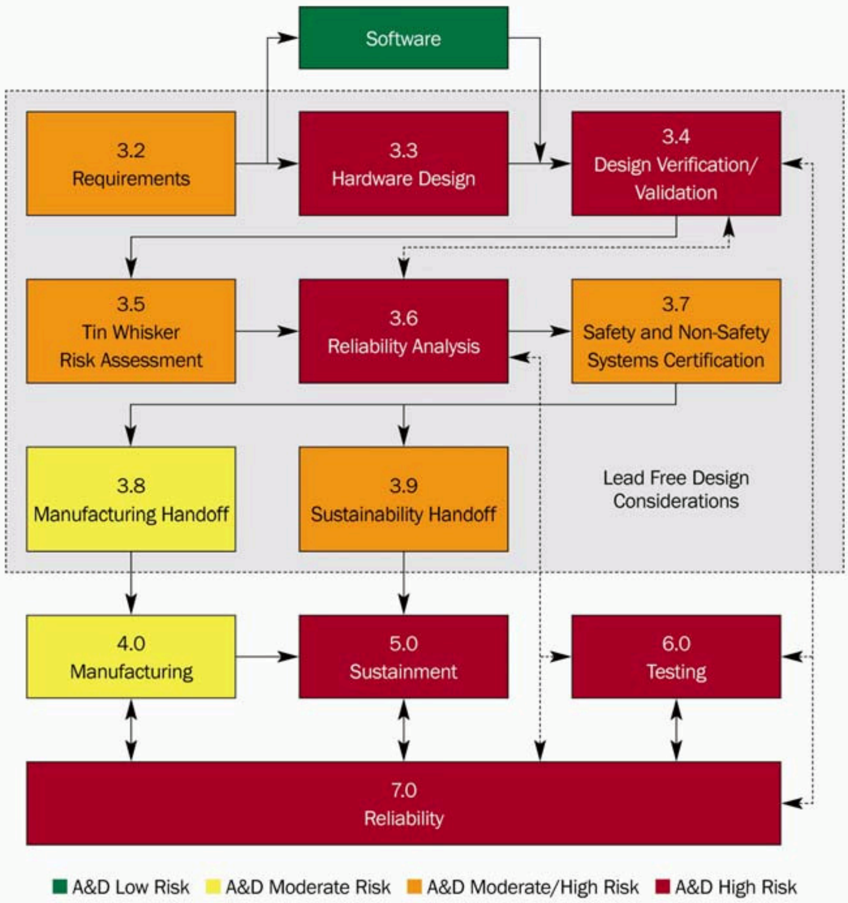

Figure 3.1 Design in Product Development Cycle. Note the risk color coding is based on having both Pb-free finished parts and Pb-free soldered assemblies.

5. Manufacturing

The advent of Pb-free solders and materials into the manufacturing stream has posed new challenges for OEMs and CMs alike. New Pb-free solder alloys are continually being developed, while investigations into new solder-less technologies are concurrently being pursued as alternates to the conventional means of attachment. Pb-free electronics manufacturing requires tighter process controls, with more rigorous attention to the detailed requirements for each process flow step, than for SnPb systems. Implementation of process control windows and variables is essential for assembly of Pb-free electronics. Understanding the importance and the method of good solder joint formation is critical to solder joint integrity. The metallurgical aspects of solder joint formation will be discussed as a prelude to the manufacturing processes, because of the critical nature of how solder joint formation, sets a foundational basis for establishing process parameters Design for manufacturing is also particularly vital as an implementation tool in the understanding of the factors related to high yield, low cost assemblies. With the addition of the new Pb-free material sets, which includes solders, finishes, and substrates, defect detection becomes more difficult because the failure mechanisms are either not fully defined, or considerably different than SnPb. Despite the lack of Pb-free "drop-in" practices, manufacturing a Pb-free assembly is possible with improved process controls, targeted design modifications, and equipment selections. The flow chart (fig 4-1) depicts the baseline practices of each step in the manufacturing flow. The blocks in the flow chart are color coded to depict areas that are impacted (and to what degree) by Pb-free processing.

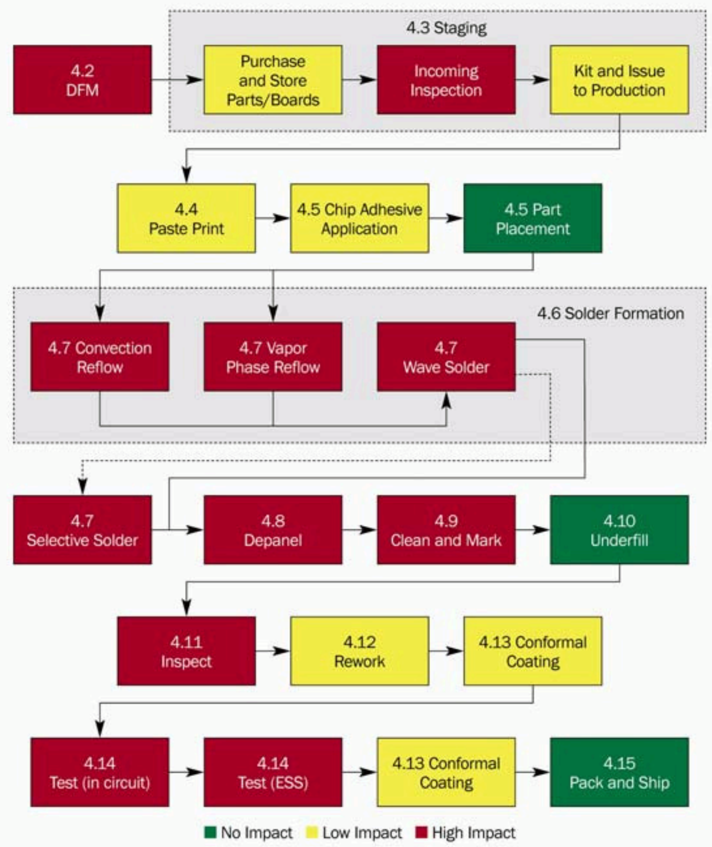

Figure 4.1 Manufacturing Flow. The blocks in the flow chart are color coded to depict areas that are impacted (and to what degree) by Pb-free processing.

6. Sustainment

Sustainment often is understood to include provisions for end-of-life of a given project, for which there currently exists a large body of knowledge, legal requirements, industry policies, processes, and practices. The existing system adequately addresses end-of-life issues. The same organizational structure (fig 5-1) can be used for addressing Pb-free issues with a greater emphasis on ensuring that the proper metrics, that compose a good sustainment process, be followed rigorously to ensure compliance. Appropriate control of parts and processes to mitigate the uncertainty introduced by the insertion of Pb-free electronics into systems, will require additional effort.

The transition to Pb-free electronics will have a profound impact on sustainment of A&D systems. Configuration control and reliability risks will rise to unacceptable levels if not understood as urgent, and managed appropriately. Those risks are driven by unique A&D requirements including:

- Long product service lifetimes.
- Rugged operating environments.
- High consequences of failure.
- Reparability at the circuit card assembly level.

If the number of solder alloys used in original assemblies proliferates, a lack of proper product identification and configuration control will result in product reliability and potential failure risks. The processes for identification of the alloys used in original assemblies will likely require enhancement, particularly for support of repair procedures, to manage these risks. The risks will increase exponentially as the number of available solder alloys and part finishes increases. In consideration of the fact that each repair facility must deal with products from scores of hardware manufacturers, and that each hardware manufacturer may choose from multiple assembly solder alloys, the potential proliferation of alloy combinations will be unacceptable, unless tighter controls are put in place to define the acceptable alloys for reworking.

Reliability risks will result if the alloys used to repair an assembly have not been qualified, verified, and documented as compatible with the alloys used for original manufacture.

In addition to the above risks, there is an enormous potential for increased life cycle cost. It is critical for the feedback loops among repair facilities, hardware design authorities, and manufacturing activities be significantly improved to accommodate Pb-free electronics. This improvement is possible in commercial A&D operations, but systemic disconnects exist in military operations, because the contracts for repair, production, and support are rarely connected. Comprehensive industry implementation of Pb-free Control Plans (LFCP), verified as compliant to GEIA-STD-0005-1[3], can facilitate the realization of these goals.

The Sustainment section of this report will describe the current baseline practices as they exist for Pb-free in the areas of Configuration Management, Logistics, and Repair. What will become apparent during the dissemination of these procedures, are the noticeable gaps, issues, and misperceptions surrounding the current practices. The report will also include conclusions from the assessments of these practices, and recommended actions to mitigate the impact on the sustainment efforts directed toward Pb-free electronics.

7. The sustainment sphere of influence

The flow chart in Figure 5-3 [4] illustrates the interrelationships and scope of how the various elements of the sustainment process interact within a program management structure. From the flow chart, it can be ascertained that manufacturing, design, reliability and test play a critical role in influencing product life cycle.

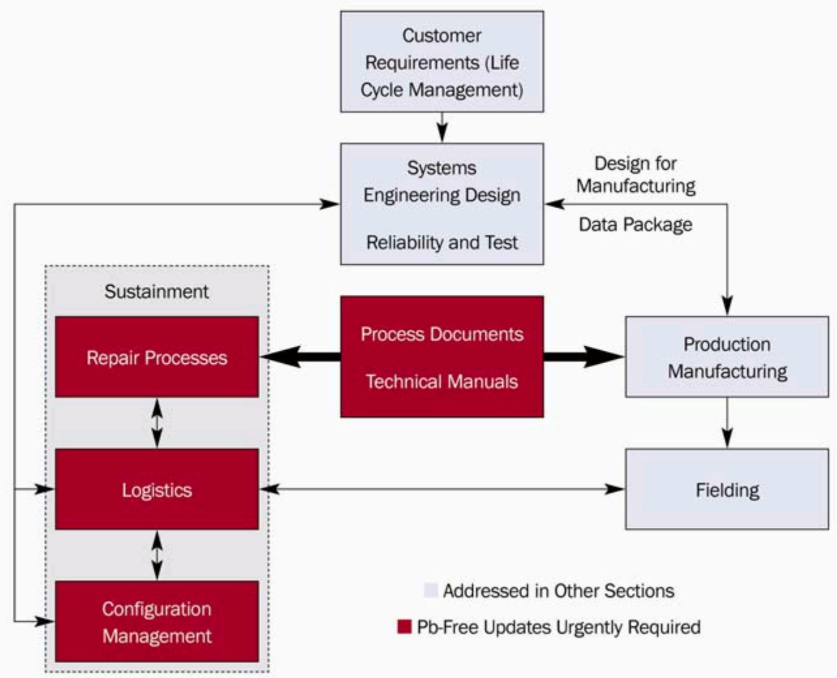

Figure 5.1 Sustainment Impact. Introduction of Pb-free materials and processes will require significant changes in sustainment practices.

Because of the large number of interactive areas, all with issues around Pb-Free, the probability of a latent manufacturing, design, or reliability problem manifesting itself and subsequently affecting the sustainment process, increases dramatically. The potential for increased reliability risk, due to configuration control issues, may coerce OEM's to consider extraordinary and often costly measures previously regarded as unnecessary, or too expensive. An example of a preventative measure may be:

- Limiting the number of assembly alloys used in product design, which can increase cost.
- Designing disposable electronic assemblies, which may be suitable for commercial applications, but not always an option for A&D applications.

8. Testing

Current test methodologies are not adequate for qualification and acceptance of Pb-free aerospace and defense (A&D) electronics. Design and production engineers rely on these tests to develop and deliver reliable electronics for the Warfighter. As a consequence, the reliability of Pb-free electronics cannot currently be guaranteed to match the functional reliability of the equivalent assemblies made using SnPb based solders. Additionally, changes in component, PCB terminations and surface finishes, adds a degree of greater variability in determining the reliability of the Pb-free electronics, which rely on test methods designed for SnPb electronics.

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. Such models exist for Sn-Pb only. Lack of these validated test procedures is exacerbated by the harsh environments of A&D applications.

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. In addition, existing whisker mitigation strategies are only partially effective (see ref in GEIA STD 0005-2) [5]. Reliable whisker test methods and mitigation strategies need to be developed, based upon a fundamental knowledge of the whisker growth mechanism for such a test to become feasible in the future.

The testing gap associated with Pb-free is not necessarily attributable to equipment capability, but in redefining the ***test parameters*** under which the equipment will perform. Environmental Stress Screening (ESS), verification, validation, acceptance, and qualification tests for Pb-free production hardware require that new test parameters (temperature extremes, dwell times, vibration environments, etc.) be defined. Validated computational models need to be developed to define these parameters, and to link them to actual field conditions and service lifetimes. These models currently do not exist or are at the very embryonic stages, and have not been validated. Furthermore, the fidelity of computational modeling predictions depends upon the development of accurate mechanical and physical property data for Pb-free solders, as well as substrate laminate and component package materials. Standardized materials testing needs to be done to provide the basic material properties required for input into and validation of the computational models for Pb-free electronics.

Other Pb-free reliability issues that have been identified, include printed wiring board (PCB) delamination, plated-through-hole (PTH) reliability, copper dissolution, conductive anodic filament (CAF) formation, pad cratering, trace cracking, corrosion, and voiding problems associated with PCB finishes during the high temperature Pb-free processing. Industry standards, while available for SnPb electronics, need to be created or modified to specifically address these issues for Pb-free electronics.

The materials test methods, acceptance, and qualification standards required for evaluating materials for Pb-free assembly, including laminates, copper, components, solder paste, and fabricated PCBs, are generally the same for consumer, commercial, and A&D applications. As a result of this shared standards base, the microelectronics industry has modified, or is in the process of modifying, all the requisite standards for assessing Pb-free CCAs. The flow of test method, verification, acceptance, and qualification standards from the individual materials, through acceptance of the CCA, is shown in Figure **6-1**

All of the standards in Figure **6-1** are dependent standards required by IPC/EIA J-STD-001 "Requirements for Soldered Electrical and Electronic Assemblies" which describes materials, methods, and verification criteria for producing soldered interconnections on CCAs. All of these underlying standards are supported by numerous additional standard test methods, many of which are in the IPC-TM-650. With the exception of tin whisker testing standards and more explicit test parameters needed for consistent Pb-free testing, the impact of the transition to Pb-free CCAs due to the additional changes in these standards will be minimal, since many have been created or modified for Pb-free. The greater impact for A&D products is in the extensive verification, validation, acceptance, and qualification testing that will be required for manufacturing Pb-free CCAs.

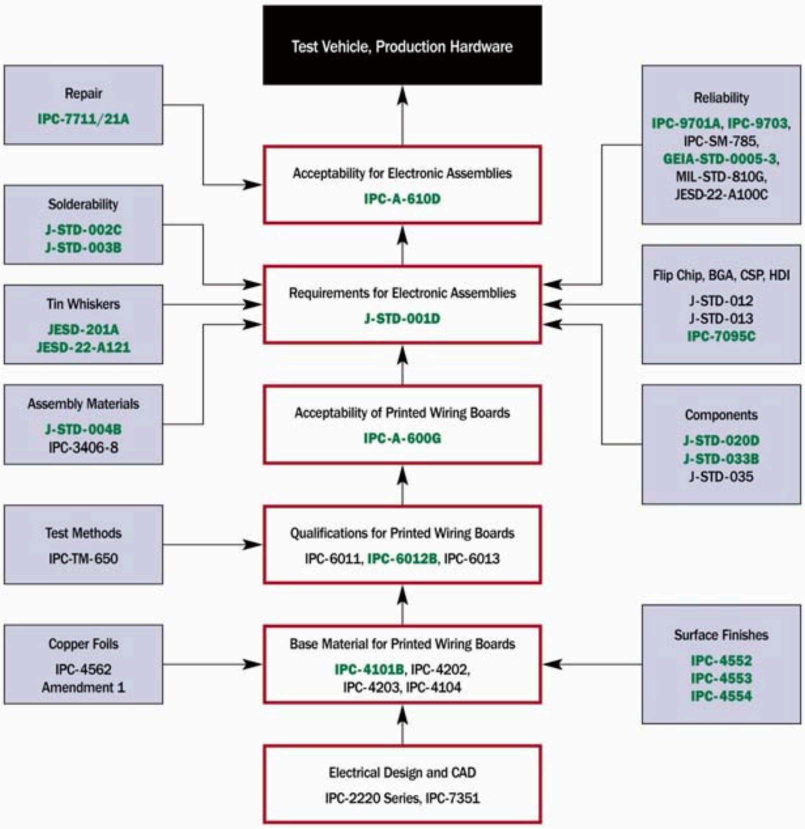

Figure 6.1 IPC Standards Chart

9. Reliability

The introduction of Pb-free materials and processes (LFM&P) into A&D electronics systems and products will significantly affect the ability to predict and verify reliability. The causes of this include:

- Incompletely characterized materials.
- Wider and changing suite of materials.
- Immature processes with narrower process windows.
- Intrinsic complexities of the physical properties and metallurgy of Pb-free solders

These factors currently confound the ability to model and interpret test results, and therefore limit the confidence in the methods used to predict reliability.

10. Reliability program activities

Reliability programs are required to ensure that systems perform their intended function, over their intended lifetime, in their intended usage environment. Nearly all A&D programs specify reliability requirements that include metrics germane to the particular system application, and under specific service life cycle conditions. Top-level system reliability and associated environmental requirements are converted into a set of derived requirements for subsystems. It is not anticipated that the standard methodologies currently employed in this flow down process, will require modification as a result of the introduction of Pb-free materials and processes.

It is standard practice for A&D programs to have a formal reliability program in place, to ensure that appropriate activities occur in all lifecycle phases of the program, and to establish that the overall reliability requirements are satisfied. The flow of reliability interaction with the product life cycle is depicted in Figure 7-1

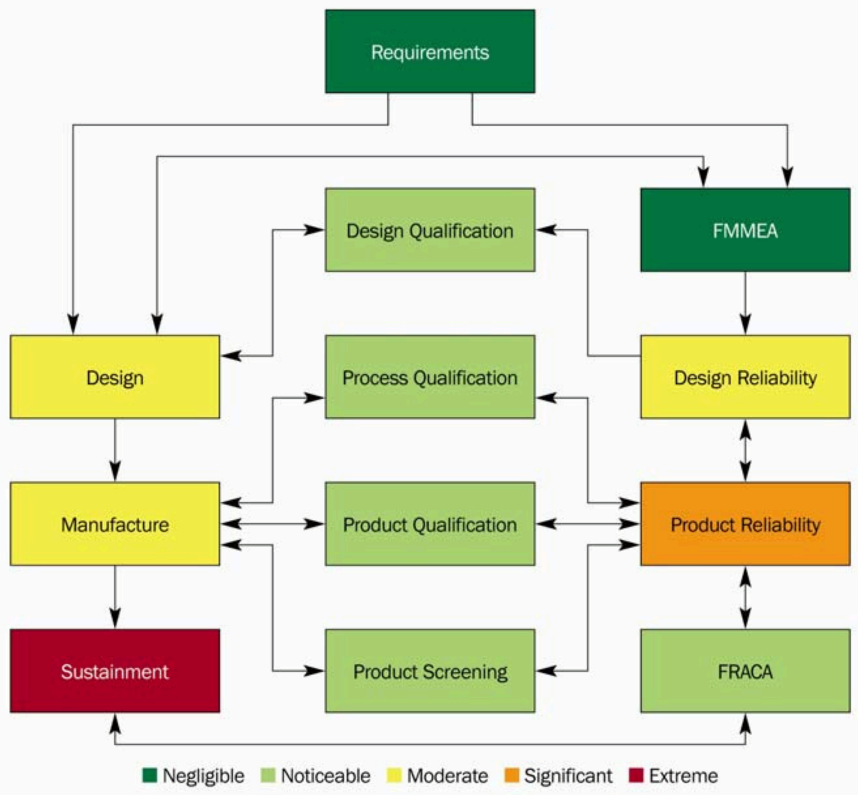

Figure 7.1 Basic elements of a reliability program. The color coding reflects the expected relative impact of LFM&P on each portion of the reliability program.

The form and structure of reliability programs are not expected to change. For A&D systems, it is commonly required that various forms of reliability predictions be performed. System level reliability predictions are typically performed in accordance with standards such as MIL-HDBK-217, which is not recommended as a best practice in IEEE-1413.1, and has not been updated in over a decade. This document is completely out of step with the majority of electronic devices being fielded today, and does not consider LFM&P at all.

Recently introduced GEIA-STD-0009 requires an understanding of failure sources in predicting system level reliability. The LEAP-WG is preparing a document (GEIA-HDBK-0005-4) that is intended to provide guidance for the performance of reliability assessments of A&D systems incorporating LFM&P. It is recommended that these documents serve as a basis for the implementation of improved practices, and that the team working on this document continue to be supported to perform future updates and refinements.

Once a system has moved past design into manufacturing and integration, new reliability tasks of verification tracking begins to take place. The overall structure of these program elements is not anticipated to require modification to accommodate the needs of LFM&P. Specific test conditions employed for qualification and screening may not necessarily change, but the interpretation of test results need to be re-examined. Material testing based on LFM&P must be supported to inform these interpretations. Ultimately, reliability must focus on the impact of LFM&P on failure mechanisms and dominant sources of failure, which are discussed in this section.

Tracking and reporting of failures should be able to proceed as with SnPb product. Enhanced tracking of pilot runs of Pb-free products will be required, however, to maximize the value of these tests.

11. Summary Conclusions

The Manhattan Phase 1 project team has collectively documented a set of baseline best practices for addressing risks associated with the use of lead-free, within the context of a product life cycle model. Drawing upon this collective body of expertise and knowledge, the following sections provide a summary of the major conclusions documented within the body of this report.

The effect of introducing Pb-free materials in A&D applications, presents potential risk issues. An appropriate amount of scrutiny and resources should be utilized to address the surplus of unknown performance and reliability of Pb-free material. The problem is real, and may manifest itself from the innocuous to the catastrophic.

The efforts of the Phase 1 Lead Free Manhattan Project have shed considerable light into the uncertainties regarding the consequences of utilizing Pb-free materials, intentionally or otherwise, in A&D programs. The various electronic material suppliers are not aware, or have little control over the supply chain and can not prevent the admission of Pb-free products into the manufacturing flow. The challenge in mitigating the entry and effects of Pb-free materials is uniformly distributed across the product life cycle.

The current best baseline practices, outlined in this report are to be considered a foundation for the subsequent research will be used to solidify the gaps in Pb-free electronics. What can be validated through experimentation and data collection, must be part of a collective and comprehensive effort on the part of Industry, DoD, consortiums and academia. The risk of a fragmented effort will only lead to both the replication and omission of critical projects, at a much higher cost, and more importantly, a remission in finding plausible solutions.

Design Summary

The process of managing Pb-free risk begins in the early stages of an assembly or CCA design, where a greater impact can be made toward controlling and mitigating effects. Based on the findings of the Manhattan SMEs in the field of design the following conclusions were drawn:

- The implementation of a Lead free Control Plan is a necessity.
- Designers must be acutely aware that there are no heritage products from which to derive design rules.
- Single drop-in replacements do not currently exist that will conform to present SnPb baselines.
- Established practices and analytical techniques such as FMEA can be used, but with an extreme caution. Modifications to these tools will need to be made to help improve detection of intermittent electrical failures.
- An accurate accounting of the environmental conditions is required for Pb-free
- These is a critical need for controlled documentation, verification and selection process for the construction of a Build Of Material or BOM
- More stringent procedures need to be implemented for product qualification due to latent damage on PCB's subjected to Pb-free processes. This may require a larger sample of qualification lots.
- Designing to mitigate the effects of vibration will be paramount in Pb-free systems. The placement location of key components and stabilizing structures onto the assemblies may be needed.
- Computational models are needed to develop test parameters for Pb-free.
- The designer should expect that new failure modes will occur with Pb-free.

Manufacturing Summary

The manufacturing process plays a fundamental role in developing the structure and morphology of solder joints, which will eventually form into an interconnection. The manufacturing processes for Pb-free are at greater maturity level than the other supporting sectors of electronic assembly production, but face difficult challenges nevertheless. Engineering changes to the manufacturing process will be necessary for adaptation to Pb-free materials, since a mixed material set of SnPb and Pb-free will need modified process parameters to form a proper solder joint. Faced with these prospects, the manufacturing experts conclude:

- The use of Design for Manufacturing (DFM) tools are critical in establishing processes and procedures that will guard against the potential consequences during the Pb-free transition. It is of paramount importance that first article inspections are adhered to with close scrutiny on the results.
- Some amount of process development will be needed to optimize manufacturing for Pb-free materials. There are no existing "*drop-in*" processes
- Plan for the need to modify equipment capability. This is particularly true for reflow ovens, wave solder, and hand soldering tools.

- The Pb-free solder will behave differently, and will look differently. Because of this, training of operators and other personnel will become crucial.

Sustainment Summary

The reduced availability and increased cost of SnPb parts has made the task of sustainment more difficult, and has had a profound effect on all the elements of logistic management. Anything from configuration control, design traceability, part replacements, and material compositions have been affected by the transition of the COTS electronic industry from SnPb to Pb-free. A common conclusion that appears throughout the entire report is the failure by suppliers to document when changes have occurred, assuming the posture that small changes in material composition (i.e. component finish) does not violate the *fit, from, and function* directive for initiating an Engineering Change Notice or ECN. This conclusion is relevant to all areas, including sustainment, where traceability of original assemblies and materials is crucial to the rework process. The sustainment experts concur that:

- There needs to be a sustainable effort to ensure that data and information regarding any constituent part or material that goes into the construction of the electronic assemblies is known, adequately documented, and properly communicated through the product life cycle.
- There should be a flow of communication between the Repair process group, logistics, and configuration management to ensure that repair documentation is updated, materials for assembly repair are defined, and part replacements are made available.
- Training of depot repair and other related sustainment personnel on Pb-Free will be required.

Testing Summary

The failure to document changes to the material composition from SnPb to Pb-free creates a risk when assessing the reliability of the assemblies. Environmental Stress Screening or ESS and other testing procedures, have been structured to provide the most accurate characterization of SnPb in actual field conditions. The test conditions simulate the long term field effects that have not been defined for Pb-free materials, thereby creating an uncertainty in the accuracy of the results in predicting failure when using SnPb test conditions. The Test team has concluded:

- Though test equipment presently exists to adequately test for Pb-free assemblies, test conditions and protocols have not yet been defined to provide adequate computational models to simulate service lifetime conditions.
- Current test methods are not adequate for Pb-free A&D electronic assemblies.

Reliability Summary

Analysis on the reliability of Pb-free electronic assemblies has shown a consistent theme, asserting that the use of SnPb constitutive and predicative models cannot behave as adequate substitutes for characterizing

Pb-free material behaviors. Essentially, the characteristic material properties of Pb-free are sufficiently different from SnPb, as to invalidate any assumptions predicated on the hypothesis, that when subjecting both materials to thermo-mechanical stress or shock, the reliability results are unchanged. There are a number of factors which are integral in providing a validated model to predict lifetime behavior of a solder joint; unfortunately, at the present time, there is insufficient information about Pb-free solders to make a reasonable lifetime prediction. The reliability team concludes:

- Data to support reliability models for Pb-free is insufficient to make predictions on the long-term behavior of Pb-free assemblies for A&D programs
- Pb-free materials are more susceptible to Mechanical shock and vibration than SnPb
- Thermo/mechanical behavior of Pb-free materials at varying temperatures is different than that of SnPb, especially at the low temperature extremities. This is a major concern for A&D products.
- There may be a need for certain pre conditioning steps prior to ESS to properly asses the effect of the respective environmental test.
- There is no exacting method of mitigating tin whiskers at the present, other than to avoid pure tin.

Tin Whisker Summary

Pb-free solder joint reliability is one major concern for the electronics industry, especially in A&D applications; the risk associated with Sn whiskers is equally serious. Tin whiskers continue to be a source of consternation for high reliability product providers. The history and the subsequent effects of tin whisker growth have been well known in an anecdotal manner over the number of years. The list of documented failures due to the discovery of whiskers continue to grow as the cause of catastrophic failures in avionic and high level infrastructure systems, while many failures due to whiskers go unreported due to liability concerns. The importance of the problem has not gone unnoticed, but in recent years has been highlighted due to the Pb-free transition.

12. Recommendations

This report documents the current baseline practices for Pb-Free electronics mitigations and usage along with corresponding technology and manufacturing gaps. Based upon this compilation of information, the following summary recommendations are provided for the purpose of minimizing risks associated with the use of Pb-free electronics in A&D products. Additional details are contained in the appropriate sections within this report.

General Design Recommendations

- As part of a risk management strategy, employ a structured and consistent use of a Pb-free control plan (LFCP), incorporating the existing GEIA documents as a guideline, while updating, where necessary, for new materials and processes. See specific section on design for further details.

- Develop a Pb-free material compatibility guideline that incorporates all facets of the material selection process, which will include specifications and recommendations for design on the basis of environmental requirements.
- Product designers should consider the complications incurred by the increased mitigation efforts to reduce whiskers, as well as increased incidences of electrical failures incurred by higher manufacturing process temperatures. In the light of this, increase the frequency and number of both "on-board" analysis and subsequent field inspections.
- Insist that the environmental conditions be defined clearly. No cognitive design recommendations for Pb-free electronics can be made without this information. This will also affect the type and severity of the test conditions for ESS where the qualification parameters are defined.
- Expand on the criteria and data needed for a preferred parts list where necessary, and define the conditions under which a Pb-free electronic part can be added to a BOM
- Design rules should include a strategy to handle modification of the way Printed Wiring Boards are designed, and subsequently assembled, and will include selection of alloys and substrates potentially more suitable than what presently exists. Specialized designs for RF should also be considered. Some of the key areas:
    1. Attachment Alloys
    2. Component finishes
    3. Printed Wiring Boards (PWB)
    4. PWB finishes
    5. Mechanical parts
- Make provisions in the design of electronic systems for field repairs, which will inevitably be subject to different soldering materials and conditions.
- An effective and rapid method of validating new designs needs to be developed which utilizes test parameters derived for Pb-free materials and conditions, which will include a variety of accelerated stress tests.
- Include tin whisker risk as part of the design criteria. Use the GEIA standards as guidelines

General Manufacturing Recommendations

- Provide a comprehensive DFM plan which includes assessing all the potential processes, materials, and in-testing modifications that will be required for the introduction of Pb-free material into the manufacturing stream. Include an emphasis on first article inspection as a critical event before proceeding to manufacturing.
- Investments in update equipment will have to be made. This includes reflow process equipment, in-process inspection, and analytical equipment. Additional investments will be needed in the area of training, which includes personnel from all the areas of manufacturing.

- It is inevitable that engineering time will have to be invested to determine the parametric process window for Pb-free electronics, with an emphasis on optimizing around reflow conditions and cleaning cycles.
- Rework processes must be re-qualified with careful consideration of the additional thermal energy that will be used as part of the processes.

General Sustainment Recommendations

- Sustainment involves a large number of interactive areas, all with issues regarding Pb-free electronics. An infrastructure presently exists to accommodate the various elements of the sustainment process, but a greater concerted effort will be needed to ensure that the details often missing for accurate management of configuration control are available for Pb-free electronics. The particulars for the proper course of action should be decided upon collaboratively among sustainment, manufacturing, design, and the customer. The specifics should include:
  - A lead free Control Plan
  - Repair procedures and metrics
  - Pb-free assessment plan
  - Feedback from the field
  - Contingency plan for unavailable parts
  - Inventory plan to maintain overage
  - An assessment of COTS as a suitable replacement for repairs
- The pressure will be great on repair depots to sustain Pb-free materials sets beyond their capability to handle. It is highly recommended that repair facilities restrict their material usage to one or two selected Pb-free solders, and more critically, that the original repair requirements be modified to reflect the change.
- The original designer of the assembly must be notified of repair modifications, which may have been necessitated by an unexpected change in SnPb component or material availability. Communication between the repair depot and the original assembly designers is critical.

General Testing Recommendations

- The upper and lower boundaries of many of the thermal cycling tests are not adequate to simulate field failures, and must be established. The same can be said for isothermal conditions for long term aging or as a prerequisite for further thermal stress testing.
- Parameters for mechanical testing such as vibration need modification, with appropriate test parameters defined.

- Validated Computational models to predict fatigue field failure must be developed. This requires detailed information on test vehicle design, test parameters, and field results.
- The JEDEC standards can be used as a guideline in the interim, but they are insufficient as an acceptance document for A&D applications.

General Reliability Recommendations

- Investment in further research and characterization of Pb-free materials is needed to prevent the uncertainties in reliability due to the disparity between existing Sn/Pb knowledge base, and the more limited Pb-free electronics data pool.
- Avoid using Pb-free attachments in mission critical A&D applications
- Research into the accumulative damage to Pb-free electronic assemblies from environmental conditions under varying loads is needed. Essentially, there is non-liner degradation that is occurring which is not accounted for in present ESS models.
- The low temperature damage (-40 C) on Pb-free assemblies is an issue. Constitutive models will have to be developed
- For applications where assemblies are subjected to sustained loads, SAC alloys with < 3% silver, are not recommended.

Summary Recommendations for Phase 2 of the Pb-free Manhattan Project

- **Using the corporate knowledge collected in the Phase I deliverable, develop a research and development roadmap for future projects**

  This requires a thorough vetting of where the gaps are and how they interact with each other. For example, a selection of a particular material set based on the current baseline practices may produce acceptable 1st tier results, but may impact other areas that may not be readily obvious. For example, the selection of SAC 305 solder is the commercial alloy of choice as a best manufacturing practice. Through a gap analysis for A&D applications, the likelihood exists that at some strain value, the composition of SAC 305 may not be suitable for high mechanical stress applications. Therefore, further work on strain point limitations would be needed, precipitating a recommendation that SAC 305 may not be the A&D alloy of choice under high strain conditions.
- **Develop statements of work and budget estimates for the research and development projects**

  Each specific area of focus (Design, Materials, Manufacturing, Sustainment, Test, and Reliability) has tangible deficiencies. Statements of Work for projects will need to be developed, estimated, and implemented to address these deficiencies.
- **Document results in a "Pb-Free Electronics Risk Mitigation Research Plan"**

  Once the data is collected on Pb-free electronics mitigation efforts, the documented results will need to be collected and analyzed and added as part of a continually updated Pb-free electronics research and development program.

- **Develop a communication package to brief the customers**

  Through the efforts of the B2PCOE and other consortium like the PERM Consortium, a concerted and organized communications plan is needed to train providers and vendors about the best Pb-free Manufacturing Practices, and offer a briefing on the specifics of the technological roadmap.

- **Use the Manhattan Pb-Free Electronics project model for other industry-pervasive issues**

  The model for the conduct of the Pb-Free Electronics Manhattan project has proven to be a successful method for integrating a diverse body of subject matter experts and creating an environment of synthesized information exchange and capture. It is recommended that this process be identified as a best practice and applied to other pervasive issues.

References

[1] ACI technologies, "Lead Free Electronics Manhattan Project – Phase 1", July 30th, 2009 Publication Pending

[2] ACI technologies, "Lead Free Electronics Manhattan Project – Phase 1", July 30th, 2009 pg 16-18 Publication Pending

[3] GEIA –STD-0005-1 "Performance Standard for Aerospace and High Performance Electronic Systems Containing Pb-free Solder".

[4] ACI technologies, "Lead Free Electronics Manhattan Project – Phase 1", July 30th, 2009 pg 174 Publication Pending

[5] GEIA-STD-0005-2 "Standard for Mitigating the Effects of Tin Whiskers in Aerospace and High Performance Electronic Systems

Appendix

LEAD FREE ELECTRONICS MANHATTAN PROJECT PARTICIPANTS

- **B2PCOE Project Management:** Carmine Meola (ACI)
- **Technical Project Leadership:** Ed Morris (Lockheed Martin) & Jerry Aschoff (Boeing)
- **Meeting Moderator:** Dr. Richard R. Reilly, Howe School of Technology Management, Stevens Institute of Technology
- **Subject Matter Experts:**
  - Dr. Peter Borgesen (Universal Instruments/Unovis)
  - Lloyd Condra (Boeing)
  - Dr. Carol Handwerker (Purdue University)

- Dr. Craig Hillman (DfR Solutions)
- Dave Hillman (Rockwell Collins)
- Dave Humphrey (Honeywell)
- Dave Locker (AMRDEC)
- Dr. Steph Meschter (BAE Systems)
- Dr. Mike Osterman (Univ. of Maryland CALCE)
- Dave Pinsky (Raytheon)
- Dr. Tony Rafanelli (Raytheon)
- Dr. Polina Snugovsky (Celestica)
- Dr. Paul Vianco (Sandia National Labs)
- Maureen Williams (NIST)
- Dr. Tom Woodrow (Boeing)
- Linda Woody (Lockheed Martin)