AEROSPACE INDUSTRIES ASSOCIATION

Joint Government and Industry Executive Forum for Lead (Pb)-free Electronics Recommendations

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AIA Technical Operations

For more information: aia-aerospace.org

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1. EXECUTIVE SUMMARY

Transitioning to lead-free electronics in the Aerospace and Defense (A&D) industry demands careful analysis and research into the performance, costs and availability of these materials. The Aerospace Industries Association sponsored a Joint Government and Industry Executive Forum for Lead-Free Electronics to examine the issues underlying implementation of these materials. The participants concluded a clear roadmap with discrete milestones, funding to accomplish these efforts and dedicated government leadership are key to the A&D industry's successful transition.

Why is this issue so important? The A&D industry designs and manufactures products that carry more than three billion passengers worldwide on any given day as well as systems which are vital to our national security. Our ability to maintain public safety and assure our warfighters' mission success cannot be compromised or risked.

In response to the 2003 European Union Directive on the Restriction of Hazardous Substances, the commercial electronics industry transitioned to lead-free (Pb-free) electronics. Although the A&D industry leverages consumer and commercial technologies to provide affordable design solutions, many of the foundational commercial material standards are inadequate when applied to A&D products. Therefore a growing technology gap between the industries has appeared. Investment is needed to bridge this gap, so that A&D systems can preserve access to affordable commercial technology, while continuing to provide the requisite performance and reliability. Based on experience, the A&D industry believes a nationally coordinated approach is the most efficient way to bridge this gap.

1.1 Three distinct Pb-free problems

Pb-free electronics are disruptive technologies for the A&D industry, displacing established materials and forcing the industry to incorporate new ones. Three primary concerns face the industry as it addresses this challenge:

- Escalation of acquisition and sustainment cost due to the major global reduction in the availability of leaded electronics materials;
- Risk of failure due to tin whiskers is exacerbated by increased use of pure tin (or majority tin) finishes on components and printed circuit boards; and
- Development of a clear understanding of the system performance and reliability of new Pb-free material sets (e.g. Pb-free solder interconnects, board laminates, part finishes, board finishes, coatings) and the test protocols needed to validate their performance.

1.2 Recommendations

In February 2014, the Aerospace Industries Association convened a forum of leading experts from government and industry to address these concerns.

The Forum concluded that immediate, concerted action between the United States government and the aerospace and defense industrial base is needed to reach a Pb-free electronics solution. Closing the critical knowledge gaps underlying a Pb-free solution requires a roadmap, funding and expertise.

1.2.1 End state

The end state of this issue for the A&D industry is to reach an acceptable technical solution to transition to Pb-free electronics. The solution will be achieved when the A&D industry has:

1. An acceptable alternative for Tin-Lead (SnPb) solders, and
2. The ability to design products that utilize available Pb-free materials and alloys and comply with A&D performance and reliability requirements.

This solution must be available no later than July 2019.

Key Commitments:

- Re-baseline the research gaps and petition for the funding needed to fill these research gaps. Reauthorizing funding for the Pb-free Electronics Manhattan Project would enable critical research to recommence.
- Select a government coordinator to optimize Pb-free electronics research and development. We recommend the aforementioned government coordinator be within the responsibility of the Special Assistant to the President for Manufacturing Policy.
- Ensure the A&D industry retains its "Out of Scope" status for the E.U. Restriction of Hazardous Substances (RoHS) directives.

1.2.2 Research requirements time-line

1. Establish a program management entity within the federal government to coordinate and manage the necessary steps to reaching the end state similar to management programs for corrosion and cyber security. Target date: January 2015.
2. Department of Commerce Survey to establish a Defense Industrial Base Assessment on Pb-free Electronics. Target date: February 28, 2015.
3. Continuation of the Pb-free Manhattan Project, Phase 2 update. Target date: December 1, 2014.
4. Reestablish and rebase the research gaps. Target date: March 31, 2015.
5. Assess the current cost of filling these research gaps. Target date: May 1, 2015.
6. Program Management Entity to submit into the federal budget funding for research and development of the industrial base and supply chain. Target date: May 30, 2015.
7. Commence research for filling identified research gaps. Target date: no later than January 2016.

1.2.3 Forward action plan

1. Establish joint effort for finding standard solutions vs. finding specific solutions.
2. Appoint a government coordinator that can work with all affected agencies and serve as a coordinator to executive branch recommendations and policies.
3. Fund research and development of the industrial base and supply chain for electronic integrated circuits and components.
4. Stockpile SnPb material and components for managing risk of obsolescence. [See Warstopper Annual Raw Material Report] "Although we will continue to mine and mill lead, zinc and copper

from our underground mines, the ability to produce primary lead metal and their alloys domestically will vanish."

5. Update the state of lead-free readiness and action plan.
6. Urge the Commerce Department's Bureau of Industry and Security (BIS) to survey industry and government to quantify the extent of transition from Pb-free electronic parts into U.S. defense supply chains.
7. Propose new Nation Network Manufacturing Institutes (NNMI) for high reliability electronics packaging (lead-free solutions included).
8. Update screening and qualification testing protocols.

2. BACKGROUND

European Union Directive 2002/95/EC on the Restriction of the use of certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) and the Waste Electrical and Electronic Equipment Directive (2002/96/EC) have changed the global supply chain for materials used in Aerospace, Defense and High Performance (ADHP) products. The European directive requires removal of lead (Pb) from electronic products. Currently, the A&D industry remains excluded from the RoHS directive, but concerns remain for two reasons:

1. The European Union is continually evaluating the scope of the directive; and
2. The A&D industry utilizes commercial products as low-cost alternative components in its systems.

The medical industry is facing a 2014 deadline to comply on some products. Also, the transition to Pb-free in the commercial industry which has been under RoHS for a number of years has created a global Pb-free marketplace. Aerospace products are a small fraction of the electronics market and therefore have little influence on supply chain decisions regarding electronics materials. Pb-free electronics continue to be a concern of the ADHP industries primarily due to the lack of material and design data and knowledge to thoroughly categorize performance under harsh service conditions.

2.1 Escalation of acquisition and sustainment cost

As the global supply chain continues to migrate away from materials and solder alloys that are used in aerospace and high performance systems, the cost of acquisition and sustainment will grow. It is the belief of industry that the global forces will eventually make the production of SnPb solders cost prohibitive. Those suppliers that remain in this market will provide these materials at a premium based on the small supply and large demand. At some point this cost will eventually be passed on to acquiring new systems designed with SnPb and increase the sustainment and total life cycle cost of legacy programs.

2.2 Tin whiskers

Tin whiskers are electrically conductive crystalline structures erupting from tin plated finishes on electrical and mechanical components. Tin whiskers can create electrical shorts (sustained and transient), metal vapor arcs, and foreign objects and debris in electronic products containing tin finishes. Tin finishes are now the predominant choice in the electronics supply chain for component leads and mechanical parts. The addition of lead to solder and finishes 40 years ago eliminated the tin whisker issue. The current elimination of lead has allowed these phenomena to reemerge and cause failures when the risk is not adequately mitigated.

2.2.1 System performance and reliability of new material sets

Pb-free material sets consist of new solder alloys, various Pb-free component and circuit board finishes, and various new laminate or resin circuit board materials. The commercial industry has been using Pb-free materials with success in consumer electronics with benign use environments and short warranty life. These Pb-free material sets and varying combinations of materials are problematic when exposed to harsh environments (environmental and mechanical) and long warranty life. In addition to performance and reliability, the overarching test and qualification protocols in use for decades for electronics containing Pb may no longer be valid. The Pb-free materials behave differently. These interactions are complex and not yet well understood.

2.3 Acknowledgement

2.3.1 Consumer electronics

Pb-free electronics are currently in wide use in the consumer electronics industry. The consumer electronics industry's transition to Pb-free electronics uncovered new and re-emerging failure mechanisms. ADHP products are subjected to harsh environments for extended periods of time. Although extensive studies have been conducted, a total Pb-free solution for ADHP harsh environments and long product life cycle remains unsolved.

2.3.2 Supply

There continues to be a diminishing supply of SnPb solder and obsolescence may be become an issue in the near future if the ADHP industry continues to lack influence over the supply chain.

2.3.3 Criticality and risk

Pb-free electronics are an issue for critical ADHP products. Pb-free electronics may be acceptable for some limited use in non-safety critical systems provided adequate risk mitigations are employed. However, the majority of ADHP products continue to be at high risk if Pb-free electronics are utilized. Until a material solution set is found we need to retain the ability to use SnPb.

2.3.4 Obsolescence and affordability

The commercial electronics industry has already transitioned to Pb-free electronics. As aerospace systems have higher consequence of failure there has been reluctance to transition in step. Thus a divergence has been created. This divergence will become unsustainable by exacerbating obsolescence issues, thus limiting the ADHP industry's ability to leverage the latest available technologies. Inability to access new technology will impair affordability.

3. THE TECHNICAL NEED

Through 50 years use of SnPb solders the ADHP community has developed a consensus on the best practices to verify the integrity and reliability of the solder joints. These best practices include both analysis processes and test protocols that apply at both the circuit card and electronic system levels. Currently, there

are numerous organizations in the ADHP industry and academia working on developing Pb-free replacement best practices to verify the integrity and reliability of the Pb-free solder joints with no overarching coordination or supervision. This parallel multi-thread development process will lead to multiple solutions for both analysis processes and testing protocols. The issue is how industry will sort through the multiple solutions to form a consensus on the right Pb-free analysis procedures and testing protocols. This consolidation step will have schedule and cost impacts to future ADHP systems. To accelerate the development of Pb-free best practices and minimize cost, a centralized program needs to organize the ongoing research, identify and minimize duplicate efforts, and identify research gaps that are not being addressed by either industry or academia. The same issues exist with tin whiskers. If left to industry and academia, multiple solutions will be developed without forming a consensus across the ADHP industry. This will result in a second round of evaluations by all levels of the ADHP industry, resulting in additional delays and cost. No one company can afford to make a comprehensive solution.

4. MISPERCEPTIONS AND HIDDEN RISKS

The ubiquitous and seemingly mundane nature of electrical connections in modern electronics can lead one into a false sense of security regarding the hidden risks associated with Pb-free solder. Pb-based electronics – or more specifically SnPb-based solder connections – have been used for decades and permeate through all aspects of aerospace and defense products. The entire suite of materials and processes used to manufacture and assemble electronics has evolved to be compatible with the SnPb solder process and the properties of the resulting solder joints. The properties of SnPb solder connections have been well-researched. The failure mechanics and the underlying physics for SnPb solder joints – and the entire suite of SnPb compatible materials – are well understood and are reflected in design criteria, test protocols and specifications used throughout our industry.

1. The removal of lead from today's solders might appear to have minimal impact to integrity of soldered assemblies; however, that is a misconception that exposes the user of such products to unforeseen risks. The substitution of SnPb solder with an alternative alloy substantially changes the characteristics and behavior of the solder and imposes a higher temperature soldering process. Engineers and scientists are only just beginning to understand the behavior of alternative Pb-free solders and the new suite of Pb-free compatible materials. Unexpected failure modes have appeared as a result of the transition to Pb-free electronics in consumer products. In aerospace applications it is unknown how Pb-free systems will be affected by more severe thermal cycles, vibratory environments, presence of other chemicals, gases, radiation, duration of life, etc. Engineers and scientists are concerned that Pb-free solder may exhibit additional undesirable characteristics that have yet to be discovered.
2. Some may think that if cellphones and HDTVs can be Pb-free, why can't an airplane or spacecraft also be Pb-free? The consumer electronics industry has spent billions of dollars over a period of many years on their transition from SnPb to Pb-free systems. As a result, their manufacturing processes are fairly mature, and their product reliability generally meets their requirements. Unfortunately, consumer electronics differ greatly from aerospace electronics in use environment, lifetime, need for repairability and reliability requirements.
3. Many in industry neither recognize nor appreciate the implications that the Pb-free material suite is profoundly different from the SnPb material suite. Anecdotal evidence suggests that electronics suppliers continue to utilize design criteria, verification and validation methods and quality assurance techniques developed for SnPb assemblies without regard to whether the assembly is Pb-free or SnPb. Because the chemical and physical behavior and failure modes of SnPb

assemblies and Pb-free assemblies are fundamentally different, this introduces significant risk into production.

4. The continued application of inappropriate design and test criteria will result in reliability challenges and premature failures of electronic assemblies.

5. GENERAL IMPACT

5.1 Consumer electronics

The consumer electronics industry was the first electronics sector to transition to Pb-free electronics as a direct result of the European Union RoHS Directive. Survival in the global marketplace required consumer electronics suppliers to convert rapidly to remain competitive. This Pb-free conversion was accomplished with limited validation and qualification protocols[1] and new materials. With the test data available at the time, most material sets were adopted for use as global replacements. This initial adoption of materials has resulted in the Pb-free material sets most popular today. Additional Pb-free materials research has taken place but the industry, heavily driven by the consumer sector, continues to use the original materials adopted during the transition. Conversion would be costly and these Pb-free electronics are performing adequately in the service environment and warranty life of consumer electronics.

Automotive and medical electronics except for implantable medical devices are facing legislative deadlines in Europe to become Pb-free. While some automotive locations have harsh thermal cycling environments, the vibration and shock are lower than many aerospace applications and the use of complex CPUs and communication parts is limited.

5.2 Defense

Development of Pb-free electronics is a major technology disruption in the ADHP industry. ADHP electronics are currently exempt from the RoHS legislation because they have more severe performance and environmental challenges, as well as longer service life and stricter safety requirements than consumer electronics. There are reliability concerns with multiple new failure modes that have been identified from Pb-free electronics; we anticipate other failure modes that are yet to be discovered. For ADHP to continue leveraging the cost advantages commercial electronics require, consensus on additional qualifications for Pb-free electronics are needed. Pb-free test protocols for ADHP products need to be developed to ensure the new materials are tested adequately to simulate product mission environment and life cycle requirements. Due to the large number of diverse configurations manufactured in relatively low volume, early failures not caught by manufacturing screening testing are of particular interest. Existing SnPb testing has 50 years of historical field mission data to support the test protocols. Greater coordination and expediency is needed for Pb-free aging test efforts, since current activities are being executed in a very slow and fragmented manner.

5.3 Sustainment of legacy programs

Sustainment of legacy programs is crucial to continued mission success for the warfighter. Several considerations must be taken into account for successful sustainability – all of which result in challenges.

[1] Validation and qualification protocols focused on consumer product environments (e.g. thermal cycling). The consumer industry has no motivation to evaluate ADHP environments (e.g. vibration, acoustic vibration, shock, pyroshock, gunfire, humidity, salt fog and atmospheric radiation).

First, older generation products present challenges – especially if Pb components are necessary to facilitate repair or rework. Consequently, original equipment manufacturers' product deliveries will be impacted by such challenges as procuring Pb components, delays in validating alternatives for discontinued Pb components and increased cost of acquiring Pb components. Subsequently, these impacts will contribute to equipment and system downtime in those cases where subsystems or assemblies require repair or replacement. Attempts to address specific impacts could increase vulnerability of exposure to counterfeit parts, especially when it is necessary to find alternative sources of leaded components. Other specific contingencies – such as lifetime buys or customized buys of Pb components – will contribute to escalating costs in a depressed fiscal environment. Should increased costs result in program or platform descoping, two risks should be acknowledged: subpar execution of major programs and potential decreased system capabilities for the warfighter.

Incorporating Pb-free components directly into legacy products and systems presents its own set of schedule and cost impacts. There are three very general approaches to address these impacts:

1. Ruggedize existing designs;
2. Impose aggressive preventative maintenance processes (i.e. swap out modules and sub-assemblies over a conservative, yet-to-be determined time); or
3. Limit or control usage and storage environments.

Each of these proposals would require increased time and cost for validation and in some instances may prove to be "non-starters". However, note that successful implementation of any of these approaches would be greatly facilitated by closure of the knowledge gaps identified by the Lead-Free Electronics Manhattan Project. Otherwise, implementation of these approaches may be slow and costly as each design group executes to its specific product applications and requirements.

6. SYSTEMS ENGINEERING IMPACT TO RELIABILITY AND PERFORMANCE

6.1 Impacts to system engineering

6.1.1 Potential for shortened life cycles and increased cost

Currently some non-flight critical Pb-free electronic systems are being qualified to historical SnPb solder based test protocols. CPU, memory and communication system functions have the highest pressure to use Pb-free parts because ADHP systems cost structures strongly leverage consumer electronics-developed software and tools. These SnPb test protocols could either over or under test the Pb-free electronics being qualified. For the case where the SnPb test protocols are over testing Pb-free electronics, the programs will incur additional non-recurring costs to over engineer the electronics systems and have a system with non-optimized size, weight and power. For the case where the SnPb test protocol is under testing Pb-free electronics, the reliability for the system could be significantly lower than required or expected and again burden the program with significant costs in additional repairs and lower system availability for the war-fighter. There could also be new failure mechanisms that are not being tested for in traditional SnPb solder based qualification programs, like pad cratering. This new failure mechanism could result in earlier than expected field failures.

As a part of the overall manufacturing process prior to qualification, Environmental Stress Screening (ESS) is used to verify the system is free of workmanship defects by exposing the system to limited vibration and

thermal cycling. Again, if the ESS test environments are based on historical systems that used SnPb solders, they may either over or under test the Pb-free system. Under testing could result in an increase in infant mortalities when the systems are fielded. Over testing will consume more life of the product than expected during ESS test and result in shorter fielded lifetimes. Either condition will result in unexpected program costs.

6.1.2 Higher costs to deliver same known reliability

The current mitigation steps to keep Pb-free components usable in SnPb solder-based ADHP systems add to program cost. These steps include replacing the Pb-free solder balls on nearly all ball grid array electronics components available today. The longer the ADHP industry holds off the conversion to Pb-free solders the more the cost impact will rise as components compatible with SnPb solder continue to decrease and become obsolete. Additional mitigation steps will be required to use SnPb solders adding more program cost.

7. ENCOURAGE STUDY OF CONVERSION OF CURRENT PRODUCTS TO PB-FREE

The transition of ADHP products to Pb-free must be performed in a responsible manner to preclude any impacts to safety and reliability. Incentives including funding and tax credits for research and development to provide publically available research data to the ADHP industry would greatly accelerate the transition effort. Individual company efforts will be more costly than a consolidated industry-wide project.

Solutions afforded by such an effort would be utilized at the program level and allow conversion of products to Pb-free as the research supports the individual requirements of the products. A timeline must be established to manage the transition and guide the necessary research. Products with less stringent mission requirements or that are not safety critical could begin conversion first, allowing for much needed data on the performance of fielded Pb-free electronics.

Finally, this conversation is absolutely necessary in order for ADHP products to continue to utilize the latest technologies in a cost effective manner. Obsolescence is a current issue that will only escalate if this transition is not prioritized and executed.

8. FAILURE MODES KNOWN AND UNKNOWN

Failure modes for SnPb electronic systems are well documented and understood. Fielded hardware for more than 50 years has provided the ADHP industry with acceptance criteria for SnPb electronic systems. Traditional failure modes for SnPb electronics include solder joint fatigue failures, corrosion failures, cathodic anodic filament failures and component failures. The removal of Pb from electronic systems has created new failure modes such as tin whiskers and pad cratering. The addition of Pb to early Sn solder systems proved to be an excellent mitigator for tin whisker growth. Removing the Pb from solder systems has created a known high risk for tin whiskers and subsequent failures from electrical shorts, current leakage, vapor arcing and risk of foreign objects and debris. Also, these new Pb-free alloys are not as ductile as traditional SnPb solders, resulting in an increased risk of pad cratering, where the stiff solder joint transfers stress into the board, cracking circuit traces. Other new failure modes are emerging from the high temperature processing of Pb-free solder systems including additional component mortality, increased failure of board materials, brittle fractures of solder joints, flux residues and silicone outgassing interactions, entrapment of more active flux residues under connectors and low standoff components causing electrical leakage and shorting, difficult to clean flux residues that are corrosive and additional risk of cathodic anodic filament failures.

9. APPLY DATA BASE THAT IS UNCERTAIN

There has been a significant amount of testing of various alloys to date. In the opinion of the ADHP industry, this research – while interesting and insightful – proves the available Pb-free alloys do not meet the performance standards needed for ADHP products. The research does not adequately cover the scope of required test protocols needed to build ADHP design data sets. There has not been a coordinated effort to date to establish the research and test programs that will ultimately fill the gaps in common baseline useable design data and protocols. The result of this deficiency leads designers to base decisions upon insufficient data, resulting in a reactive decision process using obsolete information available for electronics reliability. This instability of material choices prevents long-term reliability data sets and raises the uncertainty based on component and materials stackups.

10. CASE STUDIES

10.1 DOC study on infiltration of counterfeit electronic parts into U.S. defense supply chains

The Department of Commerce's Bureau of Industry and Security (BIS) released a study in January 2010 (Defense Industrial Base Assessment of Counterfeit Electronics – 2010) that quantifies the extent of infiltration of counterfeit electronic parts into U.S. defense supply chains. The purpose of this study is to provide statistics on the extent of the infiltration of counterfeits, to provide an understanding of industry and government practices that contribute to the problem and to identify best practices and recommendations for handling and preventing counterfeit electronics.

The BIS study documented a growth in incidents of counterfeit parts across the electronics industry from 3,300 incidents in 2005 to more than 8,000 incidents in 2008.

This sharp increase in incidents, in only three years, clearly indicates that the volume of counterfeit parts is increasing and mitigation plans must be developed and implemented

10.2 Lessons learned from other Industry segments

Other industries that rely on high performance and reliable electronic components face similar challenges to ensure a consistent long-term supply of SnPb solders and a proven alternative material alloy. While these industries may have common requirements, the A&D industry has its own specific operating parameters that few other industries consider. These parameters include shock, high vibration and atmospheric radiation.

11. RECOMMENDATIONS, ROADMAP AND TIMELINE

11.1 Appointment of a government coordinator

With many issues such as cybersecurity, energy and communications the White House has appointed coordinators to act as top-level advisors on policy related to a particular topic. It is recommended that a government coordinator be appointed to serve in this role for industry to provide guidance on material restrictions such as Pb to ensure the nation's leadership is aware of technical impacts. We recommend the

aforementioned government coordinator be within the responsibility of Special Assistant to the President for Manufacturing Policy.

11.2 Promote and standardize methods for whisker mitigation and solder material characterization

The Pb-free Electronics Risk Management (PERM) Consortium has defined acceptable levels of whisker mitigations for various classes of applications, which are specified in GEIA-STD-0005-2. However, the implementation of this standard is not universal across the ADHP industry. Promotion of the use of this standard throughout DOD and other U.S. government agencies would help to realize the benefits provided by these approaches. As new mitigation techniques are developed and new whisker science emerges, the standard will be updated to reflect the latest knowledge, in a peer-reviewed and public process. Acceptance of the standard therefore provides a vehicle for all users to maintain the currency of their mitigation requirements.

With regard to Pb-free solder attachments, a significant challenge is posed by the variety of solder alloys and their rate of introduction. Some of these alloys may be suitable for meeting the needs of ADHP products, while others will not.

11.3 Development of a process test or technique

A standard test or set of test protocols that can serve to assess the performance of various Pb-free solder alloys for their suitability for ADHP application is needed so that rational choices can be made for their use. Once developed, use of these test protocols will need to be promoted across the U.S. government, which will serve to catalyze their acceptance globally.

11.3.1 Establish technical research

In 2008 and 2009, a study was conducted by AIA, GEIA, ARINC Lead-free Electronics Working Group and the Joint Council for Aging Aircraft of research that was in play or planned. Following this study, a three-phase program – the Pb-free Electronics Manhattan Project – was commissioned by the Office of Naval Research and the Joint Defense Manufacturing Technology Panel to scope and solve the problem. The project completed Phases 1 and 2, the Current Best Practice Baseline and Technology Roadmap. Phase 3, “Integrated Risk Reduction Projects” was to fund projects that were to provide solutions to the Pb-free problem.

Unfortunately, the necessary $105 million in funding was not included in the Defense budget and Phase 3 was tabled. It is time to re-establish the funding and drive to bring these and other projects to fruition. Part of this work would be to verify that the results of the earlier gap study are still current and to reprioritize the work scope and coordinate with the appointed government coordinator, such as the Special Assistant to the President for Manufacturing Policy.

There are many institutions that could be funded to focus on the intended outcome of Phase 3. These institutions and consortia include:

- National Network for Manufacturing Innovation (NNMI)
- Aerospace Vehicle Systems Institute (AVSI) Research Consortium

- The Center for Advanced Life Cycle Engineering (CALCE)
- The Center for Advanced Vehicle and Extreme Environment Electronics ($CAVE^3$)
- Materials Genome Initiatives (NIST) Proactive – National Manufacturing Institute for Excellence
- U.S. government Strategic Environmental Research and Development Programs (SERDP)

SERDP currently funds some lead-free research projects on tin whiskers growth and mitigation and fundamental Pb-free solder reliability modeling (http://www.serdp-estcp.org/Program-Areas/Weapons-Systems-and-Platforms/Lead-Free-Electronics). While these projects have already debunked some popular Pb-free reliability claims and impacted the ADHP Pb-free design rules, much more work is needed on the diverse material set used by the ADHP industry. President Obama has proposed building the NNMI.

11.3.2 Institutes for Manufacturing Innovation

Individually and together, these regional hubs – public-private partnerships called Institutes for Manufacturing Innovation – will help to strengthen the global competitiveness of existing U.S. manufacturers, spur new ventures, and boost local and state economies.

11.3.3 Advanced electronics packaging manufacturing

Advanced electronics packaging manufacturing innovation will be critical for the U.S. industrial base to provide cutting-edge capabilities, support the DOD's need for affordability and be price competitive on the global market. AIA recommends the development of a manufacturing institute that will work with defense contractors, small businesses, defense acquisition program offices, the defense research and engineering enterprise and academia to mature and transition manufacturing technologies that make possible enhanced production and repair of DOD platforms, systems and equipment. The Institute's focus on critical design and materials manufacturing solutions will enable current and future DOD acquisition programs to achieve critical cost and production goals while maintaining safety and reliability. While the specific technical issues that the Institute addresses will vary over time – based on operational needs and technological challenges or opportunities – its focus will be to affordably deliver manufacturing technologies that are safe and reliable and have the most benefit to the warfighter.

Therefore, we propose a new NNMI for high reliability electronics packaging, including Pb-free solutions (see also Appendix 3).

- The Advanced Electronic Packaging Institute (AEPI) would work in collaboration with industry, academia, and government in the key areas (ref: TOC 2014-014-002-00 AIA - Advanced Manufacturing Institute recommendation) such as:
  - System Level Co-design – Coordinated design tools that integrate simulators into the design environment need to address the issue of chip, substrate, package and circuit card interconnect co-design.
  - Global Interconnect Systems – Electronics packaging plays a critical role in system performance where multi-component connectivity is just as critical as individual component performance.
  - 3D Stacked Die – The electronics industry is turning to closer integration, so-called 2.5D and 3D integration of individual integrated circuit dies, to achieve continued decreases in size and increases in performance.
  - Power Delivery – Smaller form factors will drive higher power densities within advanced electronics packaging.

- Thermal Management – Increased power densities and local "hot spots" will need to be modeled, measured and mitigated.
- Materials & Interfaces – Advances in materials, materials science, formulation methods and process methods continue to be integral to the development of new electronics package concepts.
- New Concepts – revolutionary concepts are needed to enable the electronics industry to reach new levels of integration in the coming decade.
- Reliability – Meeting the reliability requirements of future advanced electronics packaging components and systems will require tools and procedures that are not yet available.

11.4 Standardize

11.4.1 Standardized approach to identifying and testing alternative materials and alloys is a key need for industry

One of the challenges facing research organizations and studies that have been completed to date is that they are seen as individual efforts answering a specific need. These research studies are usually developed organically and are limited in their scope of attributes to gain broad understanding of design characteristics. A common approach to these studies that will generate a standardized set of data points would be extremely valuable to the design engineers who are responsible for their choices of the best materials alloys for their specific work product.

11.4.2 AIA standards

It is envisioned that AIA through its National Aerospace Standards Program could offer a repository of design data developed by the above resources. It is important to recognize that the data generated by any organization must be open source data, free of intellectual property claims and available to AIA for this repository.

11.5 Disseminate

Communication and acceptance of standardized approaches are essential to any successful program. Dissemination and access of useful materials is necessary to foster ubiquitous adoption of standards. It is recommended that a joint industry-government team update the state of a Pb-free readiness and action plan. It is also recommended that a joint industry-government team update the state of screening and qualification testing protocols.

11.6 Roadmap and timeline

Development of advanced solder and paste formulations that are keeping in step with shrinking electronic piece part terminations are no longer being applied to SnPb solders. Ultimately market pressures will dictate when Pb solder formulations are no longer obtainable or too costly to use in this application.

The end state is to have a Pb-free solution. Establishing a roadmap to reach the end state for the Pb-free electronics issue is dependent on how soon the critical knowledge gaps are closed. The direct approach is to rebaseline the research gaps and petition for the required funding to fill the gaps. Achieving this end state will

require a revitalization of the Pb-free Electronics Manhattan Project, selection of a government coordinator and efforts to deter the loss of the ADHP industry's "out of scope" status from the EU RoHS directives.

11.6.1 Solution

The end state is to have a Pb-free solution by July 1, 2019.

1. Having an acceptable alternative for SnPb solders, and
2. Having the ability to design products that utilize available Pb-free materials and alloys and comply with ADHP performance and reliability requirements.

11.6.2 Research requirements time-line

- Establish a program management entity within the federal government similar to management programs for corrosion and cyber security to coordinate and manage the necessary steps to reach the end state. Target date: January 2015.
- Commerce Department survey to establish a Defense Industrial Base Assessment on Pb-free Electronics. Target date: February 28, 2015.
- Continuation of the Pb-free Manhattan Project, Phase 2 update. Target date: December 1, 2014.
- Reestablish and rebase the research gaps. Target date: March 31, 2015.
- Assess the current cost of filling these research gaps. Target date: May 1, 2015.
- Program Management Entity to submit into the federal budget funding for research and development of industrial base and supply chain. Target date: May 30, 2015.
- Commence research for filling identified research gaps. Target date: no later than January 2016.

11.6.3 Regulatory Tempo

- Consultation to EU RoHS Open December 2013
- Application for exemption to EU RoHS III must be filed by December 1, 2014
- Current exemptions to EU RoHS will expire July 1, 2016
- Potential date for RoHS Open Scope 2019

APPENDICES

Appendix 1
Participants and organizations that attended the AIA Pb-free electronics forum

Last Name	First Name	Company
Arnett	Haynes	Boeing
Betza	Steve	Lockheed Martin Corporation
Blakey	Marion	Aerospace Industries Association
Bolton	Jason	Department of Commerce
Brown	Chandra	Department of Commerce
Burdick	David	Boeing
Burgess	Mark	Boeing
Carnahan	Christopher	Aerospace Industries Association
Casano	Pat	GE
Crawford	Mark	Department of Commerce
Croghan	Dennis	Ball Aerospace
DuPuis	Paul	United Technologies Aerospace Systems
Elliott	Fred	Department of Commerce
Freeman	James	Boeing
Gestautas	Sally	Raytheon
Hardwick	Dak	Aerospace Industries Association
Herndon	Craig	Naval Surface Warfare Center
Hooks	Dean C.	Boeing
Horan	Gary	FAA
Houff	Jeff	SERDP/ESTCP (HGL)
Kygonhalli	Jayanth	BGA Test Technology
Latta	Gary	Naval Surface Warfare Center
Lindberg	Barbara	FAA /AIR-120
Locker	David	US Army AMRDEC
Malloy	Maribeth	Lockheed Martin Corporation
McKamey	Jerry	SAIC
Meschter	Stephan	BAE Systems
Miller	Lisa	SERDP/ESTCP (HGL)
Mras	Gery	Aerospace Industries Association
Nelson	Scott	Harris Corp
Newland	Scott	Harris Corp
Nissan	Robin	Weapons Systems and Platforms - SERDP/ESTCP
Nitschke	Karl	United Technologies Aerospace Systems
Osterman	Michael	CALCE
Rafanelli	Anthony	Raytheon

Rentsch	James	Aerospace Industries Association
Riegle	Leslie	Aerospace Industries Association
Roelecke	Rick	L-3 Com
Snell	Richard	Boeing
Stine	John	L-3 Com
Straw	Eric	Rockwell Collins
Torp	David	IPC
Underwood	Patricia	ODUSD(I&E)
Winter	Michael	UTC Pratt & Whitney
Woody	Linda	Lockheed Martin Corporation

Appendix 2
AIA Technical Operations Council industry-government exchange on RoHS Pb-free electronic meeting presentations

The presentations of this meeting have been posted on the Pb-free Risk Management Consortia web-pages on the AIA SharePoint site. The material is available in the "Committee Documents" section of the web page in the "AIA Government Industry Information Exchange Forum for Pb-Electronics" folder.

The AIA SharePoint site can be accessed through the secure URL:
http://community.aia-aerospace.org/home.aspx

File	Title
TOC 2013-003-000-14 TOC Government Exchange on RoHS Pb-free electronics - AGENDA	Agenda
AIA conf - DAS Brown use at event [Compatibility Mode]	Chandra Brown Presentation: Deputy Assistant Secretary for Manufacturing U.S. Department of Commerce
AIA Lead-Free Presentation Final	BCA Approach to Lead-free Electronics
Implications to the Implenters-Osterman	Implications for Implementers
SMTAI 2011 Luncheon Talk Draft FOR REVIEW final UPDATED 11-9-2011 [Compatibility Mode]	How the Aerospace and Defense Industry is Responding to Pb-free (lead-free) Challenge
TOC-2014-007-000-02 Restricted Materials Breakout plan - Roadmap - as presented	Presentation: "Joint Government and Industry Executive Forum for Lead (Pb)-free Electronics" as presented
CEO_level_RoHS_awareness_-_2013-_11-21	Executive Brief: "Unsolved - The Continuing Saga of Lead-Free Electronics in Aerospace, Defense and High Performance Products"
BIOS - PB Free Forum, 2014-0206	Presenter Bios

Other reference materials

- National Network for Manufacturing Innovation (NNMI)
- http://www.aia-aerospace.org/assets/counterfeit-web11.pdf
- CEO_level_RoHS_awareness_-_2013-_11-21
- TOC 2014-014-002-00 AIA - Advanced Manufacturing Institute recommendation
- Defense Industrial Base Assessment of Counterfeit Electronics – 2010
- Lead-free Electronics Manhattan Project

Appendix 3
AIA advanced electronics packaging manufacturing National Network for Manufacturing Innovation

The aerospace industry views the investment that the U.S. government is making in the administration's National Network for Manufacturing Innovation (NNMI) as a means to enhance the nation's manufacturing capabilities for broad-scale adoption and commercialization and ultimately increase our competitiveness in the global marketplace. Manufacturers of aerospace and defense and high performance systems wish to increase the impact of these investments by establishing a future institute with a primary focus on advanced aerospace manufacturing. Producing aerospace quality hardware demands the highest levels of quality and reliability to ensure safety for the flying public and those that defend our freedom. The greatest technical challenges in adoption of advanced manufacturing processes remain in mastering the integrity and reproducibility of the processes required for aerospace qualification.

To this end, we recommend focusing the scope of a future advanced manufacturing Institute toward the Advanced Electronics Packaging Innovation (AEPI). We believe this technology would benefit and address the technical and economic challenges facing the electronics manufacturing industry by accelerating advances in electronics packaging and assembly technologies, including materials, processes, architectures, design, fabrication, and reliability, and facilitating technology transition to U.S. manufacturing enterprises.

Executive summary

For nearly five decades, the electronics manufacturing industry has benefited from Moore's Law scaling effects that have driven the size of electronics ever smaller while providing exponential increases in capability.[2] This trend has fueled tremendous economic growth in the U.S. and worldwide. The electronics industry is rapidly approaching an end to this trend and relying heavily on innovations in electronics packaging technology to continue the performance and economic benefits previously achieved through Moore's Law scaling at the device level. Compounding this challenge is the fact that most electronics packaging R&D and manufacturing has migrated to Asia with a focus on serving the needs of the high volume consumer electronics industry.

A NNMI AEPI Institute would accelerate advances in electronics packaging and assembly technologies including, materials, processes, architectures, design, fabrication, and reliability, and facilitate technology transition to U.S. manufacturing enterprises. These manufacturing advancements, in-turn, would spur the development, demonstration, and integration of new components, systems, and capabilities for DOD and commercial applications. The vision for this Institute is to bring together large and small businesses, academia, and federal and state agencies to accelerate innovation by investing in industrially-relevant advanced electronics packaging and assembly system integration manufacturing technologies. The Institute would serve as a technical center of excellence, providing the innovation infrastructure to support manufacturing enterprises of all sizes and ensure that the U.S. electronics manufacturing sector is a key pillar in an enduring and thriving economy.

[2] Moore's Law refers to the observation in 1965 by Intel Corporation co-founder Gordon E. Moore that the number of transistors in a dense integrated circuit doubles approximately every two years. While subsequent manufacturing trends confirmed the accuracy of this observation, physical limitations and ever-increasing costs of development have slowed the progress of technological innovation.

Industry trends and challenges

The modern electronics industry began in the research laboratories of Bell Laboratory in the early 1950's with DOD funding. For more than five decades, the electronics industry has distinguished itself by its rapid growth in performance and economic impact. This tremendous growth has been fueled by the exponential improvements in integrated circuit density, performance and cost. In accordance with Moore's Law, the number of transistors per chip in a semiconductor device doubled every two years with a corresponding 30 percent cost reduction and 15 percent performance increase per function every year.

This trend has long been a driving force behind major advances in computing and electronics, which has led to significant improvements in economic productivity and overall quality of life through proliferation of computers, communication and other industrial and consumer electronics. This performance improvement has enabled the electronics industry to continually produce devices and systems that are smaller, more powerful and feature-rich at lower prices. However, due to physical and economic limitations, the electronics industry is rapidly approaching an end to this trend.

Electronics packaging technology has played a key enabling role in this trend for many years, evolving to provide not only environmental protection, but also providing interconnect scaling, power delivery, heat removal and high performance capability. The electronics industry is now relying heavily on innovations in advanced electronics packaging technology to continue the performance and economic benefits previously achieved through Moore's Law scaling. Further integration on the package is a way to continue the progression of Moore's Law. Economically feasible performance increases in electronics systems will depend on ever-tighter packaging of multiple electronic components into a given volume. This new trend, known as "More than Moore," will ultimately lead to high-density, multifunctional hyper-integration of infotech, nanotech and biotech systems. This is the preeminent challenge in electronics manufacturing technology.

This challenge is compounded by the following related trends in the industry:

- Over the past 30 years the U.S. electronics industry has surrendered much of its technology leadership to Asia. U.S. electronics manufacturers have transferred much control over R&D, intellectual property and manufacturing to government subsidized companies in Taiwan and China. This trend started with the electronics packaging, assembly and test and semiconductor manufacturing sectors more than 30 years ago and accelerated during the past 10 years. The U.S. now controls only three percent of the worldwide electronics packaging capacity with the majority in Asia.

- The electronics manufacturing value chain is very heavily horizontally stratified to optimize production of mainstream electronics packaging technologies. New and innovative electronics packaging and assembly systems integration technologies will be disruptive and require coordinated changes to multiple layers of technology. The global electronics manufacturing enterprise is ill-suited to address the vertical nature of this integration challenge, outside of a few exceptional players (e.g., smart phone manufacturing). What's lacking for the majority of system integrators is an ecosystem wherein they may collaborate across multiple layers of the electronics packaging supply chain to experiment with, prototype and define innovative electronics packaging and assembly integration solutions that address applications specific to their domains.

  Forty years ago, the military was the main consumer of semiconductors and associated electronics packaging. The military was the driving force and performed the necessary R&D for bringing new electronics packaging and assembly technologies to the global marketplace with the commercial industry

following suit. An example of this transition was seen in the 1970's when the military developed and tested surface-mount devices and assembly technologies to bring surface-mount technology to military applications. This has changed over the years with the commercial industry driving new technology to enable Moore's Law scaling, leading to cost and performance improvements. End market drivers have been relatively stable for the past 20 years. The military now consumes only one percent of the microelectronics produced. As a result, most microelectronics technologies for cutting-edge military applications come from the commercial industry and not the military sector. Avionics, defense electronics and other high reliability electronic applications differ in significant ways from the vast majority of commercial and consumer electronic applications, leading to significant reliability challenges.

Global restrictions on the use of materials used for electronics products has created the need for new, innovative materials and processes for electronics packaging systems and circuit card assemblies. While solutions have been sought and implemented in the commercial industry, these solutions have proven to be less than optimal. New failure modes have emerged and new solutions are needed when developing electronics for harsh environments such as aerospace and defense. Traditional circuit board materials and solder interconnect materials are affected by these global restrictions and replacement materials are needed. This transition is a significant technology disruption to high performance electronics products.

An AEPI Institute would address the technical and economic challenges facing the electronics manufacturing industry by accelerating advances in electronics packaging and assembly technologies, including materials, processes, architectures, design, fabrication and reliability and facilitating technology transition to U.S. manufacturing enterprises. This would lead to innovations in electronics packaging technologies to provide new system-level integration capabilities to continue the performance and economic benefits previously achieved through Moore's Law scaling at the device level. This will ultimately lead to high-density, multifunctional hyper-integration of infotech, nanotech and biotech systems.

These advancements in manufacturing capability would lead to the development, demonstration and integration of new materials, interconnects, components, systems and capabilities critical for DOD and commercial applications. The Institute would bring together large and small businesses, academia and federal and state agencies to accelerate innovation by investing in industrially-relevant advanced electronics packaging system integration manufacturing technologies.

Industry, academia and the government are making investments in basic and early research, supporting the development of advanced, high performance and high density electronics packaging materials and architectures and a robust and effective ecosystem is now required to help move these promising new materials and architectures into defense and commercial systems to improve U.S. competitiveness. The AEPI Institute will serve to bridge the gap between early research and product development and introduction, provide shared assets to help companies access cutting-edge capabilities and equipment and create an unparalleled environment to educate students and train workers in advanced manufacturing skills. This Institute will serve as a technical center of excellence, providing the innovation infrastructure to support manufacturing enterprises of all sizes and ensure that the U.S. manufacturing sector is a key pillar in an enduring and thriving economy. The goal of the Institute is to increase the successful transition of new electronics packaging materials and architectures by enabling advanced manufacturing innovation. This in turn will create an adaptive workforce capable of meeting industry needs. These trends will further increase domestic competitiveness, meeting DOD and other participating commercial and civilian agency requirements.

DOD in particular requires a dynamic partnership with the U.S. industrial base to produce and integrate the use of advanced, high performance and high density electronics packaging to maintain its technological advantage. This is especially important given the migration of electronics packaging and assembly manufacturing to Asia. The AEPI Institute would play an integral role as a regional or national hub within the NNMI construct. It would foster resource leveraging and innovation in advanced electronics packaging materials, architectures, design and fabrication to significantly improve performance and reliability, decrease size, weight and power, lower life cycle costs and improve design capabilities for existing and future components and systems to provide new operational capabilities to the warfighter.

Advanced electronics packaging manufacturing innovation will be critical for the U.S. industrial base to provide cutting-edge capabilities, support DOD's need for affordability and be price competitive on the global market. The Institute will work with defense contractors, small businesses, defense acquisition program offices, the defense research and engineering enterprise and academia to mature and transition manufacturing technologies that make possible enhanced production and repair of DOD platforms, systems and equipment. The Institute's focus on critical design and materials manufacturing solutions will enable current and future DOD acquisition programs to achieve critical cost and production goals while maintaining safety and reliability. While the specific technical issues that the Institute addresses will vary over time – based on operational needs and technological challenges and opportunities – its focus will be to affordably deliver manufacturing technologies that are safe and reliable and have the most benefit to the warfighter.

The AEPI Institute would work in collaboration with industry, academia and government in the following key areas identified by industry working groups:

System Level Co-Design – Coordinated design tools that integrate simulators into the design environment need to address the issue of chip, substrate, package and circuit card interconnect co-design. Such a design environment must include tools for simultaneous thermal, electrical and mechanical analysis. These tools need to provide rapid, accurate results which in turn will allow multiple design iterations. The tools must handle new 3D packaging architectures such as stacked die, stacked package and through silicon via technologies. Additionally, reliability models are needed to predict product life at mission level environments to preclude the necessity to perform testing for every new product design. An understanding of the constitutive properties of new material set solutions is needed as well as new test protocols to ensure the appropriate mechanical and environmental tests are representative of product life. Traditional accelerated aging models and tests are not adequate for new material sets. As the materials change so do their behaviors and a thorough understanding of the mechanics of aging of the product life is required.

Global Interconnect Systems – Electronics packaging plays a critical role in system performance where multi-component connectivity is just as critical as individual component performance. The challenge is to develop power efficient high bandwidth interconnections between components. High bandwidth is enabled by low loss interconnects and by increasing the number of connections between system components in a cost effective manner. There is a need to develop new electronics packaging architectures – including optical interconnects – and also to enable and evaluate high speed performance of the global interconnects between system components for existing electronics packaging architectures. New globally acceptable material sets are needed at all levels of electronics packaging to meet the performance and reliability requirements of harsh environment electronics.

3D Stacked Die – The electronics industry is turning to closer integration – so-called 2.5D and 3D integration of individual integrated circuit dies – to achieve continued decreases in size and increases in performance. These are electronics packaging system integration technologies that address the limitations of CMOS device scaling. As military electronics continue towards high performance and smaller form factors, 3D die level integration will be required for many mission critical applications. The industry must address 2.5D/3D package manufacturing technology challenges via a solution defining ecosystem that cuts vertically across the stratified layers of the electronics manufacturing industry, accelerating the advancement and adoption of electronics manufacturing technologies, tools, methods and standards for 2.5D/3D electronics systems integration. Significant manufacturing challenges remain in the electronics industry surrounding "known good die," assembly, test, handling of thinned wafers and rework of defective dies in the stack.

Power Delivery – Smaller form factors will drive higher power densities within advanced electronics packaging. Future electronics systems will require low impedance chip-to-chip and chip-to-package interconnects capable of delivering high power or current densities with no electromigration.

Thermal Management – Increased power densities and local "hot spots" will need to be modeled, measured and mitigated. Novel cooling techniques and heat transfer techniques will need to be developed. Due to the thermally harsh environments of military applications, new or novel approaches are necessary to develop solid-state and fluidic heat removal devices. Mechanisms for degradation in thermal performance – notably at thermal interfaces – need to be explored, with development of predictive methodologies. High speed thermal models, accurate transient and steady state metrologies and efficient thermal solutions need to be addressed for both 2D and 3D applications. These applications include structures where several "hot" dies are stacked, as well as system level considerations, such as board-level heat dissipation. Coupled with the continuous drive towards miniaturization, reliable and affordable thermal management technology remains a major packaging challenge.

Materials & Interfaces – Advances in materials, materials science, formulation methods and process methods continue to be integral to the development of new electronics package concepts. New materials, materials knowledge and processes are needed with an eye to practical implementation to enable industry growth. Novel materials and processes for passive integrated devices either on the die, in the substrate, or in the package will enable next generation heterogeneous system integration. Higher dielectric constant materials and practical processes to enable stable super capacitors or thin film batteries in a package are desired, as are high permeability integration schemes for in-package high density inductors. Coatings or other materials and techniques to enable biocompatibility are desired for the development of directly implantable systems. Metrology which quickly and quantitatively characterizes interfacial behaviors such as adhesion and sub-critical de-bonding under a wide range of environmental temperature and humidity conditions continues to be needed for evaluation of material suitability for packaging applications and improved predictive reliability. There are reliability challenges associated with packaging of extremely large and thin dies, especially for 3D Packaging systems and packaging materials need to be developed or modified to have reliable compliant electronic packages. Fundamental understanding of electronics packaging materials and interface systems, such as interface fatigue behavior and thermal resistance, is needed to enable industry to design materials tailored for electronics packaging needs.

New Concepts – In addition to evolutionary changes, such as complex System-in-Package, revolutionary concepts are needed to enable the electronics industry to reach new levels of integration in the coming decade. Biological, organic and nanostructured devices will require new electronics packaging concepts and technologies. New applications for electronics are developing, from implantable retina prosthesis to

direct brain stimulation, cochlear implants, pain management, wearable electronics, wireless everywhere, energy scavenging and millimeter wave and terahertz packaging. Radical low cost packaging solutions enabling very high density systems are demanded. Innovative chip integration and interconnect techniques for die stacking, in the substrate embedding, chip in PCB, and chip on flex are needed. Materials which can be demonstrated to enable novel interconnection technologies should be developed with supporting metrology for thorough characterization. New methods of package design, architecture and system partitioning for traditional and non-traditional system applications are also required.

Reliability – Reliability of various stacked die configurations and interconnect technologies (die and all levels of packaging) is unproven. No field data yet exists and a program of reliability testing, data collection and failure analysis must be developed. Residual stresses in the fully assembled package structure are anticipated to play a role in the package interconnect reliability. Such residual stresses will depend strongly on the material set and fabrication process at all levels of packaging, further complicating the reliability assessment. In addition, avionics, defense electronics and other high reliability electronic applications differ in significant ways from the vast majority of commercial and consumer electronic applications. Field environments often include extreme temperature and humidity, high altitude, high levels of shock and vibration, underwater exposure or the extremes of space. Product lifetimes are often measured in decades, rather than in years. Contrary to most commercial practices, maintenance and repair activities are routinely performed down to replacing individual components on circuit cards. These maintenance and repair activities often occur many years after initial manufacture, at varied and distant locations and under the control of agencies not always under the direction of the original equipment manufacturer. Finally, failure of the equipment to perform may have dire consequences.

Meeting the reliability requirements of future advanced electronics packaging components and systems will require tools and procedures that are not yet available. These include:

- Failure classification standards
- Identification of failure mechanisms
- Improved failure analyzing techniques and methods
- Electrical/thermal/mechanical simulation
- Lifetime models with defined acceleration factor
- Test vehicles for specific reliability characterization
- Early Warning Structures

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