PATHWAY TO IMPLEMENTING LEAD-FREE SOLDER ALLOYS –
Comparison table of NASA-USAF Aging Aircraft solder project vs. possible future work

A Step	B Factor	C Current Project Scope	D Rational for Project Scope	E Outside of Scope (=Future Work?)	F CALCE
1. Downselect to Promising Lead-Free Solder Materials					
	Solder alloy	Sn/0.7Cu(+0.05Ni), Sn/3.9Ag/0.6Cu, and Sn/3.4Ag/1.0Cu/3.3Bi lead-free solder alloys	Most promising solder alloys currently being implemented through out the commercial sector. Solder alloys have performed well in previous testing programs	Other promising lead-free solder alloys, including variances on the Sn/Cu, Sn/Ag/Cu and Sn/Ag/Cu/Bi solder alloys as well as different materials, such as Indium	• Determine constitutive relationships of a lead-free solder from isothermal mechanical tests • Use the thermo-mechanical-microstructure test apparatus to assess the durability of the leading candidate lead-free solder alloy, Sn3.9Cu0.6Ag
	Solder flux	Low-residue, rosen mildly active (RMA) fluxes only	Recommendations from solder manufactures and vendors in conjunction with specifications in-place at the operational level	Water-based fluxes and other rosen-type fluxes (rosin(R) & rosin activated (RA)).	Project will determine if certain components in no-clean fluxes can initiate corrosive processes that will limit eutectic and lead-free solder joint lifetime
2. Conduct Baseline Performance/Reliability Testing on Common Test Board					
	Board finish	Immersion Ag surface finish only	Reflects at this time the most dominate lead-free surface finish used throughout the electronics industry	• OSP (organic solderability preservative), immersion tin and Electroless nickel/immersion gold (ENIG) surface finishes • Determine the intermetallic composition, thickness, and growth rate for the alloys under test attached to an immersion silver board finish as a function of time under isothermal conditions	Effect of intermetallic growth on the bond strength at the plating/solder interface between Sn3.8/Ag0.7Cu solder and wiring boards coated with either organic solderability preservative (OSP), immersion tin, immersion silver, or immersion gold over Electroless nickel (ENIG)

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	Circuit board layers	10-layer board	Meet IPC-9701: 0.093 inches thick and a minimum of 8 layers	Boards with fewer or greater number of layers	Characterize the dispersion and attenuation of high-frequency signals plated with alternative finishes and lead-free solder, and to determine the relationship between degradation of signals and conductor and substrate losses
	Circuit board rigidity	Rigid circuit boards that are not designed to flex	Represents most commonly used circuit boards in DoD and NASA applications	Circuit boards that are designed to flex under stress	
	Circuit boards material	FR-4 boards only	FR-4 is the industry standard. Mfg- High Tg (170C); Rwk- Low Tg (135C)	• Polyimide boards • Look at a variety of pwb thicknesses, material types (e.g . BT, Polyimide, PTFE, etc), hole/via diameters, and determine the impact on their integrity due to the higher soldering process temperatures used in Pbfree soldering	
	Component finish	Removing all gold (Au) leads via tinning	Concerns with gold embrittlement	Affect of varying thicknesses of gold and look for point of embrittlement	Assess the potential for intermetallic growth between the Pb free solder attach and the metallization on the chip, lead, or substrate surface. Determine the effect of intermetallic growth on the adhesion strength at the attach/substrate interface, or lead/attach interface and relate it to time-to-failure in assemblies
	Component size	One "typical" size of each	Budget, board sizing and board	Varying sizes of each component	

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		component type	configuration constraints	type	
	Component types	Many legacy component types and some current high-tech components	Components chosen are very common to Class 3 military electronics and represent a broad range of applications	More current and emerging high-tech components	
	Conformal coatings	Not part of study	Issue covered in the Lead-Free Surface Finish and Low-VOC Conformal Coating (CCAMTF) JG-PP project	Use conformal coatings	
	Pb contamination of solder joints	Determine quantity of Pb in reworked solder joints (after testing). However, reworked PWAs are of different material than manufactured PWAs	Obtaining a better understanding of lead contamination and the relationship to lead-free solder joint performance is an issue that all project participants consider import	• Determine the effects of varying amounts of Pb contamination on electrical reliability • Use same board material for reworked and manufactured PWAs	
	Rework	Reworking 4 representative component types	Representatives from all components types were selected, plated through hole, surface mount, surface mount 4-sided and solder ball technologies	• Rework a wider variety of component types • Investigate risk mitigation strategies for depot level rework of printed wiring assemblies of unknown alloy composition and board finish	
	Testing	IPC Class 3 environment • Vibration (“reasonable worst case”) • Mechanical Shock (2 conditions) • Thermal Cycling (2 temp ranges) • Thermal Shock • Combined Environments (temp & vibration)	Tests meet required specifications and standards required by the participating stakeholders. Represents worst-case environmental conditions that military and aerospace equipment are subjected to while in operation. Standard testing carried out by industry and required under IPC standards.	• Other test conditions, such as different vibe or mech shock spectrums or different temperature ranges, such as up to 190^{o}C (as seen in automotive apps & high temperature underground wells) • Other tests entirely, such as accelerated life tests • Mathematical long-term reliability modeling using data • Very mild temperature cycle (e.g., 0 to 70°C); there is evidence that as the thermal cycle used for testing solder joints becomes less extreme, the	• Determine the contact resistance versus contact force characteristics of Sn3.9Ag0.6Cu, Sn0.7Cu and Sn3.5Ag solder separable contact interfaces; determine the contact resistance versus contact force characteristics as a function of aging for selectively aged selected lead-free solder alloys;

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				performance of SnAgCu becomes better in comparison to SnPb • Perform some thermal testing from -55^{o}C to +150^{o}C. There is data to suggest that the 25^{o}C difference at the high end of the range has a very pronounced effect on solder joint reliability • Field Test Circuit Cards - Identify critical end-design board(s) on an existing system (e.g., F-15 radar) (those most subject to failure). • Field Test LRUs - Identify critical end-design board(s) at LRU level. Build 2 LRUs with the alternative solders. • Dem/Val Non-Destructive Evaluation of Solder Joint and CCAs - Demonstrate/validate a reliable nondestructive assessment technique to quantify microstructure damage and aging effects for existing and new circuit cards in a field environment. Field demonstrate one or more commercial units for evaluating damage of operational circuit cards for specific DoD platform applications.	determine the fretting corrosion behavior of the selected lead-free solder separable contact interface • Measure constitutive relationships of the binary tin alloy Sn3.5Ag from isothermal mechanical tests; Provide guidelines for accelerated stress testing
	Plated Through Hole	Monitoring plated through holes sized 0.036	Plated-through-hole parts prone to fail on legacy military systems.	• Compare electrical reliability of PTH parts after Pb & Pb-free processing and subsequent	

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				environmental testing. • Prepare test boards containing many different PTH sizes using Pb and Pb-free processing (reflow and wave solder operations, and rework). Expose boards to environmental conditions IAW JCAA/JG-PP JTP.	
	Tin whiskering	Look for and document any whisker growth	Very important issue which concerns all participating stakeholders	• Conditions that promote (or reduce) tin whiskering in the three (SnCu, SnAgCu, and SnAgCuBi) lead-free solder alloys • Tin Whisker Mitigation - Specifically design test coupons to grow tin whiskers rapidly (e.g., bright tin plating on brass). Apply materials (e.g., conformal coatings) over the tin plating, and expose to environmental conditions known to grow whiskers. Observe the coupons over the course of several years to determine if any of the coatings prevent/contain whisker growth.	Investigation into the drivers that precipitate tin whisker formation as well as the effectiveness of various mitigation strategies for preventing failure due to tin whiskers
	Modeling	Various modeling techniques will be incorporated as in-kind from volunteering stakeholders		• Fund the development of failure prediction models for the materials we have tested and correlate them with the empirical data	• Develop strategies to use the lead-free solder properties in order to predict the durability of lead-free surface mount assemblies, under temperature cycling and under

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					cyclic bending; Investigate the feasibility of using thermal shock test chambers to conduct high-ramp-rate thermal cycling tests; Provide test data to further validate and verify calcePWA and calceFAST models for stress and damage analysis, especially for lead-free assemblies • Calibrate the stress models for leaded packages with lead-free solder material; Provide experimental verification of material properties of lead-free solders used in the stress models; Provide guidelines to virtual qualification of leaded packages with lead-free solder interconnections
3. Conduct Customer-Specific Testing under Actual/Unique Conditions					
	Testing	Limited Class 3 testing on common test vehicle • Humidity • Salt Fog • Surface Insulation Resistance	Required specifically by particular stakeholders to meet specifications and standards that the other project participants did not require. Meet specific weapons system requirements not shared by other stakeholders.	• Other weapon/space system-specific tests • Systems-level testing • Build a certain number of assemblies, LRUs, etc. with Pb-free solder for implementation	

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		• Electrochemical Migration Resistance		in actual fielded hardware with the possibility of retrieving/replacing that hardware after some time interval in the field and doing a tear-down evaluation	
4. Optimize Manufacturing and/or Rework Processes					
	Soldering process	Not part of study	Budget and time constraints made it impossible to include this issue	• Optimize the soldering process to accommodate for differences in the physical behavior of the lead-free materials • Develop a robust process for manufacturing and repair • Wave solder other component types (e.g., chip resistors)	• CALCE investigated the effect of the higher reflow temperatures on component reliability; researched various lead-free reflow profiles and developed a composite profile from industry recommendations. • Evaluate the impact of lead-free reflow soldering process on electronic components; determine risk of increased thermo-mechanical mismatch and hygro-mechanical mismatch on various components
	Conductive adhesives	Not part of study	Budget and time constraints made it impossible to include this issue	• Research the applicability of conductive adhesives in place of leaded solders used in solder interconnects • Develop environmental testing program to evaluate conductive adhesives ability perform	Use experimental techniques and PoF simulation to assess the constitutive and thermo-mechanical durability performance of a selected anisotropic conductive

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				operational settings	adhesive (ADA)
5. Implementation					
	Lead-free implementation	Not part of study	Budget and time constraints made it impossible to include this issue Follow up issue that all participating members will embark upon following the completion of the current projects	• Labeling and tracking of lead-free parts • Field screening methods for Pb on boards (e.g., XRF)	Investigate the technological, ecological supply chain, and economic advances made in the development of environmentally-friendly electronics, by focusing on Japan as the market leader
	Quality-assurance inspection of solder joints	Not part of study	Budget and time constraints made it impossible to include this issue Follow up issue that all participating members will embark upon following the completion of the current projects	Development of new methods of QA inspection of Pb-free solder joints	