Engineering and Technical Services for Joint Group on Pollution Prevention (JG-PP) Projects

Potential Alternatives Report

for Validation of Alternatives to Eutectic Tin-Lead Solders used in Electronics Manufacturing and Repair

Final

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ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
AFMC-24	Air Force Material Command's list of 24-targeted chemicals
Ag	Silver
ATSDR	Agency for Toxic Substances and Disease Registry
Bi	Bismuth
CAA	Clean Air Act
CAS#	Chemical Abstracts Service Registry Number
CBA	Cost Benefit Analysis
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	U.S. Government Code of Federal Regulations
Cu	Copper
CWA	Clean Water Act
DCMA	Defense Contract Management Agency
DoD	Department of Defense
ENIG	Electroless Nickel/Immersion Gold (Surface Finish)
EPA	Environmental Protection Agency
EPA-17	Environmental Protection Agency's Top 17 List of Hazardous Materials
EPCRA	Emergency Planning and Community Right-to-Know Act
ESOH	Environmental, Safety, and Occupational Health
HAP	Hazardous Air Pollutants
HazMat	Hazardous Material
In	Indium
IRIS	Integrated Risk Information System
JG-PP	Joint Group on Pollution Prevention
JLC	Joint Logistics Commanders
JTP	Joint Test Protocol
JTR	Joint Test Report
LC_{50}	Lethal Concentration, 50% Kill
LD_{50}	Lethal Dose, 50% Kill
LD_{LO}	Lethal Dose Lower Limit
MSDS	Material Safety Data Sheet
NA	Not Applicable
NE	Not Established
NASA	National Aeronautics and Space Administration
NAWC	Naval Air Warfare Center
NCMS	National Center for Manufacturing Sciences
NDCEE	National Defense Center for Environmental Excellence
NEMI	National Electronic Manufacturing Initiative
Ni	Nickel
NPDES	National Pollutant Discharge Elimination System Program
NSWC	Naval Surface Warfare Center
OEM	Original Equipment Manufacturer
OSHA	Occupational Safety and Health Administration

OSP	Organic Solderability Preservative (Surface Finish)
PAR	Potential Alternatives Report
PCB	Printed Circuit Board
PEL	Permissible Exposure Limits
PPE	Personnel Protective Equipment
RCRA	Resource Conservation and Recovery Act
RQ	Reportable quantity
SnPb	Tin-Lead
Sb	Antimony
STLC	Soluble Threshold Leaching Concentration
TACOM	Tank-Automotive and Armament Command
TC_{LO}	Toxic Concentration Lower Limit
TCLP	Toxicity Characteristic Leaching Procedure
TD_{LO}	Toxic Dose Lower Limit
TLV	Threshold Limit Values
TRI	Toxic Release Inventory
TWA	Time Weighted Averaged
UA	Unavailable
VOC	Volatile Organic Compound

PREFACE

This report was prepared by the National Defense Center for Environmental Excellence (NDCEE) under Contract Number DAAE30-98-C-1050. This report was prepared on behalf of, and under guidance provided by, the Joint Group on Pollution Prevention (JG-PP) through the JG-PP Working Group. The structure, format, and depth of technical content of the report were determined by the JG-PP Working Group, government contractors, and other government technical representatives in response to the specific needs of this project.

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EXECUTIVE SUMMARY

For this project, lead found in tin-lead (SnPb) solders used on circuit card assemblies, cannon plugs, connectors, and other electronic equipment was the identified hazardous material (HazMat) targeted for elimination or reduction. The original equipment manufacturers (OEMs) participating in the Joint Group on Pollution Prevention (JG-PP) Lead-Free Solder project apply SnPb solders to printed circuit board assemblies. The solder is applied by several process methods including wave, reflow, and manual soldering. The circuit board finishes and circuit board component material to which the SnPb solder is applied also contains lead.

This Potential Alternatives Report (PAR) provides technical analyses of identified alternatives to the current SnPb solder, criteria used to select alternatives for further analysis, and a list of those alternatives recommended for testing.

The initial lead-free solder alternatives list was compiled using literature searches and OEM participant recommendations. The involved project participants initially considered approximately 30 alternative lead-free solder alloys. These lead-free alloys were variations of tin (Sn), copper (Cu), silver (Ag), indium (In), antimony (Sb), nickel (Ni), and bismuth (Bi), such as Sn/Ag, Sn/Cu, Sn/Cu/Ni, Sn/Ag/Cu, Sn/Ag/In, Sn/Ag/Bi, Sn/Ag/Cu/Bi, Sn/Ag/Cu/Sb, and Sn/Ag/Cu/Sb/Bi. In late 2001 and early 2002, stakeholders and OEM participants identified specific lead-free solder alloys as potential alternatives to the current SnPb solder. The selected lead-free solders were Sn/0.7Cu/0.05Ni, Sn/3.9Ag/0.6Cu, and Sn/3.4Ag/1.0Cu/3.3Bi. Available information about these lead-free solder alloys was used to analyze the technical merits and the potential environmental, safety, and occupational health (ESOH) impacts of these alloys. Project participants used this information to select lead-free solder alloys for testing in accordance with the *Draft, Joint Test Protocol (J-01-EM-026-P1) for Validation of Alternatives to Eutectic Tin-Lead Solders used in Manufacturing and Rework of Printed Wiring Assemblies*, dated February 14, 2003. Results of the testing will be documented in a Joint Test Report (JTR).

A preliminary cost benefit analysis (CBA), *Cost Benefit Analysis for Tin-Lead Solder used in Manufacturing and Repair Electronics*, dated April 30, 2002, was performed to determine if implementation of candidate lead-free solders is economically justified.

1.0 INTRODUCTION

The Joint Logistics Commanders (JLC) and National Aeronautics and Space Administration (NASA) co-chartered the Joint Group on Pollution Prevention (JG-PP) to coordinate joint service/agency activities affecting pollution prevention issues identified during system and component acquisition and sustainment processes. The primary objectives of the JG-PP are to:

- Reduce or eliminate the use of hazardous materials (HazMats) and hazardous processes at manufacturing, remanufacturing, and sustainment locations.
- Avoid duplication of effort in actions required to reduce or eliminate HazMats through joint service cooperation and technology sharing.

JG-PP projects typically involve at least one original equipment manufacturer (OEM) producing multiple systems for the Department of Defense (DoD) and NASA, as well as at least one facility, such as a DoD depot, maintaining the systems. The JG-PP methodology is being used by the Lead-Free Solder Team with the intent of facilitating the team's efforts to identify and use environmentally acceptable materials and processes for circuit card manufacturing and maintenance.

As part of the JG-PP program, the Potential Alternatives Report (PAR) details baseline processes, HazMats targeted for elimination, and alternative replacement technologies. The preliminary environmental safety and occupational health (ESOH) analysis provides an initial qualitative assessment of viable alternatives, identifying conspicuous ESOH issues that may be a factor when selecting an alternative to the baseline process. A technology survey was performed to identify potential solder alloy alternatives that meet manufacturing requirements. The alternatives were identified through literature searches, electronic database and Internet searches, customized surveys, previous studies performed on lead-free solder alloys, and/or contacts.

After reviewing technical information documented in the PAR, government representatives, technical representatives from the affected facilities, and other stakeholders involved in the JG-PP process will select the list of viable alternative solder alloys for consideration and testing under the project's Joint Test Protocol (JTP). Test results will be reported in a Joint Test Report (JTR) upon completion of testing. The selection rationale and conclusions are documented in the PAR.

A preliminary cost benefit analysis (CBA), *Cost Benefit Analysis for Tin-Lead Solder used in Manufacturing and Repair Electronics*, dated April 30, 2002, was prepared to quantify the estimated capital and process costs of lead-free solder alternatives and cost savings relative to the current soldering processes.

For this Lead-Free Solder project, lead, as found in tin-lead (SnPb) solders and electronic applications, was identified as the target HazMat to be eliminated. These leaded materials are used in electronic applications and wave, reflow, and manual soldering processes. Table 1 lists the target HazMat, the related process and application, current specifications, and affected programs.

Table 1. Target HazMat and Current Process Summary

Target HazMat	Lead	
Current Processes	SnPb soldering: Wave, Reflow, and Manual	
Applications	Circuit card assemblies for IPC Class 3 (high reliability) performance environments	
Current Specifications		
ANSI/J-STD-003	IPC-9201	IPC-TM-650
IPC-610	IPC-9701	MIL-STD-810F
IPC-6012	IPC-SM-785	IPC/EIA J-STD-001 Rev C
Potentially Affected Defense Systems (See Appendix A)		

2.0 BACKGROUND

The use of conventional SnPb solder in circuit board manufacturing is being threatened today by environmental concerns and increasing regulations concerning lead. This pressure to reduce or remove lead is growing at a significant rate. As a result, the DoD and defense contractors are searching for lead-free solder alternatives for wave, reflow, and manual processing methods. However, because no single lead-free solder is likely to qualify for all defense applications, it is important to begin now validating alternative solders for discrete applications.

2.1 Objectives and Scope of Work

The primary objective of this effort is to demonstrate and validate lead-free solders to replace conventional SnPb solders used on circuit card assemblies, cannon plugs, connectors, and other electronic applications. Successful completion of this project will result in one or more lead-free solders qualified for use at depot facilities and defense contractor sites participating in this project.

One of the objectives of the Phase I effort is to develop a concise, focused PAR documenting the technical, production, cost, and environmental information about the baseline soldering processes. ESOH issues pertaining to the baseline and alternative solders will be discussed.

2.2 Weapons Systems Affected

This effort focuses on the elimination of lead used in electronic applications on the affected weapons systems listed in Table 1. These electronic applications consist of leaded components, surface finishes, and solders. The main focus of this PAR is to evaluate lead-free alternatives to the currently used SnPb solders.

2.3 Lead-Free Solder Overview

Lead and lead compounds have been cited by the Environmental Protection Agency (EPA) as one of the top 17 chemicals imposing the greatest threat to human health. As of July 1, 2002, the Toxic Release Inventory (TRI) reporting threshold for lead was reduced to 100 pounds, retroactive to January 1, 2001. In addition, widely differing and uneven environmental regulations and practices across the globe have led to political and financial obstacles for the electronics industry. For example, the European Commission is entertaining proposed regulations that would "ban import, sales and production of lead and products that contain lead." As a result, most printed circuit board (PCB) manufacturers live with some fear that the consequences of these practices could overtake them suddenly due to a change in law or environmental policy.

3.0 BASELINE PROCESS

This PAR focuses on three soldering methods, wave, reflow, and manual, as required by the project participants. The following subsections describe the three different soldering processes as they relate to manufacturing and repair applications used by the participants, including a description of materials, a process flow diagram, amounts of solder used, amounts of fluxes used, and hazardous waste generated.

The baseline process information was gathered by method of survey forms sent out to OEMs and depot facilities. The descriptions below are based on "typical" and generalized SnPb solder application processes, and are not the exact processes used by any of the participants of the JG-PP Lead-Free Solder project.

3.1 Wave Solder Process Descriptions

A current soldering method used by OEMs is wave soldering, which consists of either through hole or surface mount component applications. Once the components are temporarily adhered to the circuit board, the board is moved over a "wave" of solder, in which the solder is applied to the circuit board and components. A general process flow diagram for wave solder applications is shown in Figure 1.

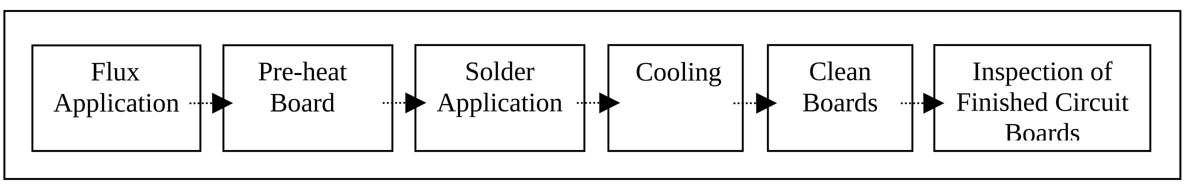

Figure 1. General Process Flow of Baseline Wave Process

The wave soldering process consists of several steps, which will vary from one OEM to another and may vary depending on the parts soldered. In general, these steps include flux application, pre-heating of the circuit board or other applicable surface, wave solder application, cooling, and cleaning of residual solder and flux from circuit boards, and inspection.

3.1.1 Baseline Material Usage, Energy Usage, and Waste Generation

The major baseline process equipment the OEMs use for soldering the circuit board assemblies includes a wave-soldering machine with an inert atmosphere. The exact equipment varies from one facility to another, and might change with implementation of lead-free solder alternatives if an inert atmosphere is not currently used.

Baseline SnPb soldering processes use fluxes free of volatile organic compound (VOC); therefore, emissions estimates are not included in the waste summary. Table 2 lists the baseline material usage, utility usage, and waste generation for a typical wave soldering process.

Table 2. Baseline Material Usage, Utility Usage, and Waste Generation for Wave Method

Material	Quantity/Year
Bar Solder	6,700 lbs/yr
Flux	5 gal/yr
Cleaning Chemistry	2,640 gal/yr
Utility	**Quantity**
Electricity	1,344,972 KWH/yr
Nitrogen Gas	Insignificant
Water	UA
Waste	**Quantity**
Solder Dross (recycled)	2,700 lbs/yr
Spent Flux	UA
Cleaning Chemistry	UA

UA = Unavailable

3.2 Reflow Solder Process Description

Another current soldering method used by OEMs is reflow soldering. Reflow soldering consists of adhering the components to the circuit board with a solder paste, then heating the board to the solder's liquidus temperature, allowing the solder within the paste to flow and complete the component/board connection. A general process flow diagram for reflow solder applications is shown in Figure 2.

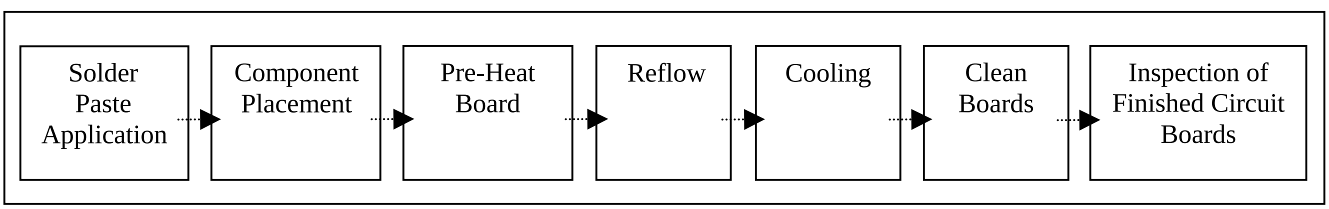

Figure 2. General Process Flow of Baseline Reflow Process

The reflow soldering process consists of several steps, which will vary from one OEM to another and may vary depending on the parts to be soldered. In general, these steps include solder paste application, component placement, pre-heating of the circuit board or other applicable surface, melting (reflow) the solder, cooling, cleaning of residual solder and flux from circuit boards, and inspection.

3.2.1 Baseline Material and Energy Usage and Waste Generation

The major baseline process equipment used for reflow soldering includes a reflow oven. The exact equipment varies from one facility to another, and might change with implementation of lead-free solder alternatives if an inert atmosphere is not currently used. Current reflow processes use VOC containing fluxes. Table 3 lists the baseline material usage, utility usage, and waste generation for a typical reflow process.

Table 3. Baseline Material, Utility Usage and Waste Generation for Reflow Method

Material	**Quantity**
Solder Paste	1,020 lbs/yr
Cleaners	255 gal/yr
Utility	**Quantity**
Electricity	1,344,972 KWH/yr
Nitrogen Gas	UA
Waste	**Quantity**
Solder dross (sludge)	900 lbs/yr
Cleaning Chemistry	UA
Emissions	**Quantity**
VOCs	3 g/L

UA = Unavailable

3.3 Manual Solder Process Description

A current soldering method used for repair work is manual soldering. Manual soldering consists of heating the items to be soldered with a soldering iron. When the board and components become hot enough, the solder will melt upon contact with the items, adhering the components to the circuit board. A general process flow diagram for manual solder applications is shown in Figure 3.

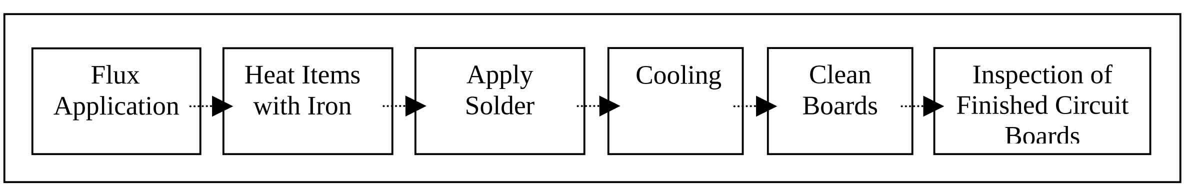

Figure 3. General Process Flow of Baseline Manual Process

The manual soldering process consists of several steps, which will vary from one facility to another and may vary depending on the parts to be soldered. In general, these steps include flux application, heating items with a soldering iron, solder application, cooling, cleaning of residual solder and flux from circuit boards, and inspection. Though OEMs use manual soldering methods for repair and rework, the OEMs surveyed did not perform manual soldering. Therefore, quantities listed in Table 4 are based on depot facilities surveyed.

3.3.1 Baseline Material Usage, Energy Usage and Waste Generation

The major baseline process equipment depots use for manually soldering circuit board assemblies includes a solder iron. Wastes and energy usage are assumed to be insignificant according to surveyed facilities. Current manual processes use VOC containing fluxes in addition to the flux-cored solder wire. Table 4 lists the baseline material usage and emissions generated for both high and low production throughputs.

Table 4. Baseline Material Usage and Emissions for Manual Method

Material	Quantity	
	High Production (over 25,000 circuit boards processed per year)	**Low Production (3,000 circuit boards processed per year)**
Wire Solder	250 lbs	50 lbs
Flux	2 gal	1.5 gal[a]
Isopropyl Alcohol	5 gal	1 gal[a]
Solder Wicks	132 lbs (800 rolls[d])	NA
Emissions	**Quantity**	
VOCs	565 g/L[b]	502 - 739 g/L[c]

NA = Not Applicable
[a] Estimated values based on baseline survey forms
[b] Based on Kester #186 Rosin Flux
[c] Based on Kester #197, #2331, and #951 Flux
[d] Assuming 5 foot rolls

3.4 Baseline Environmental, Safety, and Occupational Health Status

Lead is the HazMat targeted for elimination from currently used solders. It is listed on the EPA's list of hazardous materials targeted for voluntary reduction (EPA-17) mandated by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The chemicals on the EPA-17 are most likely to be regulated more strictly in the future. The EPA has already reduced the TRI reportable threshold for lead to 100 pounds, as of July 1, 2002. Additionally, OEMs and DoD facilities have lead as one of 24-targeted chemicals for decreased usage (AFMC-24). Finally, Executive Order 13148 requires DoD to reduce the use of targeted chemicals (currently a draft list), including lead, by 50% by December 31, 2006.

Lead is subject to the reporting requirements of Section 313 of Emergency Planning and Community Right-to-Know Act (EPCRA). Lead compounds are listed as hazardous air pollutants (HAPs) under Section 112 of the Clean Air Act (CAA). Under the Clean

Water Act (CWA) Section 307 (a), lead is considered a toxic pollutant according to U.S. Government Code of Federal Regulations (CFR), Title 40, Part 401.15 (40 CFR Part 401.15) and is on the priority pollutants list (40 CFR Part 423, Appendix A). Lead is also regulated as hazardous waste under the Resource Conservation and Recovery Act (RCRA), according to 40 CFR Part 261, Appendix VIII. Under the CERCLA, lead has a reportable quantity of 10 pounds.

3.4.1 Environmental Regulation Issues of Baseline

Federal environmental laws and regulations govern the use of any solder material. Therefore, a regulatory review of the baseline SnPb solder alloy was conducted as part of the ESOH analysis based on the criteria listed below, which consists of reporting requirements and federal regulations of the CAA, CWA, RCRA, TRI, and CERCLA, as well as lists of hazardous materials targeted for voluntary reduction under EPA-17 and AFMC-24. This assessment is primarily based on information that is readily available from CFR and the EPA.

- Air Emissions: The elements of the baseline SnPb solder were analyzed to determine if they are regulated under the CAA as HAPs or VOCs.
- Solid/Hazardous Waste Generation: The baseline SnPb solder was evaluated to determine whether its use generates solid waste, and if so, whether that waste (or any constituent) might be regulated as hazardous waste under RCRA. This analysis also addresses characteristic hazardous wastes as determined by experimental analysis of the waste presented in Environmental Impacts and Toxicity of Lead Free Solders by Edwin Smith III and presented at IPCWorks '99 An International Summit on Lead-Free Electronics Assemblies. The hazardous nature of any waste that is not specifically listed under RCRA or in the technical paper's experiment is noted as "undetermined."
- Wastewater Discharges: The constituents of the baseline SnPb solder were analyzed to determine whether its use would cause the discharge of any wastewaters regulated under the CWA.
- Reporting Requirements: The baseline SnPb solder was examined to determine if its constituents are required to be listed on TRI reports under Section 313 of EPCRA.
- CERCLA Hazardous Substances: The baseline SnPb solder was assessed to determine if its constituents are listed as hazardous substances under the CERCLA.
- EPA 17: The constituents of the baseline SnPb solder were compared to the EPA 17 list. Those substances on the EPA 17 list have been targeted because they are released in large quantities each year, they are generally identified as toxic or hazardous pollutants, and pollution prevention practices have the potential to diminish releases of these chemicals. The EPA 17 listed substances are likely to be targeted for more stringent regulation.
- AFMC-24: The constituents of the baseline SnPb solder were compared to the AFMC-24 list of hazardous materials targeted for reduction by the Air Force.

A regulatory analysis of the baseline SnPb solder alloy is provided in Table 5. The regulatory review was based on the federal environmental laws and regulations cited in the above paragraph.

Table 5. Regulatory Analysis of SnPb Solder

	Tin	Lead
CAS #	7440-66-6	7439-92-1
Weight %	63	37
CAA	--	X
CWA	--	X
RCRA	--	X
TRI	--	X
CERCLA	--	X
EPA 17	--	X
AFMC-24	--	X

The "--" indicates the element is not regulated

3.4.2 Safety and Occupational Health Issues of Baseline

The lead element in the baseline SnPb solder was evaluated to determine the relative safety and occupational health concerns caused by the toxicity and worker exposure characteristics of lead. A safety and occupational health analysis of lead can be found in Table 6.

Toxicity
Lead is a Group 2B – probable human carcinogen according to the Integrated Risk Information System (IRIS), a division of the EPA, and investigated as a tumorigen, mutagen, and reproductive effector according to available toxicity data. Lead is a poison with an oral toxic dose-lower limit (TD_{LO}) of 450 mg/kg and an oral toxic concentration-lower limit (TC_{LO}) of 10 $\mu g/m^3$ for humans. Acute health effects of lead may include irritation and chest and abdominal pain. The chronic effects of lead include poisoning, death, cancer, and central nervous and reproductive system affects.

Tin is investigated as a tumorigen according to available toxicity. The toxicity data available for tin includes an implant (rat) TD_{LO} of 395 g/kg, where the toxic effects included tumors at the site of application. The acute health affects of tin dust may include mild irritation of skin, eyes, and respiratory tract and if ingested may cause nausea and vomiting.

Exposure
The Occupational Safety and Health Administration (OSHA) was established to reduce occupational health hazards. OSHA regulations govern the required educational and informational resources (e.g., material safety data sheets (MSDS)), personal protective

equipment (PPE), and limits for exposure of workers to chemicals in the workplace. OSHA has established permissible exposure limits (PELs) for air contaminants based on an 8-hour time weighted average. OSHA has set a PEL of 0.05 mg/m^3 for lead and 2 mg/m^3 for tin. The American Conference of Governmental Industrial Hygienists (ACGIH) also has established time-weighted averages (TWA) and threshold limit values (TLV). ACGIH set a TLV/TWA of 0.05 mg/m^3 for lead and 2 mg/m^3 for tin.

Table 6. Safety and Occupational Health Analysis of SnPb Solder

	Tin	Lead
CAS #	7440-66-6	7439-92-1
Weight %	63	37
OSHA PEL	2 mg/m^3	0.05 mg/m^3
ACGIH TLV	2 mg/m^3	0.05 mg/m^3
TD_{LO}[a]	395 g/kg (implant)	450 mg/kg (oral)
TC_{LO}[a]	--	10 $\mu g/m^3$ (oral)
Toxicological Data[b]	Investigated as a tumorigen.	Investigated as tumorigen, mutagen, and reproductive effector. Group 2B carcinogen.

The "--" indicates that the element is not regulated

[a] Toxicity data from http://hazard.com/msds/

[b] Information from MSDS, http://hazard.com/msds (Mallinckrodt Baker, Inc.)

4.0 IDENTIFICATION OF ALTERNATIVES

Due to increasingly stringent regulations concerning the use of lead and lead components, research efforts have been focused on testing lead-free alternatives that would replace conventional SnPb processes for electronic applications. A set of requirements and acceptable criteria for selecting lead-free alternatives provided by project stakeholders and technical representatives was complied and is listed in Table 7.

Table 7. Requirements and Acceptable Criteria of Potential Alternative Alloys

Candidate Alloy Requirements	Acceptable Criteria
Operational Requirements	Manufacturability - Use existing equipment Metal price - Low cost. As close to SnPb solder cost as possible.
Engineering and Performance Requirements	Acceptable physical properties (strength, elongation, fatigue) - Alloy must be capable of providing the mechanical strength and reliability equal to or greater than SnPb solder. Adequate electrical conductivity Adequate thermal conductivity Compatibility with lead Repeatability - Consistency in melting point Melting point - Near eutectic Melting point below 260°C for wave and below 250°C preferably around 220°C for reflow.
ESOH Requirements	No element with an ESOH hazard equal or greater to lead
Ingredients	No lead
Availability	Currently commercially availability must be able to sustain industry-wide use

A technical survey was performed to identify potential lead-free alternatives. The survey included literature searches, electronic database and Internet searches, technical representative's input, and data from previous studies performed on lead-free alloys by National Center for Manufacturing Sciences (NCMS), National Electronic Manufacturing Initiative (NEMI), and other research groups. As a result, a preliminary alternatives list was compiled and is represented in Table 8.

Table 8. Preliminary List of Lead-Free Alloys

Alternative Alloys		Melting Point °C
SnPb (baseline)	Sn/37Pb	183 (eutectic)
Sn/Cu	Sn/0.7Cu	227 (eutectic)
Sn/Cu/Ni	Sn/0.7Cu/0.05Ni	227 (eutectic)
Sn/Ag	Sn/3.8Ag	221 (eutectic)
Sn/Ag/Cu	Sn/3.9Ag/0.6Cu	216-219
	Sn/4.0Ag/0.5Cu	216-219
	Sn/4.0Ag/1.0Cu	216-219
Sn/Ag/In	Sn/3.5Ag/1.5In	218-223
Sn/Ag/Bi	Sn/3.4Ag/4.8Bi	200-216
Sn/Ag/Cu/Bi	Sn/3.1Ag/0.5Cu/3.1Bi	209-212
	Sn/3.4Ag/1Cu/3.3Bi	205-214
Sn/Ag/Cu/Sb	Sn/2.5Ag/0.8Cu/0.5Sb	213-218
Sn/Ag/Cu/Sb/Bi	Sn/4.6Ag/1.6Cu/1Sb/1Bi	214-220

Tin is the base metal used for every candidate lead-free alloy. Tin was selected as the base metal since it is relatively inexpensive, sufficiently available, has desirable physical, electrical/thermal conductivity, and wetting properties, and is the base metal for the baseline SnPb solder alloy. The other elements used with tin for the potential alternative alloys include copper (Cu), silver (Ag), bismuth (Bi), antimony (Sb), nickel (Ni), and indium (In). These elements were selected because they tend to reduce the melting point when alloyed with tin and possess desirable mechanical, electrical, and thermal properties.

Descriptions of the selection parameters, which include material properties, manufacturability, reliability, alloy costs, and long-term availability, used to identify the potential lead-free alloy alternatives are found in Appendix B.

5.0 SELECTION OF ALTERNATIVES

From the preliminary alternatives list, the alloys were further down selected to two or three potential alloys for each of the three soldering processes (wave, reflow, and manual). Upon further review of the candidate alloys, supporting literature on lead contamination, tin whisker effects, toxicity of antimony and its potential future regulation, and solder availability, project stakeholders and technical representatives identified a shortened list of selected alloys for testing under the JTP. Project participants used information from the *NCMS Lead-Free Solder Project Final Report*, dated August 2001, to select lead-free solder alloys for testing. Table 9 contains the shortened list for testing under the JTP.

Table 9. Selected Lead-Free Alloys for Testing

Process	Candidate Lead-Free Alloys
Wave	Sn/0.7Cu/0.05Ni
	Sn/3.9Ag/0.6Cu
Reflow	Sn/3.9Ag/0.6Cu
	Sn/3.4Ag/1Cu/3.3Bi
Manual	Sn/3.9Ag/0.6Cu
	Sn/3.4Ag/1Cu/3.3Bi

<u>Sn/0.7Cu/0.05Ni</u>
This alloy is commercially available, and the general trend in Industry has been switching to the nickel stabilized tin-copper alloy over standard tin-copper due to superior performance. In addition this nickel-stabilized alloy does not require special solder pots, and has shown no joint failures in specimens with over 4 years of service.

<u>Sn/3.9Ag/0.6Cu</u>
This alloy was chosen because it was recommended for industry use by the NEMI lead-free group who believe the Sn/Ag/Cu family has the most promise as the main replacement for SnPb solder. It is commercially available and currently used in electronic applications. It has been determined that alloys with compositions within the range of Sn/3.5-4Ag/0.5-1.0Cu are close enough to have a liquidus temperature around 220°C and similar microstructures and mechanical properties.

<u>Sn/3.4Ag/1.0Cu/3.3Bi</u>
This alloy was chosen because it is commercially available, is the leading candidate system for electronics originating in the Far East market, and Bi enhances the long-term thermal cycle reliability of the solder joint. In addition Sn/3.4Ag/1.0Cu/3.3Bi was the best performer in the 2001 NCMS study. (Ref [5])

<u>Selection of Board Finish</u>
The type of surface finish on the printed board is often the initial mode of solder joint failure; therefore, selection of the surface finish was critical to the test design for the JTP. Suitable board finishes for use with SnPb and lead-free solders include immersion silver,

organic solderability preservative (OSP), and immersion tin and electroless nickel/immersion gold (ENIG). Each surface finish has its advantages and limitations. For example, ENIG is susceptible to "black pad" which can cause premature failure of solder joints. Immersion tin and OSP become non-solderable after several exposures to reflow conditions, and OSP exhibits poor wetting with some solders. However, several major electronic manufacturing companies are currently using immersion silver in production and the general consensus is that immersion silver has the best balance of desirable properties (good wetting by solders, good solder joint reliability, good long-term solderability upon storage, and retention of solderability after multiple reflow cycles). Therefore, project stakeholders and participants have selected immersion silver as the surface finish used for testing in the project's JTP.

6.0 PRELIMINARY ESOH ANALYSIS OF CANDIDATE ALTERNATIVES

Each candidate alternative was quantitatively analyzed for associated ESOH concerns. Using available resources, each element and alloy alternative was evaluated to determine the extent of its regulation under major federal environmental laws using the criteria described in Section 3.4.1 of this PAR. Each element and candidate alloy was also reviewed for toxicity and exposure potential based on lead's toxicity and exposure values in Section 3.4.

The ESOH analysis of the elements (Pb, Sb, Bi, Cu, In, Ag, Ni and Sn) is found in Section 6.1, followed by the ESOH analysis of the candidate lead-free solder alloys described in Section 6.2. The results of the ***Element*** ESOH analysis are summarized in Table 20, and the results of the ***Alloy*** ESOH analysis are summarized in Table 24.

6.1 Environmental, Safety, and Occupational Health Analysis of Elements

6.1.1 Environmental Regulation Issues of Elements

The alternative solder alloy elements were evaluated to determine the extent of which they are regulated under the major federal environmental laws. Using available resources, each element was evaluated based on regulations under the EPA-17 list, CAA, CWA, TRI reports under Section 313 of EPCRA, CERCLA, and RCRA.

6.1.1.1 EPA List of Hazardous Substances

CERCLA requires the EPA and Agency for Toxic Substances and Disease Registry (ATSDR) to prepare a list, in order of priority, of substances "which are deemed to pose the most significant potential threat to human health due to their known or suspected toxicity and potential for human exposure." Substances considered to be the most hazardous are listed in order from 1 to 275. The EPA-17 lists the first 17 substances on the list of priority substances. No alternative alloy elements are on the EPA-17. The ranking of the metals of interest are listed in Table 10.

Table 10. Metal Ranking from EPA Priority List of Hazardous Substances, CERCLA Substance list, 2001

Metal	Ranking (in order of priority)
Lead	2
Nickel	53
Copper	129
Silver	207
Antimony	222
Bismuth	Not Listed (136 in 1999 listing)

6.1.1.2 Clean Air Act

The CAA and amendments were established to protect and improve air quality and reduce damage to human health and the environment by air pollutants. The EPA mandate under Section 112(b)(1) of the CAA is required to control 188 HAPs. HAPs, also known as toxic air pollutants or air toxics, are those pollutants that cause or may cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental and ecological effects. The current list of HAPs includes Antimony, Nickel, and Lead compounds, where “compounds” are identified as including any unique chemical substance that contains the named chemical (e.g., antimony, nickel and lead) as part of the chemical’s infrastructure. No alternative elements were considered VOCs under the CAA.

6.1.1.3 Clean Water Act

The CWA regulates wastewater discharged directly into surface water or into municipal sewer systems. The elements specially regulated under the CWA are categorized as a hazardous substance, toxic pollutant, or priority pollutants. Substances defined as hazardous substances under Section 311(b)(2)(A) of the CWA are listed by the U.S. Government, under CFR, Title 40, Volume 18, Parts 116.4 (40 CFR Part 116.4). However, no alternative metal elements investigated for this PAR are listed as a hazardous substance. Toxic pollutants as defined under Section 307(a)(1) of the CWA are listed in 40 CFR Part 401.15. Priority pollutants are 126 chemicals that must be tested for as a requirement of National Pollutant Discharge Elimination System Program (NPDES) (CWA Section 402) permits. Priority pollutants are listed in 40 CFR Part 423 Appendix A. Table 11 lists the reportable quantities (RQ) of the elements regulated under the CWA.

Table 11. Alternative Elements Regulated Under CWA

Elements	Toxic Pollutant RQ (lbs.)	Priority Pollutant
Lead	10	Yes
Antimony	5000	Yes
Bismuth	Not regulated	Not regulated
Copper	5000	Yes
Indium	Not regulated	Not regulated
Nickel	100	Yes
Silver	1000	Yes
Tin	Not regulated	Not regulated

6.1.1.4 Toxic Release Inventory Section 313 of EPCRA

In 1986, Congress passed the EPCRA with previsions for emergency notification, community right to know reporting, and the TRI. Under 40 CFR Parts 300-399, it is dictated that when certain elements are released over certain quantities, the organization responsible for this must report its action. Under Section 313 of the EPCRA, also referred to as the TRI, 40 CFR Part 372.65 lists toxic chemicals for which reporting is required. 40 CFR Part 302.4 lists the "reportable quantity adjustment for each hazardous substance in pounds." TRI reportable chemicals and quantities are listed in Table 12.

Table 12. Elements Regulated Under TRI (Section 313 EPCRA)

Elements	TRI Chemicals EPCRA Sec. 313
Lead	Yes (100 lbs.)
Antimony	Yes (5000 lbs.)
Bismuth	Not regulated
Copper	Yes (5000 lbs.)
Indium	Not regulated
Nickel	Yes (100 lbs.)
Silver	Yes (1000 lbs.)
Tin	Not regulated

6.1.1.5 Resource Conservation and Recovery Act

The RCRA governs the management of hazardous waste. A solid waste is identified as a hazardous waste under 40 CFR Part 261 if it exhibits one of the following:

- Characteristics of hazardous waste (e.g., ignitable, corrosive, reactive, or toxic)
- It has been found to be fatal to humans in low doses (e.g., oral LD50 (rat) of less than 50 mg/kg, inhalation lethal concentration, 50% kill (LC50) (rat) of less than 2 mg/L, or dermal LD50 (rabbit) of less than 200 mg/kg)
- It contains any of the toxic constituents listed in 40 CFR Part 261 Appendix VIII and is capable of posing a substantial present or potential hazard to human health or the environment when improperly managed.

The alternative elements shall be characterized as "toxic" hazardous wastes, which are categorized by "D" codes, if using the Toxicity Characteristic Leaching Procedure (TCLP) test method 1311, the sample of waste contains any of the contaminants listed in Table 1 of 40 CFR Part 261.24 at the concentration equal to or greater than the respective value given in that table.

The TCLP test determines whether a solid waste is prohibited from being discarded in a landfill due to it leaching more than a pre-determined amount of a "toxic" element. Many members of the European community as well as Japan also utilize deionized water leaching tests. The State of California promulgates a Soluble Threshold Leaching Concentration (STLC) test, which mimics the landfill disposal scenario and its effects on waste leaching. Table 13 lists the alternative alloy elements regulated under RCRA, and EPA and other regulatory limits for evaluating TCLP, STLC, and deionized water leaching tests.

Table 13. Alternative Elements as Hazardous Waste Under RCRA and Regulatory Limits for TCLP, STLC, and Leaching Tests

Element	40 CFR 261 Appendix VIII	Toxic Characteristics (Leaching Tests)			
		Media	Limit (mg/L)	Source	EPA Hazardous Waste Code [b]
Lead	Yes	TLCP Leachate	5.0 [a]	EPA 40 CFR 261	D008
		Drinking Water	0.015	EPA 40 CFR 141	
		STLC	5.0	California State Reg.	
Antimony	Yes	TCLP Leachate	1.0	TNRCC 30 TAC 335 (Texas statutes)	Not regulated
		Drinking Water	0.006	EPA 40 CFR 141	
		STLC	15	California State Reg.	
Bismuth	No	All	None found		Not regulated
Copper	No	TCLP Leachate	500	State regulations	Not regulated
		Drinking Water	1.0	EPA 40 CFR 141	
		STLC	25	California State Reg.	
Indium	No	All	None found		Not regulated
Nickel	Yes	TLCP Leachate	7.0	EPA 40 CFR 261	Not regulated
		STLC	20	California State Reg.	
Silver	Yes	TCLP Leachate	5.0	EPA 40 CFR 261	D011
		Drinking Water	0.10	EPA 40 CFR 141	
		STLC	5.0	California State Reg.	
Tin	No	All	None found		Not regulated

[a] Some jurisdictions observe a 1.5mg/L limit, based on a multiple of the 0.015 mg/L drinking water limit
[b] Characteristic wastes are indicated by a "D" code, which are regulated as hazardous waste when they exhibit the characteristic or contain the toxic constituent at levels above the level of regulatory concern

Two leachate studies with several lead-free alloys and with SnPb solder were undertaken to determine if the alloys would leach toxic metals in excess of legal limits. The leachate tests used were the TCLP, STCL, and deionized water-leaching tests. Solder spheres, solder solids, solder paste, and solder dross were the physical forms of solder tested in the first study. The second study used solder reflowed onto printed wiring boards

The eight alloys chosen for the first study as outlined in "Environmental Impacts and Toxicity of Lead Free Solders", by Smith, were:

- Sn/3.2Ag/0.5Cu
- Sn/3.5Ag
- Sn/2Ag

- Sn/0.7Cu
- Sn/5Sb
- Sn/20In
- Sn/5Bi/5Ag
- Sn/57Bi

Only two of the above alloys represent the selected lead-free alloys investigated for this PAR, which are Sn/3.2Ag/0.5Cu (similar to Sn/3.9Ag/0.6Cu) and Sn/0.7Cu. The results are displayed in Tables 14-16. It should be noted that the data contained within Tables 14-16 utilized 3/8 –inch solid pieces of solder. The solder was not applied to boards such as will be the case in a production type environment.

Table 14. Complete Results of the TCLP Leach Test

3/8-Inch Solder Spheres							
Alloy	**Sn mg/L**	**Ag mg/L**	**Cu mg/L**	**Sb mg/L**	**Pb mg/L**	**In mg/L**	**Bi mg/L**
Sn-Ag-Cu	0	9.32 [a]	43.7 [b]	NA	NA	NA	NA
Sn-3.5Ag	0	11.5 [a]	NA	NA	NA	NA	NA
Sn-2Ag	0	8.46 [a]	NA	NA	NA	NA	NA
Sn-Cu	0	NA	44.5 [b]	NA	NA	NA	NA
Sn-Sb	0	NA	NA	55.5 [c]	NA	NA	NA
Sn-In	0.22	NA	NA	NA	NA	0.39	NA
Sn-Ag-Bi	0.13	NA	NA	NA	NA	NA	1.24
Sn-Bi	0.35	NA	NA	NA	NA	NA	1.61
Sn-Pb (wire)	0.08	NA	NA	NA	1002 [c]	NA	NA
-325, +500 Solder Paste							
Alloy	**Sn mg/L**	**Ag mg/L**	**Cu mg/L**	**Sb mg/L**	**Pb mg/L**	**In mg/L**	**Bi mg/L**
Sn-Ag-Cu	0	0	28.2 [b]	NA	NA	NA	NA
Sn-3.5Ag	0	0	NA	NA	NA	NA	NA
Sn-2Ag	0	0	NA	NA	NA	NA	NA
Sn-Cu	0	NA	28.1 [b]	NA	NA	NA	NA
Sn-Sb	0	NA	NA	33.0 [c]	NA	NA	NA
Sn-Bi	0.51	NA	NA	NA	NA	NA	3.78
Sn-Pb	11.3	NA	NA	NA	1800 [c]	NA	NA

NA = Not Applicable
[a] Indicates exceeding TCLP regulatory limits
[b] Indicates exceeding Drinking Water regulatory limits
[c] Indicates exceeding both TCLP and Drinking regulatory limits

Table 15. Complete Results of the Deionized Water Leach Test

3/8-Inch Solder Solids							
Alloy	**Sn mg/L**	**Ag mg/L**	**Cu mg/L**	**Sb mg/L**	**Pb mg/L**	**In mg/L**	**Bi mg/L**
Sn-Ag-Cu	12.0	0.04	0.11	NA	NA	NA	NA
Sn-3.5Ag	2.11	0.09	NA	NA	NA	NA	NA
Sn-2Ag	5.38	0.04	NA	NA	NA	NA	NA
Sn-Cu	0.57	NA	0.199	NA	NA	NA	NA
Sn-Sb	0.61	NA	NA	32.12 [b]	NA	NA	NA
Sn-In	2.07	NA	NA	NA	NA	0.08	NA
Sn-Ag-Bi	0.08	Trace	NA	NA	NA	NA	0.14
Sn-Bi	0.38	NA	NA	NA	NA	NA	Not found
3/8 Inch Solder Dross							
Alloy	**Sn mg/L**	**Ag mg/L**	**Cu mg/L**	**Sb mg/L**	**Pb mg/L**	**In mg/L**	**Bi mg/L**
Sn-Ag-Cu	5.44	0.085	0.089	NA	NA	NA	NA
Sn-3.5Ag	5.31	0.066	NA	NA	NA	NA	NA
Sn-2Ag	4.38	0.093	NA	NA	NA	NA	NA
Sn-Cu	0.853	NA	0.146 [a]	NA	NA	NA	NA
Sn-Sb	0.399	NA	NA	27.71 [b]	NA	NA	NA

NA = Not Applicable
[a] Indicates exceeding Drinking Water regulatory limits
[b] Indicates exceeding both TCLP and Drinking regulatory limits

Table 16. Complete Results of the Soluble Threshold Leaching Concentration (STLC) Test—3/8-Inch Solder Solids

Alloy	Sn mg/L	Ag mg/L	Cu mg/L	Sb mg/L	Pb mg/L	In mg/L	Bi mg/L
Sn-Ag-Cu	1.73	Not found	87.4	NA	NA	NA	NA
Sn-3.5Ag	63.2	Trace	NA	NA	NA	NA	NA
Sn-2Ag	29.3	Trace	NA	NA	NA	NA	NA
Sn-Cu	5.77	NA	86.0 [a]	NA	NA	NA	NA
Sn-Sb	2.11	NA	NA	11.1	NA	NA	NA
Sn-In	1.20	NA	NA	NA	NA	0.09	NA
Sn-Ag-Bi	0.98	0.50	NA	NA	NA	NA	46.1
Sn-Bi	0.99	NA	NA	NA	NA	NA	29.4

NA = Not Applicable
[a] Indicates exceeding STLC regulatory limits

From the test results, Sn/Ag/Cu failed the TCLP test due to leaching of silver, but passed the deionized water and STLC tests. Sn/Ag/Cu exceeded drinking water limits for copper in sphere and paste form in the TCLP test. Sn/3.9Ag/0.6Cu would therefore be considered a hazardous waste under RCRA based upon this study.

Sn/Cu alloy passed the TCLP and deionized water tests, but failed the STLC test. However, it exceeded the drinking water limits for copper in solid, paste, and dross form in both TCLP and deionized water tests. Sn/0.7Cu would also be considered a hazardous waste under RCRA based on this study.

The alloys chosen for the second study, “The Effects of Trace Amounts of Lead on the Reliability of Six Lead-Free Solders” were:

- 58Bi/42Sn
- Sn/0.7Cu
- Sn/3.4Ag/1Cu/3.3Bi
- Sn/3.4Ag/4.8Bi
- Sn/3.5Ag
- Sn/3.8Ag/0.7Cu

Of the six lead-free alloys evaluated in this study, three are representative of those selected for further testing in this PAR, i.e., Sn/3.8Ag/0.7Cu; Sn0.7Cu; and Sn/3.4Ag/1Cu/3.3Bi. Sn/0.7Cu is almost identical to that of the nickel stabilized Sn/0.7Cu/0.05%Ni.

Table 17. Leachate Test Results, “Effects of Trace Amounts of Lead on the Reliability of Six Lead-Free Solders”

Solder	Sample Weight (grams)	Solder Area (Sq. in.)	Ag (mg/L)	Bi (mg/L)	Cu (mg/L)	Pb (mg/L)	Sn (mg/L)
63Sn/37Pb	6.6	0.305	nd	nd	nd	35.7 [a]	nd
Sn/3.8Ag/0.7Cu	6.6	0.305	nd	nd	nd	nd	0.13
Sn/3.4Ag/4.8Bi	6.8	0.305	nd	0.09	0.05	nd	0.15
Sn/3.5Ag	6.7	0.305	nd	nd	0.02	nd	0.17
Sn/0.7Cu	6.7	0.305	nd	nd	0.01	nd	0.20
Sn/3.4Ag/1Cu/3.3Bi	6.7	0.305	nd	0.06	0.03	nd	0.14
58/Bi/42Sn	6.7	0.305	nd	12.7	0.09	nd	nd
Detection Limits (mg/L)			0.01	0.02	0.01	0.05	0.10

[a] Exceeds Regulatory Limits
nd = none detected

The results contained in Table 17 show that the lead-free alloys did not leach detectable amounts of silver and all metals were found below the allowable limits as set by Federal law with the exception of Pb leached from 63Sn/37Pb. This study suggests that none of the lead-free alloys tested will be considered a hazardous waste.

Along with the previously noted leach methods Table 18 contains a summary of the leachate tests that are used by various countries/communities.

Table 18. Multiple Leach Tests and Methods Employed by Various Countries and Communities.

Jurisdiction	Method Name	Leach Media	pH of Leach Media	Dilution Factor
United States	TCLP	Acetic acid buffered	4.88	20
United States	SPLP	Nitric + Sulfuric Acids	5.00	20
Texas State	7-Day	Deionized water	Neutral	4
California	STLC	Citric Acid, buffered	5.00	10
European Community	PrEN	Deionized water	Neutral	10
Japan	JST-13	Deionized water	Neutral	10

As the data collected from the above noted testing sequences appear to lead to potentially different conclusions individual applications should be thoroughly reviewed prior to choosing a solder of any kind (lead-free, or lead containing).

6.1.1.6 Comprehensive Environmental Response, Compensation, and Liability Act Hazardous Substances

The CERCLA, or more commonly known as Superfund, was enacted in 1980. CERCLA is the Act that created the Superfund hazardous substance cleanup program and set up a variety of mechanisms to address risks to public health, welfare, and the environment caused by hazardous substance release.

Substances defined as hazardous under CERCLA are listed in 40 CFR Part 302.4. Under CERCLA and other acts, the EPA has assigned a RQ to most hazardous substances as established by Section 102(a) of CERCLA; regulatory RQ's are either 1, 10, 100, 1000, or 5000 pounds (except for radionuclides). If the EPA has not assigned an RQ to a hazardous substance, typically its RQ is one pound. The RQs for the alternative elements are provided in Table 19.

Table 19. Alternative Elements Regulated Under CERCLA

Elements	Reportable Quantity (lbs.)
Lead [a, b]	10
Antimony [a, b]	5000
Bismuth	Not Regulated
Copper [a]	5000
Indium	Not Regulated
Nickel [a, b]	100
Silver [a]	1000
Tin	Not Regulated

[a] Indicates that the statutory source for designation of this hazardous substance under CERCLA is CWA Section 307 (a)

[b] Concerns compounds of the associated elements and indicates that the statutory source for designation of this hazardous substance under CERCLA is CAA Section 112

6.1.2 Safety and Occupational Health Concerns of Elements

In addition to environmental regulations, the alternative alloy elements were evaluated to determine the relative safety and occupational health concerns caused by the toxicity and worker exposure characteristics of each element.

6.1.2.1 Toxicity Rating

Toxicity was qualitatively reviewed using parameters such as TD_{LO}, lethal dose lower limit (LD_{LO}), and lethal dose 50 % kill (LD_{50}). All toxicity data was taken from the chemical toxicity data from the website http://hazard.com/msds/. Not enough data was available on the alternative elements to give them a relative toxicity rating to lead. Table 20 lists the toxicity profile and toxic effects of the alternative elements.

Table 20. Toxicity Data of Alternative Elements

Element	Limits [a] (g/kg body weight)				Toxicology Data & Health Effects [e]
	TD_{LO}	LD_{LO}	LD_{50}	Toxic Effects	
Lead [c]	0.45 [b] (human)	0.16 (pigeon)	--	Flaccid paralysis without anesthesia. Hallucinations, distorted perceptions, muscle weakness.	Investigated as tumorigen, mutagen, reproductive effector, suspected human carcinogen. Poison. May be absorbed through skin, eyes, and respiratory tract. Cause local lung irritation.
Antimony	--	--	7 (rat)	Details of toxic effects not reported.	Investigated as tumorigen. May be fatal if inhaled. May cause dermatitis. Chronic exposure may lead to kidney and liver damage.
Bismuth	--	0.221 (human)	5 (rat)	Not reported	Mild skin and eye irritation. Ingestion – headache, skin rashes, and kidney damage.
Copper	0.00012 (human)	--	--	Gastrointestinal – nausea or vomiting	Investigated as tumorigen, reproductive effector. [Fumes, dust] May cause skin, eye, respiratory tract (possible metal fume fever), and digestive tract irritation.
Indium [d]	--	--	--	(No data). Not reported	[Powder] May cause skin, eye, digestive tract, and respiratory tract irritation. May cause corneal damage, blurred vision, cardiac disturbances, and central nervous system depression.
Nickel	500 (mouse)	5 (rat)	--	Details of toxic effects not reported other than lethal dose value.	Investigated as a tumorigen, mutagen, and reproductive effector
Silver	--	10 (mouse)	--	Not reported	Investigated as tumorigen. Skin, eyes, digestive tract, and respiratory tract irritation.
Tin	--	--	--	(No data). Not reported	Investigated as tumorigen. Gastrointestinal – nausea and vomiting. Dust may cause mild irritation of skin, eyes, and respiratory tract.

The "--" indicates that toxicity data was not found for that category

[a] Route of exposure: Oral

[b] 6 year duration of exposure

[c] Toxic concentration, lower limit, for lead is 0.1 mg/m^3 (inhalation – human)

[d] No toxicity data for normal occupational routes of entry

[e] Health effects information from MSDS from http://hazard.com/msds/

6.1.2.2 Exposure Rating

This assessment is only intended to be a basis for evaluating viable alternative products, thus, a complete risk assessment was not performed. Instead, exposure level was qualitatively reviewed, and each element given a final exposure rating of high, medium, or low relative to lead's exposure limits. Parameters reviewed included OSHA promulgated PELs and the ACGIH TLV/TWAs. The inhalation toxicological effects are applied to this analysis. Table 21 lists the exposure limits of the alternative elements. The Inhalation toxicological effects are applicable for this analysis due to the potential inhalation exposures from wave solder pot maintenance activities.

Table 21. Occupational Exposure Limit and Toxicity for Alternatives

Element	OSHA PEL (mg/ m3)	ACGIH TLV (mg/m3)	Rating	Acute Toxicity	Chronic Toxicity
Lead	0.05	0.15	High	None	Nervous systems effects, anemia, kidney damage. Reproductive and development effects.
Antimony	0.5	0.5	Medium-Low	Irritation	Emphysema
Bismuth	NE	NE	NA	None	None
Copper	1 (dust) 0.1 (fume)	1 (dust) 0.2 (fume)	Medium-Low	Irritation (dust)	Irritation, metal fume fever
Indium	0.1	0.1	Medium	Irritation	None, related solely to indium metal
Nickel	1	1.5	High	None	Noted for producing nasal and lung cancer.
Silver	0.01	0.1	High-Medium	None	Permanent discoloration of skin, eyes, mucous membranes. Irritation, metal fume fever.
Tin	2	2	Low	Irritation	Difficulty breathing

NA = Not Applicable
NE = Not Established

A summary of the environmental regulations and OSHA concerns for the alternative elements from Sections 6.1.1 through 6.1.2 are collected in Table 22. Lead is the baseline element to which all the other elements are compared.

In terms of regulations, bismuth, indium, and tin are the least regulated of all the elements. Silver is the most regulated after lead, followed by antimony then copper.

Table 22. Summary of Environmental Regulations and ESOH Issues for Alternative Alloy Elements

Element	CAS#	EPA 17 (Ranking)	CAA	CWA (RQ, lbs.)	TRI	RCRA	CERCLA	Exposure (mg/m3)		Toxicity (g/kg)	
								PEL	TLV	TD_{LO}	LD_{LO}
Lead	7439-92-1	Yes (2)	Yes [a]	Yes [b,c] (10)	Yes	Yes	Yes	0.05	0.15	0.45 [b] (human)	0.16 (pigeon)
Antimony	7440-36-0	No (241)	Yes [a]	Yes [b,c] (5000)	Yes	Yes	No	0.5	0.5	--	--
Bismuth	7440-69-9	No (131)	No	No	No	No	No	NE	NE	--	0.221 (human)
Copper	7440-50-8	No (136)	No	Yes [b,c] (5000)	Yes	Yes	No	1 (dust) 0.1 (fume)	1 (dust) 0.2 (fume)	0.00012 (human)	--
Indium	7440-74-6	No	No	No	No	No	No	0.1	0.1	--	--
Nickel	7440-02-0	Yes	Yes	Yes (100)	Yes	No	Yes	1	1.5	500 (rat)	5 (rat)
Silver	7440-22-4	No (196)	No	Yes [b, c] (1000)	Yes	Yes	Yes	0.01	0.1	--	10 (mouse)
Tin	7440-31-5	No	No	No	No	No	No	2	2	--	--

The "--" indicates that toxicity data was not found for that category
NE = Not Established
[a] Compounds of the specified elements are considered hazardous air pollutants (HAPs) by EPA under Section 112(b)(1) of the CAA
[b] Toxic pollutants as defined under Section 307(a)(1) of the CWA are listed in 40 CFR Part 401.15
[c] Priority pollutants listed in 40 CFR Part 423 Appendix A

6.2 Environmental, Safety, and Occupational Health Analysis of Led-Free Candidate Alloys

6.2.1 Environmental Regulatory Issues of Candidate Alloys

The candidate alternatives were evaluated to determine the extent of their regulation under the major federal environmental laws. Using available resources, each alternative was evaluated based on the criteria summarized below. These criteria are described more fully in Section 3.4.1 and Section 6.1.1. The regulatory analysis for the selected alternative lead-free solder alloys is provided in Section 6.2.3 through Section 6.2.5.

- Air emissions
- Solid hazardous waste generation
- Wastewater discharges
- Reporting requirements
- CERCLA hazardous substances
- EPA 17 constituents
- AFMC-24 constituents.

6.2.2 Safety and Occupational Health Concerns of Candidate Alloys

The alternative lead-free alloys were evaluated to determine the relative safety and occupational health concerns caused by the toxicity and worker exposure characteristics of each lead-free alloy. The identified hazardous constituents of currently used coatings were also evaluated in terms of their potential toxicity as known or suspected human carcinogens, mutagens, or tumorigens. The results are explained in Section 6.2.3 through Section 6.2.5.

Each candidate alternative was given an exposure rating relative to how it compared to SnPb solder values. Exposure ratings of high, medium, and low were assigned to candidate alternatives based on PELs promulgated by OSHA and the TLVs issued by the ACGIH. Not enough data was available to give a relative toxicity rating to lead. A summary of the candidate alternative alloy ESOH concerns are provided in Table 24.

6.2.3 Sn/0.7Cu Alloy

A regulatory analysis of Sn/0.7Cu lead-free solder alloy is provided in Table 23. The regulatory review was based on the federal environmental laws and regulations listed in Section 6.2.1.

Table 23. ESOH Analysis of Sn/0.7Cu Alloy

	Tin	**Copper**
CAS#	7440-66-6	7440-50-8
Weight %	99.3	0.7
Regulatory Analysis		
CAA	--	--
CWA	--	X
RCRA	--	--
TRI	--	X
CERCLA	--	--
EPA 17	--	--
AFMC-24	--	--
Safety & Occupational Health Analysis		
OSHA PEL	**2 mg/m3**	**1 (dust), 0.1 (fume)**
ACGIH TLV	2 mg/m^3	1 (dust), 0.2 (fume)
TD_{LO} [a]	395 g/kg (implant)	0.00012 g/kg (human)
LD_{LO} [a]	No data	No data
LD_{50} [a]	No data	No data
Toxicological Data[b]	Investigated as a tumorigen.	Investigated as tumorigen and reproductive effector.

The "--" indicates that the element is not regulated
[a]. Toxicity data from http://hazard.com/msds/
[b]. Information from MSDS, http://hazard.com/msds (Mallinckrodt Baker, Inc.)

6.2.4 Sn/0.7Cu/0.05Ni

A regulatory analysis of Sn/0.7Cu/0.05Ni lead-free solder alloy is provided in Table 24. The regulatory review was based on the federal environmental laws and regulations listed in Section 6.2.1.

Table 24. ESOH Analysis of Sn/0.7Cu/0.05Ni

	Tin	Copper	Nickel
CAS#	7440-66-6	7440-50-8	7440-02-0
Weight %	Balance (≅ 97)	0.7	≤ 0.1
Regulatory Analysis			
CAA	--	--	--
CWA	--	X	X
RCRA	--	--	--
TRI	--	X	X
CERCLA	--	--	--
EPA 17	--	--	X
AFMC-24	--	--	--
Safety & Occupational Health Analysis			
OSHA PEL	2 mg/m^3	1 (dust), 0.1 (fume)	1 (dust), 0.1 (fume)
ACGIH TLV	2 mg/m^3	1 (dust), 0.2 (fume)	1 (dust), 0.2 (fume)
TD_{LO} [a]	395 g/kg (implant)	0.00012 g/kg (human)	0.00012 g/kg (human)
LD_{LO} [a]	No data	No data	No data
LD_{50} [a]	No data	No data	No data
Toxicological Data[b]	Investigated as a tumorigen.	Investigated as tumorigen and reproductive effector.	Investigated as tumorigen and reproductive effector.

6.2.5 Sn/3.9Ag/0.6Cu Alloy

A regulatory analysis of Sn/3.9Ag/0.6Cu lead-free solder alloy is provided in Table 25. The regulatory review was based on the federal environmental laws and regulations listed in Section 6.2.1.

Table 25. ESOH Analysis of Sn/3.9Ag/0.6Cu Alloy

	Tin	Silver	Copper
CAS#	7440-66-6	7440-22-4	7440-50-8
Weight %	95.5	3.9	0.6
Regulatory Analysis			
CAA	--	--	--
CWA	--	X	X
RCRA	--	X	--
TRI	--	X	X
CERCLA	--	X	--
EPA 17	--	--	--
AFMC-24	--	--	--
Safety & Occupational Health Analysis			
OSHA PEL	2 mg/m^3	0.01 mg/m^3	1 (dust), 0.1 (fume)
ACGIH TLV	2 mg/m^3	0.1 mg/m^3	1 (dust), 0.2 (fume)
TD_{LO} [a]	395 g/kg (implant)	No data	0.00012 g/kg (human)
LD_{LO} [a]	No data	10 (mouse)	No data
LD_{50} [a]	No data	No data	No data
Toxicological Data[b]	Investigated as a tumorigen.	Investigated as tumorigen.	Investigated as tumorigen and reproductive effector.

The "--" indicates that the element is not regulated
[a]. Toxicity data from http://hazard.com/msds/
[b]. Information from MSDS, http://hazard.com/msds (Mallinckrodt Baker, Inc.)

6.2.6 Sn/3.4Ag/1.0Cu/3.3Bi Alloy

A regulatory analysis of Sn/3.4Ag/1.0Cu/3.3Bi lead-free solder alloy is provided in Table 26. The regulatory review was based on the federal environmental laws and regulations listed in Section 6.2.1. Table 27 lists the summary of environmental regulations and ESOH issues for alternative alloys.

Table 26. ESOH Analysis of Sn/3.4Ag/1.0Cu/3.3Bi Alloy

	Tin	Silver	Copper	Bismuth
CAS#	7440-66-6	7440-22-4	7440-50-8	7440-69-9
Weight %	92.3	3.4	1.0	3.3
Regulatory Analysis				
CAA	--	--	--	--
CWA	--	X	X	--
RCRA	--	X	--	--
TRI	--	X	X	--
CERCLA	--	X	--	--
EPA 17	--	--	--	--
AFMC-24	--	--	--	--
Safety & Occupational Health Analysis				
OSHA PEL	2 mg/m^3	0.01 mg/m^3	1 (dust), 0.1 (fume)	NE
ACGIH TLV	2 mg/m^3	0.1 mg/m^3	1 (dust), 0.2 (fume)	NE
TD_{LO} [a]	395 g/kg (implant)	No data	0.00012 g/kg (human)	No data
LD_{LO} [a]	No data	10 g/kg (mouse)	No data	0.221 g/kg (human)
LD_{50} [a]	No data	No data	No data	5 (rat)
Toxicological Data[b]	Investigated as tumorigen.	Investigated as tumorigen.	Investigated as tumorigen and reproductive effector.	Mild skin and eye irritation.

The "--" indicates that the element is not regulated
NE = Not Established
[a] Toxicity data from http://hazard.com/msds/
[b] Information from MSDS, http://hazard.com/msds (Mallinckrodt Baker, Inc.)

Table 27. Summary of Environmental Regulations and ESOH Issues for Alternative Alloys

Element	EPA 17	CAA	CWA (RQ, lbs.)	TRI	RCRA	CERCLA	Exposure Rating
Sn/37Pb	Yes	Yes	Yes	Yes	Yes	Yes	Medium
Sn/0.7Cu	No	No	Yes	Yes	Yes	No	Low
Sn/0.7Cu/0.05Ni	Yes	Yes	Yes	Yes	Yes	Yes	Low
Sn/3.9Ag/0.6Cu	No	No	Yes	No	Yes	Yes	Low
Sn/3.4Ag/1.0Cu/3.3Bi	No	No	Yes	Yes	Yes	Yes	Low

7.0 PROCESS DESCRIPTIONS FOR VIABLE ALTERNATIVES

7.1 Wave Process

According to the surveyed facilities, the changes associated with alternative solder alloy implementation include reduction in environmental management activities and solder material change. No capital investment costs will be incurred, and the wave soldering process steps will not change with the implementation of solder alloy alternatives.

- Existing equipment, if equipped with an inert atmosphere, can be used for implementing an alternative material; therefore, utility usage and costs remain the same as the baseline.
- Current process steps and procedures will not be altered with the implementation of lead-free solders.
  - Material quantities for solder, flux, and cleaning chemistry will not change.
  - Waste generation, recycle/disposal costs, and waste quantities will not change from baseline.
  - Operating labor requirements remain the same.
- Concerning environmental management activities:
  - Permitting will not change with removal of lead (air permits are still needed).
  - Record keeping is expected to be reduced by 25% with the elimination of lead.
  - Annual lead training for all staff (up to 500 hours total labor) will be eliminated.
  - PPE and engineering controls are not expected to change with the removal of lead.
  - Other activities remain as active requirements as a result of the fluxes and cleaning chemicals used.

7.2 Reflow Process

According to the surveyed facilities, the changes associated with the implementation of lead-free solders include labor reduction for some ESOH activities, solder material change, and a possible equipment change. Capital investment costs for a new reflow oven might be incurred if the OEM's existing equipment lacks the capability to operate in an inert atmosphere. However, the reflow process steps will not change with implementation of alternative solders.

- Current process steps and procedures will not be altered with the implementation of lead-free solders.
  - Material quantities for solder, flux, and cleaning chemistry will not change.

  - Waste generation costs, recycle/disposal costs, and waste quantities will not change.
  - Operating labor requirements remain the same.
- Concerning environmental management activities:
  - Permitting will not change with the removal of lead (air permits are still needed).
  - Record keeping is expected to be reduced by 25% with the elimination of lead.
  - Annual lead training for all staff (estimated 500 hours total labor) will be eliminated.
  - PPE and engineering controls are not expected to change with the removal of lead.
  - Other activities remain as active requirements as a result of the fluxes and cleaning chemicals used.

7.3 Manual Process

Conversion to a lead-free manual soldering process will only involve a material cost change. Other costs such as labor, regulatory compliance, waste management, and utilities will not be affected. No capital investment will be required.

- Current process steps and procedures will not be altered with the implementation of lead-free solders.
- Baseline soldering equipment will be sufficient for use with the lead-free alternative solders.
- Waste disposal quantities are negligible for the manual soldering process and will not be affected with the implementation of lead-free solder.
- Environmental management activities such as permitting, monitoring, record keeping, personnel exposure monitoring, ESOH training, PPE, and engineering controls, are not expected to change with the removal of lead. Those activities remain as active requirements as a result of the fluxes and cleaning chemicals used.

8.0 SUMMARY

The JG-PP is a joint service/agency established to help resolve pollution prevention issues identified during system and component acquisition and sustainment processes. Lead-containing solders are currently used on circuit card assemblies, cannon plugs, connectors, and other electronic equipment. Due to the environmental and occupational health issues associated with lead, JG-PP is looking to identify, evaluate, and qualify lead-free solder alternatives.

Several alternative lead-free solder alloys were identified through literature searches and technical representative's recommendations. The JG-PP project team consisting of project stakeholders, OEMs, and technical representatives selected three lead-free solder alloys for testing under the JTP. The three alloys are Sn/0.7Cu/0.05Ni, Sn/3.9Ag/0.6Cu, and Sn/3.4Ag/1.0Cu/3.3Bi.

Implementation of the identified alternative technologies will not require a process change for the manual method; however, new ovens may need to be purchased if the current equipment lacks inert atmosphere capability.

9.0 REFERENCES

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APPENDIX A
Lead-Free Solder Affected Platforms And Equipment

Appendix A

LEAD- FREE SOLDER AFFECTED PLATFORMS & EQUIPMENT

				SERVICE						
Platform	**Equipment Title**	**Nomenclature**	**LFS OEM**	**Army**	**Navy**	**Air Force**	**Marine Corps**	**Foreign**	**NASA**	**Other**
	501	**<- Total Equipment ->**		**189**	**239**	**131**	**28**	**14**		**18**
727	Air Data Computer	ADC-80K	Rockwell Collins							X
767 Tanker			Boeing			X				
A-64 Apache			Boeing	X						
AH-1W	DIRECTION FINDER GROUP	OA-8697/ARD	Collins Avionics & Communications Div		X					
AH-1W	RADIO SET (HAVE QUICK/SINCGARS)	AN/ARC-210(V)	Collins Avionics & Comm Di		X					
AH-1W	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
AH-1W	TACAN SYSTEMS	AN/ARN-153(V)4	Collins Avionics & Communications Div		X					
AH-1W	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
AT-38B	NAV RECEIVER (TACAN)	AN/ARN-118(V)3	Collins Avionics & Communications Div			X				
AT-38B	NAV RECEIVER (VOR/LOC/GS/MB)	*AN/ARN-147(V)	Collins Avionics & Communications Div			X				

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AV-8B	AUTOMATIC TARGET HANDOFF SYSTEM	ATHS II	Collins Avionics & Communications Div		X					
AV-8B	GLOBAL POSITIONING SYSTEM (GPS) MAGR	AN/ASN-163	Collins Avionics & Communications Div		X					
AV-8B	RADIO SER (HAVE QUICK/SINCGARS)	AN/ARC-210(V)	Collins Avionics & Comm Div		X					
AV-8B	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
AV-8B	TACAN SYSTEM	AN/ARN-153	Collins Avionics & Communications Div		X					
AV-8B	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
AV-8B			Boeing				X			
B-1B	COMPUTER, FLIGHT DIRECTOR	622-3964-002	Collins Avionics& Communications Div			X				
B-1B	CONTROL DISPLAY UNIT (CDU)	CD-140/ALQ	Collins Avionics & Communications Div			X				
B-1B	CONTROL DISPLAY UNIT (CDU-900)	822-0941-001	Collins Avionics & Communications Div			X				

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B-1B	FLIGHT MANAGEMENT SYSTEM	FMS-800	Collins Avionics & Communications Div			X				
B-1B	HF-SSB RADIO	AN/ARC-190(V)	Collins Avionics & Communications Div			X				
B-1B	INTERCOM SET	AN/AIC-33(V)	Collins Avionics & Communications Div			X				
B-1B	NAV RECEIVER (TACAN)	*AN/ARN-118	Collins Avionics & Communications Div			X				
B-1B	SATCOM TERMINAL	AN/ASC-19(V)	Collins Avionics & Communications Div			X				
B-1B	UHF RADIO	AN/ARC-171(V)	Collins Avionics & Comm Systems			X				
B-1B	VLF/LF RADIO RECEIVER SET	AN/ARR-85(V)1	Collins Avionics & Comm Div			X				
B-1B			Boeing			X				
B-2			Boeing			X				
B-2A	GLOBAL POSITIONING STYTEM (GPS)	*AN/ARN-151(V)	Collins Avionics & Communications Div			X				
B-2A	HF RADIO	AN/ARC-211	Rockwell Intl Corp			X				

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B-2A	NAV RECEIVER (TACAN)	TCN-500	Collins Avionics & Communications Div			X				
B-2A	NAV RECEIVER (VOR/LOC/GS/MB)	*AN/ARN-147(V)	Collins Avionics & Communications Div			X				
B-2A	RECEIVER-TRANSMITTER (TACAN)	-RT-1578/A	Collins Avionics & Communications Div			X				
B-52H	GLOBAL POSITIONING SYSTEM (GPS)	*AN/ARN-151(V)	Collins Avionics & Communications Div			X				
B-52H	HF-SSB RADIO	AN/ARC-190(V)	Collins Avionics & Communications Div			X				
B-52H	NAV RECEIVER (TACAN)	AN/ARN-118(V)2	Collins Avionics & Communications Div			X				
B-52H	SATCOM TERMINAL	AN/ASC-19(V)	Collins Avionics & Communications Div			X				
B-52H	VHF-FM RADIO A/J	AN/ARC-210(V)	Collins Avionics & Comm Di			X				
B-52H	VLF/LF RADIO RECEIVER SET	AN/ARR-85(V)2	Collins Avionics & Comm Div			X				
Brimstone			Boeing					X (British Min.)		

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C-5					X					
C-130			Boeing		X		X			
C-17			Boeing			X				
C-17A	AUTO DIRECTION FINDER (UHF)	DF-301E	Collins Avionics & Communications Div			X				
C-17A	GLOBAL POSITIONING (GPS)	*AN/ARN-151(V)1	Collins Avionics & Communications Div			X				
C-17A	HF-SSB RADIO	AN/ARC-190(V)	Collins Avionics & Communications Div			X				
C-17A	NAV RECEIVER (TACAN)	*AN/ARN-118	Collins Avionics & Communications Div			X				
C-17A	NAV RECEIVER (VOR/LOC/GS/MB)	*AN/ARN-147(V)	Collins Avionics & Communications Div			X				
C-17A	VHF-AM/FM RADIO	AN/ARC-186(V)	Collins Avionics & Comm Di			X				
C-2A	AIRBORNE HF COMMUNICATIONS SYSTEM	AN/ARC-190	Collins Avionics & Communications Div		X					
C-2A	DIRECTION FINDER GROUP	OA-8697/ARD	Collins Avionics & Communications Div		X					

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C-2A	GLOBAL POSITIONING SYSTEM (GPS) MAGR	AN/ASN-163	Collins Avionics & Communications Div		X					
C-2A	RADIO DIRECTION FINDER SET	AN/ARN-83	Collins Avionics & Communications Div		X					
C-2A	RADIO RECEVING SET	AN/ARN-126	Collins Avionics & Communications Div		X					
C-2A	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
C-2A	UHF RADIO SET	AN/ARC-159A(V)5	Collins Avionics & Comm Systems		X					
C-32A			Boeing			X				
C-40A			Boeing		X		X			
CALCM			Boeing			X				
CH-53E	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X					
CH-53E	DIRECTION FINDER GROUP	OA-8697/ARD	Collins Avionics & Communications Div		X					
CH-53E	GLOBAL POSITIONING SYSTEM (GPS)	AN/ARN-151(V)	Collins Avionics & Communications Div		X					

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CH-53E	HF RADIO SET	AN/ARC-174A(V)2	Collins Avionics & Communications Div		X					
CH-53E	RADIO SET (HAVE QUICK/SINCGARA)	AN/ARC-210(V)	Collins Avionics & Comm Di		X					
CH-53E	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
CH-53E	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
CH-53E	VOR/ILS NAVIGATION SYSTEM	VIR-31A	Collins Avionics & Communications Div		X					
CH-53E	VOR/ILS NAVIGATION SYSTEM	VIR-31A	Collins Avionics & Communications Div		X					
DC-130A	HF LIAISON RADIO	618T-3	Collins Avionics & Communications Div		X					
DC-130A	RADIO SET	AN/ARC-186	Collins Avionics & Comm Div		X					
DC-130A	TACAN NAVIGATIONAL SET	AN/ARN-118	Collins Avionics & Communications Div		X					
E-2C	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X					

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E-2C	GLOBAL POSITIONING SYSTEM (GPS)	AN/ARN-151(V)2	Collins Avionics & Communications Div		X					
E-2C	TACAN NAVIGATIONAL SET	AN/ARN-118	Collins Avionics & Communications Div		X					
E-2C	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
E-4B	AUTO DIRECTION FINDER (UHF)	AN/ARA-50	Collins Avionics & Communications Div			X				
E-4B	HF-SSB RADIO	AN/ARC-190(V)	Collins Avionics & Communications Div			X				
E-4B	HORIZONTAL SITUATION IND (HIS)	331A-8K	Collins Avionics & Communications Div			X				
E-4B	NAV RECEIVER (MB)	51Z-4	Collins Avionics & Communications Div			X				
E-4B	RECEIVER, RADIO (ADF)	51Y-7	Collins Avionics & Communications Div			X				
E-4B	RECEIVER-TRANSMITTER (RDR ALT)	-860F-1	Collins Avionics & Communications Div			X				

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E-4B	SATCOM TERMINAL	AN/ASC-21(V)	Collins Avionics & Communications Div			X					
E-4B	VHF-AM RADIO	618M-2D	Collins Avionics & Comm Div			X					
E-6A	AIRBORNE HF COMMUNICATIONS SYSTEM	AN/ARC-190(V)	Collins Avionics & Communications Div		X						
E-6A	LF/ADF RECEIVER	51Y-4	Collins Avionics & Communications Div		X						
E-6A	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X						
E-6A	UHF/VHF RADIO SET	AN/ARC-182	Collins Avionics & Comm Div		X						
EP-3E	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X						
EP-3E	GLOBAL POSITIONING SYSTEM (GPS)	AN/ARN-151(V)	Collins Avionics & Communications Div		X						
EP-3E	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X						
ES-3A	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X						

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ES-3A	GLOBAL POSITIONING SYSTEM (GPS)	AN/ARN-151	Collins Avionics & Communications Div		X					
ES-3A	TACAN NAVIGATIONAL SET	AN/ARN-118	Collins Avionics & Communications Div		X					
ES-3A	UHF/VHF RADIO SET	AN/ARC-182	Collins Avionics & Comm Div		X					
ES-3A	VOR/ILS NAVIGATION SYSTEM	VIR-31A	Collins Avionics & Communications Div		X					
F/A-18			Boeing		X		X			
F/A-18A	DIRECTION FINDER GROUP	OA-8697/ARD	Collins Avionics & Communications Div		X					
F/A-18A	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
F/A-18A	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
F/A-18B	DATA LINK	RT-1379( )/ASW	Collins Avionics & Communications Div		X					
F/A-18B	DIRECTION FINDER GROUP	OA-8697/ARD	Collins Avionics & Communications Div		X					

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F/A-18B	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
F/A-18B	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
F/A-18C	DATA LINK	RT-1379( )ASW	Collins Avionics & Communications Div		X					
F/A-18C	DATA LINK	RT-1379/ASW-44	Collins Avionics & Communications Div		X					
F/A-18C	DIRECTION FINDER GROUP	OA-8697/ARD	Collins Avionics & Communications Div		X					
F/A-18C	DIRECTION FINDER GROUP	OA-8697A/ARD	Collins Avionics & Communications Div		X					
F/A-18C	GLOBIAL POSITIONING SYSTEM (GPS) MAGR	AN/ASN-163	Collins Avionics & Communications Div		X					
F/A-18C	RADIO SET (HAVE QUICK/SINCGARS)	AN/ARC-210(V)	Collins Avionics & Comm Di		X					
F/A-18C	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
F/A-18C	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					

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F/A-18C	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
F/A-18D	DATA LINK	RT-1379( )/ASW	Collins Avionics & Communications Div		X					
F/A-18D	DATA LINK	RT-1379A/ASW	Collins Avionics & Communications Div		X					
F/A-18D	DIRECTION FINDER GROUP	OA-8697/ARD	Collins Avionics & Communications Div		X					
F/A-18D	DIRECTION FINDER GROUP	OA-8697/ARD	Collins Avionics & Communications Div		X					
F/A-18D	GLOBAL POSITIONING SYSTEM (GPS) MAGR	AN/ASN-163	Collins Avionics & Communications Div		X					
F/A-18D	RADIO SET (HAVE QUICK/SINCGARS)	AN/ARC-210(V)	Collins Avionics & Comm Di		X					
F/A-18D	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
F/A-18D	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
F/A-18D	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					

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F/A-18D	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
F-14A	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X					
F-14A	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X					
F-14A	UHF RADIO SET	AN/ARC-159A(V)5	Collins Avionics & Comm Systems		X					
F-14A	UHF/VHF RADIO SET	AN/ARC-182	Collins Avionics & Comm Div		X					
F-14A	UHF/VHF RADIO SET	AN/ARC-182	Collins Avionics & Comm Div		X					
F-14B	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X					
F-14B	UHF RADIO SET	AN/ARC-159A(V)5	Collins Avionics & Comm Systems		X					
F-14B	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
F-14D	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X					
F-14D	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					

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F-14D	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
F-15			Boeing			X				
F-16A	GLOBAL POSITIONING SYSTEMS (GPS)	*AN/ARN-151(V)	Collins Avionics & Communications Div			X				
F-16A	NAV RECEIVER (TACAN)	*AN/ARN-118	Collins Avionics & Communications Div			X				
F-16A	VHF-AM/FM RADIO	AN/ARC-186(V)	Collins Avionics & Comm Di			X				
F-16B	GLOBAL POSITIONING SYSTEM (GPS)	*AN/ARN-151(V)	Collins Avionics & Communications Div			X				
F-16B	NAV RECEIVER (TACAN)	*AN/ARN-118	Collins Avionics & Communications Div			X				
F-16B	VHF-AM/FM RADIO	AN/ARC-186(V)	Collins Avionics & Comm Di			X				
F-16C	NAV RECEIVER (TACAN)	*AN/ARN-118	Collins Avionics & Communications Div			X				
F-16C	VHF-AM/FM RADIO	AN/ARC-186(V)	Collins Avionics & Comm Di			X				
F-16D	NAV RECEIVER (LOC/GS/MB)	AN/ARN-108	Collins Avionics & Communications Div			X				

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F-16D	NAV RECEIVER (TACAN)	*AN/ARN-118	Collins Avionics & Communications Div			X				
F-16D	VHF-AM/FM RADIO	AN/ARC-186(V)	Collins Avionics & Comm Di			X				
F-22			Boeing			X				
F-5E	TACAN NAVIGATIONAL SET	AN/ARN-118	Collins Avionics & Communications Div		X					
F-5F	TACAN NAVIGATIONAL SET	AN/ARN-118	Collins Avionics & Communications Div		X					
GBU-15			Boeing			X				
Harpoon			Boeing		X		X			
HH-1N	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X					
HH-1N	TACAN NAVIGATIONAL SET	AN/ARN-118	Collins Avionics & Communications Div		X					
HH-1N	TACAN SYSTEM	AN/ARN-153	Collins Avionics & Communications Div		X					
HH-1N	UHF RADIO SET	AN/ARC-159(V)	Collins Avionics & Comm Systems		X					
HH-1N	UHF/VHF RADIO SET	AN/ARC-182	Collins Avionics & Comm Div		X					

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HH-60H	DIERCTION FINDER GROUP	OA-8697/ARD	Collins Avionics & Communications Div		X					
HH-60H	DIRECTION FINDER GROUP	OA-8697A/ARD	Collins Avionics & Communications Div		X					
HH-60H	GLOBAL POSITIONIONG SYSTEM (GPS)	AN/ARN-151(V)2	Collins Avionics & Communications Div		X					
HH-60H	HF RADIO SET	AN/ARC-174A(V)2	Collins Avionics & Communications Div		X					
HH-60H	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
HH-60H	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
HH-60H	VOS/ILS NAVIGATION SYSTEM	AN/ARN-147(V)	Collins Avionics & Communications Div		X					
KC-10			Boeing			X				
KC-10A	AUTO DIRECTION FINDER	DF-206	Collins Avionics & Communications Div			X				
KC-10A	AUTO DIRECTION FINDER (UHF)	DF-301F	Collins Avionics & Communications Div			X				

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KC-10A	FLIGHT MANAGEMENT SYSTEM	FMS-800	Collins Avionics & Communications Div			X					
KC-10A	HF RADIO	AN/ARC-190(V)8	Collins Avionics & Communications Div			X					
KC-10A	HF-SSB RADIO	AN/ARC-190(V)	Collins Avionics & Communications Div			X					
KC-10A	HORIZONTAL SITUATION IND (HSI)	331A-84	Collins Avionics & Communications Div			X					
KC-10A	INDICATOR, ATTITUDE (ADI)	329B-8V	Collins Precision Div of Litton Systems			X					
KC-10A	NAV RECEIVER (ILS)	ILS-70	Collins Avionics & Communications Div			X					
KC-10A	NAV RECEIVER (MB)	51Z-4	Collins Avionics & Communications Div			X					
KC-10A	NAV RECEIVER (TACAN)	*AN/ARN-118	Collins Avionics & Communications Div			X					
KC-10A	NAV RECEIVER (TACAN)	AN/ARN-139(V)	Collins Avionics & Communications Div			X					

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KC-10A	NAV RECEIVER (VOR.LOC)	51RV-4B	Collins Avionics & Communications Div			X				
KC-10A	RECEIVER, RADIO (ADF)	51Y-7	Collins Avionics & Communications Div			X				
KC-10A	UHF RADIO	AN/ARC-171(V)	Collins Avionics & Comm Systems			X				
KC-10A	VHF-AM RADIO	618M-3A	Collins Avionics & Comm Div			X				
KC-135R	Air Data Computer		Rockwell Collins		X	X	X	X		
LC-130F	AIRBORNE HF COMMUNICATIONS SYSTEM	AN/ARC-190	Collins Avionics & Communications Div		X					
LC-130F	FLIGHT CONTROL SYSTEM	FCS-105	Collins Avionics & Communications Div		X					
LC-130F	HORIZONTAL SITUATION INDICATOR	HSI-45	Collins Avionics & Communications Div		X					
LC-130F	RADIO SET	AN/ARC-186	Collins Avionics & Comm Div		X					
LC-130F	TACAN NAVIGATIONAL SET	AN/ARN-118	Collins Avionics & Communications Div		X					
LC-130F	UHF RADIO SET	AN/ARC-159(V)1	Collins Avionics & Comm Systems		X					

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LC-130R	AIRBORNE HF COMMUNICATIONS SYSTEM	AN/ARC-190	Collins Avionics & Communications Div		X					
LC-130R	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X					
LC-130R	FLIGHT CONTROL SYSTEM	FCS-105	Collins Avionics & Communications Div		X					
LC-130R	HORIZONAL SITUATION INDICATOR	HSI-45	Collins Avionics & Communications Div		X					
LC-130R	RADIO RECEIVING SET	AN/ARN-126	Collins Avionics & Communications Div		X					
LC-130R	RADIO SET	AN/ARC-186	Collins Avionics & Comm Div		X					
LC-130R	TACAN NAVIGATIONAL SET	AN/ARN-118	Collins Avionics & Communications Div		X					
LC-130R	UHF RADIO SET	AN/ARC-159	Collins Avionics & Comm Systems		X					
MH-53E	DIRECTION FINDER GROUP	OA-8697/ARD	Collins Avionics & Communications Div		X					

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MH-53E	GLOBAL POSITIONING SYSTEM (GPS)	AN/ARN-151(V)	Collins Avionics & Communications Div		X					
MH-53E	HF RADIO SET	AN/ARC-174A(V)2	Collins Avionics & Communications Div		X					
MH-53E	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
MH-53E	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
MH-53E	VOR/ILS NAVIGATION SYSTEM	VIR-31A	Collins Avionics & Communications Div		X					
MH-53J	AUTO DIRECTION FINDER (UHF)	DF-301E	Collins Avionics & Communications Div			X				
MH-53J	GLOBAL POSITIONING SYSTEM (GPS)	*AN/ARN-151(V)	Collins Avionics & Communications Div			X				
MH-53J	HF-SSB RADIO	AN/ARC-190(V)	Collins Avionics & Communications Div			X				
MH-53J	NAV RECEIVER (TACAN)	*AN/ARN-118	Collins Avionics & Communications Div			X				

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MH-53J	NAV RECEIVER (VOR/LOC/GS/MB)	*AN/ARN-147(V)	Collins Avionics & Communications Div			X				
MH-60G	AUTO DIRECTION FINDER (UHF)	DF-301E	Collins Avionics & Communications Div			X				
MH-60G	GLOBAL POSITIONING SYSTEMS (GPS)	AN/ARN-151(V)2	Collins Avionics & Communications Div			X				
MH-60G	NAV RECEIVER (TACAN)	AN/ARN-118(V)2	Collins Avionics & Communications Div			X				
MH-60G	VHF-AM/FM RADIO	AN/ARC-186(V)	Collins Avionics & Comm Di			X				
P-3C	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X					
P-3C	UHF/VHF RADIO SET	AN/ARC-182	Collins Avionics & Comm Div		X					
PAC-3			Boeing	X						
RAH-66 Comanche			Boeing	X						
RC-12F	AUTOPILOT	SPZ-4000	Rockwell Collins		X					
RC-12F	VHF NAVIGATION SYSTEM	VIR-32	Collins Avionics & Communications Div		X					
RC-12F	VHF TRANSCEIVER	VHF-22B	Collins Avionics & Comm Div		X					

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S-3B	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X						
S-3B	UHF/VHF RADIO SET	AN/ARC-182	Collins Avionics & Comm Div		X						
SH-2G	DIRECTION FINDER GROUP ANTENNA	OA-8697A/ARD-1	Collins Avionics & Communications Div		X						
SH-2G	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X						
SH-2G	UHF RADIO SET	AN/ARC-159(V)1	Collins Avionics & Comm Systems		X						
SH-60B	DIRECTION FINDER GROUP	OA-8697A/ARD	Collins Avionics & Communications Div		X						
SH-60B	GLOBAL POSITIONING SYSTEM (GPS)	AN/ARN-151(V)2	Collins Avionics & Communications Div		X						
SH-60B	HF RADIO SET	AN/ARC-174A(V)	Collins Avionics & Communications Div		X						
SH-60B	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X						
SH-60B	UHF RADIO SET	AN/ARC-159(V)2	Collins Avionics & Comm Systems		X						

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SH-60B	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
SH-60F	DIRECTION FINDER GROUP	OA-8697A/ARD	Collins Avionics & Communications Div		X					
SH-60F	GLOBAL POSITIONING SYSTEM (GPS)	AN/ARN-151(V)2	Collins Avionics & Communications Div		X					
SH-60F	HF RADIO SET	AN/ARC-174(V)2	Collins Avionics & Communications Div		X					
SH-60F	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
SH-60F	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
SLAM-ER			Boeing		X		X			
T-2C	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
T-2C	UHF RADIO SET	AN/ARC-159(V)	Collins Avionics & Comm Systems		X					
T-34C	IFF TRANSPONDER	TDR-950	Collins Avionics & Communications Div		X					
T-34C	UNF RADIO SET	AN/ARC-159(V)	Collins Avionics & Comm Systems		X					

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T-34C	VHF NAVIGATION SYSTEM	VIR-30	Collins Avionics & Communications Div		X					
T-38A	TACAN NAVIGATIONAL SET	AN/ARN-118	Collins Avionics & Communications Div		X					
T-39D	FLIGHT DIRECTOR COMPUTER SYSTEM	CPU-4/A	Collins Avionics & Comm Div							X
T-44A	AUTOPILOT	AP-106	Collins Avionics & Communications Div		X					
T-44A	IFF TRANSPONDER	TDR-90	Collins Avionics & Communications Div		X					
T-44A	UHF RADIO SET	AN/ARC-159(V)	Collins Avionics & Comm Systems		X					
T-44A	VHF NAVIGATION SYSTEM	VIR-30	Collins Avionics & Communications Div		X					
T-44A	VHF RADIO SET	VHF-20	Collins Avionics & Comm Div		X					
T-45			Boeing		X		X			
T-45A	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
TA-4J	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X					

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TA-4J	RADIO RECEIVING SET	AN/ARN-126	Collins Avionics & Communications Div		X					
TA-4J	RADIO SET	AN/ARC-186	Collins Avionics & Comm Div		X					
TA-4J	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
TA-4J	UHF RADIO SET	AN/ARC-159(V)	Collins Avionics & Comm Systems		X					
TAV-8B	GLOBAL POSITIONING SYSTEM (GPS) MAGR	AN/ASN-163	Collins Avionics & Communications Div		X					
TAV-8B	TACAN NAVIGATIONAL SET	AN/ARN-118(V)	Collins Avionics & Communications Div		X					
TAV-8B	TACAN SYSTEM	AN/ARN-153	Collins Avionics & Communications Div		X					
TAV-8B	UHF/VHF RADIO SET	AN/ARC-182(V)	Collins Avionics & Comm Div		X					
TC-130G	GOBAL POSITIONING SYSTEM (GPS)	AN/ARN-151(V)	Collins Avionics & Communications Div		X					
TC-130G	RADIO RECEVING SET	AN/ARN-126	Collins Avionics & Communications Div		X					

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TC-130G	RADIO SET	AN/ARC-186	Collins Avionics & Comm Div		X					
TC-130G	TACAN NAVIGATIONAL SET	AN/ARN-118	Collins Avionics & Communications Div		X					
TC-130G	UHF RADIO SET	AN/ARC-159(V)1	Collins Avionics & Comm Systems		X					
TH-53A	GLOBAL POSITIONING SYSTEM (GPS)	*AN/ARN-151(V)	Collins Avionics & Communications Div			X				
TH-53A	HF-SSB RADIO	AN/ARC-190(V)	Collins Avionics & Communications Div			X				
TH-53A	NAV RECEIVER (TACAN)	*AN/ARN-118	Collins Avionics & Communications Div			X				
TH-53A	NAV RECEIVER (VOR)	VOR-101B	Collins Avionics & Communications Div			X				
TH-57B	UHF RADIO SET	AN/ARC-159	Collins Avionics & Communications Div		X					
TH-57B	UHF RADIO SET	AN/ARC-159	Collins Avionics & Comm Systems		X					
TH-57C	UHF RADIO SET	AN/ARC-159	Collins Avionics & Comm Systems		X					

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U-125A (Hawker 800)	Air Data Computer	ADS-86	Rockwell Collins							X
UC-12B	IFF TRANSPONDER	TRD-90	Collins Avionics & Communications Div		X					
UC-12B	VHF NAVIGATION SYSTEM	VIR-30	Collins Avionics & Communications Div		X					
UC-12B	VHF RADIO SET	VHF-20B	Collins Avionics & Comm Div		X					
UC-12F	AUTOPILOT	SPZ-4000	Rockwell Collins		X					
UC-12F	VHF NAVIGATION SYSTEM	VIR-32	Collins Avionics & Communications Div		X					
UC-12F	VHF TRANSCEIVER	VHF-22B	Collins Avionics & Comm Div		X					
UC-12M	AUTOPILOT	SPZ-4000	Rockwell Collins		X					
UC-90	Air Data Computer	ADS-82	Rockwell Collins							X
UH-1N	AUTO DIRECTION FINDER (UHF)	AN/ARA-50	Collins Avionics & Communications Div			X				
UH-1N	AUTOMATIC DIRECTION FINDER GROUP	AN/ARA-50	Collins Avionics & Communications Div		X					
UH-1N	GLOBAL POSITIONING SSYTEM (GPS)	*AN/ARN-151(V)	Collins Avionics & Communications Div			X				

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UH-1N	GLOBAL POSITIONING SYSTEM (GPS) MAGR	AN/ASN-163	Collins Avionics & Communications Div		X					
UH-1N	NAV RECEIVER (TACAN)	*AN/ARN-118	Collins Avionics & Communications Div			X				
UH-1N	NAV RECEIVER (VOR)	*AN/ARN-82	Collins Avionics & Communications Div			X				
UH-1N	NAV RECEIVER (VOR/LOC/GS/MB)	*AN/ARN-147(V)	Collins Avionics & Communications Div			X				
UH-1N	RADIO SET	AN/ARC-186(V)	Collins Avionics & Comm Di		X					
UH-1N	RADIO SET (HAVE QUICK/SINCGARA)	AN/ARC-210(V)	Collins Avionics & Comm Di		X					
UH-1N	TACAN NAVIGATIONAL SET	AN/ARN-118	Collins Avionics & Communications Div		X					
UH-1N	TACAN SYSTEM	AN/ARN-153	Collins Avionics & Communications Div		X					
UH-1N	UHF RADIO SET	AN/ARC-159(V)	Collins Avionics & Comm Systems		X					
UH-1N	UHF/VHF RADIO SET	AN/ARC-182	Collins Avionics & Comm Div		X					

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UH-1N	VHF RADIO SET	VHF-20B	Collins Avionics & Comm Div		X					
UH-1N	VHF-AM/FM RADIO	AN/ARC-186(V)	Collins Avionics & Comm Di			X				
UH-3H	RADIO RECEIVING SET	AN/ARN-126	Collins Avionics & Communications Div		X					
UH-3H	RADIO SET	AN/ARC-186(V)	Collins Avionics & Comm Di		X					
UH-3H	TACAN NAVIGATIONAL SET	AN/ARN-118	Collins Avionics & Communications Div		X					
UH-3H	UHF RADIO SET	AN/ARC-159(V)1	Collins Avionics & Comm Systems		X					
UH-3H	UHF/VHF RADIO SET	AN/ARC-182	Collins Avionics & Comm Div		X					
V-22 Osprey			Boeing				X			
VH-3A	VHF TRANSCEIVER	618M-2D	Collins Avionics & Comm Div		X					
	Advanced Cruise Missile (ACM)	Missile System	Raytheon			X				
	Advanced Targeting Forward-Looking Infrared (ATFLIR)	Air Combat & Strike System	Raytheon		X		X			
	Advanced Targeting Pod	Air Combat & Strike System	Raytheon			X				
	AGM-130	Air-to-Ground Guided Missile-130	Boeing, R. Collins			X				

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	AGM-65 Maverick	Missile System	Raytheon		X	X	X			
	AIM-54 Phoenix Missile	Missile System	Raytheon		X					
	AIM-9 Sidewinder	Missile System	Raytheon		X	X	X			
	AIM-9M Sidewinder	Missile System	Raytheon		X	X				
	AIM-9X Next Generation Sidewinder	Missile System	Raytheon, R. Collins		X	X				
	Air Defense FLIR/TV Sight System (FTS)	Combat Vehicle System	Raytheon				X			
	Airborne Low Frequency Sonar (ALFS)	Naval & Maritime Integrated System	Raytheon		X					
	Airborne Target Handover System	ATHS		X						
	Aircraft Survivability Equipment/Avionics Control System	RC-12 ASE/ACS		X						
	ALL SOURCE ANALYSIS	AN/TYQ-93(V)1,2,4		X						
	All Source Analysis System	ASAS		X						
	AMDWS	AN/GYQ-88		X						
	AMRAAM	AIM-120 Advanced Medium-Range Air-to-Air Missile	Raytheon, R. Collins			X				
	AN/AAQ-16 (3 FOV) Infrared Imaging System	Air Combat & Strike System	Raytheon	X	X	X	X			

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	AN/AAQ-26 Infrared Detecting Set	Air Combat & Strike System	Raytheon			X				
	AN/AAQ-27 MWIR Staring Sensor	Air Combat & Strike System	Raytheon				X	X		
	AN/AAR-58 Missile Warning System	Electronic Warfare	Raytheon		X	X	X			
	AN/AAS-44(V) Infrared Laser Detecting-Ranging-Tracking Set	Air Combat & Strike System	Raytheon		X					NATO
	AN/ALE-50 Towed Decoy System	Electronic Warfare	Raytheon		X	X	X			
	AN/ALQ-184 ECM Pod	Electronic Warfare	Raytheon			X				
	AN/ALQ-184(V)9 ECM Pod with Towed Decoy	Electronic Warfare	Raytheon		X	X	X			
	AN/ALQ-187 ECM System	Electronic Warfare	Raytheon			X				
	AN/ALR-67(V)3&4 Countermeasures Receiving Set	Electronic Warfare	Raytheon		X					
	AN/APG-63 Radar	Air Combat & Strike System	Raytheon			X		X		
	AN/APG-63(V)1 Radar	Air Combat & Strike System	Raytheon			X				
	AN/APG-63(V)2 AESA Radar	Air Combat & Strike System	Raytheon			X				
	AN/APG-65 Radar	Air Combat & Strike System	Raytheon		X		X	X		

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	AN/APG-70 Radar	Air Combat & Strike System	Raytheon			X				
	AN/APG-73 Radar	Air Combat & Strike System	Raytheon		X	X	X	X		
	AN/APQ-174/186 Multi-Mode Radar	Airborne Surveillance & Reconnaissance System	Raytheon	X						Special Opps Command
	AN/APQ-180 Radar	Air Combat & Strike System	Raytheon			X				U.S Special Opps Forces
	AN/APQ-181 Radar Systems	Air Combat & Strike System	Raytheon			X				
	AN/APS-137B(V)5 Radar System	Airborne Surveillance & Reconnaissance System	Raytheon		X					
	AN/AWG-9 and AN/APG-71 Weapon Control Systems	Air Combat & Strike System	Raytheon		X					
	AN/FPS-108 Cobra Dane Radar System	Air/Missile Defense System	Raytheon			X				Air Defense Command
	AN/FPS-120, AN/FPS-123 (V7), and AN/FPS-126, Ballistic Missile Early Warning System (BMEWS)	Air/Missile Defense System	Raytheon			X				U.S. Air Force Space Command

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	AN/FPS-123 (V)3 Pave Paws Early Warning Radar System	Air/Missile Defense System	Raytheon			X				U.S. Air Force Space Command
	AN/MPQ-64 Sentinel	Ground Radar	Raytheon	X						
	AN/PAS-13 Thermal Weapon Sight	Ground Night Vision	Raytheon	X						
	AN/SLQ-32(V)5 EW System	Electronic Warfare	Raytheon		X					
	AN/SLQ-48 Mine Neutralization System (MNS)	Naval & Maritime Integrated System	Raytheon		X					
	AN/SPQ-11, Cobra Judy Radar System	Air/Missile Defense System	Raytheon		X					
	AN/SPS-73 Surface Search Radar	Naval & Maritime Integrated System	Raytheon		X					Coast Guard
	AN/TPQ-36 Firefinder Weapon Locating System	Ground Radar	Raytheon	X						
	AN/TPQ-37 Firefinder Weapon Locating System	Ground Radar	Raytheon	X						
	AN/TPQ-47 Firefinder Weapon Locating System	Ground Radar	Raytheon	X						
	AN/VAS-5 Driver's Vision Enhancer (DVE)	Combat Vehicle System	Raytheon	X						

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	ARL-M Crazy Hawk	AIRBORNE RECONNAISSANCE LOW (ARL)	Raytheon	X						
	Army Tactical Missile System	ATACMS		X						
	ASARS-2	Airborne Surveillance & Reconnaissance System	Raytheon			X				
	Avenger FLIR Receiving Set	Combat Vehicle System	Raytheon	X						
	AVIATION NIGHT VISION IMAGING SYSTEM (ANVIS)	ANVIS		X						
	Battery Computer System	BCS		X						
	Black Sparrow	Missile System	Raytheon		X	X				
	Brilliant Anti-Armor (BAT) Submunition	Missile System	Raytheon	X						
	CENTRAL COMMUNICATIONS	AN/TSQ-190(V)3		X						
	CENTRAL COMMUNICATIONS	AN/TTC-50		X						
	CGS	AN/TSQ-179(V)1*		X						
	CIRCUIT SWITCH	AN/TTC-39A/D/E		X						
	Combat Vehicle Thermal Targeting System (CVTTS)	Combat Vehicle System	Raytheon	X						
	COMM CONTROL SET	AN/TYQ-40A(V)2*		X						
	COMM CONTROL	AN/TYQ-63A(V)3*		X						

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	SET									
	Commander's Independent Thermal Viewer (CITV)	Combat Vehicle System	Raytheon	X						
	Commander's Independent Viewer (CIV)	Combat Vehicle System	Raytheon	X						
	Commander's Panoramic Sight (CPS-I)	Combat Vehicle System	Raytheon	X			X			
	Commander's Tactical Terminal	CTT		X						
	COMMUNICATIONS CONTROL SET	AN/TSQ-182A/B*		X						
	COMMUNICATIONS CONTROL SYSTEM	AN/TSQ-183B/C*		X						
	COMMUNICATIONS CONTROL SYSTEM	AN/TSQ-184D/E/F*		X						
	Communications System Control Element	CSCE		X						
	Compact Digital Switch	CDS		X						
	COMPUTER GROUP, TACTICAL	AN/TYK-22(V)*		X						
	COMPUTER SET FIELD	AN/GYK-47(V)1,2,3,4,5 *		X						
	COMPUTER SYSTEM, DIGITAL	AN/TYQ-45*		X						

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	Contingency DSCS Operational Support System	CDOSS		X						
	Contingency Satellite Configuration Control Element	CSCCE		X						
	COUNTERMEASURE SET	AN/TLQ-17A(V)3		X						
	DD (X)	Naval & Maritime Integrated System	Raytheon		X					
	DECS Central Component	DECS-CC		X						
	Defense Satellite Communications System (DSCS) Frequency Division Multiple Access (FDMA) Control Subsystem	DFCS		X						
	Defense Satellite Communications System (DSCS) Operational Support System	DOSS		X						
	DIGITAL DATA SET	AN/PSG-8(V)2*		X						
	Digital Topographic Support System	DTSS		X						
	DIGITAL Topographic Support System-LIGHT	AN/TYQ-67(V)1		X						
	DIRECTION FINDER SET	AN/PRD-13(V)		X						

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	DRIVER'S VISION ENHANCER (DVE)	DVE		X						
	DSCS ECCM Control System Remote Component	DECS-RC		X						
	DTSS - HEAVY	AN/TYQ-48A		X						
	Dual Mount Stinger	Missile System	Raytheon	X						
	Electronic Key Management System	EKMS		X						
	Embedded GPS Inertial	EGI		X						
	Enhanced TRACKWOLF	E-TRACKWOLF		X						
	Evolved SeaSparrow Missile (ESSM)	Missile System	Raytheon		X			X		
	Excalibur Precision-Guided Extended Range Artillery Projectile	Missile System	Raytheon	X						
	Exoatmospheric Kill Vehicle (EKV)	Missile System	Raytheon							Ballistic Missile Defense Org
	Extended Range Guided Munition (ERGM)	Missile System	Raytheon		X					
	F-22 Common Integrated Processor (CIP)	Air Combat & Strike System	Raytheon			X				

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	FIREFINDER ARTILLERY LOCATING RADAR	AN/TPQ-37(V)5,6,8		X						
	FIREFINDER MORTAR LOCATING RADAR	AN/TPQ-36(V)5,7,8		X						
	Forward Observer Systems	FOS		X						
	GBS TGRS	AN/TSR-7		X						
	GEM	Guidance Enhanced Missile	R. Collins	X						
	Global Hawk Integrated Sensor Suite	Airborne Surveillance & Reconnaissance System	Raytheon		X			X		
	Guardrail Common Sensor	GR/CS		X						
	Gunner's Primary Tank Thermal Sight (GPTTS)	Combat Vehicle System	Raytheon					X		
	HALO Network	Space System	Raytheon							X
	HARM Targeting System (Export), HTS (E)	Missile System	Raytheon			X				
	HAWK/AMRAAM Air Defense System	Air/Missile Defense System	Raytheon	X						
	Heavy Terminal/Medium Terminal Modernization	HT/MT MOD		X						
	High-speed Anti-Radiation Missile	Missile System	Raytheon		X	X	X			

	(HARM)									
	HIRE	Combat Vehicle System	Raytheon				X	X		
	HISAR	Airborne Surveillance & Reconnaissance System	Raytheon	X		X				
	Horizontal Technology Integration	Combat Vehicle System	Raytheon	X						
	HUMRAAM	Air/Missile Defense System	Raytheon	X						
	Improved Bradley Acquisition Subsystem (IBAS)	Combat Vehicle System	Raytheon	X						
	Improved Data Modem	IDM		X						
	Improved Remotely Monitored Battlefield Sensor System	I-REMBASS		X						
	Infrared Acquisition and Designation System (IRADS)	Air Combat & Strike System	Raytheon			X				
	Initial Fire Support Automated System	IFSAS		X						
	Integrated Inertial Navigation System	ASN-132		X						
	INTEGRATED METEOROLOGICAL SYSTEM (IMETS)	AN/TMQ-40A/B*		X						

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	Intergrated Meteorological System	IMETS I		X						
	Interim Tactical Orderwire System	ITOS		X						
	JAVELIN Anti-tank Weapon System	Missile System	Raytheon	X			X			
	JDAM	Joint Direct Attack Munition (JDAM)	Boeing, R. Collins			X				
	JOINT COMBAT IDENTIFICATION (CID) ADVANCED CONCEPT TECHNOLOGY DEMONSTRATION (ACTD)	CID PANELS		X						
	Joint Land Attack Cruise Missile Defense Elevated Netted Sensor (JLENS)	Air/Missile Defense System	Raytheon	X	X	X	X			
	Joint Standoff Weapon (JSOW)	Missile System	Raytheon		X	X				
	Joint Tactical Combat Training System (JTCTS)	Naval & Maritime Integrated System	Raytheon		X	X				
	Joint Tactical Information Distribution System	JTIDS		X						
	JOINT TACTICAL TERMINAL	JTT		X						

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	LGE EXTENSION NODE SWITCHING GROUP	AN/TTC-46		X						
	LIGHTWEIGHT VIDEO RECONNAISSANCE SYSTEM	LVRS		X						
	LINE OF SIGHT RADIO TERMINAL	AN/TRC-190		X						
	LONG RANGE ADVANCED SCOUT SURVEILLANCE SYSTEM (LRAS3)	LRAS3		X						
	Long Range Advanced Scout Surveillance System (LRAS3)	Combat Vehicle System	Raytheon	X						
	Long-Range Theater Ballistic Missile (TBM) Early Warning Radar	Air/Missile Defense System	Raytheon							Ballistic Missile Defense Organization/ DoD
	LTACFIRE COMPUTER SET	AN/GYG-3(V)1,2,3,4		X						
	MANPACK	AN/PRD-12		X						
	Mark 46, Mark 48, Mark 50 Torpedoes	Naval & Maritime Integrated System	Raytheon		X					
	MCS Light	AN/PYQ-6		X						
	MESSAGE SWITCH	AN/TYC-39A		X						

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	METEOROLOGICAL MEASURING SET (MMS)	AN/TMQ-41		X						
	Meteorological Measuring System	MMS		X						
	MLRS-Fire Direction System (ADA)	MLRS-FDS		X						
	Mobile Subscriber Equipment	MSE		X						
	Moderate Resolution Imaging Spectroradiometer (MODIS)	Space System	Raytheon						X	
	MONOCULAR NIGHT VISION DEVICE	MNVD		X						
	National Missile Defense (NMD) X-Band Radar (XBR)	Air/Missile Defense System	Raytheon							National Missile Defense
	NAVSTAR Global Positioning System	NAVSTAR/GPS		X						
	NET CONTROL STATION	AN/TSQ-158(V)4*		X						
	NIGHT VISION GOGGLES	PVS-7		X						
	Nodal Control Circuit Switch - AN/TTC-39	NCCS		X						

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	Nodal Control Mobile Subscriber Access Circuit Switch	NC MS ACS		X						
	NODE CONTR SWITCH - OPERATIONS GROUP	AN/TTC-47		X						
	Patriot Missile System	Air/Missile Defense System	Raytheon	X				X		
	Paveway Laser Guided Bomb (LGB)	Missile System	Raytheon		X	X				
	Personnel Locator System	PLS		X						
	Phalanx Close-in Weapon System (CIWS)	Missile System	Raytheon		X					
	QUICKFIX COUNTERMEASURE	AN/ALQ-151(V)2		X						
	Radar Warning Receiver	AN/APR-39		X						
	RADIO REPEATER SETS	AN/TRC-138A/C		X						
	RADIO REPEATER SETS	AN/TRC-174		X						
	Radio Set	AN/ARC-220(V)1		X						
	RADIO SET	AN/ASQ-177C(V)4*		X						
	RADIO SET	AN/GRC-245(V)1,2,3*		X						
	RADIO SET	AN/PSQ-6C*		X						
	RADIO SET	AN/VRC-83		X						

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	Radio Set	AN/VRC-90F		X						
	Radio Set	AN/VRC-92F		X						
	RADIO SET	AN/VSQ-2C(V)1,2.4*		X						
	RADIO SET - AN/PRC-119 IS MANPACK	AN/PRC-119F*		X						
	RADIO SET - SINCGARS	AN/VRC-87F - 92F*		X						
	RADIO TERMINAL SET	AN/GRC-229C*		X						
	RADIO TERMINAL SETS	AN/TRC-173		X						
	RADIO TERMINAL SETS	AN/TRC-175		X						
	Rapid Airborne Mine Clearance System (RAMICS)	Naval & Maritime Integrated System	Raytheon		X					
	Raytheon 240 FLIR	Airborne Surveillance & Reconnaissance System	Raytheon							Unknown
	RECEIVER, PREC. LTWT GPS	AN/PSN-11*		X						
	Rolling Airframe Missile (RAM)	Missile System	Raytheon		X			X		
	Satellite Communications Set	SCS		X						
	Satellite Configuration Control Element	SCCE		X						
	SCAMP I	AN/PSC-11		X						
	SEA RAM	Missile System	Raytheon		X					

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	Sea Vue Surveillance Radar	Airborne Surveillance & Reconnaissance System	Raytheon							Unknown
	Second Generation Infrared Systems for Combat Vehicles	Combat Vehicle System	Raytheon	X			X			
	Ship Self-Defense System (SSDS)	Naval & Maritime Integrated System	Raytheon		X					
	Ship System Integration (SSI)	Naval & Maritime Integrated System	Raytheon		X					
	Single Channel Anti-Jam Manportable Terminal	SCAMP		X						
	Single Channel Ground to Air Radio System	SINCGARS		X						
	Single Sheltered Switch	SSS		X						
	SMALL EXTENSION NODE	AN/TTC-48		X						
	SMART-T	AN/TSC-154*		X						
	Software Loader Verifier	SLV		X						
	Space Based Infrared System Low	Space System	Raytheon							Unknown
	Sparrow	Missile System	Raytheon		X	X		X		
	STANDARD Missile	Missile System	Raytheon		X			X		
	State-of-the-Art Medium Terminal	SAMT		X						
	Stinger	Missile System	Raytheon	X						

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	TACTICAL AIRSPACE INTEGRATION SYSTEM	AN/TSQ-221*		X						
	TACTICAL ENHANCED SYNTHETIC APERTURE RADAR	TESAR		X						
	TACTICAL SATELLITE COMMUNICATIONS TERMINALS	AN/TSC-85B		X						
	TACTICAL SATELLITE COMMUNICATIONS TERMINALS	AN/TSC-93B		X						
	TARGET ACQUISITION	AN/TSQ-179(V)2*		X						
	TEAMMATE	AN/TRQ-32(V)1		X						
	TEAMMATE	TEAMMATE		X						
	Theater High Altitude Area Defense (THAAD) Radar	Air/Missile Defense System	Raytheon	X						
	THERMAL WEAPON SIGHT	TWS		X						
	TLAM	Tomahawk Land Attack Missile	R. Collins		X		X			
	Tomahawk Cruise Missile	Missile System	Raytheon		X					
	TOW Improved Target Acquisition System (ITAS)	Combat Vehicle System	Raytheon	X			X			
	TRAILBLAZER	AN/TSQ-138		X						

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	Trailblazer	TRAILBLAZER		X						
	Transportable Single Channel Transponder Receiver	TSCTR		X						
	TROPOCATTER RADIO	AN/TRC-170(V)2,3		X						
	Tube-launched, Optically engaged, WireLESS Fire & Forget (TOW F&F)	Missile System	Raytheon	X						
	Tube-launched, Optically tracked, Wire-guided (TOW 2A)	Missile System	Raytheon	X						
	Tube-launched, Optically tracked, Wire-guided (TOW 2B)	Missile System	Raytheon	X						
	UHF DAMA TERMINAL SPITFIRE	AN/PSC-5*		X						
	Undersea Coastal Surveillance System (UCSS)	Naval & Maritime Integrated System	Raytheon		X					
	W1000 Portable Weapons Sight	Ground Night Vision	Raytheon	X						
Orbiter		Space Shuttle system	United Space Alliance						X	
Space Suit		Space Shuttle system	Hamilton Sundstrand						X	

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Redesigned Solid Rocket Motor (RSRM)		Space Shuttle system	Thiokol Propulsion						X	
		AN/GSC-49		X						
		AN/GSC-52		X						
		AN/PPS-15		X						
		AN/PPS-5		X						
		AN/PRC-112		X						
		AN/PRC-118		X						
		AN/PRC138		X						
		AN/PRC-139		X						
		AN/VRC-88		X						
		BCIS		X						
		COMSEC		X						
		CSEL		X						
		CSLA		X						
		EPLRS		X						
		HUNTER		X						
		JISR		X						
		JPSD		X						
		JSTARS		X						
		JTRS		X						
		LMST		X						
		LST-5D		X						
		MELIOS		X						
		MSE (ACUS)		X						

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		NTDR		X						
		OPTIES		X						
		PROPHET		X						
		RTV		X						
		SAR/MTI		X						
		SPEAKEASY		X						
		STAR-T		X						
		TRI TAC		X						
		TROJAN SPIRIT		X						
		TUAV		X						
		UAV PAYLOADS		X						
		WIN-T		X						

APPENDIX B
Parameters to Identify Potential Alternatives

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B.1 PHYSICAL AND MECHANICAL CHARACTERISTICS

The physical and mechanical characteristics are important parameters in selecting lead-free alloys, since selected alloys must be capable of providing the mechanical strength and reliability that has been expected from tin-lead (SnPb) solder. Below are descriptions of these characteristics. The physical characteristics include properties such as melting point and range, microstructure, solder-substrate interactions, surface tension and wetting. Mechanical metallurgy characteristics include tensile and shear properties, creep behavior, isothermal fatigue behavior, and thermal fatigue behavior.

The following physical and mechanical characteristics information was taken from *A Pollution Prevention Study of Lead-Free Soldering Alloys*, dated May 21, 1998, prepared by Conceptual Engineering Group, Inc.

B.1.1 Physical Characteristics

Melting Point

The melting point and range are important because they are the determining factors in establishing a system's operating temperature, as well as the minimum processing temperature for component survival. Eutectic alloys are the most desirable for solders, due to the fact that, although the solder's alloys are two-phased, they concurrently solidify at a single temperature. Also, freezing at a single eutectic temperature gives rise to low residual stresses, unlike that of an alloy that freezes in a range of temperature, giving rise to segregation and high residual stresses.

Table B-1. Melting Points of Alternative Alloys

Alloy	Liquidus Temperature (°C)	Melting Point (°C)
Sn/37Pb	183	183 (eutectic)
Sn/0.7Cu	227	227 (eutectic)
Sn/0.7Cu/0.05Ni	227	227 (eutectic)
Sn/3.8Ag	221	221 (eutectic)
Sn/3.9Ag/0.6Cu	220	216-219
Sn/4.0Ag/0.5Cu	220	216-219
Sn/4.0Ag/1.0Cu	220	216-219
Sn/3.5Ag/1.5In	223	218-223
Sn/3.4Ag/4.8Bi	205	200-216
Sn/3.1Ag/0.5Cu/3.1Bi	210	209-212
Sn/3.4Ag/1Cu/3.3Bi	214	205-214
Sn/2.5Ag/0.8Cu/0.5Sb	213	213-218
Sn/4.6Ag/1.6Cu/1Sb/1Bi	220	214-220

Microstructure

Microstructure is defined as the combination of phases that are present in a material, and the phases' defects, morphology, and distribution. From a material's microstructure and composition, its properties can be determined, such as its thermal, mechanical, and chemical history. The primary factor of consideration for solder alloys is cooling rate, especially for electronic assemblies. At fast cooling rates, the result is a finer microstructure, since little time is allowed for diffusion to occur within the microstructure.

Solder-Substrate Interaction

Solder substrate interactions consist of phase formation and substrate dissolution. Phase formation is the phenomenon of inter-metallic compounds being formed at the interface of the solder and the substrate, often becoming sites for premature failure.

Surface Tension/Wetting

Surface tension of solders is important in the determination of wetting behavior. Wetting is the ability of the solder to flow on the substrate metal. To assure that wetting occurs, flux is used prior to soldering to clean the surface of contaminants and to reduce the surface tension at the substrate/solder/vapor interface.

B.1.2 Mechanical Metallurgy Characteristics

Tensile/Shear Stress

Tensile and shear stress occur if the material is deformed at a steady rate. The resulting deformation changes the structure by the movement of defects such as dislocations. With the continuation of applied stress to the solders, they will eventually brake.

Creep

Creep is a deformation occurring over a period of time, that relaxes a fixed imposed stress. Creep is prevalent when the temperature exceeds half of the material's melting point. Since room temperature is well above half of the melting point of most of the applicable solders, creep is the most critical and important deformation mechanism of solders.

Isothermal Fatigue

Isothermal fatigue (cyclic deformation) is defined as imposed cyclic displacement at a constant temperature. Fatigue life is determined by the number of cycles needed to start a crack and propagate it to failure. Fatigue is complex because creep occurs in parallel to both isothermal and thermal fatigue in solder alloys at room temperature.

Thermal Fatigue

Thermal fatigue is another type of cyclic deformation imposed by a change in temperature when two materials with different thermal expansion coefficients are joined. Thermal fatigue is a critical parameter in replacement of lead solders. Many of today's electronics can undergo a combination of isothermal fatigue, thermal fatigue, and creep. Data on thermal fatigue is limited for SnPb solders and scarce for lead-free solders.

B.2 COSTS AND AVAILABILITY

The cost and availability of the metal elements are important factors in selecting a lead-free alloy and must be analyzed. When considering the relative availabilities of each element, it is helpful to consider metal-use estimates. Approximately 100 million pounds worldwide of SnPb solder are consumed each year in the electronics industry, and about 35 million pounds are used in North America. These numbers will help determine the availability of the metals for use in lead-free alloys.

When selecting an alloy for wave (bar) and manual (wire) soldering, the metal cost requirement is particularly important, since high volumes of metal poundage are used and the metal cost accounts for a large percentage of the total product cost. For example, indium (In), one of the most expensive metals, is not a good choice for bar and wire solders. For reflow (paste) solder, however, the metal cost is a relatively small percentage of the overall manufacturing cost of making the paste, and therefore metal cost is not one of the most important factors in selecting a lead-free solder paste.

Along with cost, availability of the metal elements is also important. When attempting to find a solution for the solder industry, it is critical to select an alloy system whose components are sufficiently available. In is scarce in supply and would not be a good choice for industry-wide use. Bismuth (bi) is a byproduct of lead refining and is limited in supply. If the production of lead decreases then Bi production also decreases, which could cause potential supply problems in the future.

Table B-2 provides cost and availability information found in *Mineral Commodity Summaries 2002* as presented by the U.S. Department of the Interior through the U.S. Geological Survey. The listed information includes metal cost per pound, annual mine production in the US and worldwide, and relative availability for each of the candidate elements.

Table B-2. Metal Cost and Production Availability

Element	**Metal Cost per Pound [a] (average for 2001)**	**Mining Production (metric tons/yr for 2001)**		**Production Availability**
		U.S.	Worldwide	
Lead	$0.44	420,000	2,970,000	Available
Antimony	$0.65	300	115,000	Available
Bismuth	$3.80	None	5,810	Limited [b]
Copper	$0.76	1,340,000	13,200,000	Available
Indium	$66.68	None	340	Scarce [c]
Silver	$72.92	1,800	18,300	Limited
Tin	$2.46	None	242,000	Available

[a] Metal cost only - does not include fabrication costs, development, support, etc
[b] Bismuth is a byproduct of lead refining and is therefore limited by the production of lead
[c] Indium is recovered almost exclusively as a byproduct of zinc

The availability of the metal elements is important; moreover, the availability of the alternative alloy as a currently manufactured alloy is also important. Table B-3 lists the alternative alloy costs based purely on the metal cost and the current market availability of the alloy. The different solder forms (bar, wire, and paste) produced with the alloys will greatly determine the actual alloy price. For example, paste solders will probably cost between $50-$150 per 500 gram tube depending on the quantity purchased, market prices, solder supplier, and flux used. Wire solders will probably cost between $15-$130 per pound spool depending on the quantity purchased, market prices, solder supplier, flux used, wire diameter, and wire core size. Bar solder prices are basically the same as the metal prices with $1-$3 variances per pound.

Table B-3. Alloy Cost and Market Availability

Alloy	Cost per Pound [a]	Market Availability
Sn/0.7Cu [b]	$2.45	Available
Sn/3.8Ag	$5.05	Available
Sn/3.9Ag/0.6Cu [b]	$5.20	Available
Sn/4.0Ag/0.5Cu	$5.27	Available
Sn/4.0Ag/1.0Cu	$5.26	Available
Sn/3.5Ag/1.5In	$5.82	Unknown
Sn/3.4Ag/4.8Bi	$4.92	Available (patent)
Sn/3.1Ag/0.5Cu/3.1Bi	$4.68	Available
Sn/3.4Ag/1Cu/3.3Bi [b]	$4.88	Available
Sn/2.5Ag/0.8Cu/0.5Sb	$4.20	Available (patent)
Sn/4.6Ag/1.6Cu/1Sb/1Bi	$5.67	unknown

[a] Metal cost only - does not include fabrication costs, development, support, etc
[b] These are the three recommended solders for testing under the Joint Test Protocol (JTP)

B.2.1 Manufacturability and Equipment Requirements for Alternative Alloys

Several factors such as temperature and atmosphere effect current package assemblies and must be analyzed in order to assess the manufacturing processes and equipment requirements for lead-free soldering materials against the currently used lead-based baseline materials.

<u>Temperature</u>
Lead-free solders tend to have higher melting points and thus higher process temperatures (usually 195°C to 230°C) than the currently used SnPb solders (183°C). It is a concern that these increased process temperatures may have negative affects on circuit boards, components, and surface finishes.

A study was performed on board level reliability for reflow processing and all packages evaluated have a proven reliability at 260°C reflow temperature. The high temperature reflow did not cause delaminating or warpage in package assemblies.

Atmosphere

Current processes equipment operate using either air or inert (nitrogen) atmospheres. It is recommended that lead-free solders be processed in inert atmospheres to improve wetting and reduce oxidation. Nitrogen promotes increased wetting and reduces oxidation, reduces surface tension of the solderable surfaces, and reduces the amount of drose generation in solder pots. Flux consumption is also greatly reduced in an inert atmosphere.

B.3 ANALYSIS OF ALTERNATIVE ALLOY ELEMENTS

Antimony

Antimony (Sb) is inexpensive and available. Addition of Sb in solder alloys was found to act as a grain refiner Bi-doped alloys and Sn/Ag/Cu alloys. An alloy containing up to 5% (by weight) of antimony may strengthen the alloy further.

Bismuth

Bismuth (Bi) is effective in reducing solidus temperature of tin alloys, has good wetting properties and good physical properties. It is not effective at reducing the liquidus temperature, which results in a broader freezing range. A broader freezing range (pasty range) is not desirable and can cause fillet lifting especially in through-hole wave soldering. Fillet lifting increases with increase in Bi concentration and/or use with lead containing components and boards, where Bi forms a low melting point phase with lead which can lead to joint fracture. However, bismuth-containing alloys were great performers on lead-free boards and finishes. A solder containing up to 6% (by weight) Bi could supply the whole electronics solder market.

Bismuth is the second most expensive metal among the alternatives and is limited in supply since it is a byproduct of lead refining and thus limited by the production of lead. Bismuth is still recommended as an alternative element metal; however, it should be used in low weight percentages as a result of fillet lifting and limited availability.

Copper

Copper (Cu) is usually selected as a companion element with tin because it tends to reduce the melting point when alloyed with tin and possess desirable mechanical, electrical, and thermal properties. Cu metal is also inexpensive and widely available in quantities sufficient to satisfy the world’s solder demand.

Indium

Indium (In) is an effective element in reducing the melt point in tin alloys. It has exceptional physical and wetting properties; however, it is very scarce and expensive. It may not be appropriate for an industry wide solution and therefore was not selected as a potential element.

Nickel

Nickel (Ni) is a naturally occurring element (metal) and is generally more cost effective than other metals such as bismuth, silver, or gold. Factors that make nickel and its alloys valuable commodities include strength, corrosion resistance, high ductility, and good thermal and electric conductivity.

Silver

Silver (Ag) has been used for many years in lead-free solders for module assembly for the automotive industry. Ag is usually selected as a companion element with tin because it tends to reduce the melting point when alloyed with tin and possess desirable mechanical, electrical, and thermal properties.

Tin

Tin (Sn) is the base metal used for every candidate lead-free alloy and for the currently used 63Sn/37Pb alloy. Tin is selected as the base metal since it is relatively inexpensive, sufficiently available, has desirable physical, electrical/thermal conductivity, and wetting properties.

APPENDIX C
Reliability and Leachate Testing of Lead-Free Solder Joints

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Reliability and Leachate Testing of Lead-Free Solder Joints

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Abstract

A test program was started in 2000 at Boeing for the evaluation of the reliability of lead-free solder joints. One lead-free solder was tested for reflow operations (tin/3.8%silver/0.7%copper) and one solder was tested for wave soldering operations (tin/0.7%copper). Three lead-free circuit board finishes were also tested: immersion silver; electrolytic gold on top of nickel; and an OSP (organic solderability preservative). Test vehicles were assembled by reflow soldering chip resistors to the top of each test vehicle and wave soldering chip resistors to the bottom side of each test vehicle. The test vehicles were then thermally cycled and the failure rates of the lead-free solder joints were determined by electrically monitoring the solder joints during the test.

Boeing's test program was able to verify that tin/copper is a reliable replacement for the solder used in surface mount wave soldering operations. However, the lead-free candidate for reflow soldering operations (tin/silver/copper) was not as reliable as tin/lead solder and further testing will be required to identify a suitable material for reflow soldering of high reliability electronics

In addition to doing reliability studies, leachate testing was conducted on the lead-free solder joints to determine if toxic metals could be leached out under conditions found in landfills. Any alternative materials used for lead-free solder joints must not leach out elements that could be even more toxic than the lead that they are replacing. For example, silver is relatively non-toxic to mammals but is very toxic to marine life.

The leachate testing conducted showed that the lead-free solder joints did not leach detectable amounts of toxic metals (i.e., silver) but the lead-containing control solder joints leached amounts of lead in excess of that allowed by Federal law.

Objective

The objective of this study was to conduct reliability testing on lead-free solder joints to determine if they will have long term reliability comparable to that of eutectic tin/lead solder joints. Leachate testing on lead-free solder joints was also done to determine if they have the potential to leach toxic metals into landfill groundwater. The effects of lead contamination upon the reliability of the lead-free solder joints was also explored since the adoption of lead-free solders by industry might result in the accidental or intentional mixing of lead containing and lead-free solders. In addition, shear testing was conducted in order to evaluate how the shear strength of lead-free solder joints changes during thermal cycling.

Approach

Two lead free solders were selected for reliability testing. One lead-free solder was tested for reflow operations (tin/3.8%silver/ 0.7%copper; m.p. 217°C) and one solder was tested for wave soldering operations (tin/0.7%copper; m.p. 227°C). These solders were chosen for testing because a survey of domestic consortia suggested that they had the greatest potential as replacements for eutectic tin/lead. Eutectic tin/lead solder was used on some of the reliability test vehicles as a control solder.

Three lead-free circuit board finishes were tested in conjunction with the lead-free and tin/lead solders: immersion silver; electrolytic gold on top of electrolytic nickel; and an OSP (organic solderability preservative). A tin/lead HASL board finish was also used on the control test vehicles (in conjunction with the tin/lead control solder). The combinations of lead-free solders and finishes used on each test vehicle are shown in the columns in Table 1. The thickness of the gold board finish was 23 microinches as determined by x-ray fluorescence spectroscopy. Up to 31 microinches of gold is allowed by IPC on solderable surfaces but thicker gold can cause embrittlement of the solder joints[1].

The components used for the lead-free reliability testing were 1206 chip resistors whose end terminations were finished with tin/0.7%copper. Chip resistors were chosen as the test components because they are inexpensive; they have a high failure rate during thermal cycling; and they could be obtained with a lead-free finish. The tin/0.7%copper finish was applied to the nickel end terminations on the resistors by a hot dip process. Chip resistors with an electroplated tin/lead termination finish were used on the control test vehicles. Several chip resistors were mounted and cross-sectioned so that the finish thickness could be measured and so that the finish composition could be verified by EDS (energy dispersive x-ray spectroscopy). The average thickness of the electroplated tin/lead termination finish was approximately 0.25 mils. The average thickness of the hot dipped tin/0.7%copper finish was approximately 1.0 mils.

A test vehicle was designed at Boeing that had pads for forty chip resistors on the nearside of the board and forty chip resistors on the farside of the board. Pads on the periphery of the test vehicle were designed to be connected to an event detector so that the electrical continuity of the solder joints could be monitored. Forty 0.055 in. diameter plated-through holes were included on each test vehicle so that solder wetting of the holes could be examined. Round and square test pads were also include on the board design so that solder wetting could be compared on the different board finishes used. The boards were made from 0.062 in. thick FR4 which had a glass transition temperature of 140°C.

The test vehicles were assembled by reflow soldering forty chip resistors to the nearside of each test vehicle and wave soldering forty chip resistors to the farside of each test vehicle. The boards were assembled at Boeing – Irving Co. in Irving, Texas using production equipment. Some boards were assembled with lead-free solder in combination with tin/lead-plated components. This resulted in intentional contamination of the solder joints with lead. This was done in order to evaluate the effects of lead contamination on the reliability of the joints.

The solder paste stencil used was 8 mils thick with an aperture to pad ratio of 1. Calculations showed that the volume of the final reflowed solder joints (tin/lead and lead-free) should be within 2% of each other. The reflow profile used for the lead-free solder paste is shown in Figure 1. The peak reflow temperature used for the tin/lead solder paste was 229°C and for the lead-free solder paste was 239°C.

The wave soldering using tin/0.7%copper was done using an ERSA ETS 330-F wave solder machine charged with tin/0.7% copper. The temperature of the solder pot was 265°C.

After assembly and cleaning, the test boards were visually inspected. The appearance of the solder joints was recorded and cross-sections were made.

Two test vehicles of each type were then thermally cycled and the failure rates of the lead-free solder joints were determined by electrically monitoring the solder joints during the test. Solder joint failures were monitored with an AnaTech Event Detector and events were recorded on a LabView-based data acquisition system. The AnaTech was set to detect events greater than 1000 ohms in resistance and longer than 200 nanoseconds in duration. The thermal cycle (actual board temperature) was from –55°C to +125°C with 15 minute dwells at each temperature extreme and a ramp rate of 7°C per minute. The thermal cycling was continued for 4380 thermal cycles in order to get enough failures for statistical analysis.

Leachate testing on both the lead-free and the tin/lead solder joints was also done to determine if they have the potential to leach toxic metals into landfill groundwater. Both the USEPA TCLP test procedure (SW-846 Method 1311) and the State of Texas Seven-Day Distilled Water test procedure were used. The USEPA method uses a buffered acetic acid solution (which simulates the water found in a landfill) for the extraction. The State of Texas test uses distilled water as the leachant. Test vehicles were cut into test coupons; the coupons were weighed; and then they were extracted with the leachant. The lead-free specimens that were analyzed had tin/silver/copper solder on one side and tin/copper solder on the other side. The tin/lead specimens had tin/lead solder on both sides. Chemical analyses of the leachates using inductively-coupled plasma spectroscopy (ICP) were done for silver, copper, lead, and tin at Boeing – Huntington Beach. Test vehicles with and without an acrylic conformal coating were tested.

In addition, shear testing was conducted in order to evaluate how the shear strength of the reflowed tin/lead and the lead-free solder joints changed during thermal cycling. Chip resistors were sheared before thermal cycle testing began and at 363, 1316, and 3196 cycles using a Bond Test-30 (Keller Technology Corp., Buffalo, NY) with a head speed of 0.28 mm/sec. A special fixture was built to hold the test vehicles while the resistors were being sheared. Six solder joints of each type were sheared and the results were averaged to generate a data point. No shear data was generated for the solder joints that had been intentionally contaminated with lead. No shear data was generated for the wave soldered joints because their shear strength was too high to be measured on the available test equipment.

Results and Discussion

After assembly and cleaning, the test boards were visually inspected. In general, the lead-free solder joints (reflowed and wave soldered) were very grainy in appearance while the tin/lead solder joints were smoother. Reflowed tin/lead solder joints on the gold finish were generally dull in appearance as were all of the reflowed solder joints intentionally contaminated with lead (from the component finish).

Figure 2 shows photographs of a reflowed tin/lead solder joint; a reflowed tin/silver/copper solder joint; a wave soldered tin/copper joint; and a wave soldered tin/lead joint.

The solder joints were cross-sectioned and representative cross-sectional photos are shown in Figure 3. The height of the solder under the chip resistor terminations was measured and compared. It has been suggested that the reliability of the solder joint may be related to this height with higher being better. In general, the lead-free reflowed and wave soldered joints had more solder height under the chip resistors than did the tin/lead joints but the reliability test results did not show a correlation between solder height and reliability of the solder joint.

The results of the shear testing is shown in tabular form in Table 2. In general, the reflowed lead-free solder joints were slightly stronger than the reflowed tin/lead solder joints before thermal cycling. The shear strength of all of the reflowed solder joints decayed rapidly during thermal cycling (presumably due to crack formation) and at the end of 1316 cycles, the tin/lead solder joints were generally stronger than the lead-free solder joints. At the end of 3196 cycles, the situation became reversed and the remaining lead-free solder joints were significantly stronger that the remaining tin/lead solder joints. Also, all of the solder joints on the gold finish tended to be weaker than the corresponding solder joints on other finishes (before and during thermal cycling) presumably due to gold embrittlement.

The reliability data from the thermal cycling test was plotted using two parameter Weibull plots. Plotting probability of failure (p) vs. number of thermal cycles (tp) yielded a beta (shape) parameter and an alpha (characteristic life) parameter for each combination of solder and board finish (see Table 3). The results were also plotted as % failures (components) vs. number of cycles. Figure 4 shows the reliability curves for reflowed tin/lead on the various board finishes. The data shows that all of the tin/lead solder joints began to fail at approximately the same thermal cycle and the rate of failure on each finish was similar with the exception of the gold finish. The solder joints on gold appeared to have a higher failure rate probably due to gold embrittlement of the joints.

Figure 5 shows the reliability curves for wave soldered tin/lead on the various board finishes. The data shows that all of the tin/lead solder joints began to fail at approximately the same thermal cycle and the rate of failure on each finish was similar. With wave soldering, the board finish tends to dissolve in the solder of the wave becoming highly diluted which explains why embrittlement due to gold is not seen on this graph.

Figure 6 shows the reliability curves for reflowed tin/3.8%silver/0.7%copper on the various board finishes. The data shows that all of the lead-free solder joints began to fail at approximately the same thermal cycle and well before the first failure of the tin/lead control solder joints (on HASL). The failure rates for the lead-free solder joints on OSP and gold were similar while the joints on the silver finish failed more rapidly. These results suggest that reflowed tin/3.8%silver/0.7%copper is not as reliable as eutectic tin/lead. Similar results have been noted in the past for other lead-free solders[2]. In a study completed in 1997 by the National Center for Manufacturing Sciences (NCMS), it was found that 1206 chip resistors reflow soldered with tin/2.6% silver/0.8%copper/0.5%antimony (Solder F2) did not perform as well as a eutectic tin/lead control (Solder A1). A1 had its first failure at cycle 1900 while F2 had its first failure at cycle 1226. It has been suggested that tin/silver/copper solder is more reliable than tin/lead when the component has a coefficient of thermal expansion (CTE) similar to that of the circuit board but is not as reliable when the CTE of the component differs from that of the circuit board[3]. The CTE of ceramic components, such as chip resistors, is much less than the CTE of most circuit boards and the mismatch between the component and the board applies a lot of stress to the solder joints. Since chip resistors are used on many circuit boards, they may be the “weakest link” where lead-free solders are concerned.

Figure 7 shows the reliability curves for wave soldered tin/0.7%copper on the various board finishes. The data shows that all of the lead-free solder joints and the tin/lead control joints (on HASL) began to fail at approximately the same thermal cycle. The failure rates for the lead-free solder joints was initially less than that of the tin/lead control joints. These results suggest that wave soldered tin/0.7%copper is as reliable as eutectic tin/lead.

Figure 8 shows the reliability curves for reflowed tin/silver/copper intentionally contaminated with lead (from the component finish). The data shows that all of the contaminated solder joints began to fail well before the first failure of the tin/lead control solder joints. The lead contamination had a significant negative impact on the reliability of the solder joints on the gold board finish with the first failure occurring at only 243 thermal cycles. The gold content of a typical solder joint on the gold finish averaged 3.2 percent as determined by EDS (energy dispersive x-ray spectroscopy). The lead content of the same solder joint averaged 3.5 percent. The gold and the lead were not evenly dispersed but there were distinct regions of very high gold or very high lead content (see Figure 9). In addition, there were distinct regions rich in tin/silver and also regions rich in tin/gold/copper/nickel.

The leachate test results for silver, copper, lead, and tin are given in Table 4. Table 4 also gives the regulatory limits for TCLP leachates and for drinking water. The real elements of concern to us are silver (which can be toxic to marine life) and lead (which is a neurotoxin, a haematotoxin, a teratogen, and possibly carcinogenic). Copper and tin are relatively non-toxic. The leachate testing showed that the reflowed tin/silver/copper solder joints did not leach detectable amounts of toxic silver. The eutectic tin/lead solder joints, on the other hand, can leach amounts of lead well in excess of that allowed by Federal law (5.0 mg/liter)[4]. This suggests that printed wiring assemblies made with tin/silver/copper solder have little risk of being considered a hazardous waste due to leaching of toxic silver. The surface area of the tin/silver/copper solder joints would have to be increased to at least 48 square inches before regulatory limits for silver would be exceeded (assuming the weight of the leachate specimen remained the same). Not unexpectedly, application of a conformal coating to the leachate specimens greatly reduced the amount of metals leached.

Summary

In summary, the reliability of reflowed eutectic tin/lead solder is virtually the same on an OSP, immersion silver, or tin/lead HASL finish and only slightly degraded by an electrolytic gold finish (23 microinches thick). In addition, the test data shows that the reliability of wave soldered eutectic tin/lead solder is practically the same on any of the board finishes tested in this study.

As for the lead-free solders, the reflowed tin/3.8%silver/0.7%copper was not as reliable as eutectic tin/lead on any of the lead-free board finishes and other solders will need to be identified that have greater long-term reliability. It has been suggested that tin/silver/copper solder is more reliable than tin/lead when the component has a coefficient of thermal expansion (CTE) similar to that of the circuit board but is not as reliable when the CTE of the component differs from that of the circuit board. The CTE of ceramic components, such as chip resistors, is much less than the CTE of most circuit boards and the mismatch between the component and the board applies a lot of stress to the solder joints. Since chip resistors are used on many circuit boards, they may be the "weakest link" where lead-free solders are concerned.

Conversely, the wave soldered tin/0.7%copper solder joints proved to be as reliable as eutectic tin/lead on any of the lead-free board finishes tested. This suggests that tin/0.7%copper is a good candidate to replace eutectic tin/lead for surface mount wave solder operations.

The leachate testing conducted in this study suggests that tin/silver/copper is not likely to be considered a hazardous waste because of its low potential to leach silver (which is very toxic to marine life).

References

1. IPC-2221, "Generic Standard on Printed Board Design", pp. 19-20, 1998.
2. NCMS Report 0401RE96, "Lead-Free Solder Project, Final Report", National Center for Manufacturing Sciences, August 1997.
3. Private communication with Dr. Wayne Johnson, Auburn University.
4. USEPA 40 CFR 261

Table 1. Test Vehicle Matrix

	Control Boards				No-Lead Boards			Partially No-Lead Boards	
Board Finish	Silver	OSP	HASL	Ni/Au	Silver	OSP	Ni/Au	Ni/Au	Silver
Solder Paste	63tin37lead	63tin37lead	63tin37lead	63tin37lead	SnAgCu	SnAgCu	SnAgCu	SnAgCu	SnAgCu
Component Finish	63tin37lead	63tin37lead	63tin37lead	63tin37lead	Sn0.7Cu	Sn0.7Cu	Sn0.7Cu	63tin37lead	63tin37lead
Wave Solder	63tin37lead	63tin37lead	63tin37lead	63tin37lead	Sn0.7Cu	Sn0.7Cu	Sn0.7Cu	Sn0.7Cu	Sn0.7Cu

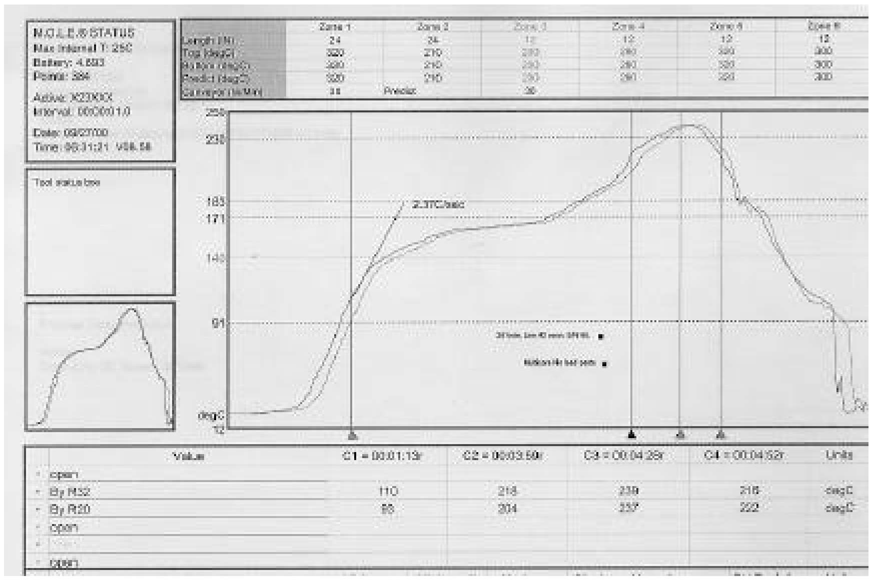

Figure 1. Lead-Free Solder Reflow Profile

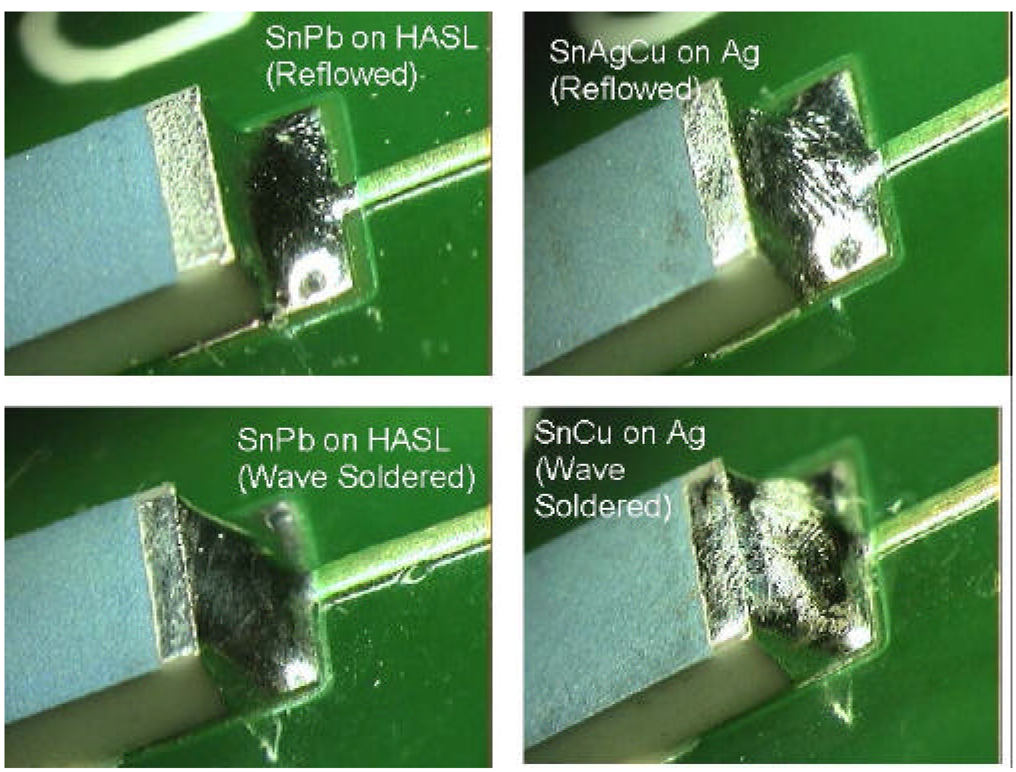

Figure 2. Solder Joint Appearances

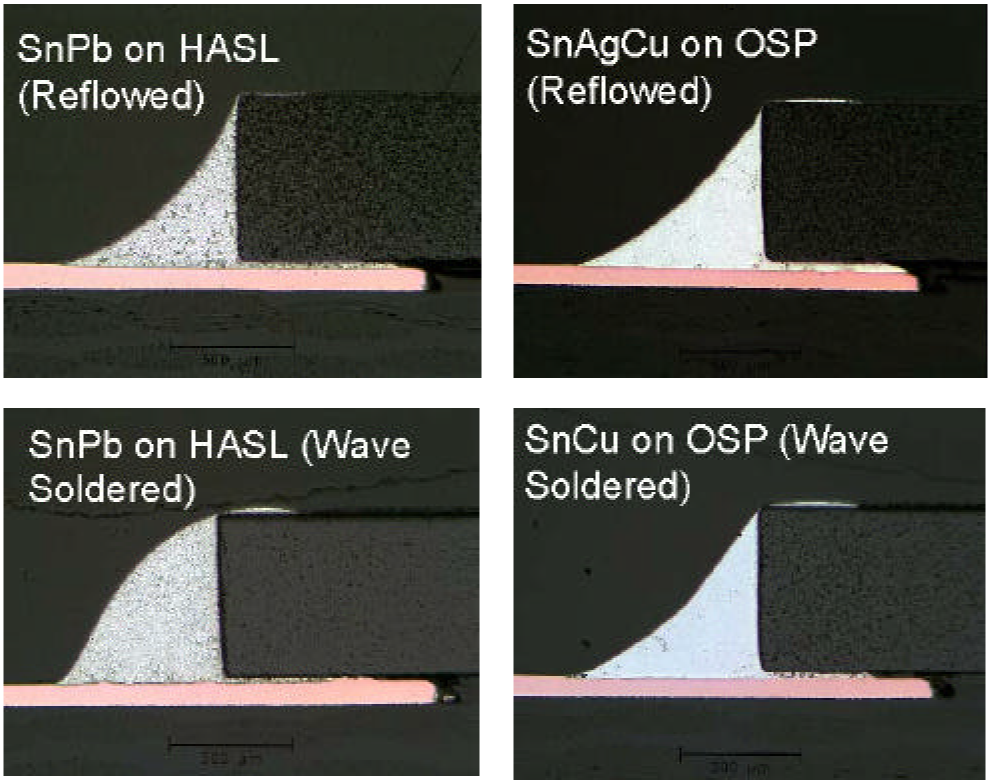

Figure 3. Representative Solder Joint Cross Sections

Table 2. Shear Load Required to Remove Resistors (after 0, 363, 1316, and 3196 Thermal Cycles)

	Control Boards				No-Lead Boards			Partially No-Lead Boards
Board Finish	Silver	OSP	HASL	Ni/Au	Silver	OSP	Ni/Au	Silver
Solder Paste	tin/lead	tin/lead	tin/lead	tin/lead	SnAgCu	SnAgCu	SnAgCu	SnAgCu
Component Finish	tin/lead	tin/lead	tin/lead	tin/lead	Sn0.7Cu	Sn0.7Cu	Sn0.7Cu	tin/lead
No. of Thermal Cycles Accumulated	**Shear Load (Kg)**							
0	9.0	10.2	10.3	8.3	11.7	11.5	9.5	11.9
363	8.5	8.4	8.5	6.1	6.0	5.7	5.6	
1316	4.1	4.6	4.7	1.8	3.4	3.5	2.9	
3196	0.39	0.46	0.63	0.26	1.45	1.21	1.31	

Table 3. Weibull Parameters

	Control Boards				No-Lead Boards			Partially No-Lead	
Board Finish	Silver	OSP	HASL	Ni/Au	Silver	OSP	Ni/Au	Ni/Au	Silver
Solder Paste	tin/lead	tin/lead	tin/lead	tin/lead	SnAgCu	SnAgCu	SnAgCu	SnAgCu	SnAgCu
Component Finish	tin/lead	tin/lead	tin/lead	tin/lead	Sn0.7Cu	Sn0.7Cu	Sn0.7Cu	tin/lead	tin/lead
Wave Solder	tin/lead	tin/lead	tin/lead	tin/lead	Sn0.7Cu	Sn0.7Cu	Sn0.7Cu	Sn0.7Cu	Sn0.7Cu
Data for Reflowed Solder Joints									
First Failure	2823	2655	2403	2476	1181	1401	1191	243	983
Characteristic Life (a)	5540	5005	5476	3249	3866	5015	4523	2760	4183
Beta	5.147	5.082	3.996	11.32	1.975	2.201	2.274	1.426	2.93
Data for Wave Soldered Joints									
First Failure	2684	2358	2656	2561	3011	2750	2514	1851	1569
Characteristic Life (a)	4428	4171	4479	4871	5023	4592	5660	4594	3966
Beta	6.765	5.677	5.073	5.722	6.922	8.901	6.43	3.478	3.069

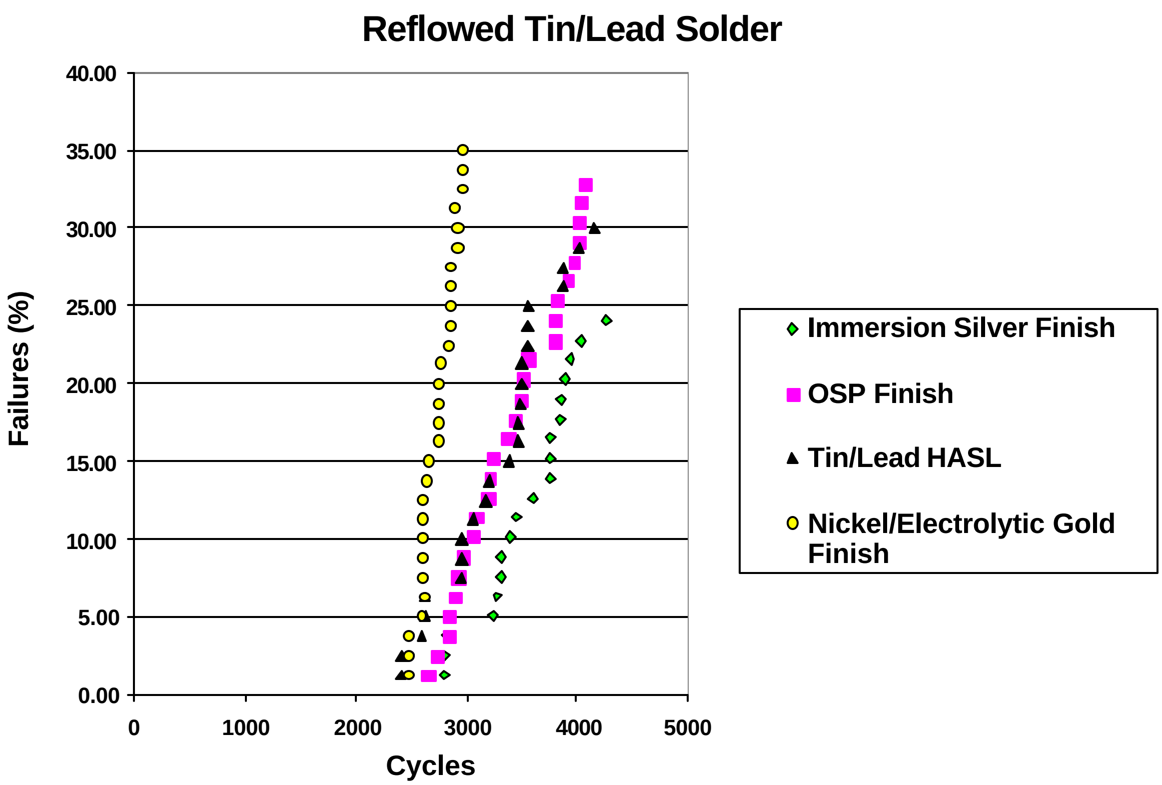

Figure 4. Reliability of Reflowed 63%Sn/37%Pb Solder Joints on Various Board Finishes

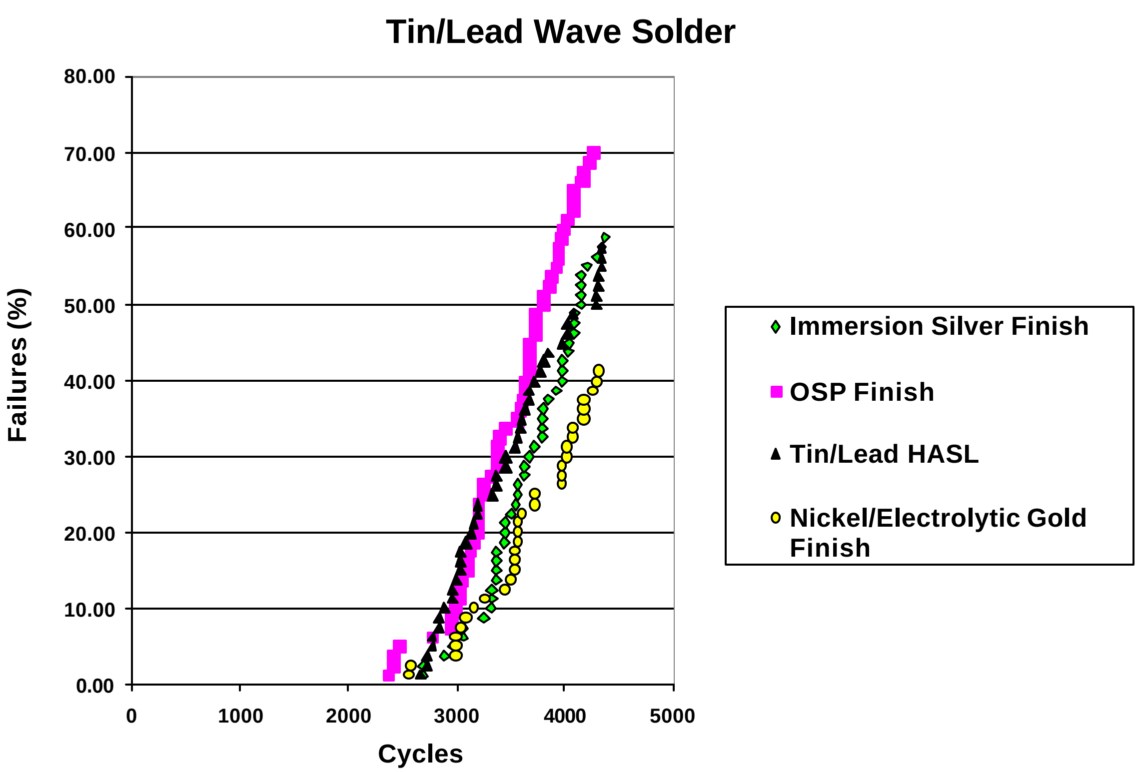

Figure 5. Reliability of Wave Soldered 63%Sn/37%Pb Solder Joints on Various Board Finishes

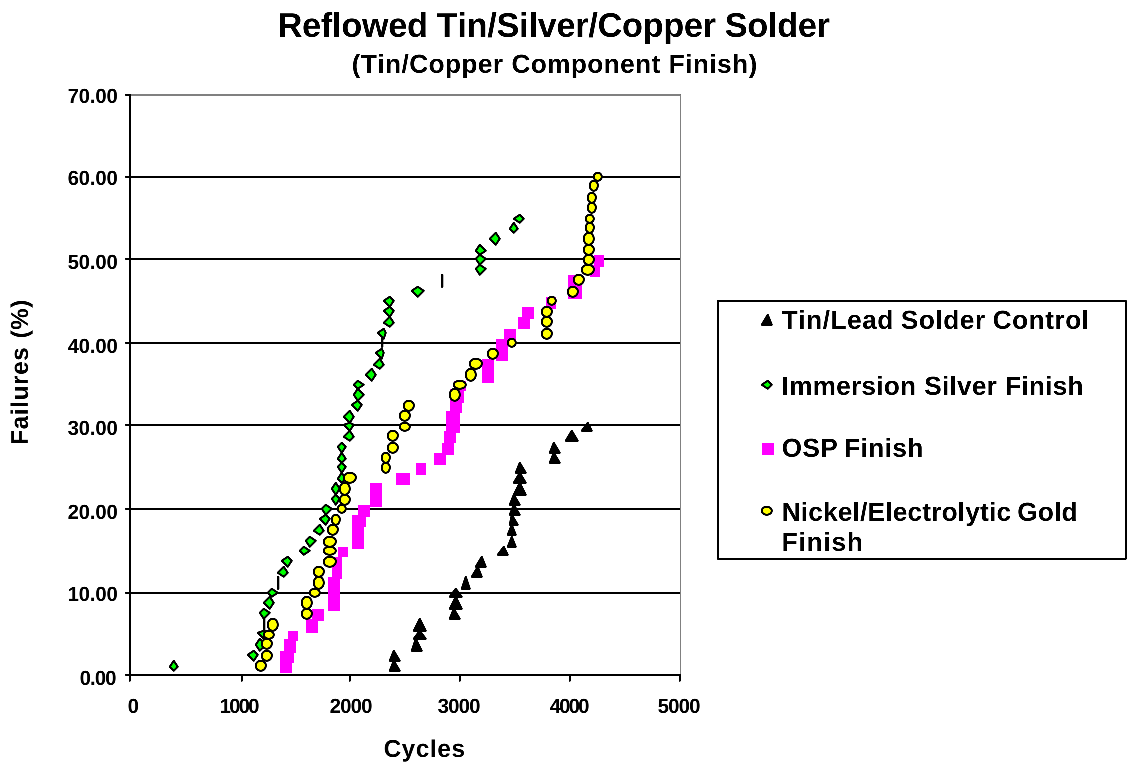

Figure 6. Reliability of Reflowed Sn/3.8%Ag/0.7%Cu Solder Joints on Various Board Finishes

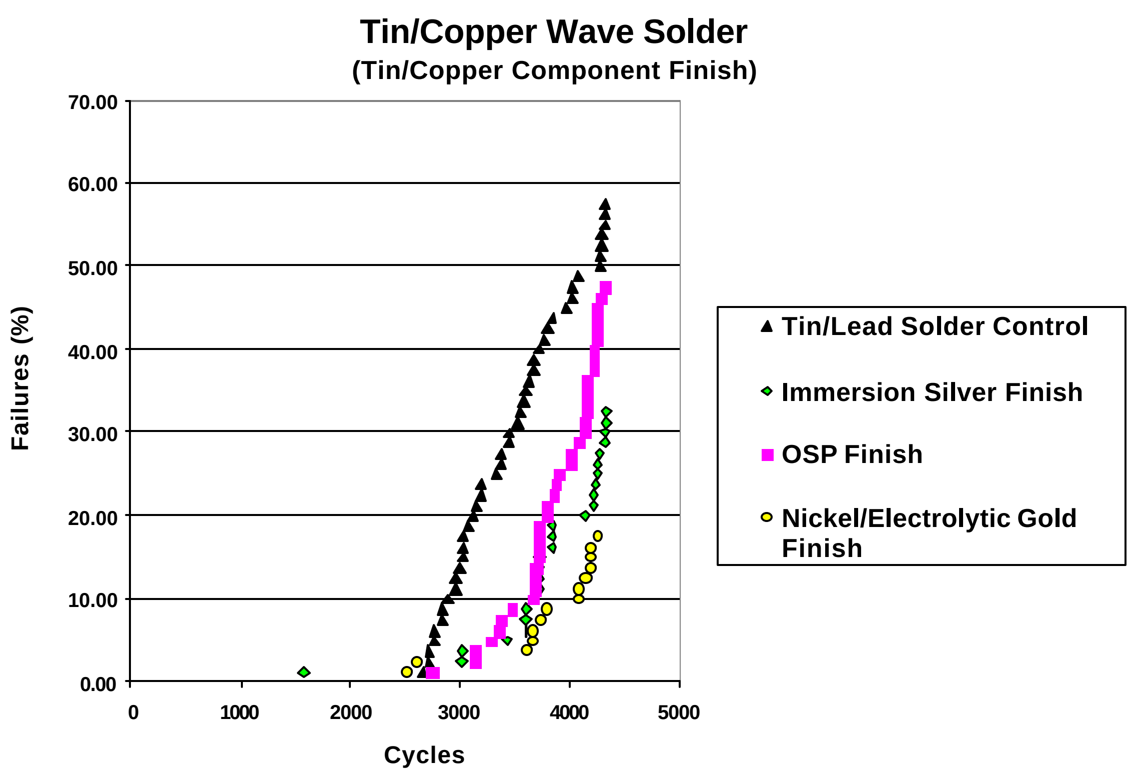

Figure 7. Reliability of Wave Soldered Sn/0.7%Cu Solder Joints on Various Board Finishes

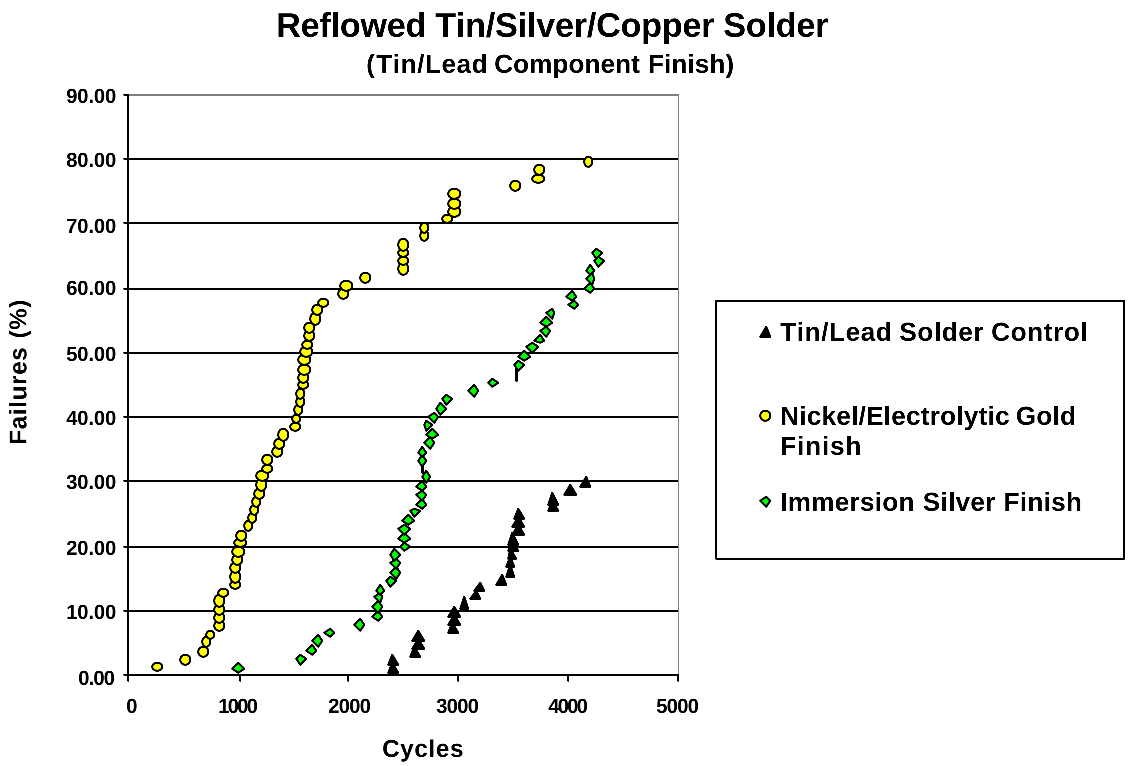

Figure 8. Reliability of Reflowed Sn/3.8%Ag/0.7%Cu Solder Joints (Contaminated with Lead) on Various Board Finishes

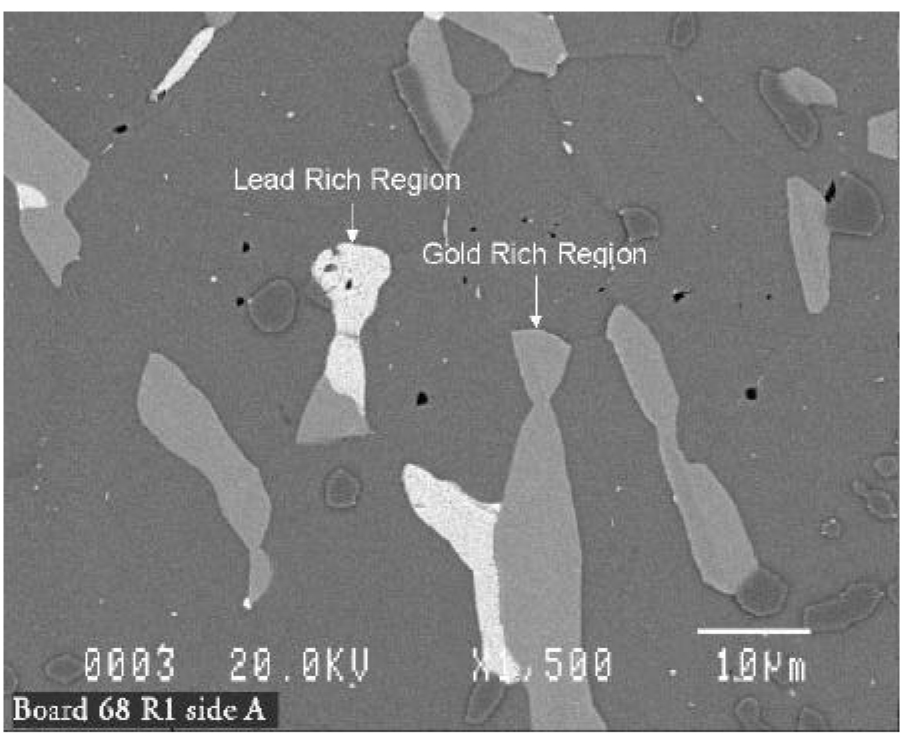

Figure 9. Cross Section of Sn/3.8%Ag/0.7%Cu Solder Joint Contaminated With Lead (Gold Board Finish; SEM Backscatter Image; 1500X)

Table 4. Leachate Test Results

Test Boards				
Board Finish	Silver	Silver	Silver	Silver
Solder Use For Reflow	Tin/Lead	Tin/Lead	Sn3.8Ag0.7Cu	Sn3.8Ag0.7Cu
Component Finish	Tin/Lead	Tin/Lead	Sn0.7Cu	Sn0.7Cu
Solder Use For Wave Solder	Tin/Lead	Tin/Lead	Sn0.7Cu	Sn0.7Cu
Conformal Coating Over Solder?	No	Yes	No	Yes
USEPA TCLP Leachate Test Results (mg/liter)				
Surface Area of Solder (sq.in.)	SnPb = 0.192	SnPb = 0.192	SnAgCu = 0.096 SnCu = 0.096	SnAgCu = 0.096 SnCu = 0.096
Silver	none detected	none detected	none detected	none detected
Copper	0.07	0.02	0.16	0.05
Lead	10.04	0.26	none detected	none detected
Tin	none detected	none detected	none detected	none detected
State of Texas Seven-Day Distilled Water Leachate Test Results (mg/liter)				
Surface Area of Solder (sq.in.)	SnPb = 0.192	SnPb = 0.128	SnAgCu = 0.096 SnCu = 0.096	SnAgCu = 0.064 SnCu = 0.064
Silver	none detected	none detected	none detected	none detected
Copper	0.05	0.07	0.04	0.04
Lead	2.30	0.09	none detected	none detected
Tin	0.07	none detected	0.09	none detected

Regulatory Limits			
Element	**Media**	**Limit (mg/liter)**	**Source**
Silver	TCLP Leachate	5.0	USEPA 40 CFR 261
Silver	Drinking Water	0.10	USEPA 40 CFR 141
Copper	TCLP Leachate	500	Various U.S. State regulations
Copper	Drinking Water	1.0	USEPA 40 CFR 141; Japanese
Copper	Drinking Water	2.0	98/83/EEC
Lead	TCLP Leachate	5.0	USEPA 40 CFR 261
Lead	Drinking Water	0.015	USEPA 40 CFR 141
Lead	Drinking Water	0.05	Japanese legislation
Lead	Drinking Water	0.010	98/83/EEC
Tin	All	None found	

Detection Limits (mg/liter)

Silver	0.01
Copper	0.02
Lead	0.05
Tin	0.05

APPENDIX D

The Effects of Trace Amounts of Lead on the Reliability of Six Lead-Free Solders

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The Effects of Trace Amounts of Lead on the Reliability of Six Lead-Free Solders

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Abstract
A test program was started in 2002 at Boeing for the evaluation of the reliability of six lead-free solders for reflow operations. The effects of trace amounts of lead (<1%) upon the reliability of the six solders was also evaluated since accidental or intentional mixing of lead and lead-free solders will occur during the transition to lead-free. The lead-free solders tested were: Sn3.8Ag0.7Cu; Sn3.4Ag4.8Bi; Sn3.5Ag; Sn0.7Cu; Sn3.4Ag1Cu3.3Bi; and 58Bi42Sn. Eutectic tin/lead solder was used as a control. A test vehicle was designed to accommodate ten dummy daisy-chained LCCC20 (leadless ceramic chip carrier) components on the topside. The test vehicles were assembled by a vapor phase reflow soldering process. After assembly, the test vehicles were thermally cycled and the failure rates of the lead-free solder joints were determined by electrically monitoring the solder joints during the test.

Boeing's test program was able to identify several solders that appear to have reliability equal to or greater than eutectic tin/lead. It was also shown that trace amounts of lead contamination improves the reliability of Sn3.8Ag0.7Cu and Sn3.5Ag but degrades the reliability of Sn0.7Cu and the bismuth–containing alloys. In the case of 58Bi42Sn, the effects of the lead contamination were catastrophic.

In addition to doing reliability studies, leachate testing was conducted on the six lead-free solders to determine if toxic metals could be leached out under conditions found in landfills. Any alternative materials used for lead-free solder joints must not leach out elements that could be even more toxic than the lead that they are replacing. For example, silver is relatively non-toxic to mammals but is very toxic to marine life.

The leachate testing demonstrated that the silver-containing solders did not leach detectable amounts of toxic silver. In contrast, the lead-containing control solder joints leached amounts of lead in excess of that allowed by Federal law.

Objective
The objective of this study was to conduct reliability testing on six lead-free solders in an attempt to find one whose long-term reliability is comparable to that of eutectic tin/lead solder. This study was initiated because earlier studies[1-4] have shown that the leading lead-free solder candidate for reflow operations (SnAgCu) was not as reliable as eutectic tin/lead solder when used with some component types (chip resistors and Alloy 42 TSOP's).

The effects of lead contamination upon the reliability of the six lead-free solders was also explored since the adoption of lead-free solders by industry might result in the accidental or intentional mixing of lead containing and lead-free solders.

Leachate testing on the six lead-free solder joints was also done to determine if they have the potential to leach toxic metals into landfill groundwater. Silver is of special interest since silver is toxic to marine life and many of the solders tested contained silver.

Approach
Long term reliability testing of the solders was conducted by soldering daisy-chained dummy electronic components onto printed wiring boards to create test vehicles. The test vehicles were then thermally cycled and the failure rates of the solder joints were determined by electrically monitoring the solder joints during the test.

Six lead free solders were selected for reliability testing. They were: Sn3.8Ag0.7Cu; Sn3.4Ag4.8Bi; Sn3.5Ag; Sn0.7Cu; Sn3.4Ag1Cu3.3Bi; and 58Bi42Sn. Eutectic tin/lead solder was used as a control solder.

The test vehicles used for the reliability testing of the six lead-free solders had an immersion silver board finish (5-7 microinches thick). A tin/lead HASL board finish was used on the control test vehicles (in conjunction with the tin/lead control solder). In addition, some reliability test vehicles combined a tin/lead HASL board finish with the lead-free solders in order to intentionally contaminate the lead-free solder joints with lead. This simulated the accidental or intentional mixing of tin/lead and lead-free solders (such as during a rework operation). The various combinations of solders and board finishes used on each test vehicle are shown in Table 1.

The components used for the lead-free reliability testing were LCCC20's (leadless ceramic chip carriers). LCCC's were chosen as the test components because they have a high failure rate during thermal cycling due to the large CTE mismatch between the LCCC and the circuit board. The higher failure rate means that fewer thermal cycles are needed to obtain enough solder joint failures for statistical analysis. The LCCC's used with the lead-free solders came from the vendor with a gold finish (over nickel-plated pads). Each LCCC was dipped into a molten solder pot to remove the gold and coat the nickel pads with a thin layer of solder. This dipping process also resulted in the castellations on each LCCC becoming filled with solder. Each LCCC was dipped into a static solder pot containing the same solder that would be used to attach the LCCC to the test vehicle. For example, if the solder paste to be used was Sn3.5Ag, the LCCC was dipped into a pot of molten Sn3.5Ag to coat the pads and fill the castellations. Each LCCC was dipped into flux and then into the molten solder where it was gently agitated back and forth for 15 seconds. The temperature of each solder pot was maintained at 500°F during the dipping operation. After dipping, the LCCC's were cleaned in detergent/water; rinsed in acetone; and dried in an oven at low heat.

A large flowing solder pot charged with eutectic tin/lead was used to dip the LCCC's for the tin/lead control test vehicles.

After the dipping process was complete, each solder pot was chemically analyzed to ensure that the gold content of the pots never reached a concentration that could cause gold embrittlement of the solder joints. None of the pots had a gold content exceeding 0.19%. The chemical analyses also verified the elemental composition of each solder alloy.

Each reliability test vehicle had pads for ten LCCC20's on the topside of the board. The LCCC's were labeled U1 through U10. Each test board was also engraved with an ID number. Pads on the periphery of the test vehicle were designed to be connected to an event detector so that the electrical continuity of the solder joints could be monitored during thermal cycling. Round and square test pads were also included in the board design so that wetting of the board finish by the various solders could be compared. A picture of the topside of a test board is shown in Figure 1. The boards were made from 0.062 in. thick Isola Laminate Systems' FR406 which has a glass transition temperature of 170°C and an LPI solder mask was used.

The test vehicles were assembled by reflow soldering ten components to the topside of each test vehicle using a CENTECH VP2000 vapor phase system. Eutectic tin/lead and the 58Bi42Sn solder pastes were reflowed using FC-5312 fluid (3M; b.p. 215°C). The balance of the lead-free solders were reflowed using FC-71 fluid (3M; b.p. 253-255°C). The reflow profiles for the solder pastes are shown in Figure 2. The stencil used was 8 mils thick with an aperture to pad ratio of 1. The metal percent by volume of each solder paste was calculated which revealed that the volumes of the finished solder joints (lead-free and tin/lead) should ideally be within 4% of each other (see Table 1).

After assembly, all test vehicles were cleaned in a semi-aqueous cleaning system. All of the test boards were then visually inspected and photographed to document the appearance of the solder joints. Solder joint cross-sections were also made.

Chemical analyses were conducted on those solder joints that had been intentionally contaminated with lead to determine the actual lead content. Fifteen solder joints of each type were removed from the test vehicles using a scapel. Each set of fifteen solder joints were dissolved in a mixture of nitric and hydrochloric acid and the solutions were analyzed by inductively coupled plasma (ICP) spectroscopy.

The test vehicles were then wired for reliability testing. The test vehicles were thermally cycled and the failures of the lead-free solder joints were determined by electrically monitoring the solder joints during the test. Solder joint failures were monitored with an AnaTech Event Detector and events were recorded on a LabView-based data acquisition system. The AnaTech was set to detect events greater than 1000 ohms in resistance and longer than 200 nanoseconds in duration. The thermal cycle (actual board temperature) was from minus 40°C to +125°C with 15 minute dwells at each temperature extreme and ramp rates of 7.9°C per minute during heating and 9.6°C per minute during cooling. The thermal cycling was continued for 3441 thermal cycles in order to get enough failures for Weibull analysis (Table 2).

Leachate testing on both the lead-free and the tin/lead solder joints was also done to determine if they have the potential to leach toxic metals into landfill groundwater. The USEPA TCLP test procedure (SW-846 Method 1311) was used. This method uses a buffered acetic acid solution (which simulates the water found in a landfill) for the extraction. Test vehicles were cut into test coupons; the coupons were weighed; and then the coupons were extracted with the leachant. Chemical analysis of the leachates were done for silver, bismuth, copper, lead, and tin.

Results and Discussion

After assembly and cleaning, the test boards were visually inspected. No significant flux residues remained on any of the solder joints after the cleaning step. Figure 3 show the appearance the LCCC solder joints that were not contaminated with lead. In general, the lead-free solder joints were very grainy and/or striated in appearance. In contrast, the tin/lead solder and the 58Bi42Sn joints were smooth and shiny. The addition of <1% of lead didn't have a major effect on the appearance of any of the lead-free solder joints.

Four solder joints of each solder type were cross-sectioned and representative cross-section photos are shown in Figure 4. One observation was that for Sn3.4Ag1Cu3.3Bi, the height of the solder under each LCCC (the heel fillet) was much smaller than for the other solders (yet this solder would turn out to have superior reliability).

The results of the chemical analyses of the solder joints contaminated with lead are shown in Table 3. The concentration of lead in the contaminated solder joints ranged from 0.23% to 0.90%.

In the case of the 58Bi42Sn solder, the trace amount of lead had an eventual catastrophic effect on the appearance and reliability of the solder joints. Figure 5 shows 58Bi42Sn solder joints with no lead contamination after 835 thermal cycles. The appearance of these solder joints is normal. In contrast, Figure 6 shows the 58Bi42Sn solder joints contaminated with 0.23% of lead after 835 thermal cycles. These joints have become extremely porous and have numerous tendrils which bridge over to the adjacent solder joints. At this point, the solder joints are extremely fragile and components have fallen off the test vehicles. A cross section of a Pb-contaminated 58Bi42Sn solder joint is shown in Figure 7. The porosity of the solder joint can be easily seen. Figure 8 shows a SEM photograph of a second contaminated 58Bi42Sn solder joint. Elemental maps for Bi and Sn were created using EDS (energy dispersive x-ray spectroscopy). Large Sn-rich and Bi-rich regions can be seen. The catastrophic effects observed are most likely due to the formation of low melting ternary and binary eutectic phases (16Sn32Pb52Bi, m.p. 96°C; 43.5Pb56.5Bi, m.p. 125°C) which melt/soften allowing redistribution of material within the solder joint[5].

After 3441 thermal cycles, enough solder joints on the reliability test vehicles had failed to allow statistical analysis of the data. The one exception was the 58Bi42Sn which had only two failures when the test was ended. The reliability data from the thermal cycling test was plotted using two parameter Weibull plots. Plotting unreliability F(t) vs. number of thermal cycles yielded a beta (shape) parameter and an alpha (characteristic life) parameter for each combination of solder and board finish (see Table 2). The characteristic life is the number of cycles required to fail 63.2% of the components.

The results were also plotted as % failures (components) vs. number of cycles. Figure 9 shows the reliability plots for all of the candidate lead-free solders and the tin/lead control. The data shows that the Sn3.8Ag0.7Cu and Sn3.5Ag solder joints have essentially all failed before the first tin/lead control failure occurs. Sn0.7Cu appears slightly more reliable but only the bismuth containing solders equal or exceed the reliability of the tin/lead control. If one ignores the 58Bi42Sn data, Sn3.4Ag1Cu3.3Bi appears to be the most reliable solder with its first failure occurring at 1624 cycles vs. 878 cycles for the tin/lead control (see Table 2). The characteristic life (alpha) of Sn3.4Ag1Cu3.3Bi is only slightly less than that of the tin/lead control (2935 vs. 3350 cycles).

At first glance, the 58Bi42Sn solder would appear to be the most reliable solder. However, there is evidence to suggest that when you use a thermal cycle whose high end is too close to the melting temperature of the solder, the solder will have a greatly reduced failure rate due to a postulated "crack healing" mechanism[2]. The solder will appear to have excellent reliability but its actual performance at more realistic use temperatures will be much poorer. 58Bi42Sn has a melting temperature of 138°C which is very close to the upper temperature of the thermal cycle used in this study (i.e., 125°C).

Figure 10 shows the reliability plot of the tin/lead control. Figures 11 through 16 show the reliability plots of the individual solders and how trace amounts of lead affect the reliability of each solder. As can be seen in Figures 11 and 13, Sn3.8Ag0.7Cu and Sn3.5Ag actually show enhanced reliability when trace amounts of lead are present. A similar enhancement was seen in Boeing's 2002 study[1] where tin/lead plated 1206 chip resistors were reflowed soldered onto a test vehicle using Sn3.8Ag0.7Cu solder paste. The tin/lead plating on the chip resistors contaminated the solder joints with lead (3.5% by EDS) and increased the reliability of the solder joints substantially.

The effects of lead contamination on the reliability of SnAgCu solder joints on components that are more compliant than LCCC's is uncertain. One study testing BGA's with SnAgCu showed a decrease in reliability[6] while another BGA study showed a slight increase in reliability due to the lead contamination[3].

The bismuth-containing solders and Sn0.7Cu all experienced a negative effect on reliability due to trace amounts of lead. The effects are catastrophic only in the case of 58Sn42Bi, however, as previously discussed. Even when contaminated with lead, the reliability of Sn3.4Ag1Cu3.3Bi is better than that of uncontaminated Sn3.8Ag0.7Cu.

Recent SnAgCu reliability studies[1-4, 7-12] suggest that SnAgCu performs better than tin/lead when the component has a coefficient of thermal expansion (CTE) similar to that of the circuit board but does not perform as well when the CTE of the component differs from that of the circuit board. The CTE of ceramic components, such as chip resistors, is much less than the CTE of most circuit boards and the mismatch between the component and the board applies a lot of stress to the solder joints. Since chip resistors and other ceramic components are used on many circuit boards, they may be the “weakest link” where lead-free solders are concerned.

The available data also suggests that the reliability of SnAgCu relative to tin/lead can increase as the magnitude of the temperature cycle decreases (e.g., going from a -55° to +125°C cycle to a 0° to +100°C cycle). However, the limited data available[2,3] shows that for ceramic components, SnAgCu is still inferior to tin/lead eutectic when cycled from 0° to +100°C.

More reliability testing of lead-free solders at various thermal cycles will need to be done so that acceleration factors can be calculated. These acceleration factors are required so that accelerated thermal cycling results can be extrapolated to more realistic use conditions.

The leachate test results for silver, bismuth, copper, lead, and tin are given in Table 4. Table 5 gives the regulatory limits for TCLP leachates and for drinking water[13]. The real elements of concern are silver (which can be toxic to marine life) and lead (which is a neurotoxin, a haematotoxin, a teratogen, and possibly carcinogenic). Bismuth, copper, and tin are relatively non-toxic. The leachate testing showed that none of the reflowed lead-free solders containing silver leached detectable amounts of silver. Eutectic tin/lead solder joints, on the other hand, leached amounts of lead well in excess of that allowed by Federal law (5.0 mg/liter) under TCLP conditions. This suggests that printed wiring assemblies made with silver-containing solders have little risk of being considered hazardous waste due to leaching of toxic silver. The surface area of the tin/silver/copper solder joints would have to be increased to at least 152.5 square inches before regulatory limits for silver would be exceeded (assuming the weight of the leachate specimen remained the same).

Summary

Accelerated thermal cycling of the six lead-free solders using ceramic components revealed the following:

Reflowed Sn3.8Ag0.7Cu, Sn3.5Ag and Sn0.7Cu solder joints are less reliable than eutectic tin/lead.

Sn3.4Ag4.8Bi is approximately as reliable as eutectic tin/lead (with a better first failure number but a worse characteristic life number).

Sn3.4Ag1Cu3.3Bi is more reliable than eutectic tin/lead (with a much better first failure number and an equivalent characteristic life number). Based upon the reliability test results, Sn3.4Ag1Cu3.3Bi appears to be a good candidate to replace reflowed eutectic tin/lead in high reliability electronics.

The current study also suggests that trace amounts of lead can increase the reliability of Sn3.8Ag0.7Cu and Sn3.5Ag but decreases the reliability of Sn0.7Cu and the bismuth–containing solders. The effects of trace amounts of lead on 58Bi42Sn are catastrophic with the solder joints essentially turning to powder during thermal cycling. This effect is probably due to the formation of a low melting 16Sn32Pb52Bi phase.

The leachate testing conducted in this study suggests that the silver-containing solders are not likely to be considered hazardous waste because of their low potential to leach silver (which is very toxic to marine life).

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Table 1. Test Vehicle Matrix

Solder Paste	Board Finishes	Solder Alloy Melting Point	Alloy Loading in Paste by Volume (%)	Reflow Method
63Tin37Lead	Sn/Pb HASL	183°C	52	Vapor Phase (Fluid FC-5312)
Sn3.8Ag0.7Cu	Immersion Ag and Sn/Pb HASL	217°C	52	Vapor Phase (Fluid FC-71)
Sn3.4Ag4.8Bi	Immersion Ag and Sn/Pb HASL	213°C	51	Vapor Phase (Fluid FC-71)
Sn3.5Ag	Immersion Ag and Sn/Pb HASL	221°C	52	Vapor Phase (Fluid FC-71)
Sn0.7Cu	Immersion Ag and Sn/Pb HASL	227°C	50	Vapor Phase (Fluid FC-71)
Sn3.4Ag1Cu3.3Bi	Immersion Ag and Sn/Pb HASL	214°C	52	Vapor Phase (Fluid FC-71)
58Bi42Sn	Immersion Ag and Sn/Pb HASL	138°C	50	Vapor Phase (Fluid FC-5312)

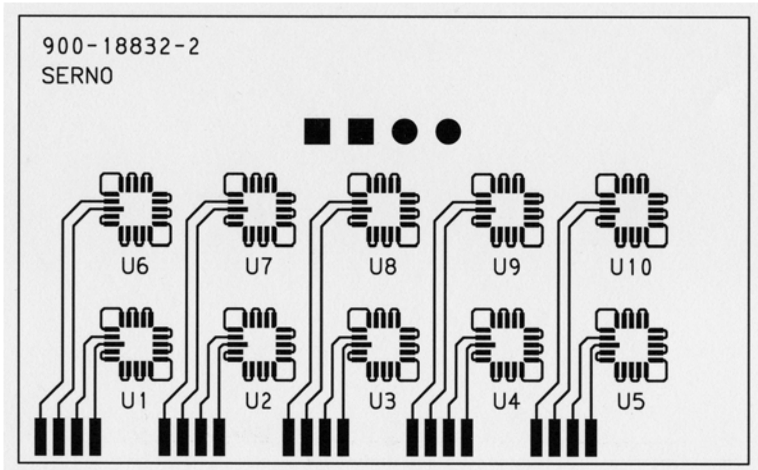


Figure 1. Test Board Design

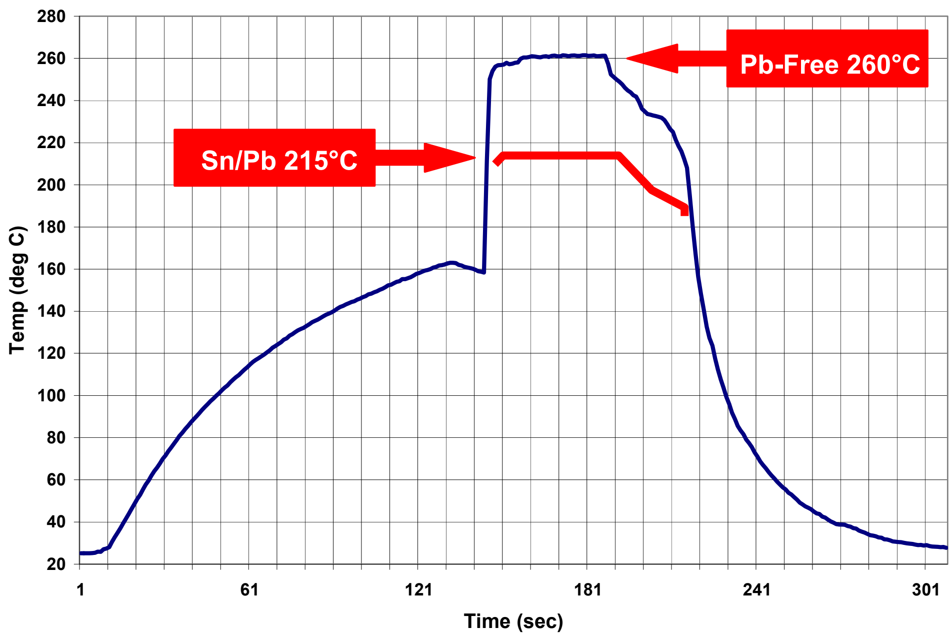


Figure 2. Solder Reflow Profiles

Table 2. Weibull Parameters

Solder	% Pb Contamination	First Failure	Characteristic Life	Beta
63Sn37Pb	N/A	878	3350	2.20
Sn3.8Ag0.7Cu	None	425	802	5.73
Sn3.4Ag4.8Bi	None	937	2342	3.87
Sn3.5Ag	None	468	806	5.50
Sn0.7Cu	None	756	1142	6.02
Sn3.4Ag1Cu3.3Bi	None	1624	2935	4.71
58Bi42Sn	None	2171	N/A	N/A
Sn3.8Ag0.7Cu	0.50	709	996	7.40
Sn3.4Ag4.8Bi	0.78	267	822	3.15
Sn3.5Ag	0.67	442	1205	3.64
Sn0.7Cu	0.32	396	591	6.63
Sn3.4Ag1Cu3.3Bi	0.90	800	1810	3.11
58Bi42Sn	0.23	614	844	9.23

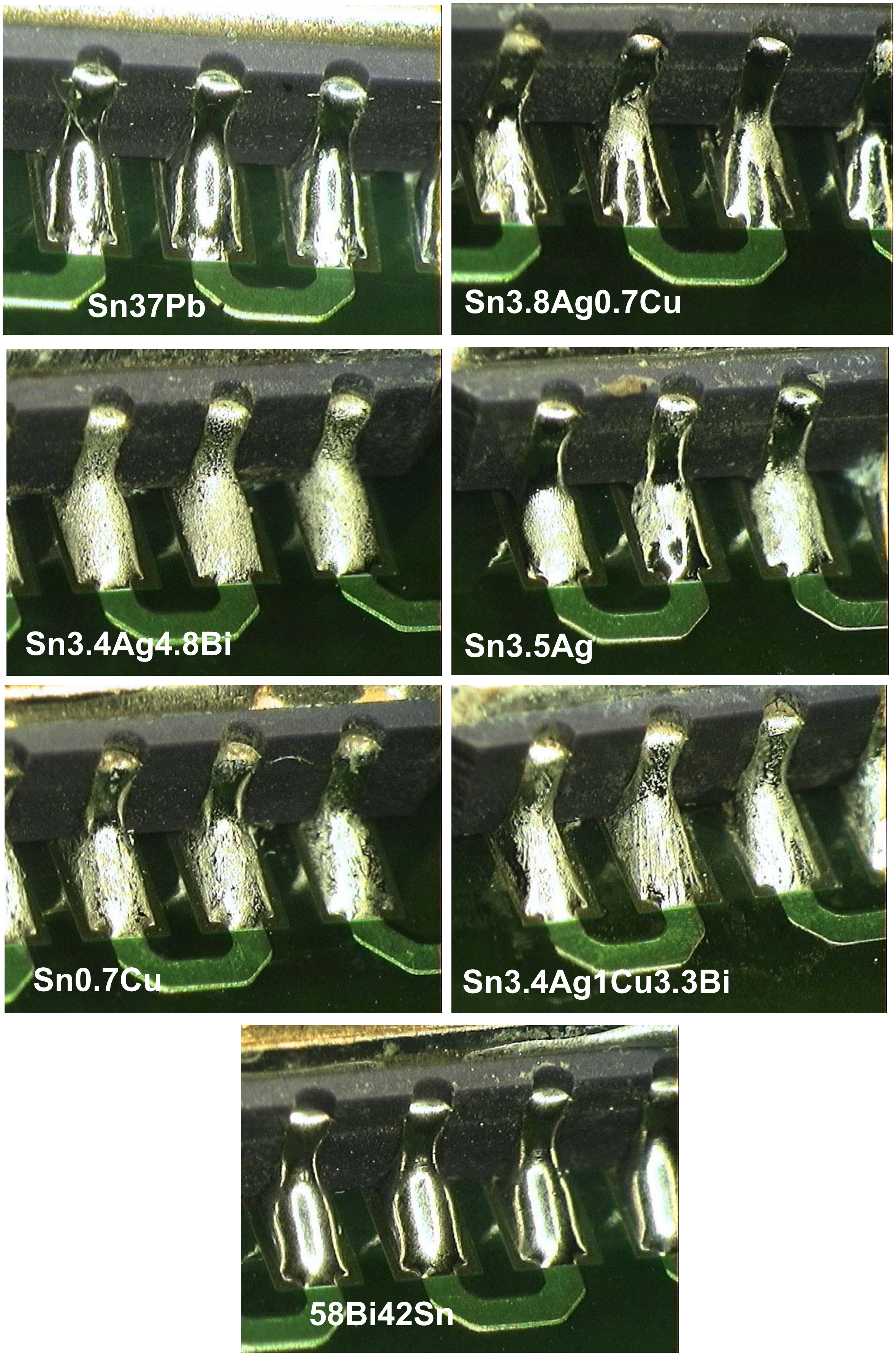


Figure 3. Solder Joint Appearances

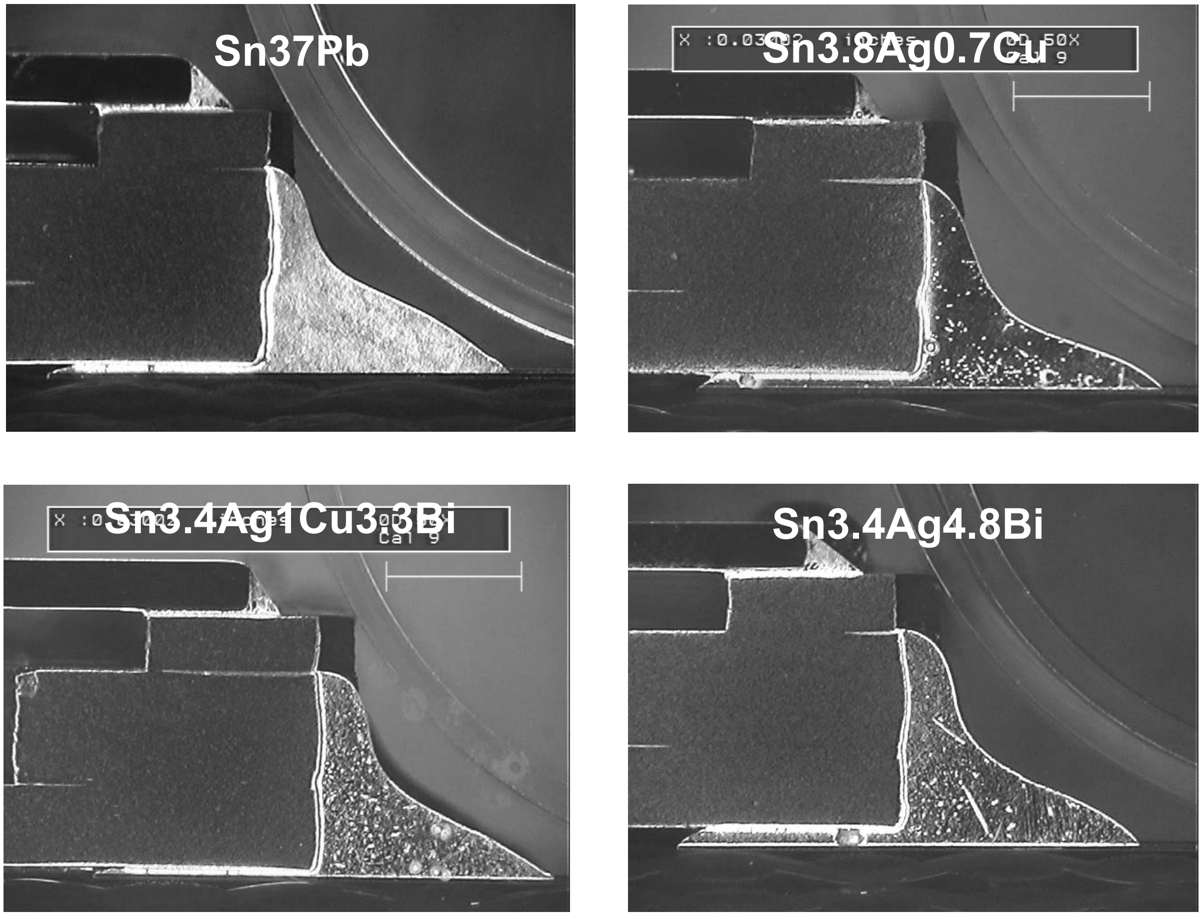


Figure 4. Representative Solder Joint Cross Sections

Table 3. Chemical Analysis of Solder Joints Contaminated with Lead

	% By ICP Spectroscopy				
Original Solder Alloy	**Ag**	**Cu**	**Pb**	**Sn**	**Bi**
95.5Sn3.8Ag0.7Cu	3.61	1.31	0.50	94.56	0.01
91.8Sn3.4Ag4.8Bi	3.19	0.96	0.78	90.24	4.84
92.3Sn3.4Ag1Cu3.3Bi	3.22	1.09	0.90	91.45	3.35
58Bi42Sn	0	1.50	0.23	42.77	55.49
96.5Sn3.5Ag	3.33	0.99	0.67	94.99	0.02
99.3Sn0.7Cu	0	1.09	0.32	98.56	0.02
63Sn37Pb	0	0.41	36.66	62.89	0.03

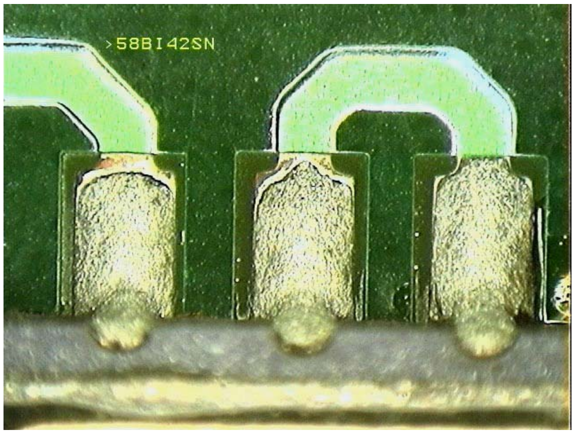


Figure 5. 58Bi42Sn Solder Joints (after 835 Thermal Cycles)

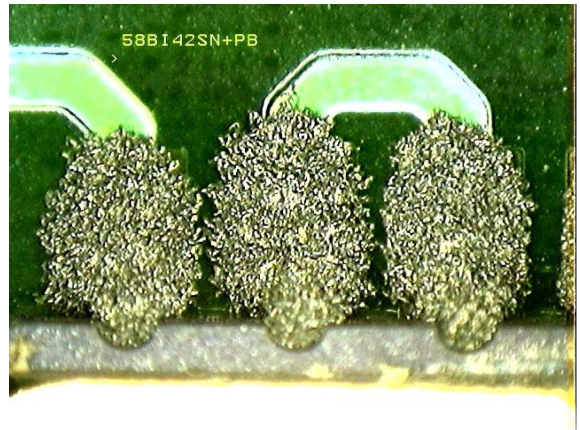


Figure 6. 58Bi42Sn Solder Joints Contaminated with Pb (after 835 Thermal Cycles)

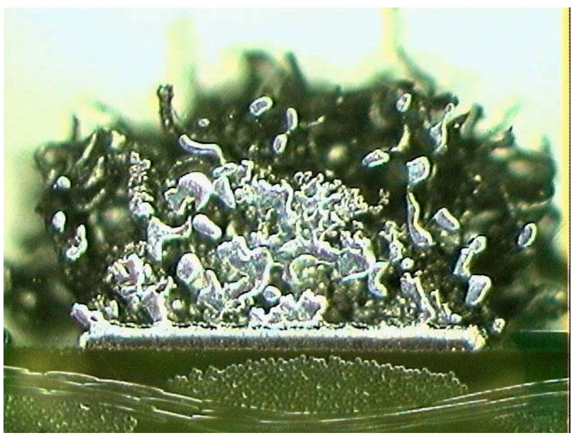
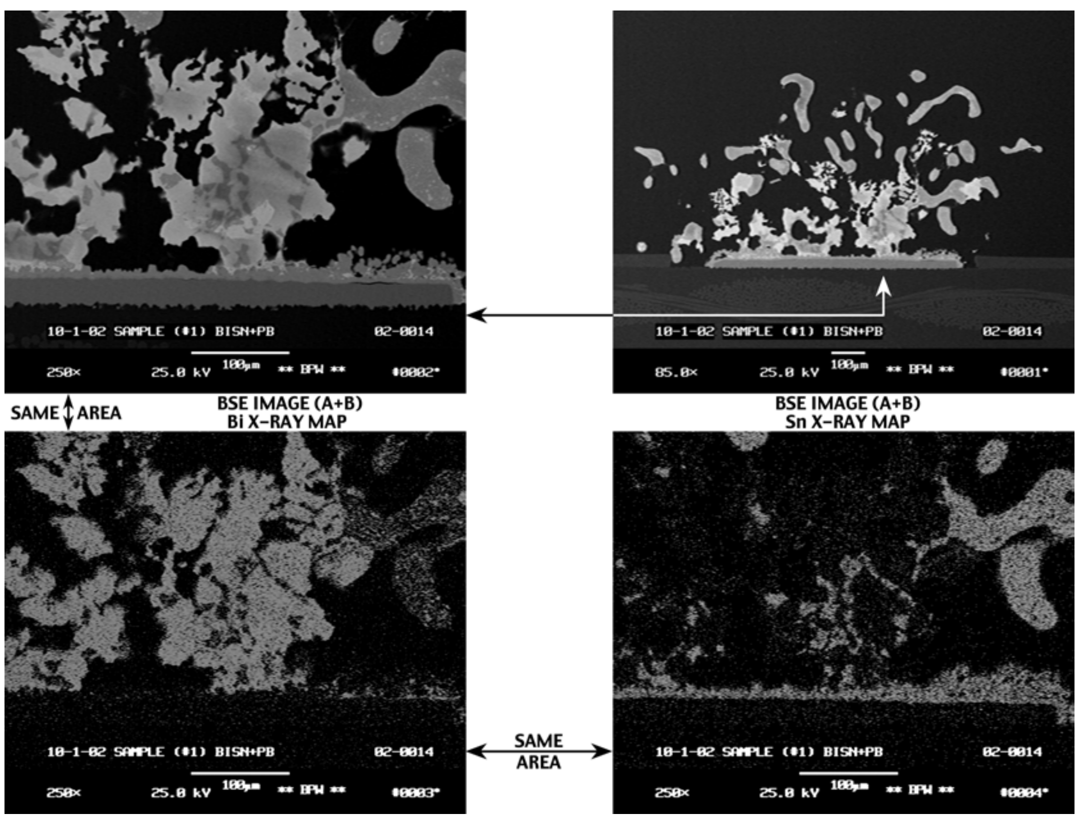


Figure 7. Cross Section of 58Bi42Sn Solder Joint Contaminated with Pb (after 835 Thermal Cycles)

Figure 8. EDS Elemental Maps of a 58Bi42Sn Solder Joint Cross Section Contaminated with Pb (after 835 Thermal Cycles)



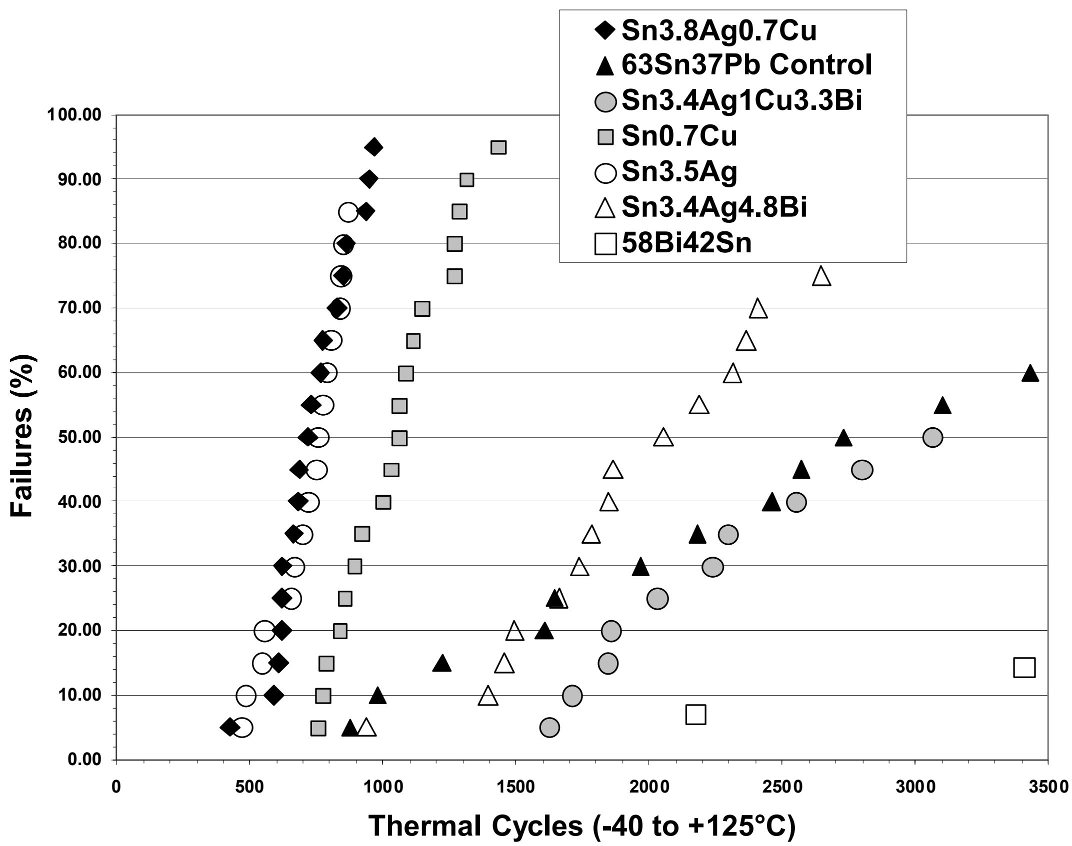


Figure 9. Reliability of the Reflowed Solder Joints

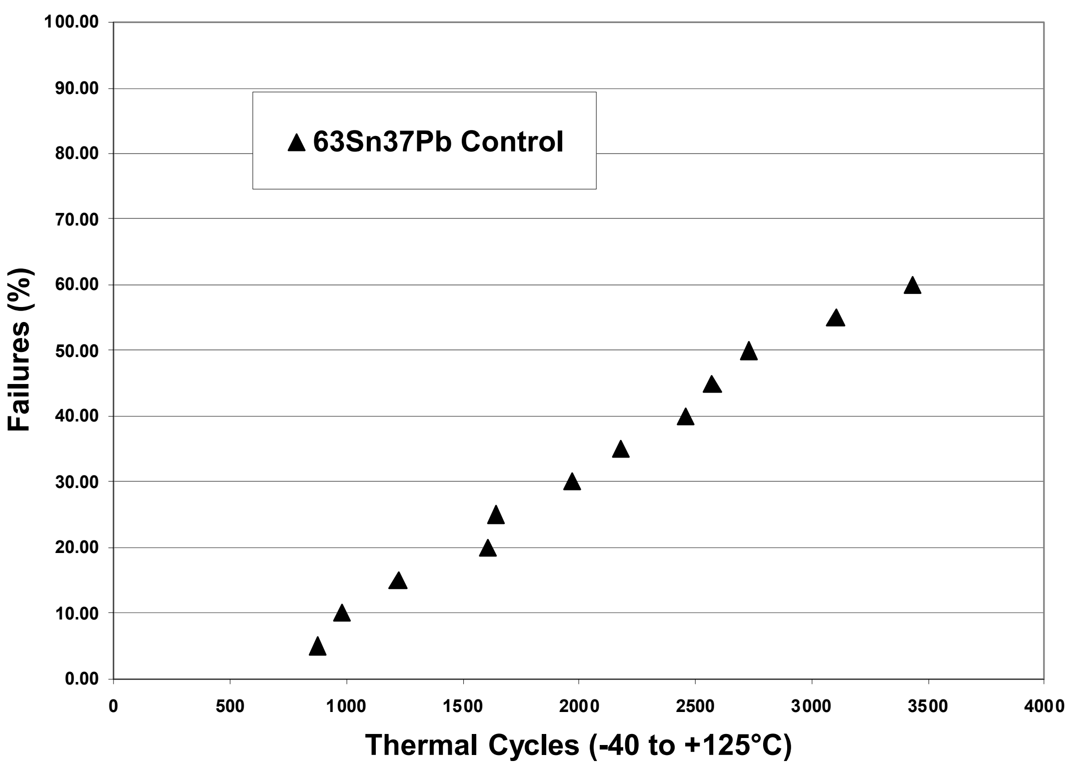


Figure 10. Reliability of 63Sn37Pb Solder on Sn/Pb HASL

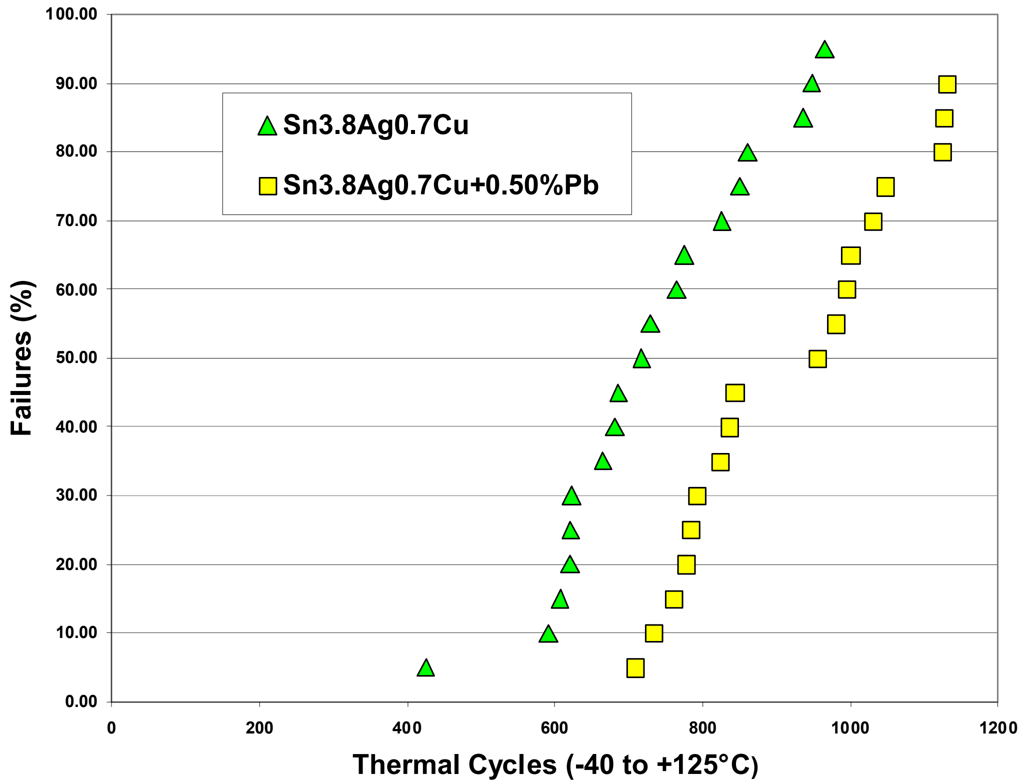


Figure 11. Reliability of Sn3.8Ag0.7Cu Solder (with and without Pb Contamination)

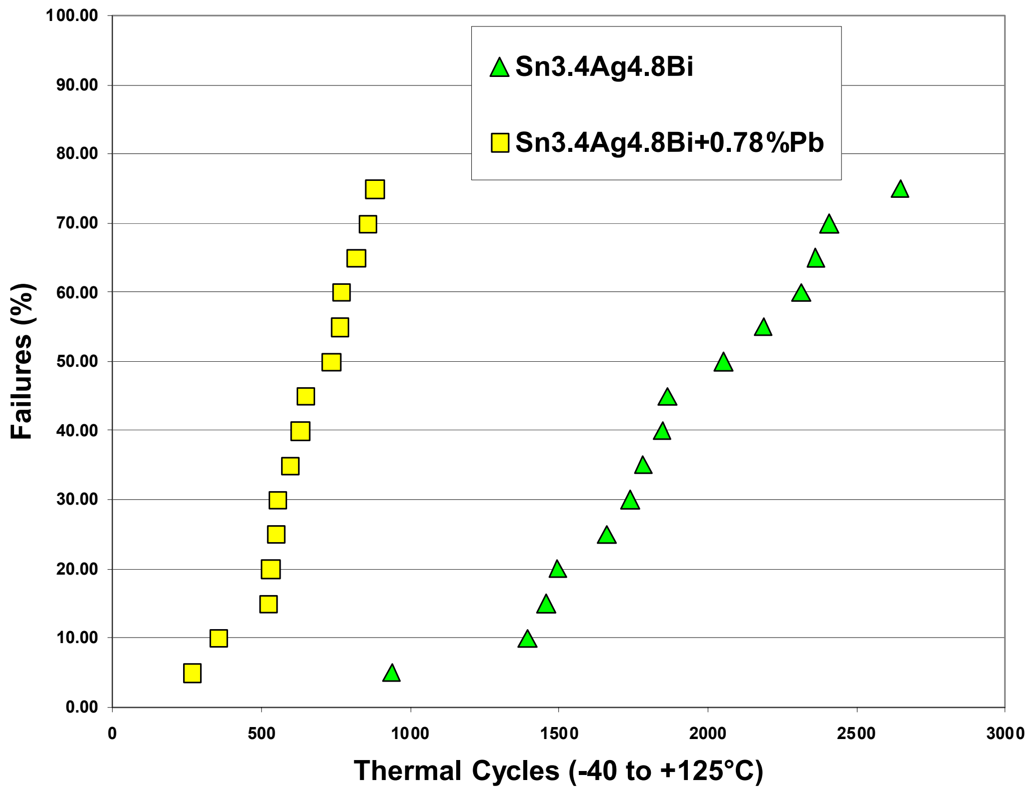


Figure 12. Reliability of Sn3.4Ag4.8Bi Solder (with and without Pb Contamination)

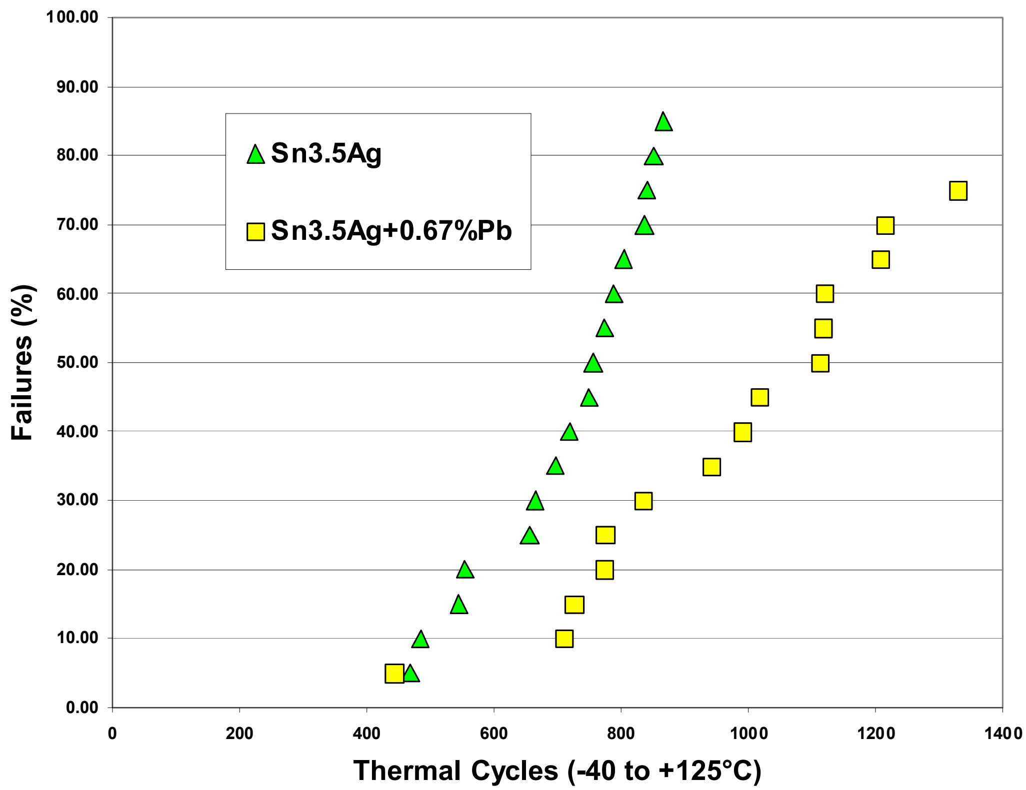


Figure 13. Reliability of Sn3.5Ag Solder (with and without Pb Contamination)

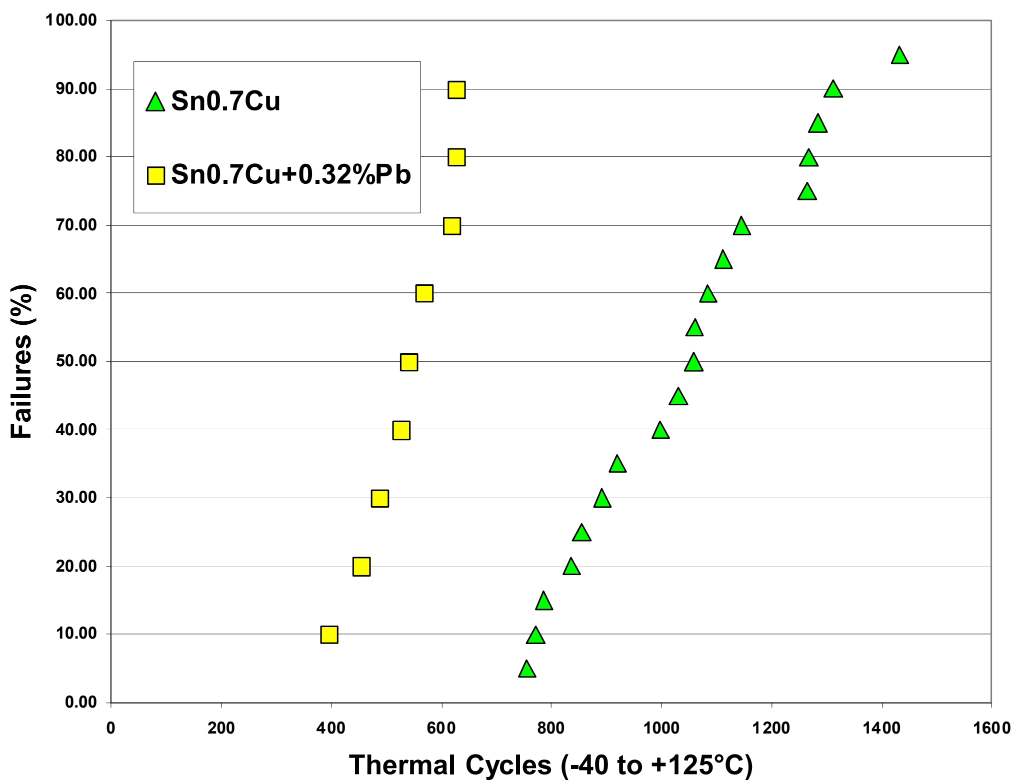


Figure 14. Reliability of Sn0.7Cu Solder (with and without Pb Contamination)

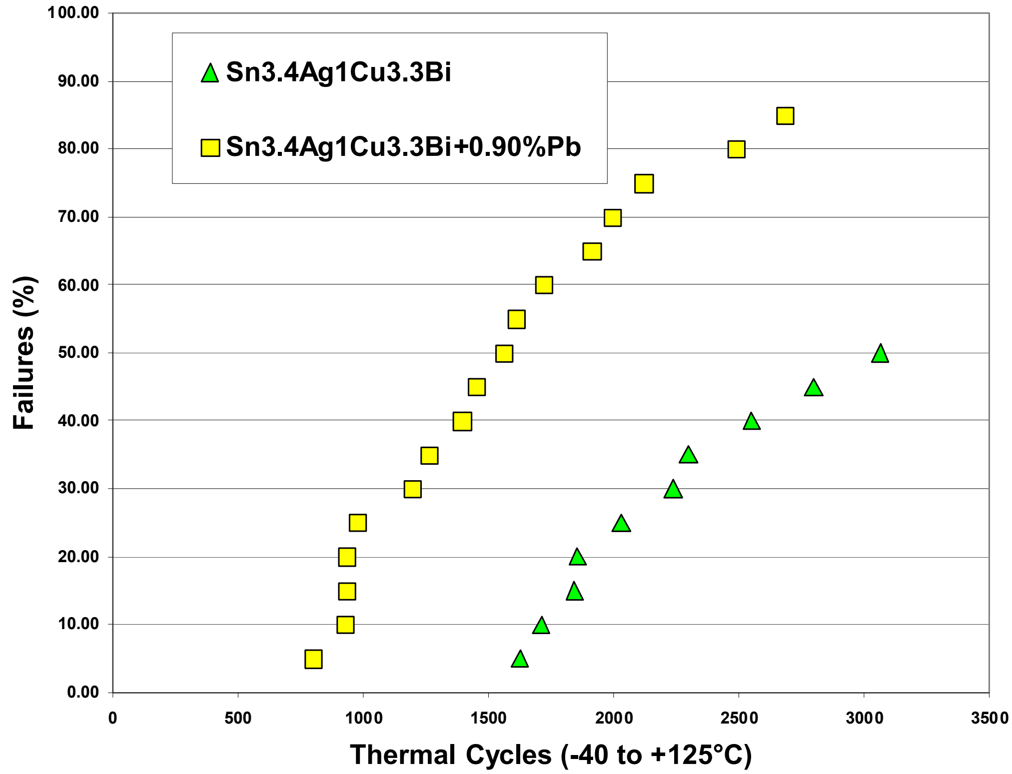


Figure 15. Reliability of Sn3.4Ag1Cu3.3Bi Solder (with and without Pb Contamination)

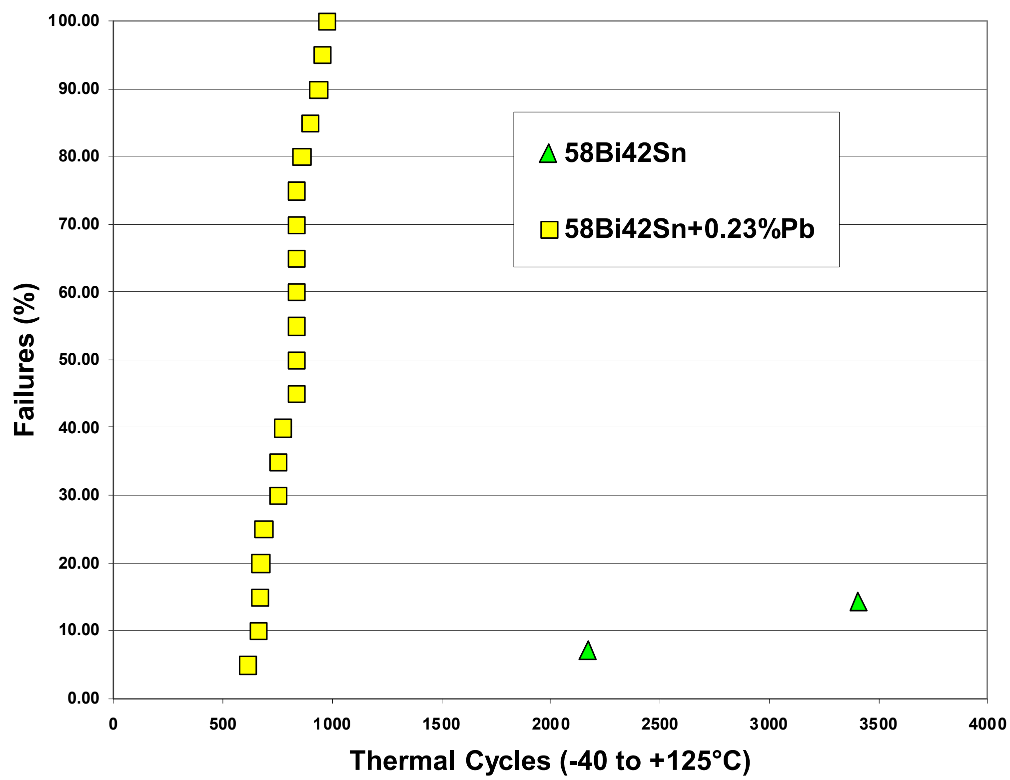


Figure 16. Reliability of 58Bi42Sn Solder (with and without Pb Contamination)

Table 4. Leachate Test Results

Solder	Sample Weight (grams)	Solder Area (sq. in.)	Ag (mg/L)	Bi (mg/L)	Cu (mg/L)	Pb (mg/L)	Sn (mg/L)
63Sn37Pb	6.6	0.305	nd	nd	nd	**35.7***	nd
Sn3.8Ag0.7Cu	6.6	0.305	nd	nd	nd	nd	**0.13**
Sn3.4Ag4.8Bi	6.8	0.305	nd	**0.09**	**0.05**	nd	**0.15**
Sn3.5Ag	6.7	0.305	nd	nd	**0.02**	nd	**0.17**
Sn0.7Cu	6.7	0.305	nd	nd	**0.01**	nd	**0.20**
Sn3.4Ag1Cu3.3Bi	6.7	0.305	nd	**0.06**	**0.03**	nd	**0.14**
58Bi42Sn	6.7	0.305	nd	**12.7**	**0.09**	nd	nd
Detection Limits (mg/L)			0.01	0.02	0.01	0.05	0.10

***Exceeds regulatory limits** **nd = none detected**

Table 5. Regulatory Limits for Leachates and Drinking Water

Regulatory Limits			
Element	**Media**	**Limit (mg/liter)**	**Source**
Silver	TCLP Leachate	5.0	USEPA 40 CFR 261
Silver	Drinking Water	0.10	USEPA 40 CFR 141
Copper	TCLP Leachate	500	Various U.S. State regulations
Copper	Drinking Water	1.0	USEPA 40 CFR 141; Japanese
Copper	Drinking Water	2.0	98/83/EEC
Lead	TCLP Leachate	5.0	USEPA 40 CFR 261
Lead	Drinking Water	0.015	USEPA 40 CFR 141
Lead	Drinking Water	0.05	Japanese legislation
Lead	Drinking Water	0.010	98/83/EEC
Bismuth	All	None found	
Tin	All	None found	

Reference: Edwin B. Smith, "Environmental Impacts and Toxicity of Lead-Free Solders", IPCWorks '99

APPENDIX E
Environmental Impacts and Toxicity of Lead Free Solders

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Environmental Impacts and Toxicity of Lead Free Solders

Including Japanese and European Union Regulations

Abstract

It is clear that lead free soldering is a foregone conclusion. There are several alternatives under investigation, some of which are already in use. These investigations of the various lead free solder alloy candidates have been in progress for the past few years. Researchers have been determining the solder alloys' physical and mechanical properties, environmental impacts, and occupational toxicity. This paper seeks to continue the research into the environmental impacts of lead free alloys. Comparisons are made between seven lead free solder alloys: Tin/Silver/Copper, Tin/Silver, Tin/Copper, Tin/Antimony, Tin/Indium, Tin/Silver/Bismuth, and Tin/Bismuth. These alloys were tested in the various physical forms most likely to occur from PCB fabrication, assembly, and finished product disposal to determine the environmental impact from each alloy. The goal of this research is not to say "no" to lead free solders, but to assist the industry in selecting the best alloy from the many available alternatives.

Waste Regulation Worldwide

Management of waste in industrialized countries ranges from highly regulated, specific, government controlled operations to practical non-existence. Within this range falls most industrialized countries which significantly regulate industrial/commercial hazardous waste, with or without also regulating household hazardous waste disposal. Hazardous waste is defined as any waste that may "pose a substantial present or potential threat to human health and the environment when improperly treated, stored, transported, or otherwise managed". When waste is disposed it is weathered by rainfall and reactions with other wastes, which allows metal elements and their salts to be leached from the metal surfaces of the waste. If the metal bearing leachate is allowed to contact stormwater, groundwater, or to migrate into groundwater, local drinking water supplies are threatened with contamination.

Deionized Water Leach Methods

Many members of the European Community, including France and Germany, as well as Japan utilize deionized (demineralized) water leaching tests. A draft European Community test method also specifies deionized water leaching. The State of Texas also publishes a seven day deionized water leach method. These methods are used to demonstrate the contamination potential to drinking water and groundwater from a waste that comes into contact with drinkable water. A portion of the material under study is mixed with some multiple of its weight in deionized water, shaken or tumbled for a specified time, then allowed to leach while being shaken, tumbled, or undisturbed. Table one highlights each leach method. After the appropriate leach time the liquid leachate is then filtered and analyzed for the constituents of interest. If the leachate shows contaminants higher than the local drinking water standards or other regulatory limits, the waste material is considered to have failed the test.

Table one. Summary of the Various Leach Methods Employed

Jurisdiction	Method Name	Leach Media	pH of Leach Media	Dilution Factor
United States	TCLP	Acetic acid, buffered	4.88	20
United States	SPLP	Nitric + Sulfuric Acids	5.00	20
California (USA)	STLC	Citric acid, buffered	5.00	10
European Community	PrEN	Deionized water	Neutral	10
Japan	JST-13	Deionized water	neutral	10

More Aggressive Leach Methods

Aside from the deionized water leaching methods there are methods which utilize leaching fluids containing various acids. These methods are used both to simulate acid rain and to simulate improper waste disposal- mixing household waste with industrial waste in the same disposal unit. The Synthetic Precipitation Leaching Procedure (SPLP) developed by the USEPA is one such test. The leaching fluid in this test contains nitric and sulfuric acids, diluted to a pH of 5.00. Some European environmental authorities use a similar leaching fluid. These fluids contain either sulfuric acid or sodium nitrate. The Toxicity Characteristic Leaching Procedure (TCLP) was developed by USEPA for determining whether a waste was hazardous by virtue of its toxicity. TCLP fluid contains dilute (pH

5.0) acetic acid, which mimics the organic acids typically found in landfill leachate where household waste is disposed in the landfill. Consumers typically dispose of their used electronic products by “throwing them in the trash”, so this scenario of electronics being disposed with food and other household waste is highly plausible. The State of California promulgates a Soluble Threshold Leaching Concentration (STLC) test, which utilizes citric acid to mimic the landfill disposal scenario and its effects on waste leaching.

Metal Toxicity and Regulatory Agency Impacts 3
There are existing environmental and toxicological regulations on both lead and lead free solder alloying elements. Among these are the following:

Silver and silver compounds can cause biological effects such as digestive tract irritation and agryria, which is characterized by a permanent blue-gray pigmentation of the skin, eyes, and mucous membranes. Ecotoxicity, reproductive effects, and mutagenicity have been observed in laboratory studies; however, toxicological data has not been fully investigated.

Antimony and antimony compounds can cause biological effects such as severe digestive tract irritation with abdominal pain, nausea, vomiting, and diarrhea. Toxicological data has not been fully investigated; however, antimony carries one of the lowest allowable concentration limits in drinking water.

Copper and copper compounds can cause biological effects such as severe digestive tract irritation with abdominal pain, nausea, vomiting, and diarrhea. Ecotoxicity has been observed in laboratory studies; however, toxicological data has not been fully investigated.

Indium and indium compounds have shown developmental toxicity in rats and mice. Particular symptoms of this developmental toxicity include fetal mortality, fetal malformation, reduced fetal weight, and malformations in the tail, ribs, digits, and kidneys. Ecotoxicity and mutagenicity have been observed in laboratory studies; however, more toxicological studies are needed.

Bismuth and/or bismuth compounds have been suggested to be a carcinogen or a co-carcinogen in rats. Also, some studies have shown that bismuth can cause chromosomal aberrations in rats. More epidemiological studies are required for a more complete determination. Little has been studied as to the potential toxic effects of bismuth.

There are regulatory concerns for the lead replacement metals regarding environmental impact and use in the workplace. PCB manufacturers and PCBA assemblers moving to lead free solder materials will need to evaluate these new materials in the workplace for environmental permitting, management, and industrial hygiene issues.

Silver and silver compounds - regulated under Superfund, SARA 313, RCRA, Clean Water Act Toxic Pollutant, California State Superfund Hazardous Substances, CAL-OSHA Director’s List of Hazardous Substances, and California HWCL Hazardous Wastes.

Antimony and antimony compounds - regulated under Superfund, SARA 313, Clean Air Act Hazardous Air Pollutant, Clean Water Act Toxic Pollutant, California State Superfund Hazardous Substances, CAL-OSHA Director’s List of Hazardous Substances, and California HWCL Hazardous Wastes.

Copper and copper compounds - regulated under Superfund, SARA 313, Clean Water Act Toxic Pollutant, California State Superfund Hazardous Substances, CAL-OSHA Director’s List of Hazardous Substances, and California HWCL Hazardous Wastes.

Except for the bismuth and indium radionuclides, bismuth and indium and their compounds are not heavily regulated by federal and state authorities. If bismuth and indium alloys are selected by the industry, their use will dramatically increase. Regulation may follow as environmental agencies deem them an adverse impact to the environment, and as the electronics industry solidifies a commitment to a given alloy or a few alloys.

The State of California, in addition to its use of the STLC and the USEPA TCLP test, also provides regulations for the Total Threshold Limit Concentration (TTLC). The TTLC is simply a measure of the physical composition of the substance under study, with no regard for its leachability. Substances containing regulated elements or compounds over the TTLC value are deemed hazardous by the State of California. Table one shows the current STLC and TTLC values, along with the associated maximum percentages a solder alloy can contain without failing the TTLC value.

Table Two. California STLC and TTLC Values for Common Solder Metal Alloys

Substance	STLC, mg/l	TTLC, mg/kg	Allowable Percent in Alloys (per TTLC value)
Antimony & cmpds	15	500	0.05
Cadmium & cmpds	1.0	100	0.010
Copper & cmpds	25	2,500	0.25
Lead & cmpds	5.0	1,000	0.10
Nickel & cmpds	20	2,000	0.20
Silver & cmpds	5.0	500	0.05
Zinc & cmpds	250	5,000	0.50

These element allowances are much smaller than alloys currently under investigation as lead free alternatives. In fact, they are much less than amounts which would be expected to materially change the properties of any tin based solder. This provides a significant issue for California based assemblers and fabricators. There is nor will there likely be a lead free alloy which will prove to pass TTLC values and thus be non-hazardous under California law.

The Surface Mount Council in its report[4] earlier this year gives a table showing the relative toxicity of the various lead free soldering elements. The table is reproduced here as Table three:

Table Three. Surface Mount Council Toxicity Data

Metal Element	OSHA PEL or ACGIH TLV (mg/m^3)
Bismuth	None
Zinc Oxide Fume	5
Tin (inorganic)	2
Tin (organic)	0.1
Antimony	0.5
Copper (dust)	1
Copper (fume)	0.1
Indium	0.1
Silver (metal dust and fume)	0.1 a
Silver (and soluble compounds)	0.01 b
Lead (inorganic)	0.05 c

Note a: OSHA PEL Note b: ACGIH TLV Note c: ACGIH TLV is 0.15 mg/m^3

Based on this data and other data cited in its report, the Surface Mount Council assigns this toxicity ranking to the common lead free solder alloying elements:

$$Bi < Zn < In < Sn < Cu < Sb < Ag < Pb$$

Experimental Methods

Experiments with eight lead free alloys were undertaken to show their toxicity relative to each other and to conventional tin-lead solders. Wire solder, solder solids, -325, +500 solder paste (with flux) and solder dross were the physical forms of solder tested. These physical forms of solder mimic the waste streams from PCB fabrication and assembly operations. The eight alloys chosen are:

96.3 Tin, 3.2 Silver, 0.5 Copper
96.5 Tin, 3.5 Silver
98 Tin, 2 Silver
99.3 Tin, 0.7 Copper
95 Tin, 5 Antimony
80 Tin, 20 Indium
90 Tin, 5 Bismuth, 5 Silver
43 Tin, 57 Bismuth

Each of the chosen alloys is commercially available today; and several are already in use. Several Japanese manufacturers are utilizing Tin-Bismuth-Silver and/or Tin-Copper alloys[5]. The National Center for Manufacturing Sciences has studied lead free solder alloys and narrowed the field to alloys of tin-bismuth, tin-bismuth-silver, and tin-silver. Nortel has manufactured wireless telephones using tin-copper solder, with the same composition as alloy four. Zinc is reported widely as giving poor solder wetting action; and it is not typically used for either PWB surface finishes or component lead finishes. Alloys of zinc have thus been excluded from this research. Various Japanese concerns are promoting tin-zinc alloys and are working to overcome the wetting and oxidation limitations of these alloys; thus, the tin-zinc eutectic will be studied in future experiments.

Sample Preparation, Leaching, and Analysis

Each metal was procured in an elemental state, then alloyed under oxygen free conditions. Solder wire was 0.032 inch diameter. Solder solids were bar stock, milled to pieces no larger than 0.375 inch by 0.375 inch. This maximum particle size is mandated by the USEPA leaching methods. Solder dross was produced by heating the alloyed solder solids in an ambient atmosphere while occasionally removing the dross from the surface of the solder melt using a titanium bar. An analysis of the oxide content of the dross produced in this manner showed it contained approximately ninety percent entrapped metal, and ten percent metal oxide.

Samples of solderpaste were prepared by alloying the appropriate elements, then blowing them into spheres under an inert atmosphere. The spheres were then sieved to give a -325 to +500 sieve size powder, which is suitable for fine pitch solder paste printing. A flux paste consisting of reagent grade rosin gum (20 percent), glycerol (ten percent), and ethanol (seventy percent) was prepared. The solder spheres and flux paste were mixed to give a ninety percent solids paste. Typical viscosity of the pastes was in the 350 to 400 Kcps range. The above ingredients were selected to provide a uniform paste chemistry, which would eliminate all variables except the metal constituents from influencing the results. Synthetic activators were not used as they might cause metallic leaching reactions. The powder sphere size was selected to give a worst case scenario (maximum leachability). Leaching is a surface phenomenon. Smaller spheres give a higher surface area to volume ratio than larger spheres and thus higher opportunity for metal leaching.

After preparation of the "waste" samples, each was leached according to USEPA, Japanese, or European protocols, and the leachate analyzed using USEPA metals analysis methods.

Results and Conclusions

A review of tables four through eight shows that lead free solders display several elements leaching at levels above USEPA and other regulatory limits in different leaching media. Most striking in its apparent toxicity is the 95Tin: 5Antimony alloy. The leachable levels found are approximately 10,000 times the maximum allowable in drinking water. The 95Tin-5Antimony alloy studied leached above regulatory limits in every physical form and in all leach methods. All lead free alloys containing silver leached above regulatory limits for the TCLP leach, except for the Tin-Bismuth-Silver, which did show some silver leaching. Silver bearing lead free alloys were close to the USEPA limit of 0.1 mg/L in drinking water for leach tests using deionized water. When groundwater was used as the leaching media, the silver levels went above the regulatory limit. Copper was leached above the STLC (California) regulatory limit in the 99.3Tin: 0.7Copper alloy. Bismuth showed little leachability regardless of leachate method or media. It was leachable using the STLC (California) test. Similarly, Tin did not leach significantly in most of the tests. Salts of tin tend to be insoluble in water at room temperature. Indium leached at 0.1 to 1.0 mg/L in all tests except for the SPLP (synthetic precipitation).

The data may also be reviewed by leaching method rather than by metal alloy element. The SPLP test was in general, ineffective at leaching all elements except for antimony. This demonstrates that acid rain poses little potential to release lead free solder metals into the environment. Deionized water test methods, such as those proposed or used in both Japan (JST-13) and the European Community (preliminary) also tend not to leach lead free solder alloys, except for antimony. The more aggressive TCLP test, which simulates disposal in a municipal landfill leaches measurable amounts of tin, silver, copper, antimony, indium, and bismuth. This demonstrates that co-disposal of electronic wastes with municipal wastes is undesirable. The STLC test used for regulatory purposes in California, leaches measurable amounts of tin, silver, copper, antimony, indium, and bismuth, with much higher levels of both copper and bismuth than the TCLP. The STLC, like the TCLP, simulates co-disposal of wastes.

Lead free solders are not a panacea for solving the potentially toxic effects from tin-lead solder alloys. The data from these experiments shows that most lead free solders leach at levels that would cause them to be classified as a hazardous waste, failing both silver and antimony levels. If lead free solders containing silver or antimony are improperly disposed and contacted groundwater, the solders could render that groundwater unsafe to drink per USEPA standards. Solder dross from these alloys carries much the same risks, as the dross behaved similarly to the parent alloys in these experiments. Bismuth and indium are not currently regulated and their toxicity has not been widely studied, thus they pose unknown challenges for adopters of lead free solders.

Reviewing the experimental leaching results above, coupled with available toxicity data, the alloys studied can be ranked as follows in order of increasing environmental and occupational impacts:

43 Tin, 57 Bismuth	least impacts
80 Tin, 20 Indium	
99.3 Tin, 0.7 Copper	
90 Tin, 5 Bismuth, 5 Silver	
98 Tin, 2 Silver	
96.5 Tin, 3.5 Silver	
96.3 Tin, 3.2 Silver, 0.5 Copper	
95 Tin, 5 Antimony	greater impacts

References

[1] Surface Mount Technology, Volume 12 Number 12 (December 1998), Page 40.

[2] IPC Review, October 1998, Page 1

[3] Sources for this and the next section include:
Registry of Toxic Effects of Chemical Substances (RTECS) published by National Institutes of Safety and Health (NIOSH); material safety data sheets for the metal elements; 29 and 40 CFR; and Waste Classification Regulation Guidance Manual, California Environmental Protection Agency, August 1994.

[4] Allenby, B. R. et al. An Assessment of the Use of Lead in Electronic Assembly; Surface Mount Council, 1999

[5] Material from this section taken from the papers presented at the lead free soldering forum at IPC PCEXPO'99, Long Beach, California; March 1999. Papers were authored by Smith, Felty, Shibata, and Tanner

Acknowledgements

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Table Four. Complete Results of the TCLP Leach

3/8 inch solder spheres							
Alloy	Sn, mg/L	Ag, mg/L	Cu, mg/L	Sb mg/L	Pb, mg/L	In, mg/L	Bi, mg/L
Sn-Ag-Cu	0.00	9.32	43.7	NA	NA	NA	NA
Sn96.5-Ag3.5	0.00	11.5	NA	NA	NA	NA	NA
Sn98-Ag2	0.00	8.46	NA	NA	NA	NA	NA
Sn-Cu	0.00	NA	44.5	NA	NA	NA	NA
Sn-Sb	0.00	NA	NA	55.5	NA	NA	NA
Sn-In	0.22	NA	NA	NA	NA	0.39	NA
Sn-Ag-Bi	0.13	NA	NA	NA	NA	NA	1.24
Sn-Bi	0.35	NA	NA	NA	NA	NA	1.61
Sn/Pb wire	0.08	NA	NA	NA	1002	NA	NA
-325, +500 solder paste							
Alloy	Sn, mg/L	Ag, mg/L	Cu, mg/L	Sb mg/L	Pb, mg/L	In, mg/L	Bi, mg/L
Sn-Ag-Cu	0.00	0.00	28.2	NA	NA	NA	NA
Sn96.5-Ag3.5	0.00	0.00	NA	NA	NA	NA	NA
Sn98-Ag2	0.00	0.00	NA	NA	NA	NA	NA
Sn-Cu	0.00	NA	28.1	NA	NA	NA	NA
Sn-Sb	0.00	NA	NA	33.0	NA	NA	NA
Sn-Bi	0.51	NA	NA	NA	NA	NA	3.78
Sn/Pb	11.3	NA	NA	NA	1800	NA	NA

Table Five. Complete Results of the Deionized Water Leach - *3/8 inch size solder solids*

Alloy	Sn, mg/L	Ag, mg/L	Cu, mg/L	Sb mg/L	Pb, mg/L	In, mg/L	Bi, mg/L
Sn-Ag-Cu	12.00	0.04	0.11	NA	NA	NA	NA
Sn96.5-Ag3.5	2.11	0.09	NA	NA	NA	NA	NA
Sn98-Ag2	5.38	0.04	NA	NA	NA	NA	NA
Sn-Cu	0.57	NA	0.199	NA	NA	NA	NA
Sn-Sb	0.61	NA	NA	32.12	NA	NA	NA
Sn-In	2.07	NA	NA	NA		0.08	NA
Sn-Ag-Bi	0.08	Trace	NA	NA	NA	NA	0.14
Sn-Bi	0.38	NA	NA	NA	NA	NA	Not found

Complete Results of the Deionized Water Leach - *3/8 inch size solder dross*

Alloy	Sn, mg/L	Ag, mg/L	Cu, mg/L	Sb mg/L	Pb, mg/L
Sn-Ag-Cu	5.44	0.085	0.089	NA	NA
Sn96.5-Ag3.5	5.31	0.066	NA	NA	NA
Sn98-Ag2	4.38	0.093	NA	NA	NA
Sn-Cu	0.853	NA	0.146	NA	NA
Sn-Sb	0.399	NA	NA	27.71	NA

These deionized water results will be comparable to the JST-13 Japanese leaching method, the EN pr method (European Community draft method), and various other deionized/demineralized water leach methods.

Table Six. Complete Results of the Groundwater Leach - *3/8 inch size solder solids*

Alloy	Sn, mg/L	Ag, mg/L	Cu, mg/L	Sb mg/L	Pb, mg/L	In, mg/L	Bi, mg/L
Sn-Ag-Cu	17.335	0.313	0.152	NA	NA	NA	NA
Sn96.5-Ag3.5	20.459	0.365	NA	NA	NA	NA	NA
Sn98-Ag2	0.187	0	NA	NA	NA	NA	NA
Sn-Cu	2.238	NA	0.078	NA	NA	NA	NA
Sn-Sb	2.003	NA	NA	68.445	NA	NA	NA
Sn-In	0.16	NA	NA	NA		0.11	NA
Sn-Ag-Bi	0.18	Not found	NA	NA	NA	NA	Not found
Sn-Bi	**0.12**	**NA**	**NA**	**NA**	**NA**	**NA**	**0.14**

Complete Results of the Seven Day Leach using Groundwater - *3/8 inch size solder dross*

Alloy	Sn, mg/L	Ag, mg/L	Cu, mg/L	Sb mg/L	Pb, mg/L
Sn-Ag-Cu	9.220	0.259	0.181	NA	NA
Sn96.5-Ag3.5	9.803	0.303	NA	NA	NA
Sn98-Ag2	2.502	0.370	NA	NA	NA
Sn-Cu	1.158	NA	0.064	NA	NA
Sn-Sb	1.912	NA	NA	53.47	NA

Table Seven. Complete Results of the Synthetic Precipitation Leaching Procedure (SPLP) - *3/8 inch size solder solids*

Alloy	Sn, mg/L	Ag, mg/L	Cu, mg/L	Sb mg/L	Pb, mg/L	In, mg/L	Bi, mg/L
Sn-Ag-Cu	0.17	Not found	0.08	NA	NA	NA	NA
Sn96.5-Ag3.5	0.21	Trace	NA	NA	NA	NA	NA
Sn98-Ag2	0.46	Trace	NA	NA	NA	NA	NA
Sn-Cu	0.39	NA	0.12	NA	NA	NA	NA
Sn-Sb	0.22	NA	NA	43.4	NA	NA	NA
Sn-In	0.78	NA	NA	NA	NA	Not found	NA
Sn-Ag-Bi	0.22	Not found	NA	NA	NA	NA	Not found
Sn-Bi	0.99	NA	NA	NA	NA	NA	Not found

Table Eight. Complete Results of the Soluble Threshold Leaching Concentration (STLC) - *3/8 inch size solder solids*

Alloy	Sn, mg/L	Ag, mg/L	Cu, mg/L	Sb mg/L	Pb, mg/L	In, mg/L	Bi, mg/L
Sn-Ag-Cu	1.73	Not found	87.4	NA	NA	NA	NA
Sn96.5-Ag3.5	63.2	Trace	NA	NA	NA	NA	NA
Sn98-Ag2	29.3	Trace	NA	NA	NA	NA	NA
Sn-Cu	5.77	NA	86.0	NA	NA	NA	NA
Sn-Sb	2.11	NA	NA	11.1	NA	NA	NA
Sn-In	1.20	NA	NA	NA	NA	0.09	NA
Sn-Ag-Bi	0.98	0.50	NA	NA	NA	NA	46.1
Sn-Bi	0.99	NA	NA	NA	NA	NA	29.4

Table Nine. Regulatory Limits for evaluating TCLP and Deionized Water Leaching Tests [a]

Element	**Media**	**Limit, mg/L**	**Source**
Indium	All	None found	
Bismuth	All	None found	
Tin	All	None found	
Silver	TCLP Leachate	5.0	USEPA 40 CFR 261
Silver	Drinking Water	0.10	USEPA 40 CFR 141
Antimony	TCLP Leachate	1.0	TNRCC 30 TAC 335b
Antimony	Drinking Water	0.006	USEPA 40 CFR 141
Antimony	Drinking Water	0.002	Japanese legislation
Antimony	Drinking Water	0.005	98/83/EEC
Copper	TCLP Leachate	500	various State (USA) regulations
Copper	Drinking Water	1.0	USEPA 40 CFR 141; Japanese legislation; Thai legislation
Copper	Drinking Water	2.0	98/83/EEC
Lead	TCLP Leachate	5.0	USEPA 40 CFR 261c
Lead	Drinking Water	0.015	USEPA 40 CFR 141
Lead	Drinking Water	0.05	Japanese legislation; Thai legislation
Lead	Drinking Water	0.010	98/83/EEC
Zinc	Drinking Water	1.0	Japanese Legislation
Zinc	Drinking Water	5.0	Thai Legislation

Notes for Table Nine:

a- TCLP leachate tests were evaluated only against TCLP limits shown in this table; groundwater and deionized water leachate tests were evaluated only against the drinking water limits shown in this table

b- TNRCC 30 TAC 335 refers to State of Texas statutes

c- some jurisdictions observe a 1.5 mg/L limit, based on a multiple of the 0.015 mg/L drinking water limit

Appendix I – Details of the various Leaching Methods Employed in this Research

Seven-Day Distilled Water Leachate Test - State of Texas (USA) Method

This test is intended only for dry, solid wastes, i.e., waste materials without any free liquids.

1. Place a 250 gm. (dry weight) representative sample of the waste material in a 1,500 ml. Erlenmayer flask.
2. Add one liter of deionized or distilled water into the flask and mechanically stir the material at a low speed for five minutes.
3. Stopper the flask and allow to stand for seven days.
4. At the end of seven days, filter the supernatant solution through a .45-micron filter, collecting the supernatant into a separate flask.
5. Subject the filtered leachate to the appropriate analysis.

Source: The provisions of this **§** 335.521 adopted to be effective May 30, 1995, 20 TexReg 3722.

Cross Reference: This Section cited in 30 TAC **§**335.503 (relating to Waste Classification and Waste Coding Required); 30 TAC **§**335.505 (relating to Class 1 Waste Determination); 30 TAC **§**335.507 (relating to Class 3 Waste Determination). Results from this leachate are compared directly against the jurisdiction's drinking water standards.

TCLP - Toxicity Characteristic Leaching Procedure – United States EPA Method

This analysis determines the soluble portion of the analytes. This is a Federal guideline and differs from the State in several ways. The alkalinity of the sample must first be determined in order to know which of two different extraction fluids should be used. Samples with a low alkalinity use extraction fluid #1 which is a sodium acetate solution with a pH of 4.93. Samples with a high alkalinity use extraction fluid #2 which is a dilute acetic acid solution with a pH of 2.8. The sample is then tumbled in the appropriate extraction fluid for 18 hours. However the choice of extraction fluids does not apply to volatiles. When analyzing for volatiles, fluid #1 is always used and a Zero Headspace Extraction (ZHE) apparatus is required. Results from this leachate are compared against TCLP regulatory limits for the analyte.

California Waste Analysis Methods

TTLC and STLC are used when determining the hazardous waste characterization under California State regulations as outlined in Title 26 of the California Code of Regulations (CCR).

TTLC - Total Threshold Limit Concentration

This analysis determines the total concentration of each target analyte in a sample. Samples are analyzed using published EPA methods. When any target analyte exceeds the TTLC limits the waste is classified as hazardous and its waste code is determined by the compound(s) that failed TTLC. The results of this analysis can be used to determine if analysis for STLC level is necessary by comparing 10 times the STLC limit to the TTLC results. A factor of ten is necessary to compensate for a 1:10 dilution factor that is present in one analysis but not the other. If the TTLC results do not exceed 10 times the STLC limit then normally no further analysis is required.

STLC - Soluble Threshold Limit Concentration

This analysis determines the amount of each analyte that is soluble in the "Waste Extraction Test", (W.E.T.) leachate. This W.E.T. leachate procedure is used for solid samples or for samples containing > 0.5% solids. The sample is tumbled in 10 times its weight of a 0.2M sodium citrate buffer for 48 hours. This leachate is then analyzed to determine the soluble concentrations.

The concentration of analyte in the leachate is compared against the STLC and TTLC regulatory values.