Center for Advanced
Vehicle Electronics (CAVE)

OVERVIEW OF LEAD FREE SOLDER RESEARCH

CAVE

Objective, Focus, and Vision

The Center Objective is:

- Develop and Implement New Technologies for the Packaging and Manufacturing of Electronics, with Special Emphasis on the Harsh Environment, Reliability, and Cost Requirements of the Vehicle Industry

The Center Focuses on:

- Electronic Packaging Reliability, Materials, and Assembly and Processing
- Harsh Environment Electronics
  - Extreme High/Low Temperatures
  - Large Temperature Excursions
  - Vibration, Shock, Drop
- High Volume Electronics Manufacturing

The Center Vision is:

- To Be the Premier Research Organization in the World Working in the Area of Harsh Environment Electronics

CAVE

Current and Past Research Sponsors

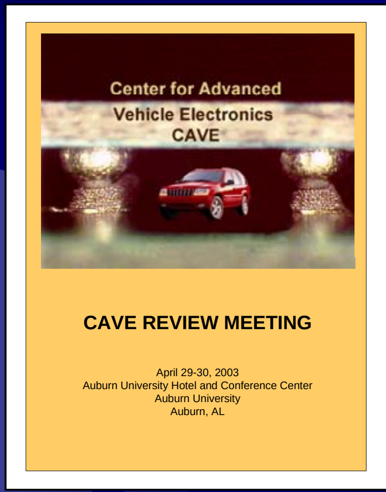
- CAVE Center Memberships
  - Full
  - Associate
  - Affiliate
- Funded Projects
  [Contract Research]

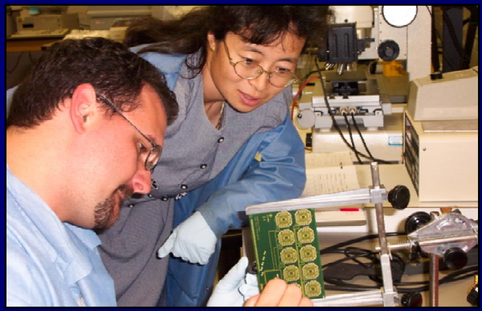
CAVE MEMBERSHIP

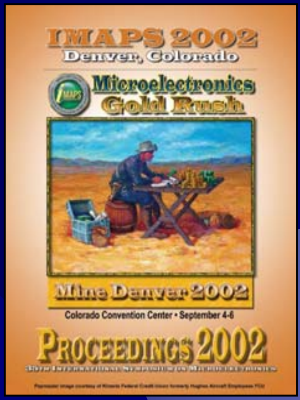
Levels of Membership

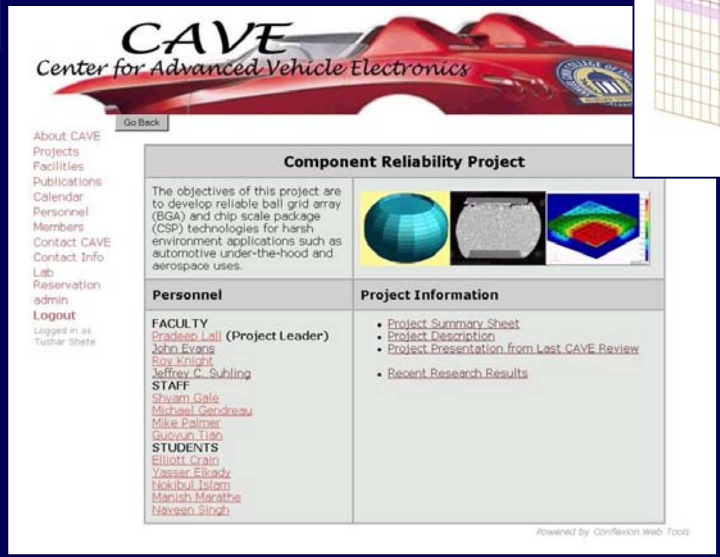
- Full Member
  - Annual Membership Fee is $75,000
  - Parent Company Membership - All Company Sites are Included and can Participate
  - Participation in All Center Projects
  - Specific Company Projects and Use of CAVE Facilities
  - Access to All CAVE Information, Software, and Activities
  - Representation on Industry Advisory Board (IAB)
- Associate Member
  - Annual Membership Fee is $37,500
  - Participation Limited to One Existing Project Area
  - Single Company Site Membership
  - Limited Company Specific Projects
- Affiliate Membership
  - Membership Fee is Negotiated
  - New Company Specified Project
  - Single Company Site Membership
  - No Consortium Information

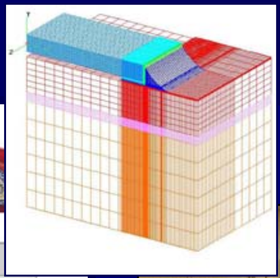
MEMBER BENEFITS

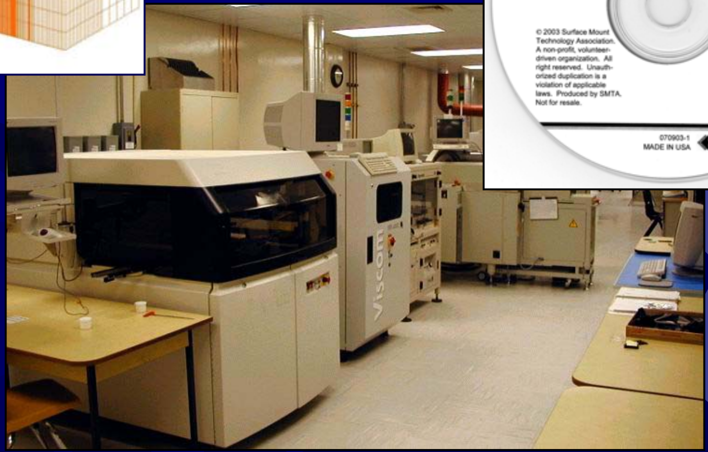


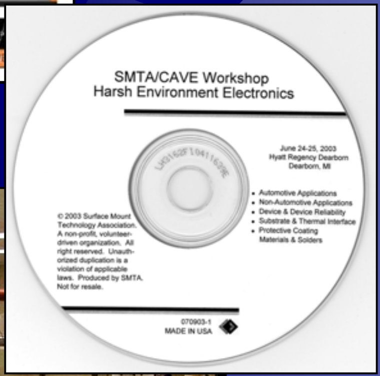












TASKS

Lead-Free Soldering Project

- **Task #1: Intermetallic Growth in Pb-Free Solders**

  Experiments to study the growth of intermetallics for four standard Pb-free alloys as a function of time and board finish (at 150ºC) has been completed. The goal was to determine the intermetallic composition, thickness, growth rate, and diffusion mechanism.

- **Task #2: Construction of Library of Pb-Free Wetting Videos**

  A digital video library documenting ~ 20 combinations of Pb-free solder alloys wetted to Pb-free substrates have been produced and are available to CAVE members by computer transfer.

- **Task #3: Mechanical Properties of Pb-Free Solders**

  The stress-strain and creep behaviors of lead free solders are being measured as a function of temperature and strain rate. We have developed methods for fabricating acceptable lead free test specimens for uniaxial tensile and shear testing. Our work also addresses the effects of temperature profile during cool down after casting on the resulting microstructure and mechanical behavior of the samples.

TASKS

Lead-Free Soldering Project

- **Task #4: Pb-Free Solder Joint Reliability and Microstructure Studies**

  Three studies are underway to evaluate the reliability and microstructural changes in lead free chip resistor solder joints during thermal cycling. The developed lead free reliability test board design includes various chip resistor sizes (0402, 0603, 0805, 1206, and 2512). The test matrices include 7 solder alloys, 2 board finishes, and 3 thermal cycling temperature ranges.

- **Task #5: Tin Whisker Growth**

  Evaluating tin whisker growth characteristics of lead-free connector finishes as compared to standard finishes

TASK 1

Identification and Growth of Intermetallic Compounds in Pb-Free Solder Alloy Systems

Goal: To determine the intermetallic composition, thickness, and growth rate for a variety of Pb-free solder alloys joined to Pb-free board finishes as a function of time under isothermal conditions (150^{o}C).

Motivation: Formation of intermetallic compounds directly impact the long-term reliability of solder joints. Intermetallics are usually brittle and lower the reliability by acting as sources of joint crack propagation. Knowledge of the intermetallics and how fast they grow allow more accurate correlation of failure models with reliability data.

EXPERIMENTAL DETAILS

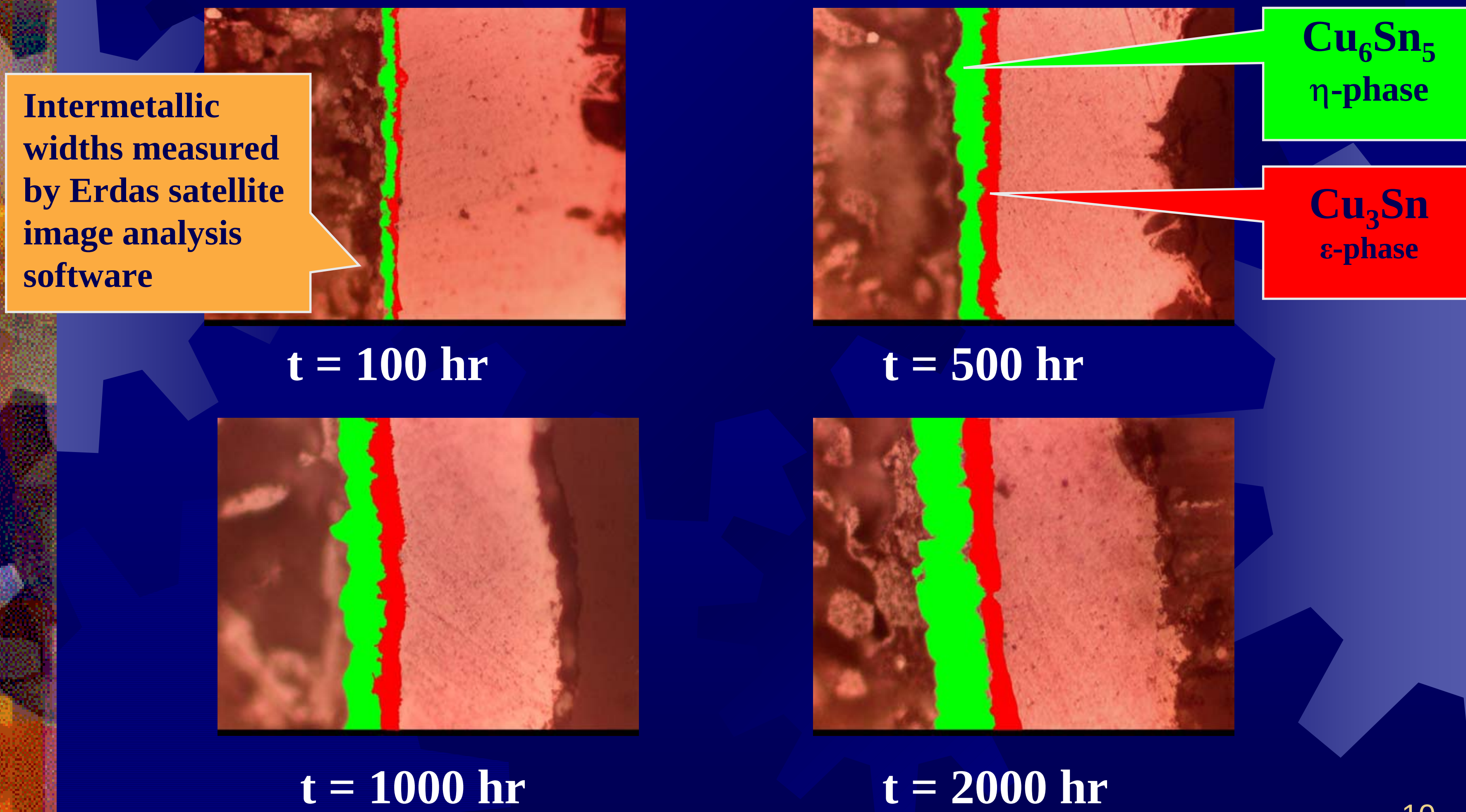
Experimental Techniques
- **Polarized Light Microscopy**
- **Metallography**
- **Thin Film Measurements**
- **SEM / EDX**

No-Pb Solder Intermetallic Study
Test Matrix (Ageing at T = 150°C)

Solder Alloy	Board Finish	Annealing Times (h)
Sn-37Pb	Sn	0
Sn-4.0Ag-0.5Cu	Ag	100
Sn-3.5Ag-1.5In	Ni-Au	500
Sn-3.5Ag	OSP	1000
Sn-0.7Cu		2000

REPRESENTATIVE RESULTS

Intermetallic Identification for Sn-37Pb on Sn (control)



TASK #2

Compilation of Wetting Videos

Goal: **To examine the real-time, in-situ melting, wetting, and spreading dynamics for a variety of Pb-free solder alloys and pastes on three classes of substrate (Ni-Au, Cu, Al_2O_3).**

Motivation: **Wetting is critical to all soldering processes. Observation of wetting at high magnification allows for early identification of potential failure modes in actual solder joints.**

Solder Alloys & Pastes

A variety of Pb-free solder alloys and pastes

Board Finishes

Ni-Au, Cu, Al_2O_3

Techniques

Real-Time Wetting Observations

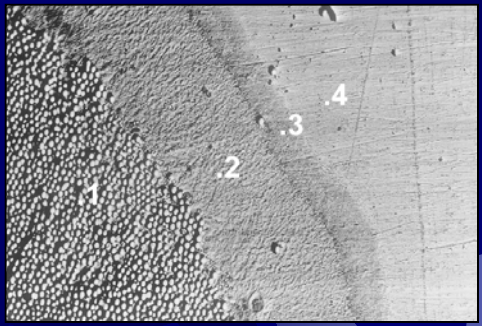
SEM / EDS

Auger Spectroscopy

CURRENT DATA

Pb-Free Interface and Wetting Studies

Real-Time Scanning Electron Microscopy Movies Completed



Wetting to Ni-Au

57Bi-42Sn-1Ag (paste)
58Bi-42Sn (paste)
Sn-0.7Cu (paste)
Sn-4.0Ag-0.5Cu (paste)
Sn-3.5Ag (paste)
Sn-3.5Cu (paste)
Sn-3.4Ag-4.8Bi (paste)

Excellent Wetting and Spreading

Wetting to Cu

Sn-3.5Ag (paste)
Sn-3.8Ag-0.7Cu (paste)
Sn-2.25Ag-0.5Sb-0.75Cu (paste)
Sn-3.5Ag-3.0Bi (paste)
Sn-3.0Ag-0.7Cu (paste)
Sn-3.4Ag-4.8Bi (paste)
Sn-2.0Ag-7.5Bi (paste)

Wetting But No Spreading

Wetting to Al

Sn-37Pb (paste)
Sn-37Pb (alloy)
Sn-3.8Ag-0.7Cu (paste)
Sn-3.8Ag-0.7Cu (alloy)
Sn-3.5Ag (paste)
Sn-3.5Ag (alloy)

Dewetting

TASK #3

Measurement of Lead Free Solder Material Behavior

- Develop specimen preparation procedure that generates:
  - Samples with the same micro-structure as Lead free solder material in manufacturing
  - Acceptable samples for testing
- Use a Micro Tension/Torsion testing machine to evaluate stress-strain, creep, fatigue and other mechanical properties of Lead free solder materials as a function of temperature, thermal cycling exposure, etc.
- Provide the basic mechanical properties of different Lead free solder material for finite element analyses

MECHANICAL PROPERTIES

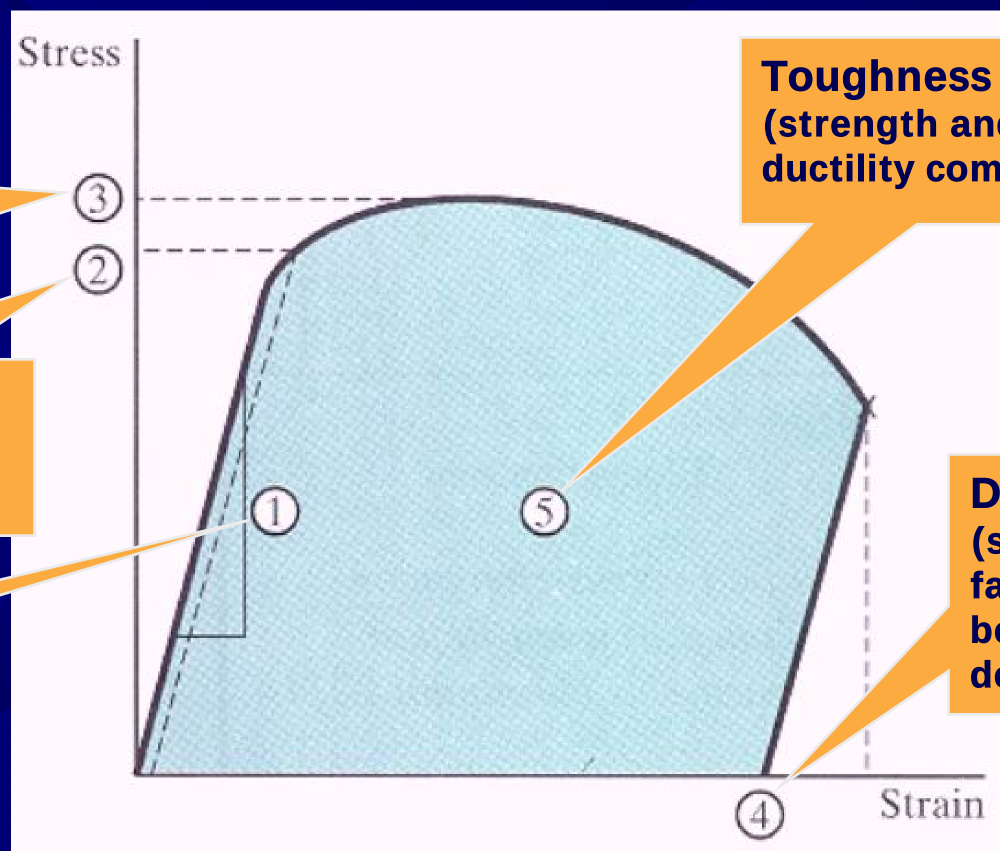
Representative Stress-Strain Curve

The information about lead free solders derivable from a tensile test is enormous

Tensile Strength
(maximum strength before necking)

Yield Strength
(stress to generate 0.2 % permanent deformation)

Young's Modulus
(stiffness)

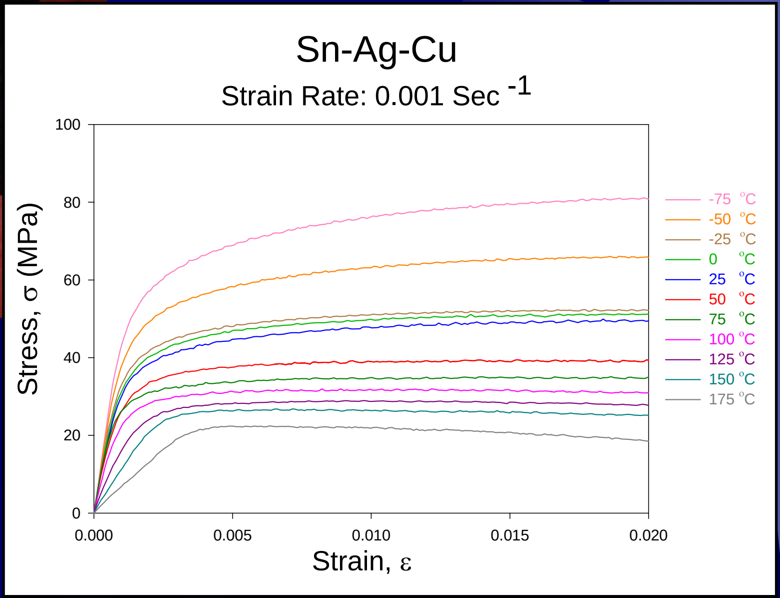


Toughness
(strength and ductility combined)

Ductility
(strain at failure; ability to be plastically deformed)

MECHANICAL PROPERTIES

Typical Lead Free Stress-Strain Curves



MECHANICAL PROPERTIES

Ongoing Work

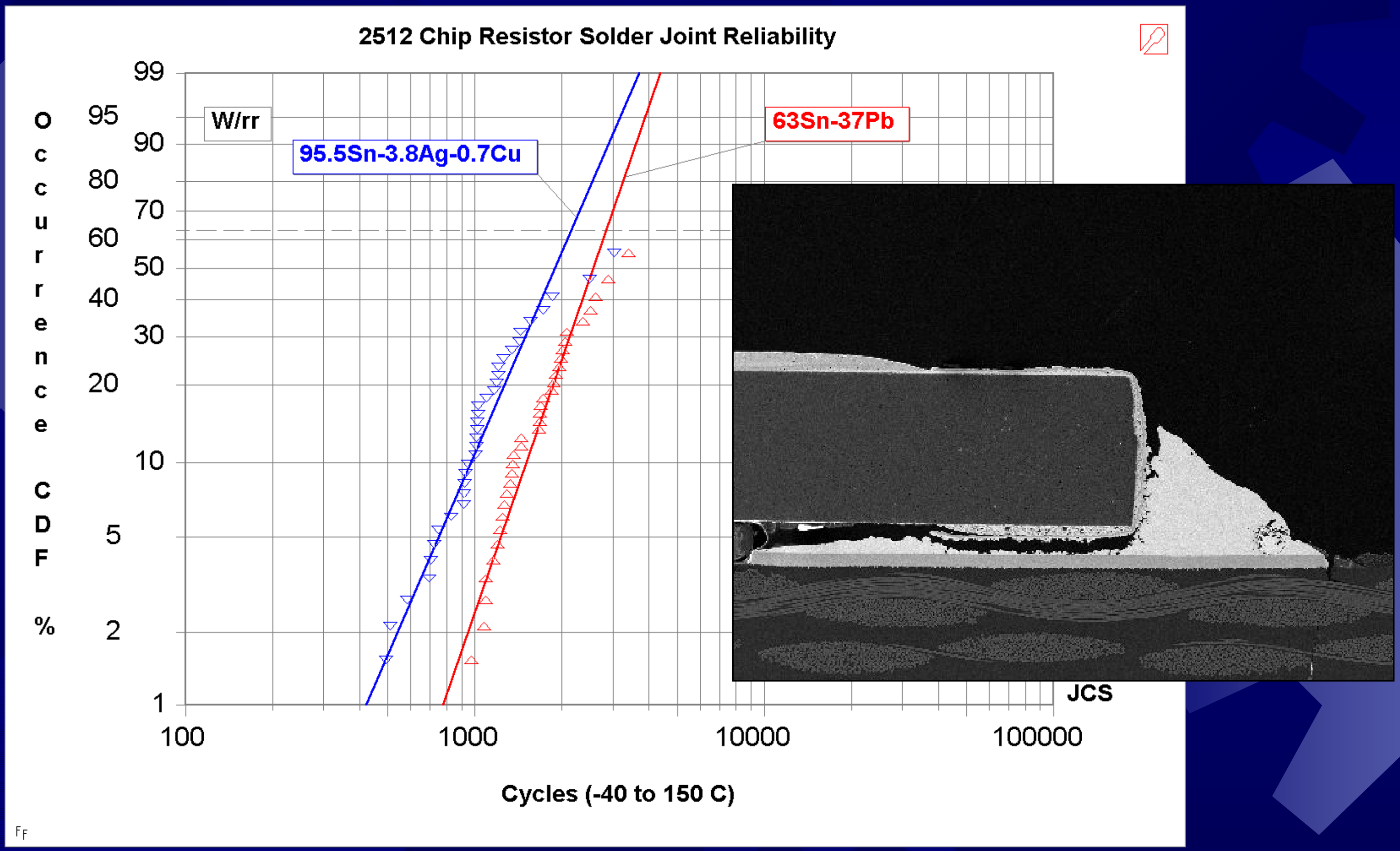
- Perform Tensile Tests to Evaluate Temperature and Strain Rate Dependent Elastic and Plastic Properties
- Perform Creep Tests at Different Temperatures and Different Stress Levels
- Perform Shear Tests to Evaluate Temperature Dependent Shear Properties
- Perform Fatigue Tests to Evaluate Temperature Dependent Fatigue Properties
- Perform Relaxation Tests to Evaluate Temperature Dependent Relaxation Properties
- Develop Material Models with the Above Tests Data for Use in Finite Element Analyses

TASK #4

Pb-Free Solder Joint Reliability and Microstructure Studies

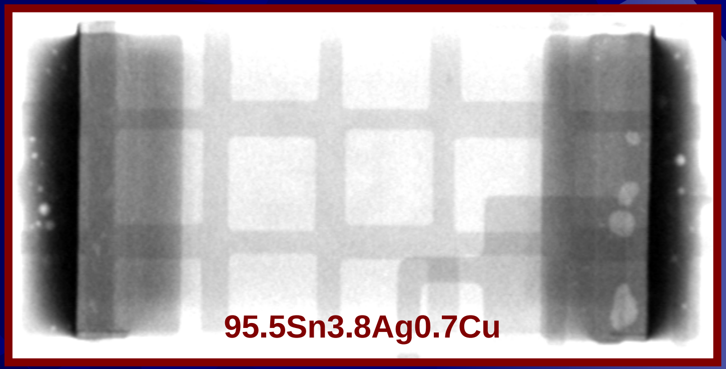
- **LF Study #1: Pb-Free Alloy Reliability**
  - **5 Alloys**
  - **-40 to 125ºC and -40 to 150ºC**
  - **Weibull plots**
  - **Microstructural Analysis (SEM, Radiography)**
  - **Crack Propagation**
- **LF Study #2: Sn-Termination**
  - **Comparison of components with Sn and Sn-Pb Terminations**
- **LF Study #3: Pb-Free Radio**
  - **Low Melting Temperature Alloys: Sn-Bi**
  - **-40 to 125ºC and -40 to 85ºC**

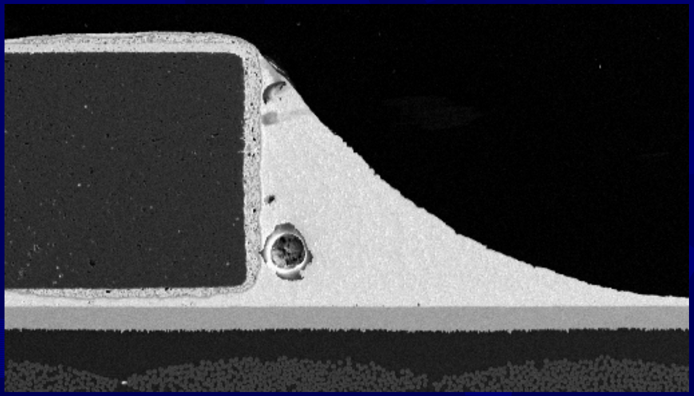
EXPERIMENTAL OBSERVATIONS



EXPERIMENTAL OBSERVATIONS

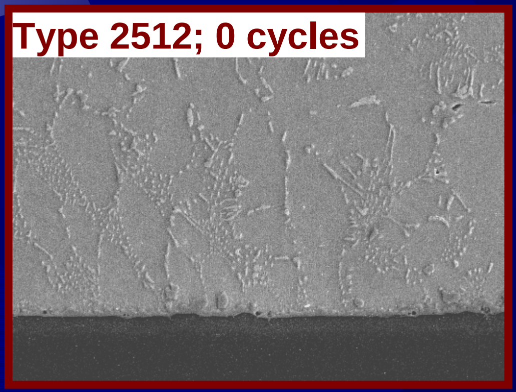
- Solder voids in all solder compositions in as-fabricated boards.





EXPERIMENTAL OBSERVATIONS

- Spheroidization and coarsening of the second phase after thermal cycling.
- No easily discernable change in the overall distribution of the elements in the x-ray maps.



95.5Sn-3.8Ag-0.7Cu

FUTURE WORK

- Microstructural characterization of types 0402, 0603, 0805, 1206 and 2512 thermally cycled from - 40 °C to + 125 °C up to 5000 cycles.
- Microstructural characterization of types 0402, 0603, 0805 and 1206 thermally cycled from - 40 °C to + 150 °C up to 5000 cycles.
- Investigate and attempt to relate the microstructure of the solders to their behavior during the reliability tests.
- Monitor the migration of the constituent elements and the change in composition of the second phases that may occur during thermal cycling.

TASK #5

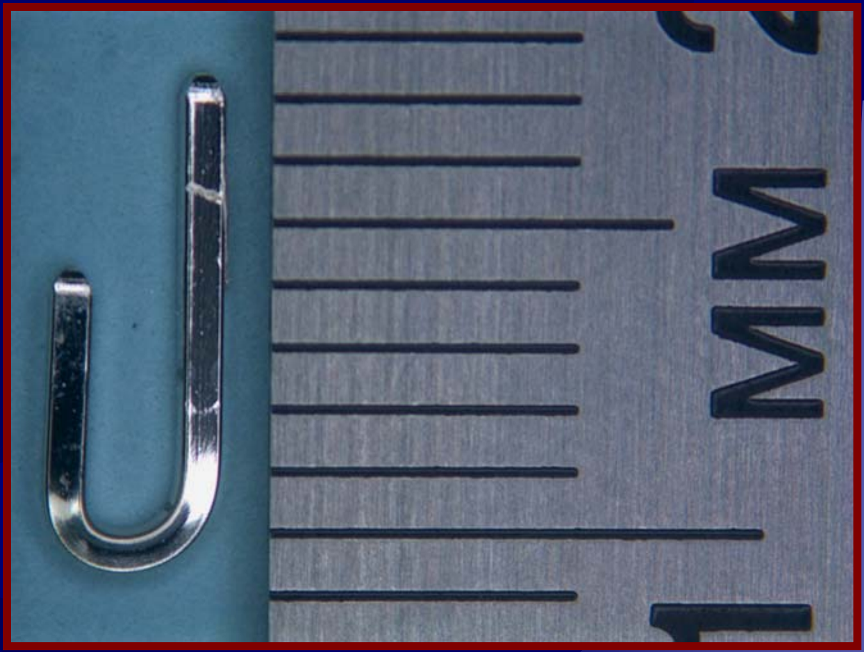
Tin Whisker Growth with Lead-Free Connector Finishes

- Objective: To evaluate the whisker growth characteristics of lead-free connector finishes as compared to standard finishes
- Two Studies are Underway:
  - Tin Whisker Study #1 (old)
    - Bending induced stress (ongoing for 18 months)
  - Tin Whisker Study #2 (new)
    - Thermal shock induced stress

ACCOMPLISHMENTS

Tin Whisker Study #1

- SnPb (90/10)
- SnCu (99/1) matte
- SnCu (99/1) matte modified
- SnCu (96/4) matte
- SnCu (96/4) matte modified
- Sn (Ni barrier) matte
- Sn (Ni barrier) matte reflowed
- Sn (Cu barrier) matte
- Sn (Ni barrier) bright
- Sn (Cu barrier) bright
- SnCu (99/1) bright
- SnCu (99/1) bright modified
- SnCu (96/4) bright
- SnCu (96/4) bright modified
- Sn “Whiskerless” 1
- Sn w/Cu alloy “Whiskerless” 1
- Sn “Whiskerless” 2
- Sn w/Cu alloy “Whiskerless” 2
- SnBi
- SnBi modified



Specimen Geometry

ACCOMPLISHMENTS

Tin Whisker Study #1

- Humidity testing at 50 °C and 90 % RH for 1, 2 and 4 months has been completed (on pins aged previously for 16 months at 50 °C).
- SEM evaluation of the pins after 1 and 2 months of exposure has been completed.
- SEM evaluation of the pins aged for 4 months is underway.

ACCOMPLISHMENTS

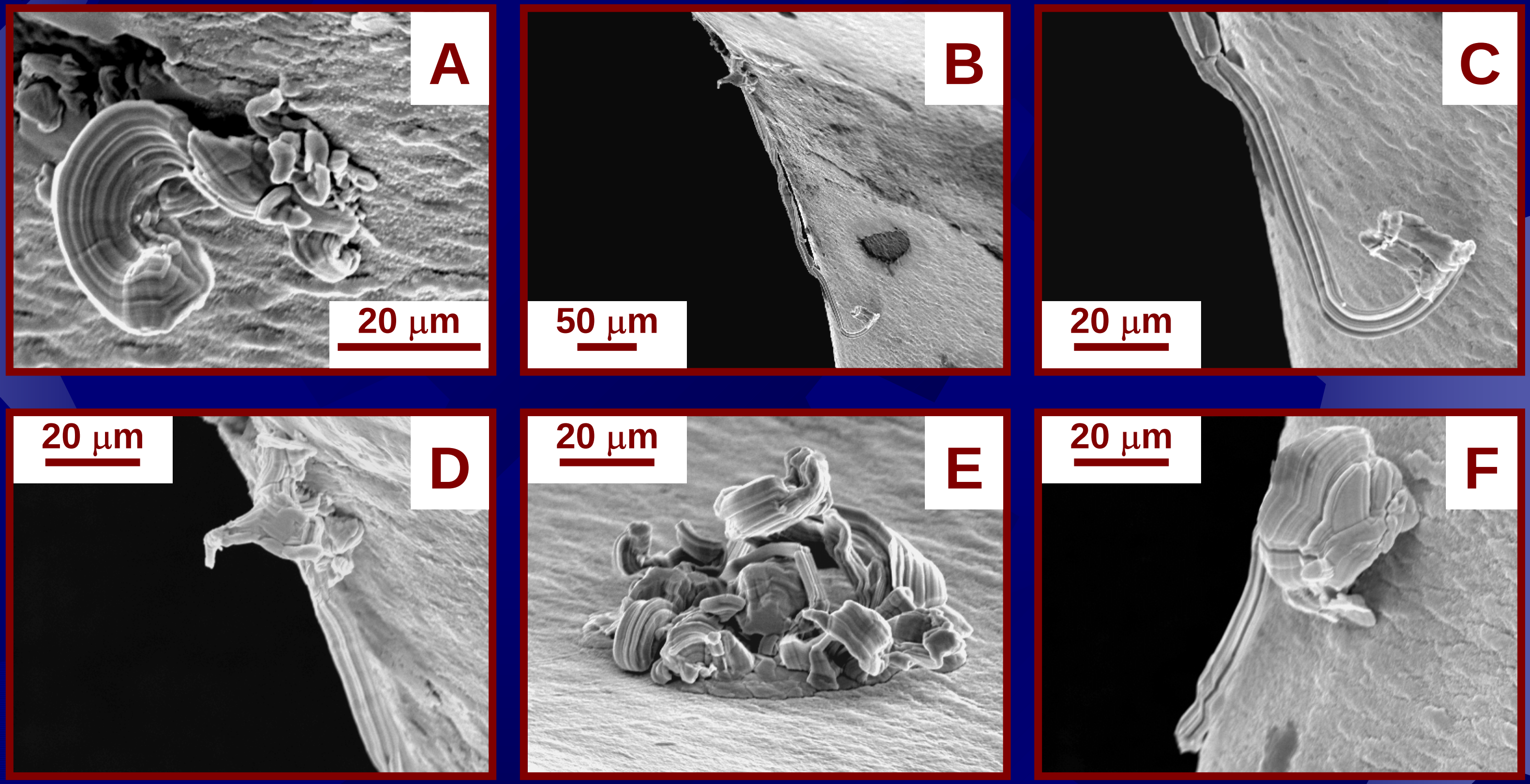
Tin Whisker Study #1

Sample ID	16	16 + 1	16 + 2
SnPb (90/10)	No	No	No
SnCu (99/1) matte	No	Yes	Yes
SnCu (99/1) matte modified	No	Yes	Yes
SnCu (96/4) matte	No	Yes	Yes
SnCu (96/4) matte modified	No	Yes	Yes
Sn (Ni barrier) matte	No	No	No
Sn (Ni barrier) matte reflowed	No	No	No
Sn (Cu barrier) matte	Yes	Yes	Yes
Sn (Ni barrier) bright	No	No	No
Sn (Cu barrier) bright	Yes	Yes	Yes
SnCu (99/1) bright	No	No	No
SnCu (99/1) bright modified	No	No	No
SnCu (96/4) bright	No	No	No
SnCu (96/4) bright modified	?	Yes	Yes
Sn “Whiskerless” 1	No	Yes	Yes
Sn/Cu alloy “Whiskerless” 1	No	No	Yes
Sn “Whiskerless” 2	No	No	No
Sn/Cu alloy “Whiskerless” 2	No	No	Yes
SnBi	No	Yes	Yes
SnBi modified	No	No	Yes

A change in surface morphology is marked as yes. These may or may not be related to whisker formation.

ACCOMPLISHMENTS

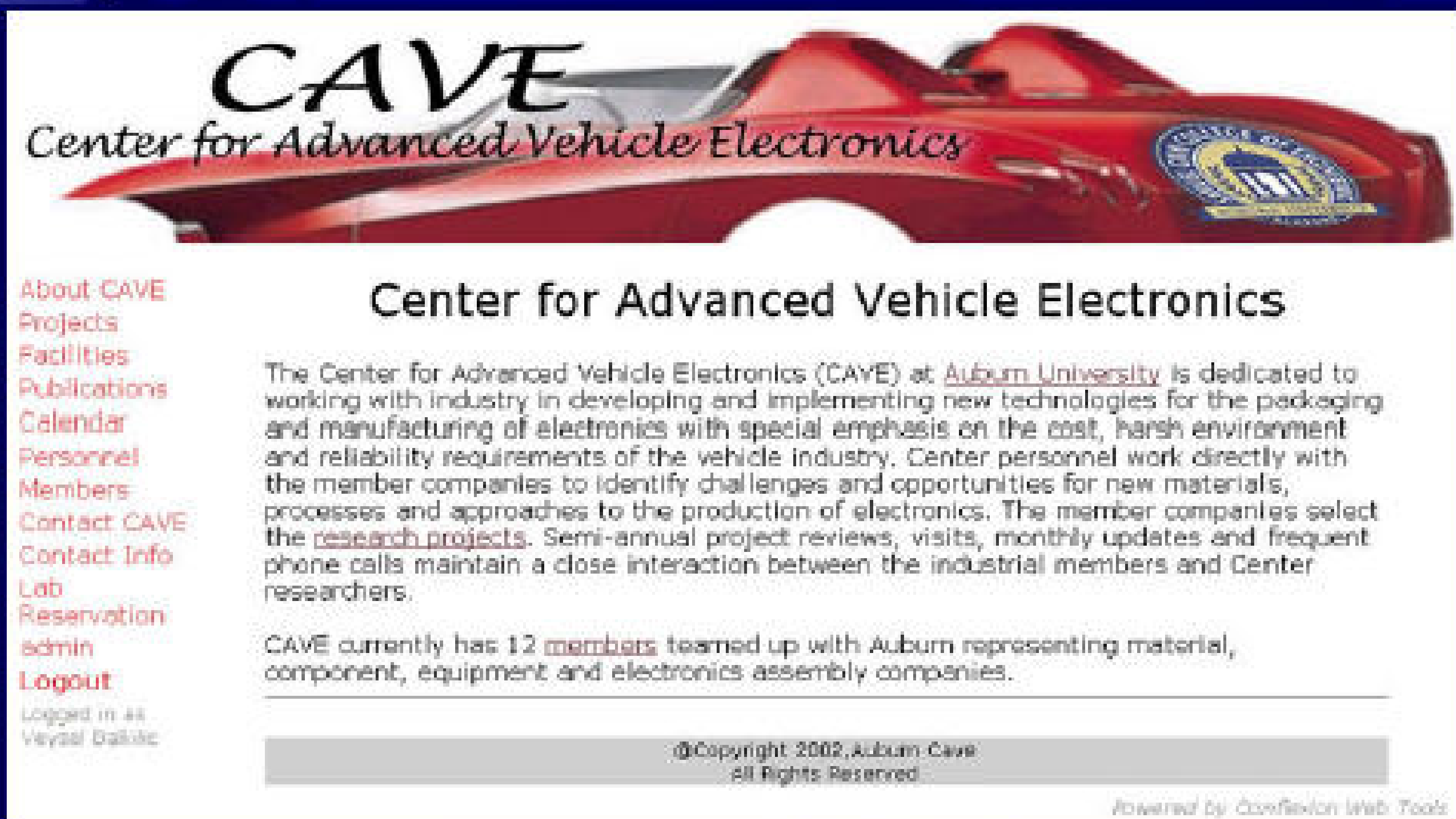
Tin Whisker Study #1



Sn with Cu Barrier (Bright) at 16+2 Months

CAVE WWW SITE

http://cave.auburn.edu



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Joint (NASA-DoD-OEM) Lead-Free Solder Project

JG-PP Pb-Free Solder Project Overview

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Objective:

Joint project to qualify and validate lead-free solder alloys for use in manufacture and repair of electronic equipment

Scope:

- The interconnection of components to substrates with a lead free solder alloy
- Test for functional (electrical) reliability, not integrity
- Indirectly test effectiveness of repairing Pb-containing PWBs with Pb-free solder
- Test board to reflect 50+% of circuits now on defense/space systems
  - Surface Mount Technology and Plated Through Hole
  - Mixture of old and new components

Industry Solder Recommendations

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NEMI – recommends **Sn/3.9Ag/0.6Cu** for reflow; **Sn/0.7Cu** for wave solder (1/24/2000)

SOLDERTEC (ITRI) – recommends **Sn/[3.4-4.1]Ag/[0.45-0.9]Cu** for reflow (10/99)

NCMS – recommends Sn/58Bi, Sn/3.5Ag/4.8Bi, Sn/3.5Ag for further study (8/97)

IDEALS - recommends **Sn/3.8Ag/0.7Cu/0.5Sb** for general purpose & wave soldering (5/96-4/99)

HDPUG is investigating **SnAgCu** alloys for telecommunications applications

JEDO/JEITA evaluated **Sn/3.5Ag/0.75Cu** for general purpose soldering; Sn/0.7Cu/0.3Ag for wave soldering; and Sn/2Ag/3Bi/0.75Cu, Sn/2Ag/4Bi/0.5Cu/0.1Ge, Sn/3.5Ag/5Bi/0.7Cu, Sn/3.5Ag/6Bi, Sn/57Bi/1Ag for reflow soldering. Results/reports not yet available (1/99-3/00)

Lead-Free Solder Alloys

JG-PP selected the following lead-free solder alloys:

* 99.3Sn-0.7Cu-.05Ni (for wave soldering)
* 99.5Sn-3.9Ag-0.6Cu (for wave, reflow and manual soldering)
* 92.3Sn-3.4Ag-1.0Cu-3.3Bi (for wave, reflow and manual soldering)

Proposed Test Vehicle

- Surface finishes:

  Immersion Ag & Pb HASL

- Component styles:

  CLCC, PLCC, TSOP, TQFP, BGA, CSP, PDIP, chip capacitors (0402, 0805, 1206), resistor (1206), and hybrids

- Component finishes:

  Four (4) Pb-free (Sn, Au/Pd/Ni, SnCu, & SnAgCu) & baseline (Sn/Pb)

- Component sizes: “typical” I/O size
- Generally five (5) of each component per test vehicles (TV) and five (5) TV per test

  ⇨ 25 total of each component per test [7 tests]

Test PWA

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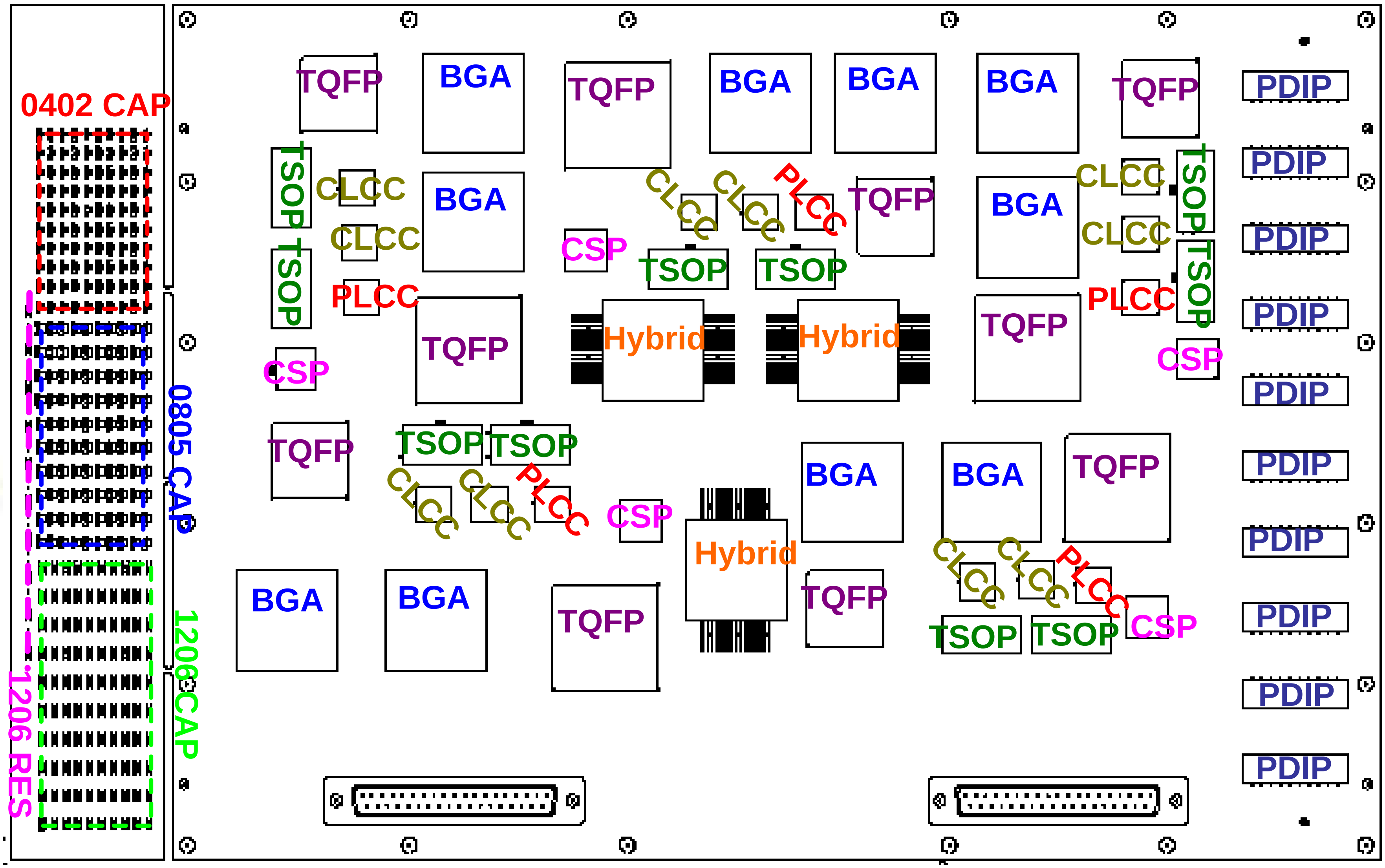

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Test Vehicle Design

Manufacturing Test Vehicle Build

Type	Laminate	Surface Finish	Reflow Solder	Wave Solder
Lead-Free	High Tg, Glass Fiber	Immersion Silver	Tin-Silver-Copper	Tin-Silver-Copper
			Tin-Silver-Copper-Bismuth	Tin-Copper
Base-line (control)	High Tg, Glass Fiber	Immersion Silver	Eutectic Tin-Lead	Eutectic Tin-Lead

Rework Test Vehicle Build

Type	Laminate	Surface Finish	Reflow & Wave Solder Alloy	Repair Solder Alloy SMT	Repair Solder Alloy PTH
Rework	Low Tg, Glass Fiber	Hot Air Solder Leveled (HASL)	Eutectic Tin-Lead	Tin-Silver-Copper-Bismuth	Tin-Copper
				Tin-Silver-Copper	Tin-Silver-Copper
Repair Control	Low Tg, Glass Fiber	Hot Air Solder Leveled (HASL)	Eutectic Tin-Lead	Eutectic Tin-Lead	Eutectic Tin-Lead

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JTP Common Tests

Validation Test	JTP Section	Reference	Electrical Test	Acceptance Criteria [(a)]
Vibration	3.2.1	MIL-STD-810F, Method 514.5, Procedure I	Electrical continuity failure	Better than or equal to tin/lead controls
Mechanical Shock	3.2.2	MIL-STD-810F, Method 516.5, Procedure I	Electrical continuity failure	Better than or equal to tin/lead controls
Thermal Shock	3.2.3	MIL-STD-810F, Method 503.4, Procedure I	Electrical continuity failure	Better than or equal to tin/lead controls at 10% Weibull cumulative failure
Thermal Cycling	3.2.4	IPC-SM-785	Electrical continuity failure	Better than or equal to tin/lead controls at 10% Weibull cumulative failure
Combined Environments Test	3.2.5	MIL-STD-810F, Method 520.2, Procedure I	Electrical continuity failure	Better than or equal to tin/lead controls at 10% Weibull cumulative failure

[a] Failure of a test board in a specific test does not necessarily disqualify a lead-free solder alloy for use in an application for which that test does not apply. Electrical performance requirements for a particular circuit apply only to parts containing that circuit.

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JTP Extended Tests

Validation Test	JTP Section	Reference	Measurement	Acceptance Criteria [a]
Salt Fog	3.3.1	MIL-STD-810F, Method 509.4	Visual pass/fail criteria per referenced standard	Better than or equal to tin/lead controls
Humidity	3.3.2	MIL-STD-810F, Method 507.4	Visual pass/fail criteria per referenced standard	Better than or equal to tin/lead controls
Surface Insulation Resistance, Fluxes	3.3.3	IPC-TM-650, Method 2.6.3.3	Resistance Measurements	$\geq 10^8$ ohms (Ω)
Electrochemical Migration Resistance Test	3.3.4	IPC-TM-650, Method 2.6.14.1	Visual pass/fail criteria per referenced standard	$\geq 10^5$ ohms (Ω)

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Probable Testing Sites

JTP Test	Number of Test Vehicles		Rockwell Collins	Boeing-Irving	Boeing-Seattle	Raytheon	ACI
	Manufacturing	Rework					
Procurement; Boards and Components	119	86	X				
PWA Assembly	119	86		X			
PWA Characterization	10	10		X			
Pretest PWA	3	3		X			
Vibration (MIL-STD-810F, Method 514.5, Procedure I)	15	15			X		
Mechanical Shock (MIL-STD-810F, Method 516.5, Procedure I)	13	13			X		
Thermal Shock (MIL-STD-810F, Method 503.3, Procedure I)	15	15			X		
Combined Environments Testing (MIL-STD-810F Method 520.2 Procedure I)	15	15				X	
Thermal Cycling: Manufacturing -55°C to +125°C (IPC-SM-785)	15	N/A	X				
Thermal Cycling: Manufacturing -20°C to +80°C (IPC-SM-785)	15	N/A			X		
Thermal Cycling: Rework -55°C to +125°C (IPC-SM-785)	N/A	15	X				
Salt Fog (MIL-STD-810F, Method 509.4)	9	N/A					X
Humidity (MIL-STD-810F, Method 507.4)	9	N/A					X
Surface Insulation Resistance (IPC-TM-650, Method 2.6.3.3)	35 IPC-B-24 boards						X
Electrochemical Migration Resistance (IPC-TM-650, Method 2.6.14.1)	35 IPC-B-25A boards						X

Project Milestones

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☑ Early customer-interface mtg.	May 2001
☑ Project added to website	Jun 2001
☑ Complete CBA-A	Jun 2002
☑ Complete PAR	Mar 2003
☑ Complete JTP	Feb 2003
• Begin PWA builds	Mar 2004
• Begin testing	May2004

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Next Steps

Business

- Agree to testing locations
- Set up subcontracts for board builds and testing

Technical

- Gather JTP endorsements from Program Managers
- Procure components, boards, and solders
- Build test vehicles

Point of Contact

JCAA/JG-PP Web site: http://www.jgpp.com

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