

# **Database for Solder Properties with Emphasis on New Lead-free Solders**

National Institute of Standards and Technology  
&  
Colorado School of Mines

## **Properties of Lead-Free Solders**

**Release 4.0**

**Dr. Thomas Siewert**

National Institute of Standards and Technology

**Dr. Stephen Liu**

Colorado School of Mines

**Dr. David R. Smith**

National Institute of Standards and Technology

**Mr. Juan Carlos Madeni**

Colorado School of Mines

Colorado, February 11, 2002

## Properties of Lead-Free Solders

**Disclaimer:** In the following database, companies and products are sometimes mentioned, but solely to identify materials and sources of data. Such identification neither constitutes nor implies endorsement by NIST of the companies or of the products. Other commercial materials or suppliers may be found as useful as those identified here.

**Note:** Alloy compositions are given in the form “Sn-2.5Ag-0.8Cu-0.5Sb,” which means: 2.5 % Ag, 0.8 % Cu, and 0.5 % Sb (percent by mass), with the leading element (in this case, Sn) making up the balance to 100 %.

### Abbreviations for metallic elements appearing in this database:

<b>Ag:</b> silver	<b>Cu:</b> copper	<b>Pt:</b> platinum
<b>Al:</b> aluminum	<b>In:</b> indium	<b>Sb:</b> antimony
<b>Au:</b> gold	<b>Mo:</b> molybdenum	<b>Sn:</b> tin
<b>Bi:</b> bismuth	<b>Ni:</b> nickel	<b>W:</b> tungsten
<b>Cd:</b> cadmium	<b>Pb:</b> lead	<b>Zn:</b> zinc
<b>Cr:</b> chromium	<b>Pd:</b> palladium	
<b>Sn-Ag-Cu:</b> Refers to compositions near the eutectic		

### Table of Contents:

1. **Mechanical Properties:** creep, ductility, activation energy, elastic modulus, elongation, strain rate, stress relaxation, tensile strength, yield strength

Table 1.1. Strength and Ductility of Low-Lead Alloys Compared with Alloy Sn-37Pb (NCMS Alloy A1), Ranked by Yield Strength (15 Alloys) and by Total Elongation (19 Alloys)

Table 1.2. Tensile Properties of Lead-Free Solders (two parts)

Table 1.3. Elastic Properties of Sn-37Pb (eutectic) and Sn-3.5Ag

Table 1.4. Elastic Properties of Sn-2.5Ag-0.8Cu-0.5Sb (Castin™) and Sn-37Pb Eutectic-A

Table 1.5. Elastic Properties of Sn-2.5Ag-0.8Cu-0.5Sb (Castin™) and Sn-37Pb Eutectic-B

Table 1.6. Parameters for Strain Rate: Norton Equation,  $d\epsilon/dt = A \cdot \sigma^n \cdot \exp(-Q/(RT))$ ; Dorn Equation,  $d\epsilon/dt = A \cdot (\sigma^n/T) \cdot \exp(-Q/(RT))$ ; Stress-relaxation Rate,  $d\sigma/dt = A \cdot (\sigma - \sigma_i)^n \cdot \exp(-Q/(RT))$ ; and Strain-Rate Sensitivity,  $\sigma = C \cdot (d\epsilon/dt)^m$ ; for Two Lead-Free Solder Alloys, Sn-3.5Ag and Sn-9Zn.

Table 1.7. Steady-State Creep Properties and Associated Mechanisms for Three Lead-Free Solders and Sn-37Pb Eutectic

Table 1.8. Stress Exponents and Activation Energies for Dorn Equation for Tin and Four Lead-Free Solder Alloys

Table 1.9. Activation Energy versus Strain Rate for Two Lead-Free Eutectic Solders (Sn-3.5Ag and Sn-9Zn)

Table 1.10. Elastic Properties of Metallic Elements Used In Electronic Packaging

Table 1.11. Material Properties of a Via-in-Pad Chip-Scale Package Printed Circuit Board (PCB) Assembly

Table 1.12. Elastic Properties and Thermal Expansion Coefficient of Electronic-Packaging Materials and Lead Solder Alloys

Table 1.13. Lead-Free Solder Alloys: Tensile and Shear Strengths

Table 1.14. Lead-Containing Solder Alloys: Tensile and Shear Strengths

Table 1.15. Shear Strengths of Three Lead-Free Solders and Tin-Lead Eutectic (by Ring-and-Plug Test)

Table 1.16. Mechanical Properties of Tin, Tin-Lead, and Four Lead-Free Solder Alloys (by Ring-and-Plug Tests)

Table 1.17. Shear Strengths, Solidus and Liquidus Temperatures, and Wetting Angles of Experimental Sn-Ag-Cu Solder Alloys

Table 1.18. Physical and Mechanical Properties of Lead-Free Alloys and Sn-37Pb (eutectic)

Table 1.19. Pure Copper, Tin and Nickel, and Their Intermetallics: Room-Temperature Physical and Thermal Properties

Table 1.20. Effects of Transition Metals on Vickers Hardness and Ultimate Tensile Strength of Sn-4.7Ag-1.7Cu Solder Alloys

Table 1.21.1. SnAgCu Dynamic Elastic Constant

Table 1.21.2. SnAgCu Dynamic Elastic Constant (cont.)

Table 1.22.1. SnAgCu Elastic Properties vs. Temperature

Table 1.22.2. SnAgCu Elastic Properties vs. Temperature (cont.)

Table 1.22.3. SnAgCu Elastic Properties vs. Temperature (cont.)

Table 1.22.4. SnAgCu Elastic Properties vs. Temperature (cont.)

Table 1.22.5. SnAgCu Elastic Properties vs. Temperature (cont.)

Table 1.22.6. SnAgCu Elastic Properties vs. Temperature (cont.)

Table 1.23. SnAgCu - Coefficient of Thermal Expansion Data. Sample As-cast #1

Table 1.24. SnAgCu - Coefficient of Thermal Expansion Data. Sample As-cast #2

Table 1.25. SnAgCu - Coefficient of Thermal Expansion Data. Sample Aged #1

Table 1.26. SnAgCu - Coefficient of Thermal Expansion Data. Sample Aged #2

Table 1.27. Mechanical Properties of Three Selected Pb-free Alloys: Sn-3.2Ag-0.8Cu, Sn-3.5Ag, and Sn-0.7Cu

Figure 1.1. Creep data at 75°C for Sn-Ag-Cu, Sn-Ag-Bi, Sn-Ag, Sn-Bi, and Sn-Pb solder alloys

## **2. Thermal Properties**

### **2.1. Solidus, Liquidus, and Melting-Point Temperatures**

Table 2.1.1. Liquidus and Reflow Temperatures of Candidate Lead-Free Solder Alloys for Replacing Eutectic Tin-Lead Solder

Table 2.1.2. Melting Temperatures of Lead-Free Solders (two parts)

### **2.2. Thermal Properties: Miscellaneous**

Table 2.2.1. Thickness ( $\mu\text{m}$ ) of Intermetallics in Solder Alloys Aged at 150 °C

Table 2.2.2. Thermal and Electrical Properties of Castin™ (Sn-2.5Ag-0.8Cu-0.5Sb)

Table 2.2.3. Physical and Mechanical Properties of Sn-2.8Ag-20.0In and Sn-37Pb Eutectic Solders

Table 2.2.4. Some Physical Properties of Materials Used as Electronic Packaging Conductors

Table 2.2.5. Thermophysical Properties of Metallic Elements Used In Electronic Packaging

Table 2.2.6. Some Properties of Materials Commonly Used In Electronics – A

Table 2.2.7. Some Properties of Materials Commonly Used In Electronics – B

Table 2.2.8. Electrical Resistivity and Temperature Coefficient of Resistance (TCR) of Pure Metallic Elements Used in Electronic Packaging

Table 2.2.9. Wetting Properties of Sn-2.8Ag-20.0In and Sn-37Pb Eutectic Solders

Table 2.2.10. Wetting Times and Forces (at 300 °C): Lead-Free Solder Alloys, and Eutectic Tin-Lead

Table 2.2.11. Wetting Times (at 250 °C) of Lead-free Solder Alloys

Table 2.2.12. Onset of Melting Temperatures for Five Sn-Ag-Cu Lead-Free Solder Alloys

Table 2.2.13. Solidus Temperatures and Wetting Contact Angles of Selected Lead-Free Solder Alloys with Use of RMA (GF-1235) Flux

Table 2.2.14. Solidus and Liquidus Temperatures and Wetting Angles of Some Lead-Free Alloys on Copper

Table 2.2.15. Melting Properties, Resistivity, Wettability and Hardness of Lead-Free Solders

Table 2.2.16. Wetting Contact Angles of Sn-Ag, Sn-Bi, and Sn-Zn Alloys on Copper: Eutectic, and With 1% Addition of Ternary Elements

Table 2.2.17. Wetting Contact Angles on Copper of Sn-Bi Alloys: Eutectic, and With 1% Addition of Ternary Elements

Table 2.2.18. Wetting Properties of Pure Tin, Four Lead-Free Tin Alloys and Three Lead-Tin Alloys

Table 2.2.19. Lead-Free Solder Alloys: Solidus and Liquidus Temperatures, Coefficient of Thermal Expansion, Surface Tension, and Electrical Resistivity

Table 2.2.20. Fluid Properties of Some Molten Lead-Free Solders

Table 2.2.21. Densities and Costs of Popular Solder Metals and Alloys – A

Table 2.2.22. Densities and Costs of Popular Solder Metals and Alloys – B

Table 2.2.23. Cost of Lead-Free Solder Alloys Relative to That of Sn-37Pb Eutectic

A. Solder Alloys for Plated-Through Holes

### 3. Candidate Alloys for Replacing Lead-Alloy Solders

Table 3.1. Criteria for Down-Selection of Lead-Free Alloys

Table 3.2. Chemical Compositions of 79 Lead-Free Solder Alloys Down-Selected for Preliminary Testing by the National Center for Manufacturing Sciences (NCMS).

### 4. Miscellaneous

A. Major Considerations for Replacement Lead-Free Solders

Table 4.1. Designation and Composition of Lead-Free Solders.

### 5. Useful References

5.1. References to Tabular Data

5.2. Reference Books

5.3. Useful URLs

**Key words:** alloys, aluminum, antimony, atomic weight, bibliography, bismuth, Castin, chemical, chromium, coefficient, composition, conductivity, copper, costs, creep, ductility, elastic, electrical, electronic, elements, elongation, eutectic, expansion, gold, hardness, indium, intermetallic, lead, lead-free, liquidus, material, mechanical, melting, metallic, modulus, molybdenum, nickel, packaging, palladium, physical, platinum, Poisson ratio, PCB, printed circuit board, properties, replacement, resistivity, silver, solders, solidus, strength, surface tension, temperature, tensile, thermal, thermophysical, tin, tungsten, viscosity, wetting, Young's modulus, zinc

### Useful Conversion Factors

**Standard Acceleration of Gravity, g:**

$$g = 32.174 \text{ f/s}^2 = 9.80665 \text{ m/s}^2 \text{ (not to be confused with "gram", g)}$$

**Electrical Conductivity:**

$$1 \text{ S (siemens)} = 1 \Omega^{-1} \text{ (reciprocal ohm)}$$

**Density:**

$$1 \text{ g/cm}^3 = 0.036127 \text{ lb}_m/\text{in}^3 = 62.428 \text{ lb}_m/\text{ft}^3$$

**Energy:**

$$1 \text{ cal} = 4.187 \text{ J (joule)}$$

$$1 \text{ Btu} = 1055.056 \text{ J} = 252 \text{ cal} = 0.252 \text{ kcal (kilocalories)}$$

**Force:**

$$1 \text{ lb}_f = 4.4482 \text{ N (newton)}$$

$$1 \text{ kg}_f = 9.80665 \text{ N}$$

$$1 \text{ dyne} = 10^{-5} \text{ N}$$

**Length:**

$$1 \text{ in} = 2.54 \text{ cm} = 0.0254 \text{ m (exact)}$$

$$1 \text{ ft} = 30.48 \text{ cm} = 0.3048 \text{ m (exact)}$$

**Mass:**

$$1 \text{ lb}_m = 0.45359 \text{ kg}; \quad 1 \text{ kg} = 2.20463 \text{ lb}_m$$

**Pressure (or Tensile stress):**

$$1 \text{ Pa (pascal)} = 1 \text{ N/m}^2$$

$$1 \text{ psi} = 6894.76 \text{ Pa} = 6.89476 \text{ kPa}$$

$$1 \text{ kps} = 6.89476 \text{ MPa}$$

**Specific Heat (Capacity):**

$$1 \text{ cal}/(\text{g}\cdot\text{K}) = 1 \text{ Btu}/(\text{lb}_m\cdot\text{F}) = 4.187 \text{ J}/(\text{kg}\cdot\text{K})$$

**Temperature; temperature intervals:**

Fahrenheit temperature  $F = 1.8\cdot C + 32$ , where C is Celsius temperature

Kelvin temperature  $K = C + 273.15$

$1 \text{ K (1 kelvin)} = 1 \text{ }^\circ\text{C (1 Celsius degree)} = 1.8 \text{ }^\circ\text{F (1 Fahrenheit degree = temperature interval)}$

**Thermal Conductivity:**

$$1 \text{ W}/(\text{m}\cdot\text{K}) = 0.5778 \text{ Btu}/(\text{ft}\cdot\text{hr}\cdot\text{F})$$

**Explanatory Note:**

This version (11 February 2002) represents our present collection of information on properties of lead-free solders. We are just now beginning to have enough properties data to begin consolidating duplicate data, to better organize the tables into a more useful order, and to begin some evaluation of uncertainties. Also, no systematic mining of resources from journals that publish articles on relevant properties of lead-free solders has yet been done by us, but is a planned next step. However these next steps await further funding. We hope to greatly extend the work beyond this present state into a larger and more useful one. Your patience is appreciated. – the authors

**1. Mechanical Properties:** creep, ductility, activation energy, elastic modulus, elongation, strain rate, stress relaxation, tensile strength, yield strength

**Table 1.1. Strength and Ductility of Low-Lead Alloys Compared with Alloy Sn-37Pb (NCMS Alloy Code A1), Ranked by Yield Strength (15 Alloys) and by Total Elongation (19 Alloys)**

Alloy Code	Alloy Composition	Yield Strength (psi)	Alloy Code	Alloy Composition	Total Elongation (%)
C5	Sn-2Ag-9.8Bi-9.8In	14,560	B6	Sn-56Bi-2In	116
F1	Sn-2Ag-7.5Bi-0.5Cu	12,370	F15	Sn-57Bi	77
F11	Sn-2.5Ag-19.5Bi	12,070	D2	Sn-57Bi-2In	72
D10	Sn-3Ag-54Bi-2Cu-2Sb	11,440	D5	Sn-57Bi-1Sb	60
F7	Sn-31.5Bi-3Zn	10,500	B2	Sn-52Bi	57
D9	Sn-3Ag-54Bi-2In-2Sb	5,055	B1	Sn-50Bi	53
F8	Sn-3.5Ag-1.5In	4,616	A8	Sn-75Pb	53
A1	Sn-37Pb	3,950	F7	Sn-31.5Bi-3Zn	53
F10	Sn-0.2Ag-2Cu-0.8Sb	3,758	A1	Sn-37Pb	48
F3	Sn-0.5Ag-4Cu	3,724	D4	Sn-57Bi-2Sb	47
A5	Sn-5Sb	3,720	A6	Sn-58Bi	46
A8	Sn-75Pb	3,426	D7	Sn-3Ag-55.5Bi-1.5Sb	45
F2	Sn-2.6Ag-0.8Cu-0.5Sb	3,311	D8	Sn-3Ag-55Bi-2Sb	44
A4	Sn-3.5Ag	3,256	F13	Sn-55Bi-2Cu	41
A3	Sn-97Pb	1,126	F2	Sn-2.6Ag-0.8Cu-0.5Sb	9
			C5	Sn-2Ag-9.8Bi-9.8In	7
			D10	Sn-3Ag-54Bi-2Cu-2Sb	4
			E9	Sn-10Bi-20In	4
			B5	Sn-2Ag-46Bi-4Cu	3

**Source:** Technical Reports for the Lead Free Solder Project: Properties Reports: "Room Temperature Tensile Properties of Lead-Free Solder Alloys;" Lead Free Solder Project CD-ROM, National Center for Manufacturing Sciences (NCMS), 1998



**Table 1.2. Tensile Properties of Lead-Free Solders**  
**(A.C.: Alloy Code (NCMS); Blank cells: no values reported)**

A.C.	Chemical Composition	Elastic Modulus		Yield Strength (0.2 % offset)		Tensile Strength		Relative Elongation (%)		Strength Coefficient		Hardening Exponent	
		% by Mass	(ksi)	GPa	(psi)	MPa	(psi)	MPa	Uni-form	Total	(psi)		MPa
A1	Sn-37Pb		2,273	15.7	3,950	27.2	4,442	30.6	3	48	4,917	33.9	0.033
A2	Sn-2Ag-36Pb		2,617	18.0	6,287	43.3	6,904	47.6	1	31	7,223	49.8	0.011
A3	Sn-97Pb		2,753	19.0	1,126	7.8	2,383	16.4	27	38	3,934	27.1	0.235
A4	Sn-3.5Ag		3,793	26.2	3,256	22.5	3,873	26.7	3	24	4,226	29.1	0.026
A5	Sn-5Sb		6,460	44.5	3,720	25.7	5,110	35.2	3	22	4,177	28.8	0.031
A6	Sn-58Bi		1,720	11.9	7,119	49.1	8,766	60.4	3	46	9,829	67.8	0.029
A7	Sn-3.5Ag-0.5Sb-1Cd				7,545	52.0				15			
A8	Sn-75Pb				3,426	23.6				53			
B1	Sn-50Bi				8,263	57.0	8,965	61.8		53			
B2	Sn-52Bi				6,414	44.2	8,834	60.9		57			
B5	Sn-2Ag-46Bi-4Cu				9,806	67.6	10,070	69.4		3			
B6	Sn-56Bi-2In				7,224	49.8	8,429	58.1		116			
C1	Sn-2Ag-1.5Sb-29Pb				6,489	44.7	6,865	47.3		25			
C2	Sn-3Ag-4Cu				6,276	43.3	7,006	48.3		22			
C3	Sn-2.5Ag-2Bi-1.5Sb				7,070	48.7	8,117	56.0		21			
C4	Sn-3Ag-1Bi-1Cu-1.5Sb				8,361	57.6	9,256	63.8		21			
C5	Sn-2Ag-9.8Bi-9.8In				14,560	100.4	15,380	106.0		7			
D2	Sn-57Bi-2In				7,304	50.4	8,436	58.2		72			
D3	Sn-2Ag-57Bi				9,487	65.4	10,390	71.6		31			
D4	Sn-57Bi-2Sb				8,521	58.8	9,586	66.1		47			
D5	Sn-57Bi-1Sb				8,285	57.1	8,944	61.7		60			
D6	Sn-2Ag-56Bi-1.5Sb				9,063	62.5	9,946	68.6		27			
D7	Sn-3Ag-55.5Bi-1.5Sb				8,665	59.7	9,379	64.7		45			
D8	Sn-3Ag-55Bi-2Sb				8,984	61.9	9,807	67.6		44			
D9	Sn-3Ag-54Bi-2In-2Sb				5,055	34.9	11,640	80.3		13			
D10	Sn-3Ag-54Bi-2Cu-2Sb				11,440	78.9	12,280	84.7		4			

### Tensile Properties of Lead-Free Solders (cont.)

(A.C.: Alloy Code (NCMS); Blank cells: no values reported)

A.C.	Chemical Composition	Elastic Modulus		0.2% Yield Strength		Tensile Strength		Relative Elongation (%)		Strength Coefficient		Hardening Exponent
	% by Mass	(ksi)	GPa	(psi)	MPa	(psi)	Mpa	Uni-form	Total	(psi)	MPa	
E1	Sn-3Ag-2Sb			5,749	39.6	6,124	42.2		25			
E2	Sn-3Ag-2Cu-2Sb			6,684	46.1	7,655	52.8		32			
E3	Sn-3Ag-2Bi-2Sb			6,918	47.7	9,212	63.5		36			
E4	Sn-3Ag-2Bi			5,463	37.7	7,930	54.7	6	30	8,946	61.7	0.041
E5	Sn-2.5Ag-2Bi			6,592	45.5	7,564	52.2		26			
E6	Sn-2Bi-1.5Cu-3Sb			7,343	50.6	9,350	64.5		28			
E7	Sn-2Bi-8In			7,160	49.4	7,970	55.0		25			
E9	Sn-10Bi-20In			--	--	6,938	47.8		4			
E10	Sn-9Zn			7,478	51.6	7,708	53.1		27			
F1	Sn-2Ag-7.5Bi-0.5Cu			12,370	85.3	13,440	92.7		12			
F2	Sn-2.6Ag-0.8Cu-0.5Sb			3,311	22.8	3,749	25.8	2	9	4,536	31.3	0.049
F3	Sn-0.5Ag-4Cu			3,724	25.7	4,312	29.7		27			
F4	Sn-8.8In-7.6Zn			6,033	41.6	6,445	44.4		14			
F5	Sn-20In-2.8Zn			5,095	35.1	5,381	37.1		31			
F7	Sn-31.5Bi-3Zn			10,500	72.4	11,210	77.3		53			
F8	Sn-3.5Ag-1.5In			4,616	31.8	4,987	34.4		26			
F9	Sn-2Ag-0.5Bi-7.5Sb			8,230	56.7	8,773	60.5		19			
F10	Sn-0.2Ag-2Cu-0.8Sb			3,758	25.9	4,323	29.8		27			
F11	Sn-2.5Ag-19.5Bi			12,070	83.2	13,450	92.7		17			
F12	Sn-3Ag-41Bi			9,287	64.0	10,130	69.8		39			
F13	Sn-55Bi-2Cu			8,985	62.0	9,478	65.4		41			
F14	Sn-48Bi-2Cu			8,899	61.4	9,495	65.5		19			
F15	Sn-57Bi			7,972	55.0	8,540	58.9		77			
F16	Sn-56.7Bi-0.3Cu-1In			8,359	57.6	8,985	62.0		38			
F17	Sn-3.4Ag-4.8Bi			6,712	46.3	10,349	71.4	5	16	17,795	122.7	0.153

**Source:** Technical Reports for the Lead Free Solder Project: Properties Reports: "Room Temperature Tensile Properties of Lead-Free Solder Alloys;" Lead Free Solder Project CD-ROM, National Center for Manufacturing Sciences (NCMS), 1998

**Table 1.3. Elastic Properties of Sn-37Pb (eutectic) and Sn-3.5Ag**

Property		Sn-37Pb	Sn-3.5Ag	Sn-5Sb
Melting Point,	°C	183	221	
UTS*	MPa	31 – 46	55	
Elongation,	%	35 – 176	35	
Shear Strength,	MPa	28.4	32.1	
Young's Modulus <sup>§</sup> ,	GPa	35 <sup>§</sup>	56 <sup>§</sup>	58 <sup>§</sup>

\*Ultimate Tensile Strength

Jeff D. Sigelko and K.N. Subramanian, "Overview of lead-free solders," Adv. Mat. & Proc., pp. 47-48 (March 2000)

<sup>§</sup> Rodney J. McCabe and Morris E. Fine, "Athermal and Thermally Activated Plastic Flow in Low Melting Temperature Solders at Small Stresses," Scripta Materialia **39**(2), 189 (1998)

**Table 1.4. Elastic Properties of Sn-2.5Ag-0.8Cu-0.5Sb (Castin™) and Sn-37Pb Eutectic - A**

<b>Tensile Properties</b> (1 ksi = 6.895 MPa)				
	<b>Castin™</b>		<b>Sn-37Pb</b>	
	(ksi)	(MPa)	(ksi)	(MPa)
Young's Modulus	7420	51.16 (GPa)	4870	33.58 (GPa)
Yield Strength	4.86	33.5	4.38	30.2
UTS*	5.73	39.5	4.92	33.92
Elongation (%)	50.00		52.87	
<b>Compressive Properties</b>				
	(ksi)	(MPa)	(ksi)	(MPa)
Elastic Modulus	4260	29.37 (GPa)	3990	27.51 (GPa)
Yield Strength	4.33	29.85	4.52	31.16
Stress (25 °/u)	8.54	58.88	7.17	49.44
Rockwell Hardness (15 W scale hardness)	18.28		10.08	

\*Ultimate Tensile Strength

Karl Seelig and David Suraski, "The Status of Lead-Free Solder Alloys," Proc. 50<sup>th</sup> IEEE 2000 Electronic Components and Technology Conference (May 21-24, 2000), Las Vegas, NV

**Table 1.5. Elastic Properties of Sn-2.5Ag-0.8Cu-0.5Sb (Castin™) and Sn-37Pb Eutectic – B**

<b>Tensile Properties</b> (1 ksi = 6.895 MPa)				
	<b>Castin™</b>		<b>Sn-37Pb</b>	
	(ksi)	(MPa)	(ksi)	(MPa)
Young's Modulus	4300	29.65 (GPa)	5740	39.58 (GPa)
Yield Strength	4.03	27.8	4.07	28.1
UTS*	5.56	38.3	5.91	40.7
Elongation (%)	50.00		43.66	
<b>Compressive Properties</b>				
	(ksi)	(MPa)	(ksi)	(MPa)
Young's Modulus	10890	75.08 (GPa)	16600	11.45 (GPa)
Yield Strength (0.2% strain)	4.53	31.2	4.84	33.4
Stress (25 ° strain)	10.07	69.4	9.88	68.1
Rockwell Hardness (16 W scale hardness)	13.5		12.2	

\*Ultimate Tensile Strength

**Note:** It is not stated explicitly, but accompanying textual description suggests that the measured specimens of these alloys may have been first soaked at 125 °C before the properties listed in this table were measured. This may explain the differences in measured properties between this table and the previous one (A) comparing Castin™ with Sn-37Pb.

Karl Seelig and David Suraski, "The Status of Lead-Free Solder Alloys," Proc. 50<sup>th</sup> IEEE 2000 Electronic Components and Technology Conference (May 21-24, 2000), Las Vegas, NV

**Table 1.6. Parameters for Strain Rate (Norton Equation,  $d\varepsilon/dt = A \cdot \sigma^n \cdot \exp(-Q/RT)$ ); and Dorn Equation,  $d\varepsilon/dt = A \cdot (\sigma^n/T) \cdot \exp(-Q/(RT))$ ); Stress-relaxation Rate,  $d\sigma/dt = A \cdot (\sigma - \sigma_t)^n \cdot \exp(-Q/(RT))$ ); and Strain-rate Sensitivity,  $\sigma = C \cdot (d\varepsilon/dt)^m$ ; for Two Lead-Free Solder Alloys, Sn-3.5Ag and Sn-9Zn.**

Here  $\varepsilon$  is strain,  $t$  is the time variable,  $d\varepsilon/dt$  is strain rate ( $s^{-1}$ ),  $A$  and  $C$  are constants,  $\sigma$  is stress (MPa),  $\sigma_t$  is a threshold stress for stress relaxation,  $n$  is the stress exponent,  $Q$  is an activation energy (kJ/mol),  $R$  is the universal gas constant,  $T$  is absolute temperature, and  $m$  is the strain-rate sensitivity.

Alloy		Norton		Dorn		Stress Relaxation	Temperature (°K)	
		Tensile	Creep	Tensile	Creep		25	80
Sn-3.5Ag	A	$6.62 \cdot 10^{-3}$	$1.50 \cdot 10^{-3}$	5.83	$1.36 \cdot 10^{-3}$			
	n	12	11.3	12	11.3	6		
	Q	108.5	79.5	111.2	82.3	33.5		
	m						0.080	0.083
	$\sigma_t$					9.8		
Sn-9Zn	A	9.27	0.0217	8220	19.1			
	n	8.1	5.7	8.1	5.7	4.2		
	Q	99.9	65.2	102.6	68.0	106.9		
	m						0.122	0.124
	$\sigma_t$					3		
Sn-37Pb	n		6.2*					
	Q		64*					

\*E.W. Hare and R.G. Stang, *J. Electronic Mater.* 21, 599 (1992)

H. Mavoori, J. Chin, S. Vaynman, B. Moran, L. Keer and M. Fine, "Creep, Stress Relaxation, and Plastic Deformation in Sn-Ag and Sn-Zn Eutectic Solders," *J. Electronic Materials*, 26(7), 783 (1997)

**Table 1.7. Steady-state Creep Properties and Associated Mechanisms for Three Lead-free Solders and Sn-37Pb Eutectic**

Alloy	Deformation Mechanism	B* (MPa <sup>-n</sup> ·s <sup>-1</sup> )	ΔH (eV)	n (40 °C)	n (140 °C)
Sn-4Cu-0.5Ag	Athermal, short-range Cu clustering	4.229×10 <sup>-12</sup>	0.062	8.36	8.36
Sn-2Cu-0.8Sb-0.2Ag	Dislocation glide / climb	3.031	0.85	8.91	7.37
Sn-36Pb-2Ag	Dislocation glide / climb	0.04423	0.50	5.25	5.25
Sn-37Pb	Dislocation glide / climb	0.205	0.49	5.25	5.25

Y.-H. Pao, S. Badgley, R. Govila and E. Jih, “An Experimental and Modeling Study of Thermal Cyclic Behavior of Sn-Cu and Sn-Pb Solder Joints,” Mat. Res. Soc. Symp. Proc. Vol. 323, p. 128 (MRS, 1994)

[Here the steady-state creep behavior was assumed to be described by (Norton’s Law; see previous table, “Parameters for Strain Rate”),  $d\gamma_{crp}/dt=B*\tau^n \exp(-\Delta H/(kT))$ , with  $d\gamma_{crp}/dt$  as the rate of shear creep strain,  $\tau$  the shear stress,  $n$  a stress exponent,  $\Delta H$  an activation energy,  $kT$  the product of Boltzmann’s constant and absolute temperature, and  $B^*$  a material constant.]

**Table 1.8. Stress Exponents and Activation Energies for Dorn Equation for Tin and Four Lead-Free Solder Alloys**

Alloy	Region 1		Region 2		Region 3	
	Activation Energy, Q (kJ/mol)	Stress Exponent, n	Activation Energy, Q (kJ/mol)	Stress Exponent, n	Activation Energy, Q (kJ/mol)	Stress Exponent, n
Sn					66	8.4
Sn-2.6Sb			115	5.9	87	9.0
Sn-5Sb			103	5.7	85	11.6
Sn-7.8Sb	68	0.9	52	6.2	49	9.8
Sn-2Sb-2In			71	5.9	96	9.3

Rodney J. McCabe and Morris E. Fine, “The Creep Properties of Precipitation-Strengthened Tin-Based Alloys,” JOM, p. 33 (June 2000)

**Table 1.9. Activation Energy versus Strain Rate for Two Lead-Free Eutectic Solders (Sn-3.5Ag and Sn-9Zn)**

<b>Strain Rate (s<sup>-1</sup>)</b>	<b>Activation Energy (J/mol)</b>	
	<b>Sn-3.5Ag</b>	<b>Sn-9Zn</b>
10 <sup>-2</sup>	8.56	12.3
10 <sup>-3</sup>	9.97	12.5
10 <sup>-4</sup>	7.90	12.1
10 <sup>-5</sup>	9.70	12.6

H. Mavoori, Semyon Vaynman, Jason Chin, Brian Moran, Leon M. Keer and Morris E. Fine, "Mechanical Behavior of Eutectic Sn-Ag and Sn-Zn Solders," Mat. Res. Soc. Symp. Proc. Vol. 390, p. 161 (MRS, 1995)

**Table 1.10. Elastic Properties of Metallic Elements Used In Electronic Packaging**

<b>Metal</b>	<b>Condition</b>	<b>E (Elastic) (GPa)</b>	<b>G (Shear) (GPa)</b>	<b>Tensile Strength (MPa)</b>	<b>Yield Strength* (MPa)</b>
Aluminum 99.996	Annealed	68.9	26.5	47.4	12.2
Antimony		77.8		11	
Copper 99.997	Rod, cold- drawn	127.7	46.8	351	340
Gold 99.99	Cast	74.4		124	
Lead 99.90	Rolled, aged				9.5 (0.5 %)
Molybdenum	Pressed, sintered sheet	340		690	
Nickel >99.0	Wrought, annealed	210		482	138
Platinum 99.99	Annealed	147		120-130	
Silver	Strained 5 %, heated 5 hr at 350 C	71 – 78			
Tin	Pure, cast	41 – 45		21.4	
Tin-5Ag	Sheet, aged at room temp.			31.7	24.8
Tungsten		340	135		
Zinc	Hot-rolled			134-160	
<0.10 Pb	strip				

\*(0.2 % offset)

D.E. Gray, ed., *American Institute of Physics Handbook*, pp. 2-61 ff. (McGraw-Hill, New York, 1957) [Note: original units were in dyn/cm<sup>2</sup>; 10 dyn/cm<sup>2</sup> = 1 N/m<sup>2</sup> = 1 Pa]



[FOLLOWING TABLE STILL NEEDS A COMPLETE DOCUMENTATION OF SOURCE]:

**Table 1.11. Material Properties of a Via-in-Pad Chip-Scale Package Printed Circuit Board Assembly**

<b>Material</b>	<b>Young's Modulus, E (GPa)</b>	<b>Poisson's Ratio (ν)</b>	<b>Thermal Exp. Coefficient (10<sup>-6</sup>/K)</b>
FR-4 epoxy-glass PCB substrate	22	0.28	18.5
Copper VIP (via-in-pad)	76	0.35	17
Sn-37Pb (eutectic) solder	E=32.0-0.088·t (0 ≤ t ≤ 100, t is Celsius temp.)	0.4	21
Underfill	6	0.35	30
Silicon chip	131	0.3	2.8
Solder mask	6.9	0.35	19
*AL	69	0.33	22.8
*Si <sub>3</sub> Ni <sub>4</sub>	314	0.33	3
Micro-via filler	7	0.3	35
Bismaleimide	26	0.39	15
Triazene (BT)			

J. Lau, C. Chang, R. Lee, T.-Y. Chen, D. Cheng, T.J. Tseng, D. Lin, "Thermal-Fatigue Life of Solder Bumped Flip Chip on Micro Via-In-Pad (VIP) Low Cost Substrates"

\*J.H. Lau and S.-W. Ricky Lee, "Fracture Mechanics Analysis of Low Cost Solder Bumped Flip Chip Assemblies with *Imperfect* Underfills," Proceedings: NEPCON West Conference (February 28 – March 2, 1995), Anaheim, CA

**Table 1.12. Elastic Properties and Thermal Expansion Coefficient of Electronic-Packaging Materials and Lead Solder Alloys**

<b>Material</b>	<b>Temp. (°C)</b>	<b>Young's Modulus, (GPa)</b>	<b>Poisson's Ratio (ν)</b>	<b>Thermal Exp. Coefficient (10<sup>-6</sup>/K)</b>
Sn-37Pb (eutectic) solder	-70	38.1	0.4	24.0
	20	30.2	0.4	24.0
	140	19.7	0.4	24.0
Pb-10Sn	-55	13.4	0.4	27.8
	22	9.78	0.4	28.9
	100	4.91	0.4	30.5
Alumina (substrate)	-55	303	0.21	3.9
	22	303	0.21	4.5
	100	303	0.21	6.7
Silicon chip	-73	162	0.22	1.40
	27	162	0.22	2.62
	127	162	0.22	3.23
Polyimide PWB	-55 to 125	14.5	0.16	13.0
Hysol FP4526 Underfill	-73	9.78	0.3	33.0
	25	9.51	0.3	33.0
	52	9.23	0.3	33.0
	77	8.82	0.3	33.0
	102	7.72	0.3	33.0
	127	5.37	0.3	33.0

Tim Wong and A.H. Matsunaga, "Ceramic Ball Grid Array Solder Joint Thermal Fatigue Life Enhancement," Proceedings: NEPCON West Conference (February 28 – March 2, 1995), Anaheim, CA

**Table 1.13. Lead-free Solder Alloys: Tensile and Shear Strengths**

<b>Lead-free Solder Alloy</b>	<b>Temperature (°F)</b>		<b>Tensile Strength (psi)</b>	<b>Shear Strength (psi)</b>	<b>Density (g/cm<sup>3</sup>)</b>
	<b>Solidus</b>	<b>Liquidus</b>			
Sn (pure)	450	450	1800	2560	7.31
Sn-3.5Ag	430	430	8900	4600	7.36
Sn-5Ag	430	473	10100	8400	7.45
Sn-3Cu	441	635	6420	NA	7.34
Sn-5Sb	450	464	5900	6200	7.26

Solder Data Sheet, Welco Castings, 2 Hillyard Street, Hamilton, Ontario, Canada

**Table 1.14. Lead-containing Solder Alloys: Tensile and Shear Strengths**

<b>Solder (Lead) Alloy</b>	<b>Temperature (°F)</b>		<b>Tensile Strength (psi)</b>	<b>Shear Strength (psi)</b>	<b>Density (g/cm<sup>3</sup>)</b>
	<b>Solidus</b>	<b>Liquidus</b>			
Pb (pure)	621	621	1780	1800	11.34
Pb-1Sn-1.5Ag			3600		
Pb-5Sn	518	596	4190	3000	11.13
Pb-10Sn	514	576	4400	3780	10.94
Pb-15Sn	437	553	4700	4470	10.7
Pb-20Sn	362	533		4740	10.5
Pb-25Sn	362	514	5770	5310	10.3
Pb-30Sn	362	490	6140	5500	9.8
Pb-35Sn	362	475	6230	5590	9.6
Pb-38Sn	362	465	6285	5640	9.81
Pb-40Sn	362	460	6320	5680	9.34
Pb-45Sn	362	440	6400	5780	9.13
Pb-50Sn	362	420	6450	5870	8.91
Pb-60Sn	362	375	6400	5700	8.67
Pb-62Sn	362	363	6700	6060	8.50
Pb-63Sn	362	362	6700	6060	8.42
(eutectic)					
Pb-95Sn			5900		
Sn-36Pb-4Ag	350	378	8500	7000	8.88

Solder Data Sheet, Welco Castings, 2 Hillyard Street, Hamilton, Ontario, Canada

**Table 1.15. Shear Strengths of Three Lead-Free Solders and Tin-Lead Eutectic (by Ring-and-Plug Test)**

Solder	Load		Stress (area = 0.046 in <sup>2</sup> )	
	(lbs)	(N)	(psi)	(MPa)
Sn-37Pb (eutectic)	269 ± 11	1197 ± 49	5840 ± 240	40.27 ± 1.65
Sn-3.5Ag	367 ± 24	1632 ± 107	7970 ± 530	54.95 ± 3.65
Sn-3.33Ag-4.83Bi	540 ± 80	2402 ± 356	11,800 ± 1700	81.36 ± 11.7
Sn-3.15Ag-5.0Bi-5.0Au	560 ± 15	2491 ± 67	12,170 ± 330	83.91 ± 2.28

Cynthia L. Hernandez, Paul T. Vianco, Jerome A. Rejent, “Effect of Interface Microstructure on the Mechanical Properties of Pb-Free Hybrid Microcircuit Solder Joints,” IPC/SMTA Electronics Assembly Expo (1998), p. S19-2-1

**Table 1.16. Mechanical Properties of Tin, Tin-Lead, and Four Lead-Free Solder Alloys (by Ring-and-Plug Tests)**

Alloy	Shear Strength at 1mm/min (MPa)		Stress to Rupture in 1000 hr (MPa)		Fatigue Strength in 1000 cycles (MPa)	
	Temperature		Temperature		Temperature	
	Room	100 °C	Room	100 °C	Room	100 °C
Sn (pure)	22.6	19.3	8.4	2.2	13.7	9.0
Sn-1Cu	28.5	21.2	7.8	2.2	14.9	8.3
Sn-3.5Ag	39.0	23.5	14.0	5.5	18.6	10.5
Sn-5Sb	38.7	21.3	11.0	3.6	20.9	14.1
Sn-58Bi	48.0	15.6	3.3	0.9	16.0	7.9
Sn-40Pb	34.5	21.6	3.5	1.1	16.2	10.2

International Tin Research Institute, Publ. No. 656; through: William B. Hampshire, “The Search for Lead-Free Solders,” Proc. Surface Mount International Conference (Sept. 1992) San Jose, CA, p. 729

**Table 1.17. Shear Strengths, Solidus and Liquidus Temperatures, and Wetting Angles of Experimental Sn-Ag-Cu Solder Alloys**

Alloy	Shear Strength (MPa) (Cross-head speed: 0.1 mm/min; gap thickness: 76.2 μm)					T <sub>sol</sub> /T <sub>liq</sub> (°C)	Wetting Angle (deg)
	Test temperature						
	22 °C			170 °C			
	A*	B*	C*	# D	B*		
Sn-3.5Ag	20.9	61.2		27	20.5	221	33
Sn-0.7Cu	--	29.8		32	10.1	227	
Sn-3.60Ag-1.00Cu (gap thickness: 152.4 μm)	54.0	67.0 ±2.4	70.8 ± 2.3 (59.4 ± 4.4)		24.4	217/217.9	
Sn-3.59Ag-0.99Cu-0.15Co	65.4	65.5			22.8	217/218.5	
Sn-3.59Ag-0.99Cu-0.30Co	53.5	56.1			17.5	217/219.3	
Sn-3.58Ag-0.99Cu-0.45Co	56.7	65.7 ±3.8	56.2 ± 6.2		21.2	217/218.9	
Sn-4.70Ag-1.70Cu	47.0	58.0			21.6	217	21
Sn-4.68Ag-1.69Cu-0.30Co	54.5	57.8			22.9	217/218.1	18
Sn-4.68Ag-1.69Cu-0.30Ni	50.2	65.5			23.2	217/218.1	24
Sn-3.8Ag-0.7Cu	--	63.8		27	25.1	217	
Sn-3.8Ag-0.7Cu-0.5Sb	--	64.1			28.9		44
Sn-40Pb	37.4	36.5		26	4.5	183/188	17

\*A: Cooling rate in soldering (test) butt joints=1.5 °/s

\*B: Cooling rate=10 °/s

\*C: "Refined" test, (solderability and microstructure)

Measurements A, B and C by Asymmetric Four-Point Bend [AFPB] method

# D: Values from technical literature (two different sources); by ring-and-plug method

# Iver E. Anderson, Tamara E. Bloomer, Robert L. Terpstra, James C. Foley, Bruce A. Cook and Joel Harringa, "Development of Eutectic and Near-Eutectic Tin-Silver-Copper Solder Alloys for Lead-Free Electronic Assemblies," IPCWorks '99: An International Summit on Lead-Free Electronics Assemblies," (October 25-28, 1999), Minneapolis, MN

# Iver E. Anderson, Tamara E. Bloomer, Robert L. Terpstra, James C. Foley, Bruce A. Cook and Joel Harringa, "Development of Eutectic and Near-Eutectic Tin-Silver-Copper Solder Alloys for Lead-Free Joining Applications," p. 575

**Table 1.18. Physical and Mechanical Properties of Lead-free Alloys and Sn-37Pb (eutectic)**

Property		Sn-3.5Ag	Sn-3.5Ag-0.7Cu	Sn-3.8Ag-0.7Cu <sup>@</sup>	Sn-0.7Cu (“Alloy 99C” <sup>*</sup> )	Sn-37Pb (eutectic)
Density, g/cm <sup>3</sup>		7.5		7.5	7.3	8.4
Melting Point (°C)		221		217	227-240*	183
Electrical Conductivity, %IACS <sup>#</sup>		14	13*	13	13*	11.9
Electrical Resistivity, μΩ·cm		12.3		13		14.5
Brinell Hardness, HB		15		15		17
Tensile Strength (20 °C), N/mm <sup>2</sup> at Strain Rate: 0.004 s <sup>-1</sup>		58	48*	48		40
Stress to Rupture	+/- 5 N/mm <sup>2</sup>				4300*	
	+/- 10 N/mm <sup>2</sup>				1460*	
Joint Shear Strength, N/mm <sup>2</sup> at 0.1 mm/min	20 °C	27		27	23 20*	23
	100 °C	17		17	16 21*	14
Creep Strength, N/mm <sup>2</sup> at 0.1 mm/min	20 °C	13.7	13*	13.0	8.6	3.3
	100 °C	5.0	5*	5.0	2.1	1.0

<sup>@</sup>Proprietary (patented) alloy (“Ecosol TSC”) of Multicore Solders

<sup>\*</sup>Peter Biocca, “Global Update on Lead-free Solders,” *Proc. Surface Mount International* (San Jose, CA, 1998), pp. 705-709

<sup>#</sup>100 %IACS = 58.00 MS/m

**Table 1.19. Pure Copper, Tin and Nickel, and Their Intermetallics: Room-Temperature Physical and Thermal Properties**

<b>Property</b>	<b>Cu</b>	<b>Sn</b>	<b>Ni</b>	<b>Cu<sub>6</sub>Sn<sub>5</sub></b>	<b>Cu<sub>3</sub>Sn</b>	<b>Ni<sub>3</sub>Sn<sub>4</sub></b>
Density (g/cm <sup>3</sup> )	8.9	7.3	8.9	8.28	8.9	8.65
Young's Modulus (GPa)	117	41	213	85.56	108.3	133.3
Shear Modulus (GPa)				50.21	42.41	45.0
Toughness (MPa·m <sup>1/2</sup> )				1.4	1.7	1.2
Vickers Hardness (kg/mm <sup>2</sup> )	30	100	15	378	343	365
Electrical Resistivity (μΩ·cm)	1.7	11.5	7.8	17.5	8.93	28.5
Thermal Conductivity (W/(m·K))	3.98	0.67	0.905	34.1	70.4	19.6
Thermal Diffusivity (cm <sup>2</sup> /s)				0.145	0.24	0.083
Specific Heat (J/(kg·K))	0.385	0.227	0.439	286	326	272
Thermal Expansion (10 <sup>-6</sup> /K)	17.1	23	12.9	16.3	19.0	13.7

D.R. Frear, S.N. Burchett, H.S. Morgan, and J.H. Lau, eds., *The Mechanics of Solder Alloy Interconnects*, p. 60 (Van Nostrand Reinhold, New York, 1994)

**Table 1.20. Effects of Transition Metals on Vickers Hardness and UTS of Sn-4.7Ag-1.7Cu Solder Alloys**

Alloy	Designation	As Drawn				Annealed		
		VHN	Std. Dev.	UTS (MPa)	Ratio, VHN: UTS	VHN	Std. Dev.	Est. UTS (MPa)
Sn-3.5Ag	eutectic	13.25	0.35	52	0.255	13.90	0.46	54.6
Sn-4.7Ag-1.7Cu	eutectic	10.25	0.35	44	0.233	12.45	0.14	53
Sn-4.69Ag-1.69Cu-0.3Fe	eutectic+Fe	6.25	0.07			15.05	0.35	
Sn-4.68Ag-1.69Cu-0.5Co	Eutectic+Co	17.95	0.21	76	0.236	15.20	0.14	64
Sn-4.69Ag-1.69Cu-0.3Ni	eutectic+Ni	16.55	0.35	70	0.236	13.75	0.35	58
Sn-3.59Ag-1.00Cu-0.3Ni	lean eutectic+Ni	15.70	0.42	61.5	0.255	13.55	0.49	53

VHN: Vickers Hardness Number

UTS: Ultimate Tensile Strength

Iver E. Anderson, Özer Ünal, Tamara E. Bloomer and James C. Foley, "Effects of Transition Metal Alloying on Microstructural Stability and Mechanical Properties of Tin-Silver-Copper Solder Alloys," Proc. Third Pacific Rim International Conference on Advanced Materials and Processing (PRICM 3) (The Minerals, Metals and Materials Society, 1998)



**Table 1.21.1. SnAgCu Dynamic Elastic Constant.**

Test Temperature (°C)	As-cast #1 Young's Modulus (GPa)	As-cast #2 Young's Modulus (GPa)	Aged #1 Young's Modulus (GPa)
-50	57.3	56.46	56.43
-25	55.79	54.66	54.65
0	54.22	52.79	52.79
25	52.62	50.86	50.86
50	50.97	48.87	48.88
75	49.29	46.83	46.84
100	47.57	44.73	44.75
125	45.83	42.59	42.61
150	44.05	40.42	40.44
175	42.26	38.21	38.23
200	40.44	35.98	36

Vianco P. T., Sandia National Laboratories, 2001

**Table 1.21.2. SnAgCu Dynamic Elastic Constant (cont.)**

Material	Parameter	Quadratic Function Coefficients ( $a + bT + cT^2$ )		
		a	b	c
As-cast #1	Young's Modulus	54.21	$-6.358 \times 10^{-2}$	$-2.685 \times 10^{-5}$
	Shear Modulus	20.24	$-2.635 \times 10^{-2}$	$-6.503 \times 10^{-5}$
	Bulk Modulus	56.19	$-5.461 \times 10^{-3}$	$-4.223 \times 10^{-5}$
	Poisson's ratio	0.3392	$-1.722 \times 10^{-4}$	$4.879 \times 10^9$
As-cast #2	Young's Modulus	52.77	$-7.637 \times 10^2$	$-3.885 \times 10^5$
	Shear Modulus	19.59	$-3.110 \times 10^2$	$-1.077 \times 10^5$
	Bulk Modulus	57.39	$-1.258 \times 10^2$	$-2.703 \times 10^5$
	Poisson's ratio	0.3467	$1.874 \times 10^4$	$1.096 \times 10^7$
Aged #1	Young's Modulus	52.76	$-7.606 \times 10^2$	$-3.961 \times 10^5$
	Shear Modulus	19.59	$-3.110 \times 10^2$	$-1.075 \times 10^5$
	Bulk Modulus	57.31	$-9.213 \times 10^3$	$-2.810 \times 10^5$
	Poisson's ratio	0.3465	$1.957 \times 10^4$	$9.912 \times 10^8$

Vianco P. T., Sandia National Laboratories, 2001

**Table 1.22.1. SnAgCu Elastic Properties vs. Temperature**

<b>Test Temperature (°C)</b>	<b>Mean Yield Stress As-Cast (MPa)</b>	<b>Min. Yield Stress As-cast (MPa)</b>	<b>Max. Yield Stress As-cast (MPa)</b>
-25	41.645	41.51	41.78
25	31.835	30.13	33.54
75	20.975	16.45	25.5
125	13.635	13.47	13.8
160	10.19	9.63	10.75

Vianco P. T., Sandia National Laboratories, 2001

**Table 1.22.2. SnAgCu Elastic Properties vs. Temperature (cont.)**

<b>Test Temperature (°C)</b>	<b>Mean Elastic Modulus As-Cast (MPa)</b>	<b>Min. Elastic Modulus As-cast (MPa)</b>	<b>Max. Elastic Modulus As-cast (MPa)</b>
-25	3978.3	2863.6	5093
25	5357.75	4956.5	5759
75	4455.5	4021.6	4889.4
125	3837.25	2836.8	4837.7
160	3309.05	2217.3	4400.8

Vianco P. T., Sandia National Laboratories, 2001

**Table 1.22.3. SnAgCu Elastic Properties vs. Temperature (cont.)**

<b>Test Temperature (°C)</b>	<b>Mean Yield Strain As-Cast</b>	<b>Min. Yield Strain As-cast</b>	<b>Max. Yield Strain As-cast</b>
-25	0.01505	0.011	0.0191
25	0.00845	0.008	0.0089
75	0.0062	0.0053	0.0071
125	0.00565	0.0045	0.0068
160	0.0056	0.0047	0.0065

Vianco P. T., Sandia National Laboratories, 2001

**Table 1.22.4. SnAgCu Elastic Properties vs. Temperature (cont.)**

<b>Test Temperature (°C)</b>	<b>Mean Yield Stress Aged (MPa)</b>	<b>Min. Yield Stress Aged (MPa)</b>	<b>Max. Yield Stress Aged (MPa)</b>
-25	38.655	36.77	40.54
25	21.925	21.21	22.64
75	17.005	16.97	17.04
125	12.15	10.71	13.59
160	11.35	10.79	11.91

Vianco P. T., Sandia National Laboratories, 2001

**Table 1.22.5. SnAgCu Elastic Properties vs. Temperature (cont.)**

<b>Test Temperature (°C)</b>	<b>Mean Elastic Modulus Aged (MPa)</b>	<b>Min. Elastic Modulus Aged (MPa)</b>	<b>Max. Elastic Modulus Aged (MPa)</b>
-25	3495.95	3415.9	3576
25	4312.55	3828.7	4796.4
75	4004.8	3752.6	4257
125	3336.3	2742.4	3930.2
160	3663.7	2715.7	4611.7

Vianco P. T., Sandia National Laboratories, 2001

**Table 1.22.6. SnAgCu Elastic Properties vs. Temperature (cont.)**

<b>Test Temperature (°C)</b>	<b>Mean Yield Strain Aged</b>	<b>Min. Yield Strain Aged</b>	<b>Max. Yield Strain Aged</b>
-25	0.0178	0.0165	0.0191
25	0.00715	0.0067	0.0076
75	0.00615	0.0058	0.0065
125	0.00555	0.0054	0.0057
160	0.0055	0.0049	0.0061

Vianco P. T., Sandia National Laboratories, 2001



**Table 1.23. SnAgCu - Coefficient of Thermal Expansion Data. Sample: As-cast #1.**

Parameter	-50°C to -25°C	-25°C to 0°C	0°C to 25°C	25°C to 50°C	50°C to 75°C	75°C to 100°C	100°C to 125°C	125°C to 150°C	150°C to 175°C	175°C to 200°C
$\Delta L/\Delta T$	9.25E-06	1.42E-05	1.55E-05	1.57E-05	1.59E-05	1.62E-05	1.68E-05	1.69E-05	1.73E-05	1.71E-05
$CTE = \Delta L/L_0 \times \Delta T$	1.27E-05	1.94E-05	2.12E-05	2.15E-05	2.17E-05	2.22E-05	2.30E-05	2.31E-05	2.37E-05	2.35E-05

Vianco P. T., Sandia National Laboratories, 2001

**Table 1.24. SnAgCu - Coefficient of Thermal Expansion Data. Sample: As-cast #2.**

Parameter	-50°C to -25°C	-25°C to 0°C	0°C to 25°C	25°C to 50°C	50°C to 75°C	75°C to 100°C	100°C to 125°C	125°C to 150°C	150°C to 175°C	175°C to 200°C
$\Delta L/\Delta T$	1.00E-05	1.43E-05	1.58E-05	1.64E-05	1.71E-05	1.70E-05	1.71E-05	1.69E-05	1.74E-05	1.59E-05
$CTE = \Delta L/L_0 \times \Delta T$	1.37E-05	1.95E-05	2.16E-05	2.24E-05	2.33E-05	2.32E-05	2.34E-05	2.30E-05	2.37E-05	2.17E-05

Vianco P. T., Sandia National Laboratories, 2001

**Table 1.25. SnAgCu - Coefficient of Thermal Expansion Data. Sample: Aged #1.**

Parameter	-50°C to -25°C	-25°C to 0°C	0°C to 25°C	25°C to 50°C	50°C to 75°C	75°C to 100°C	100°C to 125°C	125°C to 150°C	150°C to 175°C	175°C to 200°C
$\Delta L/\Delta T$	1.01E-05	1.36E-05	1.53E-05	1.57E-05	1.61E-05	1.62E-05	1.63E-05	1.68E-05	1.72E-05	1.70E-05
$CTE = \Delta L/L_0 \times \Delta T$	1.42E-05	1.92E-05	2.16E-05	2.22E-05	2.28E-05	2.30E-05	2.30E-05	2.38E-05	2.44E-05	2.41E-05

Vianco P. T., Sandia National Laboratories, 2001

**Table 1.26. SnAgCu - Coefficient of Thermal Expansion Data. Sample: Aged #2.**

Parameter	-50°C to -25°C	-25°C to 0°C	0°C to 25°C	25°C to 50°C	50°C to 75°C	75°C to 100°C	100°C to 125°C	125°C to 150°C	150°C to 175°C	175°C to 200°C
$\Delta L/\Delta T$	1.07E-05	1.45E-05	1.58E-05	1.62E-05	1.66E-05	1.72E-05	1.71E-05	1.70E-05	1.71E-05	1.61E-05
$CTE = \Delta L/L_0 \times \Delta T$	1.46E-05	1.98E-05	2.16E-05	2.20E-05	2.26E-05	2.35E-05	2.33E-05	2.32E-05	2.32E-05	2.20E-05

Vianco P. T., Sandia National Laboratories, 2001

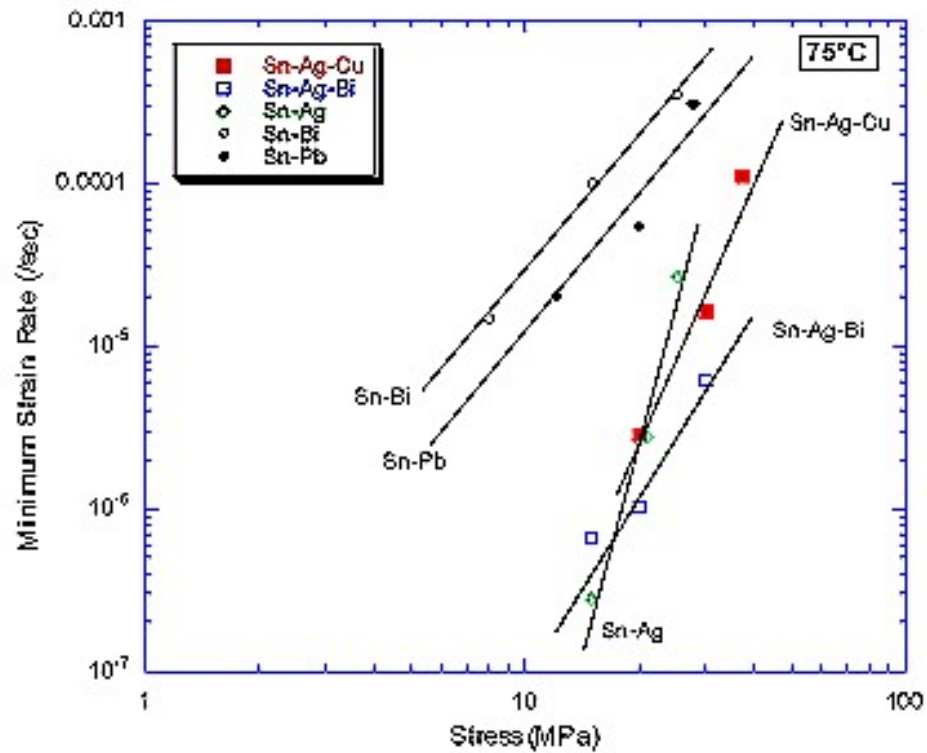
**Table 1.27. Mechanical Properties of Three Selected Pb-free Alloys: Sn-3.2Ag-0.8Cu, Sn-3.5Ag, and Sn-0.7Cu**

Sample	Process	YS (MPa)	UTS (MPa)	Uniform Elongation (%)	Total Elongation (%)
Sn-3.2Ag-0.8Cu	Q	26	31	4.2	24.5
Sn-3.2Ag-0.8Cu	Q	32	34	1.9	21.6
Sn-3.2Ag-0.8Cu	Q	25	30	4.0	20.2
<b>Average</b>	<b>Q</b>	<b>28</b>	<b>32</b>	<b>3.4</b>	<b>22.1</b>
<b>Sn-3.2Ag-0.8Cu</b>	<b>AC</b>	<b>20</b>	<b>30</b>	<b>6.2</b>	<b>26.1</b>
Sn-3.5Ag	Q	30	31	2.9	26.3
Sn-3.5Ag	Q	20	25	4.3	20.1
Sn-3.5Ag	Q	23	28	5.0	16.2
<b>Average</b>	<b>Q</b>	<b>24</b>	<b>28</b>	<b>4.1</b>	<b>20.9</b>
<b>Sn-3.5Ag</b>	<b>AC</b>	<b>19</b>	<b>28</b>	<b>6.4</b>	<b>15.9</b>
Sn-0.7Cu	Q	15	20	5.7	27.7
Sn-0.7Cu	Q	15	20	8.5	22.2
Sn-0.7Cu	Q	16	18	2.0	12.6
<b>Average</b>	<b>Q</b>	<b>15</b>	<b>19</b>	<b>5.4</b>	<b>20.8</b>
<b>Sn-0.7Cu</b>	<b>AC</b>	<b>16</b>	<b>22</b>	<b>9.1</b>	<b>41.2</b>
63Sn-37Pb <sup>#</sup>	-	27.2	30.6	3	48

\* Q: water quenched, AC: air cooled

**Source:** J. Madeni, S. Liu, and T. Siewert, "Casting of Lead-Free Solder Specimens with Various Solidification Rates", ASM- International Conference, Indianapolis 2001.

# Data for the eutectic 63Sn-37Pb extracted from [Table 1.2](#).for comparison.



**Figure 1.1. Creep properties at 75°C for Sn-Ag-Cu, Sn-Ag-Bi, Sn-Ag, Sn-Bi, and Sn-Pb solder alloys.**

Alan Woosley, Geoff Swan, T.S.Chong, Linda Matsushita, Thomas Koschmieder and Kennon Simmons, "Development of Lead (Pb) and Halogen Free Peripheral Leaded and PBGA Components to Meet MSL3 260C Peak Reflow", Work presented by the research team from Motorola at EGG, 2001

## 2. Thermal Properties: Solidus, Liquidus, and Melting-point Temperatures

### 2.1. Solidus, Liquidus and Melting Temperatures

**Table 2.1.1. Liquidus and Reflow Temperatures of Candidate Lead-Free Solder Alloys for Replacing Eutectic Tin-Lead Solder**

Alloy Composition	Liquidus Temp. (°C)	Reflow Temp. (°C)	Melting Range <sup>#</sup> (°C)
Sn-2Ag			221-226
Sn-3.5Ag	221	240 – 250	221
Sn-0.7Cu	227	245 – 255	227
Sn-3.0Ag-0.5Cu*	220**	238 – 248	
Sn-3.2Ag-0.5Cu	218	238 – 248	217-218
Sn-3.5Ag-0.75Cu*	218	238 – 248	
Sn-3.8Ag-0.7Cu	210**	238 – 248	217-210
Sn-4.0Ag-0.5Cu			217-219
Sn-4.0Ag-1.0Cu*	220**	238 – 248	217-220
Sn-4.7Ag-1.7Cu*	244**	237 – 247	217-220
Sn-5Sb			232-240
Sn-0.2Ag-2Cu-0.8Sb*	285**	246 - 256	226-228 <sup>%</sup>
Sn-2.5Ag-0.8Cu-0.5Sb*	225	233 – 243	
Sn-2Ag-7.5Bi*	216**	220 – 230	
Sn-3Ag-3Bi*	218**	233 – 243	
Sn-3Ag-5Bi*	216**	230 – 240	
Sn-3.4Ag-4.8Bi*	215**	225 – 235	200-216
Sn-3.5Ag-3Bi*	217**	230 – 240	
Sn-58Bi			138
Sn-3.2Ag-1.1Cu-3Bi*	240**	230 – 240	
Sn-3.5Ag-3In-0.5Bi*	215**	230 – 240	
Sn-3Bi-8Zn			189-199

V. Solberg, “No-Lead Solder for CSP: The Impact of Higher Temperature SMT Assembly Processing,” Proc. NEPCON West 2000 Conf. (Feb. 28 - Mar. 2, 2000) Anaheim, CA (Source: Indium Corp.)

<sup>#</sup>N.-C. Lee, “Lead-Free Chip-Scale Soldering of Packages,” Chip Scale Review, March-April 2000

\*Patented compositions; may require licensing or royalty agreements before use.

\*\*For more information see: [Phase Diagrams & Computational Thermodynamics, Metallurgy Division of Materials Science and Engineering Laboratory, NIST.](#)

<sup>%</sup>Kester, SAF-ALLOY



**Table 2.1.2. Melting Temperatures of Lead-Free Solders**

<b>Alloy</b>	<b>Melting Temperature Range (°C)</b>	<b>Comments<sup>#</sup></b>
Sn-25Ag-10Sb	233 (m.p.)	High strength; patented by Motorola (“Alloy J”)
Sn-0.7Cu	227 <sup>@</sup>	Excellent strength and wetting
Sn-3.5Ag	221 <sup>@</sup>	
Sn-2Ag	221 – 226	
Sn-2.8Ag-20In	175 – 186	
Sn-5Sb*	232 – 240	
Sn-58Bi	138 <sup>@</sup>	Good high-temperature shear strength Well established history; Inexpensive
Sn-9Zn	199*	Corrosion; high dross
Sn-0.5Ag-4Cu	217 – 350	Very wide and high melting range; Engelhard’s lead-free plumbing solder
Sn-2Ag-0.75Cu	217 – 219	
Sn-3.2Ag-0.5Cu	217 – 218	
Sn-3.8Ag-0.7Cu	217 – 220	
Sn-4Ag-0.5Cu	217 – 225	
Sn-4Ag-1Cu	217 – 220	
Sn-4.7Ag-1.7Cu	217 – 244	
Sn-8Zn-3Bi	192 – 197	
Sn-0.2Ag-2Cu-0.8Sb	287 – 218	High melting range; Kester Solder Co.’s Aquabond  (205 – 210) <sup>%</sup> (m.p.: 220 °C) <sup>%</sup>
Sn-2.5Ag-0.8Cu-0.5Sb (Castin)	217 – 225	
Sn-2Ag-7.5Bi	190 – 216	
Sn-3.4Ag-4.8Bi	201 – 205	
Sn-3.5Ag-3Bi	208 – 217	
Sn-2Ag-3Bi-0.75Cu <sup>%</sup>	205 – 217	
Sn-3.5Ag-5Bi-0.7Cu <sup>%</sup>	198 – 213	
Sn-2Ag-4Bi-0.5Cu-0.1Ge <sup>%</sup>	202 – 217	
Sn-57Bi-0.1Ag <sup>%</sup>	138 – 140	
Sn-52In	118*	

\*Eutectic

N.-C. Lee and W. Casey, “Soldering Technology for Area Array Packages,” Proceedings: NEPCON WEST 2000 (February 27 – March 2, 2000), Anaheim, CA

#N.-C. Lee, J.A. Slattery, J.R. Sovinsky, I. Artaki, P.T. Vianco, "A Drop-In Lead-Free Solder Replacement," Proceedings: NEPCON West Conference (February 28 – March 2, 1995), Anaheim, CA

\*Ning-Cheng Lee, "Lead-Free Soldering of Chip-Scale Packages," Chip Scale Review, p. 42 (March-April 2000)

%Rao Mahidhara, "A Primer on Lead-Free Solder," Chip Scale Review (March-April 2000)

## 2.2. Thermal Properties: Miscellaneous

**Table 2.2.1. Thickness ( $\mu\text{m}$ ) of Intermetallics in Solder Alloys Aged at 150 °C**

<b>Alloy:</b>	<b>Sn-3.5Ag</b>		<b>Sn-4Ag-.5Cu</b>	
<b>Inter-metallics:</b>	<b>Cu<sub>3</sub>Sn</b>	<b>Cu<sub>6</sub>Sn<sub>5</sub></b>	<b>Cu<sub>3</sub>Sn</b>	<b>Cu<sub>6</sub>Sn<sub>5</sub></b>
<b>Time (h)</b>				
0	0.25	2	0.25	2
48	0.5	3.25	0.5	2.5
96	0.75	2.5	0.75	2.5
264	1.0	2.5	1.0	3
480	1.5	3	1.5	4.5
984	2.5	4	2.5	(nonuniform morphology)

Angela Grusd, "Lead Free Solders in Electronics," SMI97, p. 648

**Table 2.2.2. Thermal and Electrical Properties of Castin™ (Sn-2.5Ag-0.8Cu-0.5Sb)**

Melting Point	215 – 217 °C
Thermal Diffusivity	35.82 +/- 0.18 mm <sup>2</sup> /s
Specific Heat	218.99 J/(kg.K)
Thermal Conductivity	57.26 W/(m.K)
Electrical Resistivity	1.21×10 <sup>-7</sup> ohm.m
Electrical Conductivity	8.25 MS/m

Karl Seelig and David Suraski, "The Status of Lead-Free Solder Alloys," Proc. 50<sup>th</sup> IEEE 2000 Electronic Components and Technology Conference (May 21-24, 2000), Las Vegas, NV

**Table 2.2.3. Physical and Mechanical Properties of Sn-2.8Ag-20.0In and Sn-37Pb Eutectic**

Property (measured at 20 °C, except where otherwise noted)	Alloys	
	Sn-2.8Ag- 20.0In	Sn-37Pb (eutectic)
Density (g/cm <sup>3</sup> )	7.25	8.36
Electrical Resistivity (10 <sup>-6</sup> ohm.m)	0.170	0.146
Thermal Conductivity (W/(m.K)) (30 °C)	53.5	50.9
Thermal Expansion (10 <sup>-6</sup> .K <sup>-1</sup> )	28	25
Tensile Strength (psi)	6800	3900
Tensile Elongation (%)	47	35
Shear Strength (psi)	4800	3450
Poisson's Ratio	0.40	0.40
Young's Modulus (kpsi)	5600	4500

N.-C. Lee, J.A. Slattery, J.R. Sovinsky, I. Artaki, P.T. Vianco, "A Drop-In Lead-Free Solder Replacement," Proceedings: NEPCON West Conference (February 28 – March 2, 1995), Anaheim, CA

**Table 2.2.4. Some Physical Properties of Materials Used as Electronic Packaging Conductors**

Metal	Melting Point (°C)	Electrical Resistivity (μohm.cm)	Thermal Expansion Coeff. (10 <sup>-6</sup> /°C)	Thermal Conductivity (W/(m.K))	#Surface Tension, σ	
					(dyn/cm)	(°C)
Aluminum	660.1	4.3	23.0	240	520	750
Antimony	630.5		11.0*	24.0*	383	635
Bismuth	271.0		13.4*	8.0*	376	300
Chromium	1900	20	8.2	66		
Copper	1083	1.7	16.6	393; 401*		
Gold	1063	2.2	14.2	297		
Indium	156.4		32.1*	82.0*	340	170
Lead	327.3				431	500
Molybdenum	2625	5.2	5.0	146		
Nickel	1455	6.8	12.8	92; 91*		
Palladium	1552	10.8	11.8	70		
Platinum	1774	10.6	9.0	71		
Silver	960.8	1.6	18.9	418; 429*	923	995
Tin	231.9		22.0*	73.0*	550%	232%
					526	300
					510	500
Tungsten	3415	5.5	4.5	200		
Zinc	419.5				785	510
					761	640
Invar	1500	46	1.5	11		
Kovar	1450	50	5.3	17		
Silver-palladium	1145	20	14.0	150		
Gold-platinum	1350	30	10.0	130		
Au-20Sn	280	16	15.9	57		
Sn-37Pb	183				470%	280%
Pb-5Sn	310	19	29.0	63		
Cu-W(20%Cu)	1083	2.5	7.0	248		
Cu-Mo(20%Cu)	1083	2.4	7.2	197		

*Microelectronics Packaging Handbook*, R.R. Tummala and E.J. Rymaszewski, eds. (Van Nostrand Reinhold, 1989, NY)

# N.A. Lange, *Handbook of Chemistry*, p. 100 (Handbook Publishers, Sandusky, Ohio, 1956)

%M. Abtew, "Wetting Characteristics of Lead Free Solders for High Volume Surface Mount Application," Proc. NEPCON West 2000 Conf. (Feb. 28 - Mar. 2, 2000) Anaheim, CA

\*J.S. Hwang, "Overview of Lead-Free Solders for Electronics & Microelectronics," Proc. SMI Conf. , p. 405

**Table 2.2.5. Thermophysical Properties of Metallic Elements Used In Electronic Packaging**

Metal	At. Wt.	Density (20°C)	Melt. Point	Lat. Ht. Fusion	Heat capacity (25°C)		Thermal Exp. coef. (20°C)	Electrical Resistivity (20°C)	#Thermal conductivity
		(g/cm <sup>3</sup> )	(°C)	(kg-cal/g.atom)	(g-cal/g-at.K)	J/(kg.K)	(10 <sup>-6</sup> K <sup>-1</sup> )	(10 <sup>-6</sup> Ω.cm)	(W/(m.K))
Aluminum	26.98	2.702	*660.46	2.6	5.817	902.1	23.03	2.62; 2.828 <sup>#</sup>	238.
Antimony	121.76	6.684	*630.75	4.8	6.08	209.0	11.4	39; 39.1 <sup>#</sup>	24.5; 23.8 <sup>§</sup>
Bismuth	208.98	9.8	*271.44	2.63	6.1	122.1	13.4 <sup>§</sup>	115; 119.0 <sup>#</sup>	11.2; 9 <sup>§</sup>
Chromium	51.996	7.1	1860 <sup>§</sup>	3.5	5.58	449.0	8.2	2.6 (0°C)	91.3 <sup>§</sup>
Copper	63.54	8.92	*1084.9	3.11	5.85	385.2	16.6	1.69	416; 397 <sup>§</sup>
Gold	196.97	19.3	*1064.4	3.03	6.0	127.5	14.2	2.4; 2.44 <sup>#</sup>	311; 315.5 <sup>§</sup>
Indium	114.82	7.3	*156.63	0.78	6.55	238.7	33; 24.8 <sup>§</sup>	9; 8.37 <sup>#</sup>	80.0 <sup>§</sup>
Lead	207.2	11.34	*327.50	1.22	6.41	129.4	29.1	21.9; 19.8 <sup>#</sup>	35.0
Molybdenum	95.94	10.2	*2623	6.66	5.61	244.8	4.	4.77; 5.14 <sup>#</sup>	138.
Nickel	58.69	8.90; 8.8 <sup>#</sup>	*1455	4.2	6.21	442.6	12.8	6.9; 7.24 <sup>#</sup>	76.; 88.5 <sup>§</sup>
Palladium	106.42	12.	*1554	4.12	6.3	247.7	11.8	10.8; 10.21 <sup>#</sup>	75.2
Platinum	195.08	21.45	*1769	5.2	6.35	136.2	8.9	10.5; 9.83 <sup>#</sup>	69.9; 73.4 <sup>§</sup>
Silver	107.87	10.5	*961.93	2.70	6.092	236.3	18.9	1.62; 1.47 <sup>#</sup>	417.; 425 <sup>§</sup>
Tin	118.71	7.31	*231.97	1.69	6.30	222.1	20.; 23.5 <sup>§</sup>	11.4; 11.5 <sup>#</sup>	66.6; 73.2 <sup>§</sup>
Tungsten	184.83	19.3	*3387	8.42	5.97	135.9	4.	5.48; 5.51 <sup>#</sup>	169.; 174 <sup>§</sup>
Zinc	65.39	7.14; 7.04 <sup>#</sup>	*419.58	1.595	5.99	383.3	33.	6; 5.75 <sup>#</sup>	125.; 119.5 <sup>§</sup>

N.A. Lange, *Handbook of Chemistry* pp. 100-107 (pp. 854-861) (Handbook Publishers, Sandusky, Ohio, 1956)

\*Thermometric fixed point; E.A. Brandes, *Smithells Metals Reference Book*, 6<sup>th</sup> ed., p. 16-2 (Butterworths, London, 1983)

<sup>#</sup>D.E. Gray, ed., *American Institute of Physics Handbook*, pp. 2-17 (density), 4-40 (ht. cap.), 5-204 (resistivity), 4-78 (th. cond.) (McGraw-Hill, New York, 1957)

<sup>§</sup>E.A. Brandes, *Smithells Metals Reference Book*, 6<sup>th</sup> ed., p. 14-1 (th. cond.: 0-100°C) (Butterworths, London, 1983)

**Table 2.2.6. Some Properties of Materials Commonly Used In Electronics - A**

<b>Metal</b>	<b>CTE (10<sup>-6</sup>/°C)</b>	<b>Thermal Cond. (W/(m.K))</b>	<b>Elastic Mod. (GPa)</b>	<b>Density (g/cm<sup>3</sup>)</b>	<b>Poisson's Ratio (ν)</b>
Aluminum	22.3	237	69	2.7	0.31
Copper	16.5 16.9 <sup>#</sup> 17.3*	398	124 125 <sup>#</sup> 117*	8.9	
Molybdenum	5.0	140	324	10.2	
Cu/ Invar/Cu	5.2	167 <sup>%</sup>	--	8.4	0.27
Kovar	5.9	17	138	8.3	
Silicon Carbide	2.6	--	412	3.17	
Solder (95/5)	28	36	23.5	11.	
Diamond	1.7	2300	785	3.51	0.23
Silicon	2.8 3.2 <sup>#</sup>	150	190 110 <sup>#</sup>	2.3	
Alumina	6.7 7.0 <sup>#</sup>	21	306 375 <sup>#</sup>	3.9	0.25
Aluminum Nitride	4.5 4.03 <sup>#</sup>	250	327 320 <sup>#</sup>	3.2	
Beryllia	8.0	275	345	2.9	
Epoxy / Glass (FR4; T<T <sub>g</sub> )	12 / 70 x,y: 15.8* z: 80-90*	1.7	17.2 x,y: 7.0* z: 7.5*	1.9	
(FR4; T>T <sub>g</sub> )	x,y: 20* z: 400*		x,y:17.0* z: 0.6*		
Polyimides	45	8	4.2	1.6	

(CTE: Coefficient of thermal expansion)

%In plane

Walter L. Winterbottom, "Converting to Lead-Free Solders: An Automotive Industry Perspective," JOM, 20-24 (July 1993)

\*M.A. Korhonen, D.D. Brown and C.-Y. Li, "Mechanical Properties of Plated Copper," Mat. Res. Soc. Symp. Proc. Vol. 323, p. 104 (MRS, 1994) ("plated [thin foil] copper")

<sup>#</sup>S.M. Spearing, M.A. Tenhover, D.B. Lukco, L. Viswanathan and D.K. Hollen, "Models for the Thermomechanical Behavior of Metal/Ceramic Laminates," Mat. Res. Soc. Symp. Proc. Vol. 323, p. 128 (MRS, 1994)

**Table 2.2.7. Some Properties of Materials Commonly Used In Electronics – B**

<b>Material</b>	<b>Melt. Pt. (°C)</b>	<b>Density (g/cm<sup>3</sup>)</b>	<b>CTE (10<sup>-6</sup>/°C)</b>	<b>Young's Modulus E (GPa)</b>	<b>Tensile Strength (MPa)</b>
Alumina (Al <sub>2</sub> O <sub>3</sub> )	2050	3.985	5.8	380	620
Beryllia (BeO)	2530	3.01	8.4 – 9.0	311	172 - 275
Silica (SiO <sub>2</sub> ) (vitreous)	1710	2.19	0.54	69	110
Zirconia (ZrO <sub>2</sub> ) / (Yttria: Y <sub>2</sub> O <sub>3</sub> )	2960	5.56	10.	138	>300
AlN	2400	3.25	5.3	350	270
Si <sub>3</sub> N <sub>4</sub>	>1750	3.19	3.3	304	>400
Al	660	2.70	23.5	69	50 -195
Cu	1083	8.96	17.0	180	
Ni	1453	8.9	13.3	199	660
Mo	2617	10.22	5.1	324.8	458-690
W	3410	19.3	4.5	411.	550-620

S.D. Brandi, S. Liu, J.E. Indacochea and R. Xu, "Brazeability and Solderability of Engineering Materials," ASM Handbook, Vol. 6: Welding, Brazing and Soldering (ASM International, 1993)

**Table 2.2.8. Electrical Resistivity and Temperature Coefficient (TCR) of Pure Metallic Elements Used in Electronic Packaging**

<b>Metal</b>	<b>Temp. (K)</b>	<b>Resistivity (ohm.cm)</b>	<b>TCR (<math>10^{-3} \text{ K}^{-1}</math>)</b>
Aluminum	293	2.61	4.2
Antimony	293	37.6	5.1
Bismuth	293	115	4.6
Chromium	300	12.9	5.9
Copper	293	1.58	4.3
Gold	293	2.01	4.0
Indium	293	8.0	5.2
Lead	293	19.3	4.2
Molybdenum	300	5.3	4.35
Nickel	293	6.2	6.8
Palladium	300	10.5	4.2
Platinum	300	10.4	3.0
Silver	300	1.47	4.1
Tin	293	10.1	4.6
Tungsten	300	5.3	4.8
Zinc	293	5.45	4.2

E.A. Brandes, Smithells Metals Reference Book, 6<sup>th</sup> ed., p. 16-2 (Butterworths, London, 1983)



**Table 2.2.9. Wetting Properties of Sn-2.8Ag-20.0In and Sn-37Pb Eutectic Solders**

Fluxes	Sn-2.8Ag-20.0In*			
	Wetting Time (seconds)		Wetting Force (mN/mm)	
	200 °C	240 °C	200 °C	240 °C
A	10.60	4.60	0.70	0.71
B	1.53	0.42	0.72	0.56
C	5.08	2.40	0.72	0.64
D	5.73	2.09	0.67	0.67
Geometric Mean	4.66	1.76	0.70	0.64
	<b>Sn-37Pb</b>			
A	2.87	1.48	0.73	0.72
B	1.03	0.50	0.71	0.61
C	1.65	1.00	0.75	0.72
D	2.50	1.44	0.73	0.73
Geometric Mean	1.87	1.02	0.73	0.69

N.-C. Lee, J.A. Slattery, J.R. Sovinsky, I. Artaki, P.T. Vianco, "A Drop-In Lead-Free Solder Replacement," Proceedings: NEPCON West Conference (February 28 – March 2, 1995), Anaheim, CA

\*J.A. Slattery and C.E.T. White, U.S. Patent 5,256,370 (Oct. 26, 1993)

**Table 2.2.10. Wetting Times and Forces (at 300 °C): Lead-Free Solder Alloys, and Eutectic Tin-Lead**

Alloy	$T_0$	$T_{2/3}$	Force (2 s)	Force <sub>max</sub>
	Mean $\pm$ $\sigma$	Mean $\pm$ $\sigma$	Mean $\pm$ $\sigma$	Mean $\pm$ $\sigma$
	(s)	(s)	( $\mu$ N/mm)	( $\mu$ N/mm)
Sn-3.5Ag	0.0 $\pm$ 0.0	1.23 $\pm$ 0.01	549 $\pm$ 42	579 $\pm$ 47
Sn-5Sb	0.11 $\pm$ 0.08	0.74 $\pm$ 0.07	403 $\pm$ 14	413 $\pm$ 15
Sn-2.8Ag-20In	0.0 $\pm$ 0.0	1.28 $\pm$ 0.04	250 $\pm$ 24	290 $\pm$ 31
Sn-37Pb	0.0 $\pm$ 0.0	1.00 $\pm$ 0.06	470 $\pm$ 24	485 $\pm$ 19

M.A. Kwoka and D.M. Foster, "Lead Finish Comparison of Lead-Free Solders versus Eutectic Solder," Proc. Surface Mount International Conference (1994), p. 433

**Table 2.2.11. Wetting Times (seconds; at 250 °C) of Lead-free Solder Alloys**

Alloy	Pure Rosin		Actiec 5 Flux	
	Tb	T2/3	Tb	T2/3
Sn-40Pb	0.6	1.0	0.4	0.5
Sn-3.6Ag	0.9	1.4	0.6	0.8
Sn-3.6Ag-0.7Cu	0.6	1.0	0.5	0.7
Sn-0.7Cu	1.0	1.4	0.7	1.0

<sup>%</sup>Rao Mahidhara, "A Primer on Lead-Free Solder," Chip Scale Review (March-April 2000)

**Table 2.2.12. Onset of Melting Temperatures for Five Sn-Ag-Cu Lead-Free Solder Alloys**

Alloy	Spec. No.	Temperature, Onset of Melting (°C)	
		This Work	Other (Ref.)
Sn-3.6Ag-1.5Cu	1	217.0	225 (1)
Sn-4.7Ag-1.7Cu	2a	216.7	
Sn-4.7Ag-1.7Cu	2b	216.8	
Sn-4.1Ag-0.9Cu	3	216.5	
Ave. onset temp., specimens 1-3		216.8	
Reference Samples:			
Sn-3.8Ag-2.3Cu	--		217.4 (3)
Sn-3.5Ag-0.0Cu	4	220.8	221 (2)
Sn (pure)	5	231.2	231.97 (2)

Chad M. Miller, Iver E. Anderson and Jack F. Smith, "A Viable Tin-Lead Solder Substitute: Sn-Ag-Cu," J. Electronic Matls. 23(7) 595-601 (1994)

(1) E.Gebhardt and G. Petzow, Z. Metallkde. 50, 597 (1950)

(2) T.B. Massalski, *Binary Phase Diagrams*, 2<sup>nd</sup> ed. (Amer. Soc. Metals, 1990)

(3) Miller, Anderson and Smith, Note added in proof, J. Electronic Matls. 23(7) 601 (1994)

**Table 2.2.13. Solidus Temperatures and Wetting Contact Angles of Selected Lead-Free Solder Alloys with Use of RMA (GF-1235) Flux**

<b>Alloy</b>	<b>Solidus (°C)</b>	<b>Contact Angle (degrees)</b>
Sn-4.7Ag-1.7Cu	217 (eutectic)	32
Sn-3.33Ag-4.83Bi	212	n.a.
Sn-5Ag-2Bi	214.5	30
Sn-8Ag-3Sb	224	39
Sn-4.5Ag-6Bi-5.4Sb-4In	214	36
Sn-4.4Ag-6Bi-5.3Sb-6In	217	34
Sn-37Pb (control)	183 (eutectic)	16

Iver E. Anderson, "Tin-Silver-Copper: A Lead-Free Solder for Capacitor Interconnects," p. 16, Proc. 16<sup>th</sup> Capacitor and Resistor Technology Symposium (CARTS 96), 11-15 March, 1996;

**Table 2.2.14. Solidus and Liquidus Temperatures and Wetting Angles of Some Lead-free Alloys on Copper** (Note opposing effects on wetting angle of increasing temperature for alloys with or without zinc)

Alloy	Solidus (°C)		Liquidus (°C)		Wetting Angle (deg) (with Kester Flux No. 197)		
	Calc.	Exptl.	Calc.	Exptl.	250 °C	295 °C	340 °C
Sn-1Ag-1Sb	222	222	232	232	38		43
Sn-1Ag-1Sb-1Zn					41	41	42
Sn-4Ag-7Sb	229	230	230	230	35		39
Sn-4Ag-7Sb-1Zn					48	46	36
Sn-2Ag-0.8Cu-6Zn	190	217	195	217	77	67	62
Sn-2Ag-0.8Cu-8Zn	191	215	200	215	86	70	52
Sn-10Bi-0.8Cu	178	185	218	217	32		42
Sn-10Bi-0.8Cu-1Zn					33	38	27
Sn-10Bi-5Sb	186	193	228	232	39		48
Sn-10Bi-5Sb-1Zn					50	42	29
Sn-45Bi-3Sb	147	145	168	178			37
Sn-45Bi-3Sb-1Zn					98	46	27
Sn-37Pb (eutectic)							14

M.E. Loomans, S. Vaynman, G.Ghosh and M.E. Fine, "Investigation of Multi-component Lead-free Solders," J. Elect. Matls. 23(8), 741 (1994)

**Table 2.2.15. Melting Properties, Resistivity, Wettability and Hardness of Lead-Free Solders**

Alloy	T <sub>ex</sub> (°C)	T <sub>p</sub> (°C)	T <sub>ob</sub> (°C)	Electrical Resistivity* (μΩ-cm)	Wetta- bility Ratio	Hard- ness (VHN)
Sn-3.5Ag	221.5	226.5	220.0	7.7	97, 95	17.9
Sn-5Bi	219.4	228.7	196.0	11.0	97, 97	25.6
Sn-10Bi	209.1	221.2	165.0	17.7	98, 97	33.0
Sn-5In	219.7	223.4	211.5	8.3	99, 97	20.8
Sn-5Sb	236.8	244.9	231.6	17.1	96, 96	17.2
Sn-3Ag -5Bi	214.4	218.1	191.6	11.6	98, 98	29.9
Sn-3Ag-10Bi	201.5	214.3	164.4	8.8	---	---
Sn-3Ag-3In	210.7	214.7	193.3	7.7	99, 99	21.3
Sn-3Ag-5Sb	225.0	235.9	216.3	10.5	99, 99	25.4
Sn-3Ag-1Zn	215.9	220.9	210.0	10.4	98, 97	18.2
Sn-3Ag-3Zn	217.8	222.5	206.8	4.8	97, 97	21.9
Sn-5Bi-5In	205.5	218.4	177.0	19.1	98, 95	28.0
Sn-5Sb-3In	226.7	240.3	211.7	9.8	98, 97	31.9
Sn-1Cu-5Bi	216.7	226.7	184.8	10.5	96, 95	31.9
Sn-1Cu-5Bi-5In	204.9	211.0	167.5	14.1	96, 95	40.6
Sn-1.5Cu-2Bi-3Sb	224.1	234.5	207.0	8.0	98, 96	32.9
Sn-3Ag-2Cu -2Sb	218.6	230.1	212.8	11.2	98, 98	28.6
Sn-3Ag-3Cu -2Bi	211.1	222.2	195.7	10.6	97, 96	34.5
Sn-3Ag-5Bi-5In	195.7	209.0	158.9	12.1	---	---
Sn (pure)				11.2	---	10.5
Sn-37Pb (eutectic)				17.0	95, 91	12.9

T<sub>ex</sub> is the extrapolated onset melting temperature by differential scanning calorimetry (DSC)

T<sub>p</sub> is the peak melting temperature by DSC

T<sub>ob</sub> is the observed onset melting temperature

\*Method of Van der Pauw

S.K. Kang et al., "Pb-Free Solder Alloys for Flip Chip Applications," 49<sup>th</sup> Electronic Components Technology Conf. (1999), June 1-4, San Diego CA

**Table 2.2.16. Wetting Contact Angles of Sn-Ag, Sn-Bi, and Sn-Zn Alloys on Copper: Eutectic, and With 1% Addition of Ternary Elements**

Solder Alloy	SnCl <sub>2</sub> , Saturated Solution		Kester Rosin Flux No. 197			20 % Rosin in Isopropyl Alcohol		
	165 °C	200 °C	165 °C	200 °C	250 °C	165 °C	200 °C	250 °C
Sn-3.5Ag					38			45
Sn-3.5Ag-1Cu					36			44
Sn-3.5Ag-1In					35			39
Sn-3.5Ag-1Sb					35			35
Sn-3.5Ag-1Bi					28			38
Sn-3.5Ag-5Bi					31			42
Sn-58Bi	10	15	27	28		40	32	
Sn-58Bi-1Ag	14	17	35	44		43	39	
Sn-58Bi-1Cu	9	12	36	38		40	30	
Sn-58Bi-1In	7	12	40	35		56	43	
Sn-58Bi-1Sb	20	15	31	35		38	42	
Sn-58Bi-1Zn	18	12	58	54		50	--	
Sn-8.9Zn					59			58
Sn-8.9Zn-1In					63			53

M.E. Loomans, S. Vaynman, G.Ghosh and M.E. Fine, "Investigation of Multi-component Lead-free Solders," J. Elect. Matls. 23(8), 741 (1994)

**Table 2.2.17. Wetting Contact Angles on Copper of Sn-Bi Alloys: Eutectic, and With Addition of Ternary Elements**

<b>Solder Alloy</b>	<b>SnCl<sub>2</sub>, Saturated Solution</b>		<b>Kester Flux No. 197</b>		<b>20 % Rosin in Isopropyl Alcohol (IPA)</b>		<b>20 % Rosin in IPA + 1% SnCl<sub>2</sub></b>	
	<b>165 °C</b>	<b>200 °C</b>	<b>165 °C</b>	<b>200 °C</b>	<b>165 °C</b>	<b>200 °C</b>	<b>165 °C</b>	<b>200 °C</b>
Sn-58Bi	10	15	27	28	40	32	43	35
Sn-58Bi-1Ag	14	17	35	44	43	39	93	45
Sn-58Bi-1Cu	9	12	36	38	40	30	46	31
Sn-58Bi-1In	7	12	40	35	56	43		
Sn-58Bi-1Sb	20	15	31	35	38	42		
Sn-58Bi-1Zn	18	12	58	54	50	--		

M.E. Loomans, S. Vaynman, G.Ghosh and M.E. Fine, "Investigation of Multi-component Lead-free Solders," J. Elect. Matls. 23(8), 741 (1994)

**Table 2.2.18. Wetting Properties of Pure Tin, Four Lead-Free Tin Alloys and Three Lead-Tin Alloys**

Solder Alloy	Temp. (°C)	Wetting Time, Mean (std.dev.) (s)	Max. Wetting Force, mean (std.dev.) (mg)	Wetting Rate		Area of Spread (cm <sup>2</sup> )	
				mean (std.dev.) (mV/s)	Normalized (Sn = 1)	Fluxite	Power flow Flux
Sn (pure)	282	0.68 (0.10)	607 ( 84)	138 ( 43)	1.00	0.5	0.55
Sn-1Cu	300	0.60 (0.11)	565 ( 82)	120 ( 43)	0.87	0.5	0.5
Sn-3Cu	365	0.19 (0.08)	648 ( 61)	365 (122)	2.64	0.7	0.8
Sn-3.5Ag	260	0.60 (0.12)	533 (109)	124 ( 30)	0.90	0.5	0.6
Sn-5Sb	280	0.83 (0.12)	393 (117)	97 ( 24)	0.70	0.5	0.55
Sn-40Pb	234	0.45 (0.14)	602 (114)	146 ( 43)	1.06	2.2	--
Sn-50Pb	265	0.37 (0.09)	523 (115)	191 (119)	1.38	2.5	2.6
Sn-60Pb	285	0.55 (0.09)	623 ( 68)	100 ( 17)	0.72	1.7	1.9

M.E. Warwick, "The Wetting and Mechanical Properties of Lead-Free Capillary Plumbing Solders," ATB Metallurgie XXV, No. 1, 43-50 (1985)



**Table 2.2.19. Lead-Free Solder Alloys: Solidus and Liquidus Temperatures, Coefficient of Thermal Expansion, Surface Tension, and Electrical Resistivity**

Alloy	T <sub>sol</sub> * (°C)	T <sub>liq</sub> (°C)	CTE (20 °C) (x 10 <sup>+5</sup> /°C)	Surface Tension (at T <sub>liq</sub> + 50 °C) (mN/mm)		Intermetallic Phases	Electrical Resistivity (μΩ-cm)
				Air	Nitrogen		
Sn (pure)	232		2.6				11.5
Sn-37Pb	183		2.5	417	464		14.5
Sn-3.5Ag	221			431	493	Ag <sub>3</sub> Sn	10 – 15
Sn-4Cu-0.5Ag	216	222				Ag <sub>3</sub> Sn, Cu <sub>6</sub> Sn <sub>5</sub>	10 – 15
Sn-0.7Cu	227			491	461	Cu <sub>6</sub> Sn <sub>5</sub>	10 – 15
Sn-58Bi	138		1.5	319	349		30 – 35
Sn-52In §	120		2.0				10 – 15
Sn-9Zn	199			518	487		10 – 15

\*Where no liquidus temperature is given, the alloy is eutectic and has a single, definite fusion temperature. (For pure tin the melting point is given.)

§ (Eutectic: Sn-50.9In)

Judith Glazer, “Microstructure and Mechanical Properties of Pb-free Solder Alloys for Low-Cost Electronic Assembly: A Review,” *J. Electronic Materials* 23(8), 693 (1994)

**Table 2.2.20. Fluid Properties of Some Molten Lead-Free Solders**

<b>Solder Alloy</b>	<b>Liquidus temperature</b>	<b>Contact angle</b>	<b>Wetting rate</b>	<b>Surface tension</b>
	<b>(°C)</b>	<b>(deg)</b>	<b>(dyne/sec)</b>	<b>(dyne/cm)</b>
Sn-58Bi	138	43	350	300
Sn-2.8Ag-20In	114 (low-temp. peak); 178 (primary peak)	44	650	390
Sn-3.5Ag-4.8Bi	212	31	2420	420
Sn-2.5Ag-0.8Cu-0.5Sb	217	44	4280	510
Sn-37Pb (eutectic)	183	17	2030	380

I. Artaki, D.W. Finley, A.M. Jackson, U. Ray and P.T. Vianco, "Wave Soldering with Pb-Free Solders," *Proc. Surface Mount International* (San Jose, CA, August 27-31, 1995), p. 495.

**Table 2.2.21. Densities and Costs of Popular Solder Metals and Alloys – A**

Metal	Price per kg (2 <sup>nd</sup> Q. 1999)		Density (g/cm <sup>3</sup> )	Price per cm <sup>3</sup> (2 <sup>nd</sup> Q. 1999)	
	(\$)	Normalized (Pb = 1)		(\$)	Normalized (Pb = 1)
Pb	0.55	1.00	11.36	0.00625	1.00
Sb	2.00*	2.5*	6.684	0.0134	2.14
Cu	1.50	2.73	8.92	0.0134	2.14
Bi	6.60*	8.25*	9.8	0.0647	10.35
Sn	5.70	10.36	7.31	0.0416	6.57
Ag	170.	309.1	10.5	1.78	285.
In	242.50*	303.1*	7.3	1.77	283.
Sn-37Pb	3.80	6.91	8.4	0.0319	5.10
Sn-Pb (solder paste)	90.00	163.6	8.4	0.756	121.
Sn-0.7Cu	5.66	10.29	7.30	0.0413	6.61
Sn-4Ag-0.5Cu	12.25	22.27	7.39	0.0905	14.5

*Adapted from Alan Rae and Ronald C. Lasky, "Economics and Implications of Moving to Lead-Free Assembly," Proc. NEPCON WEST 2000 (February 27 – March 2, 2000), Anaheim, CA*

*\*(1992 prices; Pb: \$0.80/kg) Paul T. Vianco, "General Soldering," ASM Handbook, Vol. 6, Welding, Brazing, and Soldering (ASM International, 9639 Kinsman Road, Materials Park, Ohio 44073 USA, 1993)*



**Table 2.2.22. Densities and Costs of Popular Solder Metals and Alloys – B**

Element		Cost/(unit mass) [2/3/99]		Density (25 °C)		Cost/(unit volume)		Comment
		\$/lb	\$/kg	lb/in <sup>3</sup>	g/cm <sup>3</sup>	\$/in <sup>3</sup>	\$/cm <sup>3</sup>	Availability
Lead		0.45	0.99	0.41	11.35	0.18	0.011	limited
Zinc		0.50	1.10	0.258	7.14	0.13	0.008	
Copper		0.65	1.43	0.324	8.97	0.21	0.013	
Antimony		0.80	1.76	0.239	6.61	0.19	0.012	
Bismuth		3.40	7.48	0.354	9.80	1.20	0.073	
Tin		3.50	7.70	0.264	7.31	0.92	0.056	
Silver		84.20	185.24	0.379	10.50	31.91	1.947	
Indium		125.00	275.00	0.264	7.31	33.00	2.014	
Alloy	Melt. Range (°C)							Patented
Sn-37Pb	183	2.37	5.21	0.318	8.80	0.75	0.046	
Sn-3.5Ag	221	6.32	13.90	0.268	7.42	2.33	0.142	
Sn-0.7Cu	227	3.48	7.66	0.264	7.31	0.92	0.056	
Sn-58Bi	139	3.44	7.57	0.316	8.75	1.09	0.067	
Sn-5Sb	232-240	3.37	7.41	0.263	7.28	0.88	0.054	
Sn-9Zn	199	3.23	7.11	0.263	7.28	0.85	0.052	
Sn-4Ag-0.5Cu	217-218	6.55	14.41	0.269	7.44	1.76	0.107	
Sn-3.4Ag-4.8Bi	208-215	6.24	13.73	0.272	7.53	1.70	0.104	Y
Sn-3.5Ag-3Bi	216-220	5.92	13.02	0.269	7.44	1.59	0.097	
Sn-2.8Ag-20In	179-189	30.06	66.13	0.267	7.39	8.02	0.489	Y
Sn-3.5Ag-1.5In	218	8.15	17.93	0.268	7.42	2.18	0.133	
Sn-2Ag-0.5Cu-7.5Bi	186-212	5.09	11.20	0.273	7.56	1.39	0.085	
Sn-2.5Ag-0.8Cu-0.5Sb	213-219	5.48	12.06	0.267	7.39	1.46	0.089	Y (Castin™)

Authors not listed; “Lead-Free Alloy Trends for the Assembly of Mixed Technology PWBs”, Proc. NEPCON-West 2000 (Feb. 27-Mar. 2) Anaheim, CA

**Table 2.2.23. Cost of Lead-Free Solder Alloys Relative to That of Sn-37Pb Eutectic**

Alloy	Relative Cost	
	Bar	Paste
Sn-37Pb	1.000	1.000
Sn-3.5Ag	2.29	1.07
Sn-3Ag-2Bi	2.17	1.06
Sn-3.4Ag-4.8Bi	2.26	1.06
Sn-3.2Ag-0.7Cu	2.21	1.06
Sn-3.5Ag-1.3Cu	2.28	1.06
Sn-4.7Ag-1.7Cu	2.56	1.08
Sn-2.6Ag-0.8Cu-0.5Sb	2.06	1.05
Sn-3.5Ag-0.5Cu-1Zn	2.27	1.06
Costs of pure metals (relative to Pb=1): Zn: 1.7; Cu: 3.0; Sb: 3.9; Bi: 8.6; Sn: 11; Ag: 260; Au: 15000		

Ning-Cheng Lee, "Lead-Free Soldering of Chip-Scale Packages," *Chip Scale Review*, p. 42 (March/April 2000)

### A. Solder Alloy for Plated Through Holes

A series of investigations to reduce the solidus temperature and strength of lead-free solders (by adding indium, which is very ductile) was carried out by NCMS. Beginning with three alloys: (1) Sn-3.5Ag ( $T_{\text{melt}}=221\text{ }^{\circ}\text{C}$ ), (2) Sn-3Ag-2Bi ( $T_{\text{onset}}=216\text{ }^{\circ}\text{C}$ ), and (3) Sn-3.33Ag-4.83Bi ( $T_{\text{onset}}=212\text{ }^{\circ}\text{C}$ ). A solder alloy with composition Sn-3.5Ag-5.0In, with addition of either 1 % or 2 % (by mass) Cu was found to reduce the alloy's melting temperature by 5 °C and also desirably decreased the alloy's strength, reducing the probability of its cracking due to buildup of residual stress during thermal cycling (cooling after a soldering operation).

**Source:** Technical Reports for the Lead Free Solder Project: Properties Reports: "Solder Alloy Development for Plated Through-Hole Applications: DSC Analyses and Ring-in-Plug Mechanical Tests;" Lead Free Solder Project CD-ROM, National Center for Manufacturing Sciences (NCMS), 1998

### 3. Candidate Alloys for Replacing Lead-Alloy Solders

**Table 3.1. Criteria for Down-Selection of Lead-Free Alloys**

Property	Definition	Minimum Acceptance Level
Liquidus temperature Pasty Range	Temperature at which solder alloy is completely molten Range of temperature between solidus and liquidus, where alloy is part solid and part liquid.	< 30 (°C)
Wettability	Assessed by force required to wet a copper wire with molten solder. A large force indicates good wetting, as does short duration $t_0$ at zero wetting force and time $t_{2/3}$ to reach two thirds of maximum wetting force.	$F_{max} > 300 \mu N$ $t_0 < 0.6 s$ $t_{2/3} < 1 s$
Area of Coverage Drossing	Measures coverage of copper test piece by solder Measured by amount of oxide formed in air on surface of molten solder after a fix duration at soldering temperature	> 85 % Qualitative
TMF Thermal Mismatch	Lifetime at a given failure rate compared to that of (eutectic) Sn/37Pb, for a specific configuration of board and solder joint Difference in coefficients of thermal expansion that causes unacceptable thermal stress	> 75 % < 29 ppm/°C
Creep Yield Strength Elongation	Stress load to failure at room temperature, in 10,000 minutes (~167 hours) Relative elongation of material under uniaxial tension at room temperature	> 500 psi >2000 psi > 10 %

**Source:** Technical Reports for the Lead Free Solder Project: Properties Reports: "Down Selection;" on Lead Free Solder Project CD-ROM, National Center for Manufacturing Sciences (NCMS), 1998

**Table 3.2. Chemical compositions of 79 lead-free solder alloys down-selected for preliminary testing by the National Center for Manufacturing Sciences (NCMS).** The seven lead-free alloys in bold type are those down-selected for extensive testing and measurement from the initial pool of 79. Selection process is detailed in Technical Reports for the Lead Free Solder Project: Properties Reports: "Down Selection," on Lead Free Solder Project CD-ROM, National Center for Manufacturing Sciences (1998).

NCMS Alloy Code	Chemical Composition (% by mass)	Alloy Code	Chemical Composition (% by mass)	Alloy Code	Chemical Composition (% by mass)
A1*	Sn-37Pb	D8	Sn-3Ag-55Bi-2Sb	F5	Sn-20In-2.8Zn
A2	Sn-2Ag-36Pb	D9	Sn-3Ag-54Bi-2In-2Sb	F6	Sn-5Bi-7Zn
A3	Sn-97Pb	D10	Sn-3Ag-54Bi-2Cu-2Sb	F7	Sn-31.5Bi-3Zn
A4*	Sn-3.5Ag			F8	Sn-3.5Ag-1.5In
A5	Sn-5Sb	E1	Sn-3Ag-2Sb	F9	Sn-2Ag-7.5Bi-0.5Cu
A6*	Sn-58Bi	E2	Sn-3Ag-2Cu-2Sb	F10	Sn-0.2Ag-2Cu-0.8Sb
A7	Sn-3.5Ag-0.5Sb-1Cd	E3	Sn-3Ag-2Bi-2Sb		
A8	Sn-75Pb	E4	Sn-3Ag-2Bi	F11	Sn-2.5Ag-19.5Bi
		E5	Sn-2.5Ag-2Bi	F12	Sn-3Ag-41Bi
B1	Sn-50Bi	E6	Sn-2Bi-1.5Cu-3Sb	F13	Sn-55Bi-2Cu
B2	Sn-52Bi	E7	Sn-2Bi-8In	F14	Sn-48Bi-2Cu
B3	Sn-55Bi-3Cu	E8	Sn-10Bi-10In	F15	Sn-57Bi
B4	Sn-48Bi-4Cu	E9	Sn-10Bi-20In	F16	Sn-56.7Bi-0.3Cu-1In
B5	Sn-2Ag-46Bi-4Cu	E10	Sn-9Zn	F17	Sn-3.4Ag-4.8Bi
B6	Sn-56Bi-2In			F18	Sn-3Ag-15In
		EN1	Sn-5Ag-8.6In	F19	Sn-3Ag-5Bi-10In
C1	Sn-2Ag-1.5Sb-29Pb	EN2	Sn-5.6Ag-14.4In	F20	Sn-5Bi-10In
C2	Sn-3Ag-4Cu	EN3	Sn-6.8Ag-20In		
C3	Sn-2.5Ag-2Bi-1.5Sb	EN4	Sn-3.1Ag-6.1Bi	F21	Sn-2.8Ag-20In
C4	Sn-3Ag-1Bi-1Cu-1.5Sb	EN5	Sn-3.5Ag-10Bi	F22	Sn-0.1Ag-1Bi-3.9Sb
C5	Sn-2Ag-9.8Bi-9.8In	EN6	Sn-3.3Ag-15Bi	F23	Sn-0.5Ag-1.5Bi-3Sb
		EN7	Sn-6.8Ag-30Bi	F24	Sn-55Bi-2Zn
D1	Sn-45Bi	EN8	Sn-3.3Ag-11.2Bi-5.5In	F25	Sn-0.5Ag-56Bi
D2	Sn-57Bi-2In	EN9	Sn-2.5Ag-11.2Bi-5.5In	F26	Sn-4.5Ag-1.6Cu-5Sb
D3	Sn-2Ag-57Bi			F27	Sn-3.5Ag-0.5Cu-1Zn
D4	Sn-57Bi-2Sb	F1	Sn-2Ag-7.5Bi-0.5Cu	F28	Sn-3Ag-10.9In-0.4Sb
D5	Sn-57Bi-1Sb	F2#	Sn-2.6Ag-0.8Cu-0.5Sb	F29	Sn-4.7Ag-1.7Cu
D6	Sn-2Ag-56Bi-1.5Sb	F3	Sn-0.5Ag-4Cu	F30	Sn-3.2Ag-0.7Cu
D7	Sn-3Ag-55.5Bi-1.5Sb	F4	Sn-8.8In-7.6Zn	F31	Sn-3.5Ag-1.3Cu

\*Eutectic composition

#Composition F2 is a proprietary composition, Castin®



#### **4. Miscellaneous**

##### **A. Major considerations for replacement of lead-free solders:**

- ◆ Melting (or solidus) temperature similar to that of Sn-37Pb solder
- ◆ Other physical properties (such as ductility, tensile strength, thermal conductivity and expansion, electrical conductivity) as good as, or better than, those of Sn-37Pb solder
- ◆ Narrow plastic range
- ◆ Capability of being fabricated into contemporary physical forms of solder, such as wire, preforms, ribbon, spheres, powder, and paste
- ◆ Adequate wetting properties and viscosity
- ◆ Acceptably low dross formation when used in wave soldering
- ◆ Compatibility with existing systems of liquid flux
- ◆ For paste, adequate shelf life and performance
- ◆ No toxicity problems



**Table 4.1. Designation and Composition of Lead-Free Solders.**

A.C. = "Alloy Code"; L = liquidus; S = solidus; P.R. = pasty range; CTE = coefficient of thermal expansion. Blank cells indicate either zero composition or no available data.

[Due to space limitations, source is documented at end of this series of tables.]

A. C.	Composition (% by Mass)								Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g·m.°C)	CTE (µm per m.°C)
	Sn	Ag	Bi	Cu	In	Sb	Zn	Pb		L	S	P. R.	Meas.	Calc.		
A0	100								Reference: pure Sn				7.31	7.30		
A1*	63							37	Baseline (eutectic) alloy, properties used as reference.	183	183	0	8.39	8.42	45.	18.74
A2	62	2						36	Popular surface-mount alloy	180	179	1	8.44	8.44	47.	25.70
A3	3							97	Low-usage, low-lead content, very-high-temp, C4 alloy used by IBM; very good in thermal fatigue.	318	318	0	11.13	11.21	22.	29.72
A4*	96.5	3.5							Baseline (eutectic) alloy, properties used as reference.	221	221	0	7.37	7.38	64.	20.04
A5	95					5			Popular high-temp. alloy.	241	234	7	7.25	7.27	57.	20.09
A6*	42		58						Baseline (eutectic) alloy, properties used as reference.	138	138	0	8.57	8.57	46.	14.26
A7	95	3.5				0.5		Cd: 1.0	Alpha alloy #38, low usage; contains cadmium.	223	221	2	7.39	7.39	64.	20.54
A8	25							75		264	183	81	9.68	10.00	17.	

**Designation and Composition of Lead-Free Solders (cont.)**

A. C.	Composition (% by Mass)								Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g K)	CTE (µm per m.°C)
	Sn	Ag	Bi	Cu	In	Sb	Zn	Pb		L	S	P. R.	Meas.	Calc.		
B1	50		50						Similar to B2, wider pasty range and lower elongation (21%)	152	138	14	8.37	8.37	43.	
B2	48		52						Compare solderability results with B1, choose one. High Bi content	151	138	13	8.42	8.42	40.	12.13
B3	42		55	3					High Cu, wide pasty range, high liquidus, low elongation	>400	-			8.55		
B4	48		48	4					High Cu, wide pasty range, high liquidus, low elongation	>400	-			8.39		
B5	48	2	46	4					Poor ductility (2.7% elongation)	146	137	9	8.44	8.4	36.	14.38
B6	42		56			2			Quenched alloy shows ternary melting (99°C solidus), 116% total elongation.	140	126	14	8.52	8.52	45.	16.01

<b>Designation and Composition of Lead-Free Solders (cont.)</b>																
A. C.	Composition (% by Mass)								Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g K)	CTE (µm per m.°C)
	Sn	Ag	Bi	Cu	In	Sb	Zn	Pb		L	S	P. R.	Meas.	Calc.		
C2	93.	3		4					95 °C pasty range, liquidus > 300 °C.	221	221	0	7.42	7.42	61.	14.83
C3	94.	2.5	2			1.5			Similar to E3, same pasty range and YS but lower % elongation.	226	219	7	7.4	7.38	59.	
C4	93.5	3	1	1		1.5			A complex system, but meets acceptance criteria.	224	220	4	7.34	7.39	65.	19.9
C5	78.4	2	9.8		9.8				32 C pasty range, 7.1% total elongation, high indium content (\$12.8 / lb).	195	163	32	7.48	7.54	46.	11.86

Designation and Composition of Lead-Free Solders (cont.)																
A. C.	Composition (% by Mass)								Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g·M <sup>+</sup> m.°C)	CTE (µm per m.°C)
	Sn	Ag	Bi	Cu	In	Sb	Zn	Pb		L	S	P. R.	Meas.	Calc.		
D2	41.		57.		2.				Similar to B6, lower % elongation (71.8%)	140	127	13	8.55	8.54	44.	15.85
D3	41.	2.	57.						Meets acceptance criteria but questionable value over A6	147	140	7	8.61	8.60	44.	14.39
D4	41.		57.				2.		Similar to D5, lower elongation, wider (sic) pasty range	150	141	9	8.53	8.52	45.	15.8
D5	42.		57.				1.		Meets acceptance criteria, high Bi	149	138	11		8.53		
D6	40.5	2.	56.				1.5		Similar to D7, lower % elongation (26.8%)	145	137	8	8.59	8.56	44.	13.15
D7	40.	3.	55.5				1.5		Meets acceptance criteria but questionable value over D5	147	137	10		8.58		
D8	40.	3.	55.				2.		Similar to D7, same % elongation, wider pasty range (12 °C)	150	138	12		8.56		
D9	39.	3.	54.		2.	2.			99 °C solidus, wide pasty range (39 °C)	138	99	39	8.56	8.54	40.	15.25
D10	39.	3.	54.				2.		3.7 % elongation	154	138	16	8.61	8.58	40.	15.24

Designation and Composition of Lead-Free Solders (cont.)																
A. C.	Composition (% by Mass)								Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g·M <sup>+</sup> m.°C)	CTE (µm per m.°C)
	Sn	Ag	Bi	Cu	In	Sb	Zn	Pb		L	S	P. R.	Meas.	Calc.		
E2	93	3		2		2			Meets acceptance criteria; other alloys more promising	224	221	3	7.36	7.38	62.	13.44
E3	93	3	2			2			Meets acceptance criteria; good yield strength and elongation	226	219	7	7.39	7.39	60.	
E4	95	3	2						Meets acceptance criteria; similar to F17, good candidate	220	216	4	7.39	7.41	59.	14.84
E5	95.5	2.5	2						Similar to E4; lower % elongation, wider pasty range	221	215	6		7.39		
E6	93.5		2	1.5		3			Quaternary alloy; high Cu content	231	225	6	7.34	7.34	57.	16.81
E7	90		2		8				Meets acceptance criteria; high In content, lower elongation	215	206	9	7.33	7.34	49.	20.73
E8	80		10		10				30-degree pasty range	200	170	30	7.47	7.49	38.	19.68
E9	70		10		20				Potentially expensive (high In content) and 3.6% elongation					7.49		15.69
E10	91						9		High dross; low Fmax	198	198	0	7.26	7.29	69.	31.77

Designation and Composition of Lead-Free Solders (cont.)																
A. C.	Composition (% by Mass)								Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g·m <sup>3</sup> ·°C)	CTE (µm per m·°C)
	Sn	Ag	Bi	Cu	In	Sb	Zn	Pb		L	S	P. R.	Meas.	Calc.		
EN2	80	5.6	-	-	14.4	-	-	-	High liquidus, high In; similar to EN1 and F18	199	189	10	7.45	7.43		
EN3	73.2	6.8	-	-	20	-	-	-	Low solidus, very wide pasty range	242	113	129	7.49	7.46		
EN4	90.8	3.1	6.1	-	-	-	-	-	From quench, 78 degree pasty range, 137 °C solidus	215	202	13	7.49	7.49	56.	
EN5	86.5	3.5	10	-	-	-	-	-	Wide pasty range	208	137	71	7.6	7.57		
EN6	81.7	3.3	15	-	-	-	-	-	Wide pasty range	200	137	63	7.7	7.67		
EN7	63.2	6.8	30	-	-	-	-	-	Very wide pasty range	282	137	145	8.12	8.10		
EN8	80	3.3	11.2	-	5.5	-	-	-	Wide pasty range	221	170	51	7.66	7.59		
EN9	80.8	2.5	11.2	-	5.5	-	-	-	Wide pasty range	200	169	31	7.61	7.57	46.	



Designation and Composition of Lead-Free Solders (cont.)																
A. C.	Composition (% by Mass)								Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g·M <sup>+</sup> m.°C)	CTE (µm per m.°C)
	Sn	Ag	Bi	Cu	In	Sb	Zn	Pb		L	S	P. R.	Meas.	Calc.		
F1	90	2	7.5	0.5					ITRI alloy, meets acceptance criteria; lower elongation	213	193	20		7.50		
F2	96.1	2.6		0.8		0.5			AIM "Castin" alloy. Meets acceptance criteria, good results in mfg. Trials	226	211	15		7.37		26.2
F3	95.5	0.5		4					Englehart alloy. Meets acceptance criteria; high liquidus	226	218	8		7.37		
F4	83.6				8.8-		7.6		Midrange, Indium alloy. Low elongation. Zinc crossing	195	178	17		7.29		
F5	77.2				20		2.8		Indium alloy; wide pasty range	180	106	74		7.30		
F6	88		5				7		Alpha midrange alloy; Zinc crossing	194	185	9		7.38		20.5
F7	65.5		31.5				3		Alpha alloy, wide pasty range	171	133	38		7.93		
F8	95	3.5			1.5				Alpha high-indium alloy; meets acceptance criteria; lower yield strength may be beneficial	220	214	6		7.38		20.4
F9	90	2	0.5			7.5			Alpha quaternary alloy	238	229	9		7.30		

Designation and Composition of Lead-Free Solders (cont.)																
A. C.	Composition (% by Mass)								Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g K)	CTE (µm per m.°C)
	Sn	Ag	Bi	Cu	In	Sb	Zn	Pb		L	S	P. R.	Meas.	Calc.		
F10	97	0.2		2		0.8			Kester alloy, meets acceptance criteria; lower yield strength may be beneficial	230	219	11		7.33		21.8
F11	78	2.5	19.5						Kester alloy; wide pasty range	196	138	58		7.74		
F12	56	3	41						IBM Endicott alloy; low elongation (38.9%)	166	138	28		8.24		
F13	43		55	2					High Cu, similar to A6; lower elongation, wider pasty range	140	138	2		8.53		
F14	50		48	2					Similar to F13 and A6; lower elongation (18.5%), wider pasty range	153	138	15		8.35		
F15	42		57		1				IBM alloy; high Bi content, improved elongation over A6, meets acceptance criteria; poor wetting	138	132	6		8.54		16.5
F16	42		56.7	0.3	1				IBM alloy; similar to F15, lower elongation	138	132	6		8.54		
F17	91.8	3.4	4.8						SNL alloy #1. Similar to E4; small peak at 137 °C from quench.	215.9	211	4.9		7.47		22.3

Designation and Composition of Lead-Free Solders (cont.)																
A. C.	Composition (% by Mass)								Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g·M <sup>+</sup> )	CTE (µm per m.°C)
	Sn	Ag	Bi	Cu	In	Sb	Zn	Pb		L	S	P. R.	Meas.	Calc.		
F19	82	3	5		10								7.46			
F20	85		5		10								7.40		20.3	
F21	77.2	2.8			20				187	175	12		7.36		23.1	
F22	95	0.1	1			3.9							7.29			
F23	95	0.5	1.5			3							7.32			
F24	43		55					2					8.49			
F25	43.5	0.5	56										8.53			
F26	88.9	4.5		1.6		5							7.39			
F27	95.5	3.5		0.5				1	221	219	2		7.38			
F28	85.7	3			10.9	0.4			217.6	201	16.6		7.37			
F29	93.6	4.7		1.7									7.43			
F30	96.1	3.2		0.7									7.38			
F31	95.2	3.5		1.3									7.40			

**Note:** Following alloys F32 to F65 and A0 were experimental or reference alloys prepared to investigate failures due to fillet-lifting observed in through-hole joints when soldered with certain lead-free solder alloys. Because these alloys were not intended to replace tin-lead solder, their property values were not systematically collected.

A. C.	Composition (% by Mass)						Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g K)	CTE (µm per m.°C)
	Sn	Ag	Bi	Cu	In	Pb		L	S	P. R.	Meas.	Calc.		
F32	95.54	3.47			0.99		Alloy A4, plus 1% In; Sn/Ag ratio preserved	223	218.8	4.2		7.38		
F33	93.69	3.40			2.91		Alloy A4, plus 3% In; Sn/Ag ratio preserved	216	214.1	1.9		7.38		
F34	91.90	3.33			4.76		Alloy A4, plus 5% In; Sn/Ag ratio preserved	214.7	210.4	4.3		7.38		
F35	94.06	2.97	1.98		0.99		Alloy E4, plus 1% In; Sn/Ag ratio preserved	221.1	215.2	5.9		7.40		
F36	92.23	2.91	1.94		2.91		Alloy E4, plus 3% In; Sn/Ag ratio preserved	215.1	208.9	6.2		7.40		
F37	90.48	2.86	1.90		4.76		Alloy E4, plus 5% In; Sn/Ag ratio preserved	210.1	202.8	7.3		7.40		
F38	90.89	3.37	4.75		0.99		Alloy E4, plus 1% In; Sn/Ag ratio preserved	215.9	210.4	5.5		7.47		
F39	89.13	3.30	4.66		2.91		Alloy E4, plus 3% In; Sn/Ag ratio preserved	212.6	206.1	6.5		7.46		
F40	87.43	3.24	4.57		4.76		Alloy E4, plus 5% In; Sn/Ag ratio preserved	208.0	199.1	8.9		7.46		
F41	89.5	3.5	7					202.0	185	17		7.51		
F42	86.5	3.5	10					213.3	205.5	7.8		7.57		

Designation and Composition of Lead-Free Solders (cont.)														
A. C.	Composition (% by Mass)						Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g·M <sup>+</sup> )	CTE (µm per m.°C)
	Sn	Ag	Bi	Cu	In	Pb		L	S	P. R.	Meas.	Calc.		
F43	91.5	2.5		1	5		Ag reduced to increase ductility; Cu added to improve wetting. Same room-temperature strength as for F2.	205	140			7.37		
F44	91.5	1.5		2	5		Ag reduced to increase ductility; Cu added to improve wetting. Same room-temperature strength as for F2.	205	140			7.36		
F45	91.5	0.5		3	5		Ag reduced to increase ductility; Cu added to improve wetting. Same room-temperature strength as for F2.	212				7.35		
F46	95		5				Ag replaced by 5% Bi to lower melting point.	222				7.39		
F47	94		5		1		Ag replaced by 5% Bi to lower melting point; 1% In added to increase ductility, lower melting pt.	221				7.39		

Designation and Composition of Lead-Free Solders (cont.)														
A. C.	Composition (% by Mass)						Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g K)	CTE (µm per m.°C)
	Sn	Ag	Bi	Cu	In	Pb		L	S	P. R.	Meas.	Calc.		
F48	92		5		3		Ag replaced by 5% Bi to lower melting point; 3% In added to increase ductility, lower melting pt.	215				7.39		
F49	90		5		5		Ag replaced by 5% Bi to lower melting point; 3% In added to increase ductility, lower melting pt.	210				7.39		
F50	95				5		Sn only, with 5% In added to increase ductility, lower melting pt	221				7.30		
F51	93.5	0.5		1	5		Reintroduce Ag; add Cu at eutectic composition; complements F43-F45.					7.33		
F52	92.5	1.5		1	5		Add more Ag; add Cu at eutectic composition; complements F43-F45.					7.35		

Designation and Composition of Lead-Free Solders (cont.)														
A. C.	Composition (% by Mass)						Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g K)	CTE (µm per m.°C)
	Sn	Ag	Bi	Cu	In	Pb		L	S	P. R.	Meas.	Calc.		
F53	94		1		5		Reintroduce 1% Bi to lower melting point; keep In at 5%.					7.32		
F54	92		3		5		Increase Bi; keep In at 5%.					7.36		
F55	94.5	0.5			5		Remove Bi, reintroduce Ag; keep In at 5%.					7.31		
F56	93.5	1.5			5		Increase Ag; keep In at 5%.					7.33		
F57	94.15	3.41				2.44	2.5% Pb added to A4; Sn/Ag ratio maintained same as in A4					7.44		
F58	91.90	3.33				4.76	5% Pb added to A4; Sn/Ag ratio maintained same as in A4					7.50		
F59	89.56	3.32	4.68			2.44	2.5% Pb added to F17; Sn/Ag ratio maintained same as in F17					7.53		
F60	87.43	3.24	4.57			4.76	5% Pb added to F17; Sn/Ag ratio maintained same as in F17					7.59		

Designation and Composition of Lead-Free Solders (cont.)														
A. C.	Composition (% by Mass)						Comments	Melting Temperature (°C)			Density (g/cm <sup>3</sup> )		Specific Heat (J/g K)	CTE (µm per m.°C)
	Sn	Ag	Bi	Cu	In	Pb		L	S	P. R.	Meas.	Calc.		
F61	92.68				4.88	2.44	2.5% Pb added to F50; Sn/In ratio maintained same as in F50					7.37		
F62	90.48				4.76	4.76	5% Pb added to F50; Sn/In ratio maintained same as in F50					7.43		
F63	97.5	2.5										7.36		
F64	95.12	2.44				2.44	2.5% Pb added to F63; Sn/Ag ratio maintained same as in F63					7.42		
F65	92.86	2.38				4.76	5% Pb added to F63; Sn/Ag ratio maintained same as in F63					7.48		

**Source:** Technical Reports for the Lead Free Solder Project: Alloy Descriptions: "Lead-Free Solder Alloy Designation and Composition;" Lead Free Solder Project CD-ROM, National Center for Manufacturing Sciences (NCMS), 1998



## 5. Useful References:

### 5.1. References to Tabular Data:

1. Authors not listed; "Lead-Free Alloy Trends for the Assembly of Mixed Technology PWBs", Proc. NEPCON-West 2000 (Feb. 27-Mar. 2) Anaheim, CA
2. M. Abteu, "Wetting Characteristics of Lead Free Solders for High Volume Surface Mount Application," Proc. NEPCON West 2000 Conf. (Feb. 28 - Mar. 2, 2000) Anaheim, CA
3. Chad M. Miller, Iver E. Anderson and Jack F. Smith, "A Viable Tin-Lead Solder Substitute: Sn-Ag-Cu," J. Electronic Mater. 23(7) 595-601 (1994)
4. Iver E. Anderson, "Tin-Silver-Copper: A Lead-Free Solder for Capacitor Interconnects," p. 16, Proc. 16<sup>th</sup> Capacitor and Resistor Technology Symposium (CARTS 96), 11-15 March, 1996
5. Iver E. Anderson, Özer Ünal, Tamara E. Bloomer and James C. Foley, "Effects of Transition Metal Alloying on Microstructural Stability and Mechanical Properties of Tin-Silver-Copper Solder Alloys," Proc. Third Pacific Rim International Conference on Advanced Materials and Processing (PRICM 3) (The Minerals, Metals and Materials Society, 1998)
6. Iver E. Anderson, Tamara E. Bloomer, Robert L. Terpstra, James C. Foley, Bruce A. Cook and Joel Harringa, "Development of Eutectic and Near-Eutectic Tin-Silver-Copper Solder Alloys for Lead-Free Electronic Assemblies," IPCWorks '99: An International Summit on Lead-Free Electronics Assemblies," (October 25-28, 1999), Minneapolis, MN
7. Iver E. Anderson, Tamara E. Bloomer, Robert L. Terpstra, James C. Foley, Bruce A. Cook and Joel Harringa, "Development of Eutectic and Near-Eutectic Tin-Silver-Copper Solder Alloys for Lead-Free Joining Applications," p. 575 (complete citation not available)
8. Artaki, D.W. Finley, A.M. Jackson, U. Ray and P.T. Vianco, "Wave Soldering with Pb-Free Solders," *Proc. Surface Mount International* (San Jose, CA, August 27-31, 1995), p. 495.
9. Peter Biocca, "Global Update on Lead-free Solders," *Proc. Surface Mount International* (San Jose, CA, 1998), pp. 705-709
10. E.A. Brandes, *Smithells Metals Reference Book*, 6<sup>th</sup> ed. (Butterworths, London, 1983)
11. S.D. Brandi, S. Liu, J.E. Indacochea and R. Xu, "Brazeability and Solderability of Engineering Materials," ASM Handbook, Vol. 6: Welding, Brazing and Soldering (ASM International, 1993)
12. D.R. Frear, S.N. Burchett, H.S. Morgan, and J.H. Lau, eds., *The Mechanics of Solder Alloy Interconnects*, p. 60 (Van Nostrand Reinhold, New York, 1994)

13. E.Gebhardt and G. Petzow, *Z. Metallkde.* 50, 597 (1950)
14. Judith Glazer, "Microstructure and Mechanical Properties of Pb-free Solder Alloys for Low-Cost Electronic Assembly: A Review," *J. Electronic Materials* 23(8), 693 (1994)
15. D.E. Gray, ed., *American Institute of Physics Handbook*, (McGraw-Hill, New York, 1957)
16. Angela Grusd, "Lead Free Solders in Electronics," SMI97, p. 648
17. William B. Hampshire, "The Search for Lead-Free Solders," Proc. Surface Mount International Conference (Sept. 1992) San Jose, CA, p. 729
18. E.W. Hare and R.G. Stang, *J. Electronic Mater.* 21, 599 (1992)
19. Cynthia L. Hernandez, Paul T. Vianco, Jerome A. Rejent, "Effect of Interface Microstructure on the Mechanical Properties of Pb-Free Hybrid Microcircuit Solder Joints," IPC/SMTA Electronics Assembly Expo (1998), p. S19-2-1
20. J.S. Hwang, "Overview of Lead-Free Solders for Electronics & Microelectronics," Proc. SMI Conf. , p. 405
21. S.K. Kang, J. Horkans, P.C. Andricacos, R.A. Carruthers, J. Cotte, M. Datta, P. Gruber, J.M.E. Harper, K. Kwietniak, S. Sambucetti, L. Shi, G. Brouillette and D. Danovitch, "Pb-Free Solder Alloys for Flip Chip Applications," 49<sup>th</sup> Electronic Components Technology Conf. (1999), June 1-4, San Diego CA
22. M.A. Korhonen, D.D. Brown and C.-Y. Li, "Mechanical Properties of Plated Copper," *Mat. Res. Soc. Symp. Proc.* Vol. 323, p. 104 (MRS, 1994) ("plated [thin foil] copper")
23. M.A. Kwoka and D.M. Foster, "Lead Finish Comparison of Lead-Free Solders versus Eutectic Solder," Proc. Surface Mount International Conference (1994), p. 433
24. N.A. Lange, *Handbook of Chemistry*, p. 100 (Handbook Publishers, Sandusky, Ohio, 1956)
25. J. Lau, C. Chang, R. Lee, T.-Y. Chen, D. Cheng, T.J. Tseng, D. Lin, "Thermal-Fatigue Life of Solder Bumped Flip Chip on Micro Via-In-Pad (VIP) Low Cost Substrates"
26. J.H. Lau and S.-W. Ricky Lee, "Fracture Mechanics Analysis of Low Cost Solder Bumped Flip Chip Assemblies with *Imperfect* Underfills," Proceedings: NEPCON West Conference (February 28 – March 2, 1995), Anaheim, CA
27. N.-C. Lee, J.A. Slattery, J.R. Sovinsky, I. Artaki, P.T. Vianco, "A Drop-In Lead-Free Solder Replacement," Proceedings: NEPCON West Conference (February 28 – March 2, 1995), Anaheim, CA

28. N.-C. Lee and W. Casey, "Soldering Technology for Area Array Packages," Proceedings: NEPCON WEST 2000 (February 27 – March 2, 2000), Anaheim, CA
29. Ning-Cheng Lee, "Lead-Free Soldering of Chip-Scale Packages," *Chip Scale Review*, p. 42 (March/April 2000)
30. M.E. Loomans, S. Vaynman, G.Ghosh and M.E. Fine, "Investigation of Multi-component Lead-free Solders," *J. Elect. Matls.* 23(8), 741 (1994)
31. Rao Mahidhara, "A Primer on Lead-Free Solder," *Chip Scale Review* (March-April 2000)
32. T.B. Massalski, *Binary Phase Diagrams*, 2<sup>nd</sup> ed. (Amer. Soc. Metals, 1990)
33. H. Mavoori, Semyon Vaynman, Jason Chin, Brian Moran, Leon M. Keer and Morris E. Fine, "Mechanical Behavior of Eutectic Sn-Ag and Sn-Zn Solders," *Mat. Res. Soc. Symp. Proc.* Vol. 390, p. 161 (MRS, 1995)
34. H. Mavoori, J. Chin, S. Vaynman, B. Moran, L. Keer and M. Fine, "Creep, Stress Relaxation, and Plastic Deformation in Sn-Ag and Sn-Zn Eutectic Solders," *J. Electronic Materials*, 26(7), 783 (1997)
35. Rodney J. McCabe and Morris E. Fine, "Athermal and Thermally Activated Plastic Flow in Low Melting Temperature Solders at Small Stresses," *Scripta Materialia* 39(2), 189 (1998)
36. Rodney J. McCabe and Morris E. Fine, "The Creep Properties of Precipitation-Strengthened Tin-Based Alloys," *JOM*, p. 33 (June 2000)
37. NCMS, Technical Reports for the Lead Free Solder Project: Properties Reports: "Room Temperature Tensile Properties of Lead-Free Solder Alloys;" Lead Free Solder Project CD-ROM, National Center for Manufacturing Sciences (NCMS), 1998
38. Y.-H. Pao, S. Badgley, R. Govila and E. Jih, "An Experimental and Modeling Study of Thermal Cyclic Behavior of Sn-Cu and Sn-Pb Solder Joints," *Mat. Res. Soc. Symp. Proc.* Vol. 323, p. 128 (MRS, 1994)
39. Alan Rae and Ronald C. Lasky, "Economics and Implications of Moving to Lead-Free Assembly," *Proc. NEPCON WEST 2000* (February 27 – March 2, 2000), Anaheim, CA
40. Karl Seelig and David Suraski, "The Status of Lead-Free Solder Alloys," *Proc. 50<sup>th</sup> IEEE 2000 Electronic Components and Technology Conference* (May 21-24, 2000), Las Vegas, NV
41. Jeff D. Sigelko and K.N. Subramanian, "Overview of lead-free solders," *Adv. Mat. & Proc.*, pp. 47-48 (March 2000)
42. J.A. Slattery and C.E.T. White, U.S. Patent 5,256,370 (Oct. 26, 1993)

43. V. Solberg, "No-Lead Solder for CSP: The Impact of Higher Temperature SMT Assembly Processing," Proc. NEPCON West 2000 Conf. (Feb. 28 - Mar. 2, 2000) Anaheim, CA (Source: Indium Corp.)
44. S.M. Spearing, M.A. Tenhover, D.B. Lukco, L. Viswanathan and D.K. Hollen, "Models for the Thermomechanical Behavior of Metal/Ceramic Laminates," Mat. Res. Soc. Symp. Proc. Vol. 323, p. 128 (MRS, 1994)
45. R.R. Tummala and E.J. Rymaszewski, eds. *Microelectronics Packaging Handbook*, (Van Nostrand Reinhold, 1989, NY)
46. Paul T. Vianco, "General Soldering," ASM Handbook, Vol. 6, Welding, Brazing, and Soldering (ASM International, 9639 Kinsman Road, Materials Park, Ohio 44073 USA, 1993)
47. M.E. Warwick, "The Wetting and Mechanical Properties of Lead-Free Capillary Plumbing Solders," ATB Metallurgie XXV, No. 1, 43-50 (1985)
48. Welco Castings, Solder Data Sheet, 2 Hillyard Street, Hamilton, Ontario, Canada
49. Walter L. Winterbottom, "Converting to Lead-Free Solders: An Automotive Industry Perspective," JOM, 20-24 (July 1993)
50. Tim Wong and A.H. Matsunaga, "Ceramic Ball Grid Array Solder Joint Thermal Fatigue Life Enhancement," Proceedings: NEPCON West Conference (February 28 – March 2, 1995), Anaheim, CA

## 5.2. Reference Books:

1. **ASM Handbook, Vol. 6, Welding, Brazing, and Soldering** (ASM International, 9639 Kinsman Road, Materials Park, Ohio 44073 USA, 1993)
2. P. Borgesen, K.F. Jensen and R.A. Pollak, eds., "**Electronic Packaging Materials Science VII**," Matls. Res. Soc. Symp. Proc. Vol. 323, (MRS, Pittsburgh, 1994)
3. E.A. Brandes, **Smithells Metals Reference Book**, 6<sup>th</sup> ed. (Butterworths, London, 1983)
4. J.R. Davis, ed., **Metals Handbook, Desk Edition** (2<sup>nd</sup> ed.), (ASM International, Materials Park, Ohio 44073-0002 USA, 1998)
5. D.R. Frear, W.B. Jones and K.R. Kinsman, eds., **Solder Mechanics** (TMS, 1991)
6. D.R. Frear, H.S. Morgan, S.N. Burchett, and J.H. Lau, eds., **The Mechanics of Solder Alloy Interconnects** (Van Nostrand Reinhold. New York, 1994)

7. D.E. Gray, ed., **American Institute of Physics Handbook**, (McGraw-Hill, New York, 1957)
8. R.J. Klein Wassink, **Soldering in Electronics** (Electrochemical Publications, Ltd., 1989)
9. N.A. Lange, **Handbook of Chemistry**, p. 100 (Handbook Publishers, Sandusky, Ohio, 1956)
10. Lieberman, **Modern Soldering and Brazing Techniques** (Business News Publishing Co., 1988)
11. H.H. Manko, **Solders and Soldering**, 3<sup>rd</sup> ed. (McGraw-Hill, 1992)
12. R. Skipp, **Soldering Handbook** (McGraw-Hill, 1964)
13. R.R. Tummala and E.J. Rymaszewski, eds. **Microelectronics Packaging Handbook**, (Van Nostrand Reinhold, 1989, NY)
14. Paul T. Vianco, “General Soldering,” **ASM Handbook, Vol. 6, Welding, Brazing, and Soldering** (ASM International, 9639 Kinsman Road, Materials Park, Ohio 44073 USA, 1993)
15. R.W. Woodgate, **The Handbook of Machine Soldering**, 2<sup>nd</sup> ed. (John Wiley & Sons, 1988)

### 5.3. Useful URLs

#### **Organizations Involved in Lead-Free Solder Issues:**

[Japan Electronic Industry Development Association \(JEIDA\)](#): “Challenges and Efforts Toward Commercialization of Lead-free Solder – Road Map 2000 for Commercialization of Lead-free Solder” – Ver 1.2

[Lead Free Soldering Technology Centre \(Soldertec\)](#)  
( [www.lead-free.org/](http://www.lead-free.org/) and <http://www.solderworld.com/> )

IPC: Association Connecting Electronics Industries (“Get the Lead OUT!”)  
( <http://www.leadfree.org/> )

[Materials Properties and Data, Materials Science and Engineering Laboratory \(MSEL\), NIST](#)