Effect of Long Term Elevated Temperature Aging on the Electrical Resistance of Soldered Copper Joints

Single lap joints made with 40% Sn-60% Pb (vs. 60% Sn-40% Pb) have greater long term stability at elevated temperatures, and joints with 3T overlap made with both solders show only slight increases in electrical resistance during the equivalent of aging for 10 years at 105°C or 40 years at 85°C

BY W. J. REICHENECKER

ABSTRACT. Electrical resistance measurements have been made on soldered copper single lap joints to determine the effects of two Sn-Pb solder compositions, overlap length, solder film thickness and elevated temperature aging on the resistance of the joints. Data covering the effects of long term aging at moderately elevated temperatures show a tendency for joint electrical resistance to increase a modest amount.

Introduction

Soldered copper joints are used in a wide range of electrical applications wherein the long term electrical stability of the joint is critical to the performance of the product. Design life requirements vary widely among electrical devices, and a useful service life of 10 years or more is anticipated for many electrical products. For example, large electrical generators are expected to perform for periods on the order of 40 years.

Operating temperatures to which soldered joints are exposed are often above room temperature, and the trend toward smaller packages or more output from the same package size tends to increase operating temperatures. Consequently, the effects of exposure to elevated temperatures on the electrical reliability of soldered copper joints must be considered if long term performance of the product is to be assured.

It was deemed desirable to establish a data base relative to assessing the long term stability of soldered copper joints when exposed to elevated temperatures. To this end, an experimental evaluation was made to determine the effect of solder composition, solder film thickness, joint overlap and elevated temperature aging on the electrical conductivity of soldered copper single lap joints.

Specimen Preparation

All specimens were prepared from electrolytic tough pitch, square corner, rectangular copper bar, ⅛ × ½ in. (3 × 13 mm), which had been annealed in argon for 45 minutes (min) at 500°C (932°F). Joints were made with 1T and 3T overlaps where T is the thickness of the copper conductor. Solder film thicknesses in the various joints were 0.003, 0.010, 0.030 and 0.060 in. (0.08, 0.25, 0.8 and 1.5 mm) and the specimens were prepared with both 60% tin-40% lead (60% Sn-40% Pb) and 40% tin-60% lead (40% Sn-60% Pb) solder alloys.

Approximately 1 in. (25 mm) of one end of each copper rectangular bar was bright dipped in a mixed acids solution and thoroughly rinsed in water immediately prior to soldering the joints. The bright dip solution consisted by volume of 55% sulfuric acid, 15% nitric acid, 0.5% hydrochloric acid, and the remainder water. The two copper bars of each single lap joint were fixtured to provide the desired joint overlap and spacing for the solder film. A feeler gauge was used to check the joint clearance.

After the specimens were appropriately fixtured, several drops of an acid type flux were applied to the joint by eye dropper. The flux used was an aqueous solution of zinc chloride, ammonium chloride and stannous chloride slightly acidified with hydrochloric acid. Specimens were then carefully heated with an oxyacetylene torch, and solder in the form of 1/16 in. (1.5 mm) diameter wire was hand fed to complete the joint. Duplicate specimens were prepared in all instances covering the various conditions shown in Table 1. Upon completion of soldering, the specimens were thoroughly washed to remove flux residue and carefully hand filed to remove excess solder from the joint.

Tests and Results

Initial measurements of the electrical resistance of the joints were made at room temperature using a Kelvin double bridge and a 3 in. (76 mm) gauge length, including the joint. Reference specimens of ⅛ × ½ × 12 in. (3 × 13 × 305 mm) square corner, electrolytic tough pitch copper which had been annealed in argon for 45 min at 500°C (932°F), were also measured to obtain a resistance value per unit length of the copper bar. Joint resistance ratios were then calculated using the following relationship:

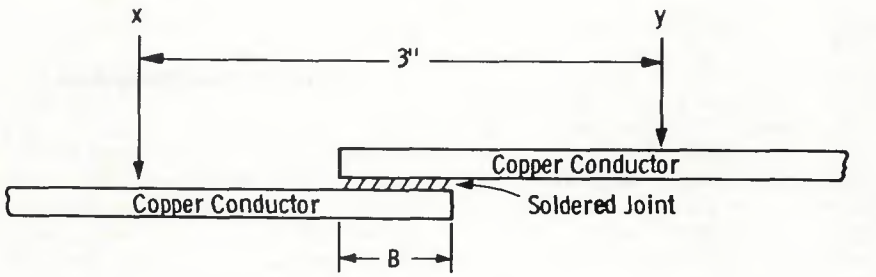
W. J. REICHENECKER is Senior Research Scientists, Metals Joining and Processing, Research and Development Center, Westinghouse Electric Corporation, Pittsburgh, Pennsylvania.

$$R_r = \frac{R_l - R_c\,(l - B)}{R_c\,B}$$

where R_r = joint resistance ratio; R_l = measured resistance in ohms over gauge length of soldered specimen; R_c = resistance in ohms per unit length of solid copper conductor; l = gauge length of soldered specimen; and B = length of joint overlap.

With this relationship, a resistance ratio can be calculated for each soldered joint comparing it to the electrical resistance of an equivalent length of solid copper—Fig. 1.

Upon completion of the electrical resistance measurements on the "as made" specimens, all soldered samples and the solid copper reference bars were placed in an oven and aged at 105°C (221°F) in air until an equivalent of 36 months aging time was accumulated. At accumulated aging times of 2, 6, 12, 24, and 36 months, the specimens were removed from the oven for electrical resistance measurements at room temperature. Then, in order to further accelerate the effects of aging, the specimens were returned to the aging oven for an additional 8 months at 140°C (284°F). Again, electrical resistance measurements were



$$\text{Joint resistance ratio} = \frac{\text{resistance of joint}}{\text{resistance of same length of copper conductor}}$$

$$R_r = \frac{R_{xy} - R_{at} \cdot (3 - B)}{R_{at} \cdot B}$$

R_r = resistance ratio

R_{xy} = resistance in ohms of 3" gage length including joint

R_{at} = resistance in ohms/inch of copper conductor

B = overlap length in inches

Fig. 1—Sketch illustrating the calculation of resistance ratio

Table 1—Data Pertaining to the Preparation of Single Lap Soldered Joints

Specimen number	Solder	Joint Overlap	Joint Thickness, in.[a]
226 A	40% Sn-60% Pb	1T	0.003
226 B			0.003
227 A			0.010
227 B			0.010
228 A			0.030
228 B			0.030
229 A			0.060
229 B			0.060
230 A	40% Sn-60% Pb	3T	0.003
230 B			0.003
231 A			0.010
231 B			0.010
232 A			0.030
232 B			0.030
233 A			0.060
233 B			0.060
234 A	60% Sn-40% Pb	1T	0.003
234 B			0.003
235 A			0.010
235 B			0.010
236 A			0.030
236 B			0.030
237 A			0.060
237 B			0.060
238 A	60% Sn-40% Pb	3T	0.003
238 B			0.003
239 A			0.010
239 B			0.010
240 A			0.030
240 B			0.030
241 A			0.060
241 B			0.060

(a) 25.4 ×in. = mm.

Table 2—Resistance Ratios of Soldered Copper Single Lap Joints "As Made" and Aged at Elevated Temperatures in Air

Specimen number[a]	Resistance ratios for months of aging at 105 and 140°C[b] As made	2 105°C	6 105°C	12 105°C	24 105°C	36 105°C	+8[c] 140°C
226 A	1.23	1.36	1.33	1.35	1.55	1.61	1.70
226 B	1.60	1.65	1.50	1.68	1.85	1.82	1.93
227 A	3.13	3.26	3.30	3.25	3.31	3.31	3.07
227 B	1.92	2.02	1.89	1.97	2.13	2.11	2.21
228 A[d]	3.81	3.69	3.68	3.69	3.78	–	–
228 B[e]	3.68	4.53	7.50	12.64	[e]	–	–
229 A	6.71	6.82	6.72	6.84	7.28	7.02	7.11
229 B	3.24	3.25	3.14	3.23	3.23	3.26	3.49
234 A[e]	1.20	1.30	1.43	1.40	[e]	–	–
234 B[e]	1.49	1.56	1.94	2.02	[e]	–	–
235 A	2.26	2.39	2.33	2.42	2.44	2.37	2.69
235 B	2.41	2.48	2.46	2.49	3.21	3.17	3.35
236 A	3.45	3.54	3.45	3.48	3.73	3.70	4.15
236 B	3.40	3.48	3.42	3.42	3.43	3.46	3.55
237 A	3.32	3.39	3.35	3.46	3.38	3.42	2.15
237 B	3.77	3.84	3.80	3.80	3.45	3.88	3.96
230 A	0.76	0.74	0.70	0.71	0.74	0.72	0.76
230 B	0.76	0.78	0.75	0.76	0.78	0.78	0.82
231 A	0.91	0.96	0.92	0.93	[f]	–	–
231 B	0.83	0.93	0.76	0.84	0.80	–	–
232 A	1.15	1.17	1.14	1.16	1.17	1.15	1.19
232 B	0.99	0.96	0.93	0.96	1.07	0.95	0.99
233 A	1.05	1.07	1.04	1.07	1.07	1.06	1.14
233 B	1.24	1.24	1.19	1.19	1.23	1.19	1.23
238 A[e]	0.65	0.75	1.29	1.41	[e]	–	–
238 B	0.70	0.72	0.72	0.71	0.72	0.76	0.84
239 A[d]	0.80	0.81	0.83	0.84	0.84	–	–
239 B	0.83	0.89	0.88	0.88	0.93	0.91	0.99
240 A	0.89	0.91	0.89	0.89	1.03	1.05	1.06
240 B	0.81	0.81	0.85	0.86	0.88	0.86	0.89
241 A	0.91	0.92	0.90	0.92	0.98	0.99	1.01
241 B	1.17	1.20	1.19	1.19	1.22	1.22	1.24

(a) See Table 1 for corresponding solder compositions and joint data.
(b) 105°C = 221°F; 140°C = 284°F.
(c) 8 months aging at 140°C is in addition to 36 months at 105°C.
(d) Selected for reference, essentially stable electrical resistance.
(e) Specimens with increasing electrical resistance selected for examination after 12 months aging.
(f) Specimen broke during handling.

made on the specimens at room temperature.

Joint resistance ratios calculated for all specimens from the electrical resistance measurements "as made" and "aged" are shown in Table 2. A resistance ratio of 1.00 indicates that the soldered joint has an electrical resistance equal to that of a solid copper conductor of the same cross section as the conductor used to make the joint. A resistance ratio of less than 1.00 shows the joint to be lower in electrical resistance than an equal length of copper conductor; similarly, resistance ratios greater than 1.00 show the joint to have higher electrical resistance than an equal length of solid copper conductor.

Examination of the joint resistance ratios in Table 2 shows that, after 12 months aging, 4 specimens (228B, 234A, 234B and 238A) showed an increase in resistance ratio greater than that of the other specimens. Further aging of these specimens was discontinued in order to try to determine the cause of the increasing electrical resistance. Visual, metallographic, scanning electron microscope and EDS studies were conducted on the four specimens, and comparisons were made with one "as made" and three soldered specimens (228A, 231B, 239A) after aging for 24 months at 105°C (221°F).

One specimen (228B) was found to contain a large macro crack throughout most of the length of the joint. The joint resistance ratio of this specimen "as made" was consistent with that of the duplicate specimen (228A). As a result, it is believed that the joint was initially sound and that the crack was generated during subsequent handling of the specimen.

The joint resistance ratio of specimen 228B increased drastically during the 12 month aging period. For this reason, it is probable that the crack grew progressively larger with handling for electrical resistance measurements and loading and unloading of the specimen in the aging oven. Such mechanical damage is not unlikely, because specimen 228B had only a small overlap (1T) to support any strain inadvertently applied to the joint. No specific cause was identified to explain the increasing joint resistance ratio with aging for the other three specimens.

Analysis of the data in Table 2 for the specimens which completed the full aging treatment shows that, in most cases, the electrical resistance of the soldered joints increased as a result of aging at elevated temperature. The effect is shown more clearly in Table 3 where the percentage change in joint resistance ratio is given for two conditions: "as made" vs. aged 36 months at 105°C (221°F) and "as made" vs. aged 36 months at 105°C (221°F) plus 8 months at 140°C (284°F).

One specimen, 237A, showed a slight increase in joint resistance ratio after 36 months aging at 105°C (221°F) but exhibited a large (35%) decrease in electrical resistance after the additional 8 months at 140°C (284°F). Rechecks of the electrical resistance of this specimen confirmed this result; no explanation for this behavior is apparent at this time.

The most interesting result of these aging tests is that 3T overlap joints soldered with 40% Sn-60% Pb exhibited the best long term stability of any of the specimen groups—Table 3.

Discussion

Long term electrical stability of soldered copper joints at moderately elevated temperatures is critical to the satisfactory performance of many types of electrical equipment. However, no published data

Table 3—Change in Joint Resistance Ratios of Single Lap Soldered Copper Joints With Elevated Temperature Aging in Air

Specimen number[a]	Joint resistance ratio[b]			Resistance ratio change, %[b]	
	As made	105°C × 36 months	105°C × 36 months plus 140°C × 8 months	After 105°C × 36 months	After 105°C × 36 months plus 140°C × 8 months
226 A	1.23	1.61	1.70	+31	+38
226 B	1.60	1.82	1.92	+14	+21
227 A	3.13	3.31	3.07	+6	−2
227 B	1.92	2.11	2.21	+10	+15
228 A	3.81			—	—
228 B	3.68			—	—
229 A	6.71	7.02	7.11	+5	+6
229 B	3.24	3.26	3.49	+1	+8
234 A	1.20			—	—
234 B	1.49			—	—
235 A	2.26	2.44	2.69	+8	+19
235 B	2.41	3.21	3.35	+33	+39
236 A	3.45	3.73	4.15	+8	+18
236 B	3.40	3.43	3.55	+1	+5
237 A	3.32	3.38	2.15	+2	−35
237 B	3.77	3.45	3.96	−8	+5
230 A	0.76	0.72	0.76	−5	0
230 B	0.76	0.78	0.82	+3	+8
231 A	0.91	++	++	—	—
231 B	0.83			—	—
232 A	1.15	1.15	1.19	0	+3
232 B	0.99	0.95	0.99	−4	0
233 A	1.05	1.06	1.14	+1	+9
233 B	1.24	1.19	1.23	−5	−1
238 A	0.65			—	—
238 B	0.70	0.76	0.84	+9	+20
239 A	0.80			—	—
239 B	0.83	0.91	0.99	+10	+19
240 A	0.89	1.05	1.06	+18	+19
240 B	0.81	0.86	0.89	+6	+10
241 A	0.91	0.99	1.01	+9	+11
241 B	1.17	1.22	1.24	+ 5	+6

(a) See Table 1 for corresponding solder compositions and joint data.
(b) 105°C = 221°F; 140°C = 284°F.
(c) Selected for metallographic examination prior to 36 months aging.
(d) Broke during handling.

could be found relating to the effect of elevated temperatures and time of exposure on the electrical resistance of soldered copper joints. For this reason the work described here was undertaken. The effects of aging time and temperature were examined. In addition, other factors such as the effect of joint overlap length, solder film thickness and solder alloy composition were included in the studies, since data relating to these factors likewise could not be located in the published literature.

Electrical resistance measurements on the joints in the "as made" condition show clearly that, for even the thinnest solder film thickness, a joint overlap equal to the thickness of the copper conductors (1T) is insufficient to provide electrical resistance as good as that of an equal length of the conductor. On the other hand, joints made with an overlap length three times the thickness of the copper conductors (3T) display electrical resistances less than or equal to that of an equal length of copper conductor; an exception occurs when the solder film thickness is greater than about 0.030 in. (0.8 mm).

The above comparisons are true for both the 60% Sn-40% Pb and 40% Sn-60% Pb solders. The "as made" data show that joints soldered with the 60% Sn-40% Pb alloy tend to be somewhat lower in electrical resistance than those made with the 40% Sn-60% Pb alloy. However, the difference does not appear to be of sufficient practical significance to recommend one alloy over the other. The aging data suggest that joints made with 40% Sn-60% Pb solder have greater long term stability at elevated temperature than those soldered with 60% Sn-40% Pb solder.

Electrical resistance measurements made at room temperature at various intervals during the accumulation of 36 months aging at 105°C (221°F) showed that joint electrical resistances tend to increase with aging time. However, the increases were relatively small, less than 10% increase in most instances. After the first 12 months of aging at 105°C (221°F), four specimens were found to show increases in electrical resistance greater than exhibited by the other specimens. Investigation of the four specimens along with several that showed little change failed to reveal a specific cause for this behavior. An exception occurred with the one specimen which showed the greatest increase in electrical resistance; this was found to contain a large crack in the joint.

Upon completion of the 36 months aging at 105°C (221°F), aging was further accelerated by increasing the aging temperature to 140°C (284°F). Specimens were run an additional 8 months at this higher temperature.

A rule of thumb often used with regard to chemical reaction rates is that the rate approximately doubles for every 10°C (18°F) increase in temperature. Eight months at 140°C (284°F) is approximately equivalent to about 88 months at 105°C (221°F); (8 months $\times 2^{3.5}$). Then the total aging time represented by these experiments is roughly equivalent to 124 months (36 months + 88 months) or about 10 years at 105°C (221°F).

Soldered copper joints in heavy electrical equipment may typically be exposed to temperatures on the order of 85°C (185°F) for long periods of time. Using the rule of thumb that reaction rates double for each 10°C (18°F) increase in temperature, the effect of aging at 85°C (185°F) would be approximately one-fourth that observed at 105°C (221°F); 105°C-85°C = 20°C or a factor of 2^2.

The effect of time and temperature upon the electrical stability of soldered copper joints is shown graphically in Figs. 2-5 for both 85°C (185°F) and 105°C (221°F).

Conclusions

It is somewhat hazardous to extrapolate short term aging data to long term performance. Nonetheless, the following conclusions are offered:

1. Copper lap joints with an overlap of three times the thickness of the copper conductor and soldered with 40% Sn-60% Pb alloy show less than a 10% increase in joint electrical resistance as a

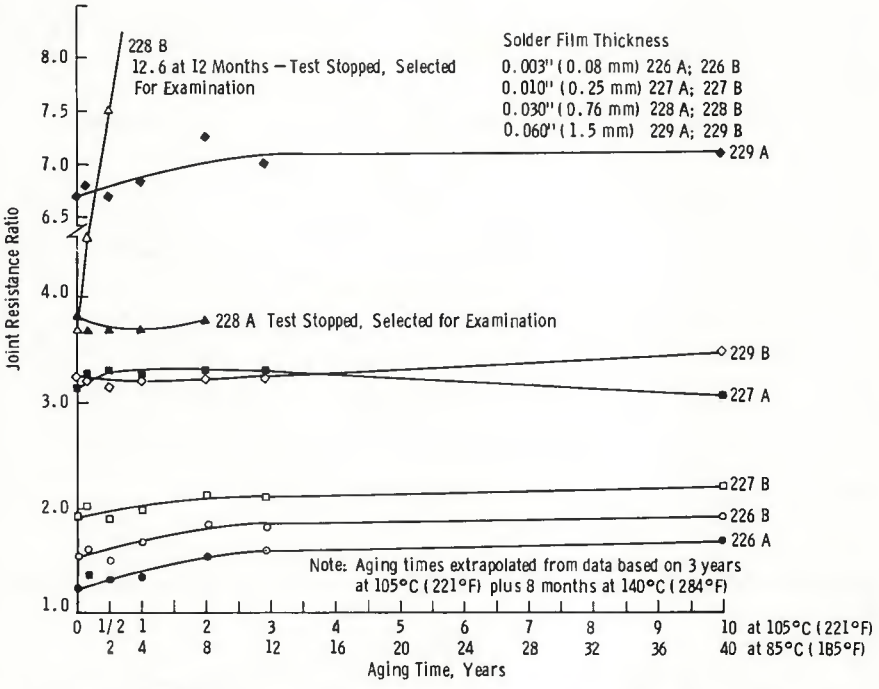


Fig. 2—Effect of aging at elevated temperature on electrical resistance of single lap soldered copper joints soldered with 40% Sn-60% Pb with a 1T overlap and various solder film thicknesses

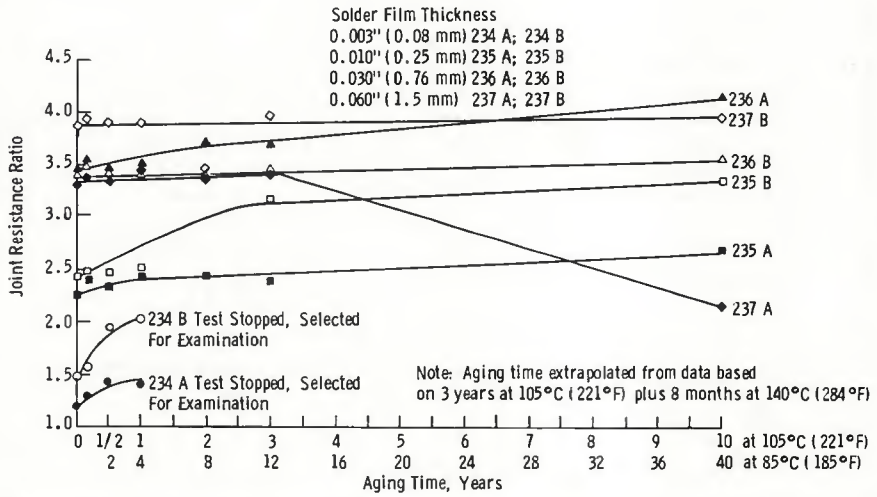


Fig. 3—Effect of aging at elevated temperature on electrical resistance on single soldered copper joints soldered with 60% Sn-40% Pb with a 1T overlap and various solder film thicknesses

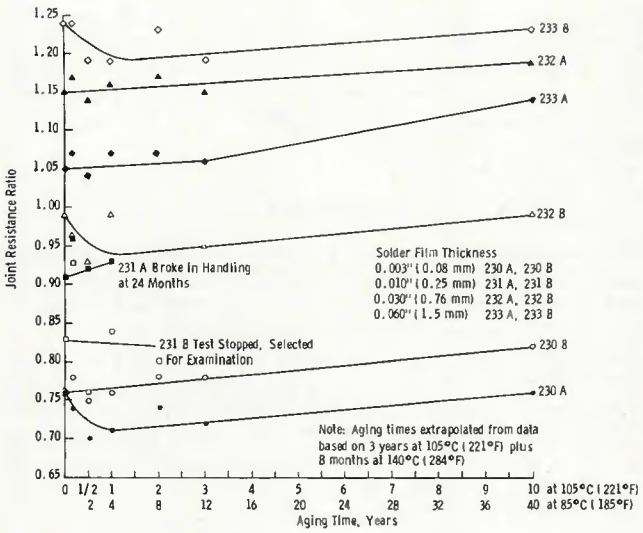


Fig. 4—Effect of aging at elevated temperature on electrical resistance of single lap soldered copper joints with 40% Sn-60% Pb with a 3T overlap and various solder film thicknesses

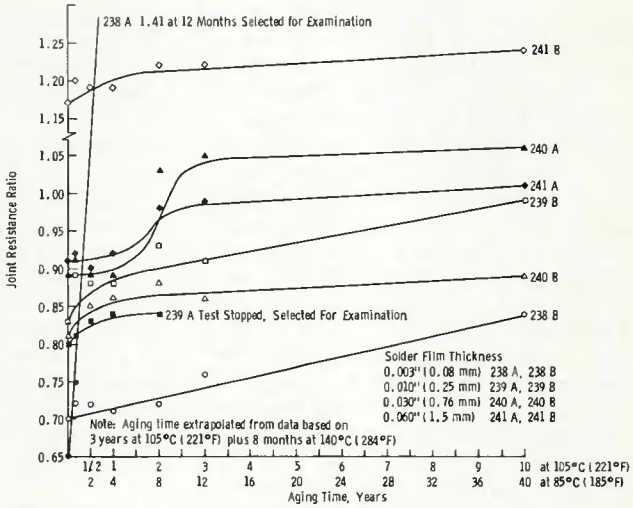


Fig. 5—Effect of aging at elevated temperature on electrical resistance ratio of single lap soldered copper joints soldered with 60% Sn-40% Pb with a 3T overlap and various solder film thicknesses

result of elevated temperature aging equivalent to 10 years at 105°C (221°F) or approximately 40 years at 85°C (185°F) for solder film thicknesses in the range of 0.003 to 0.060 in. (0.08 to 1.5 mm).

2. Copper lap joints with an overlap of three times the thickness of the copper conductor and soldered with 60% Sn-40% Pb solder alloy show less than a 20% increase in joint electrical resistance as a result of exposure to elevated temperature aging equivalent to 10 years at 105°C (221°F) or approximately 40 years at 85°C (185°F) for solder film thicknesses in the range of 0.003 to 0.060 in. (0.08 to 1.5 mm).

3. Copper lap joints with a joint overlap equal to the copper conductor thickness (1T) are not electrically equivalent to the solid copper conductor regardless of solder film thickness or the choice of solder alloy, 40% Sn-60% Pb or 60% Sn-40% Pb.

Acknowledgments

The author wishes to thank R. L. Berrier for specimen preparation and specimen monitoring during aging and J. Valentich, J. J. Irha, D. M. Siemon and R. P. Sadusky for electrical resistance measurements and joint resistance ratio calculations and R. Songer for manuscript preparation.

Reference

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WRC Bulletin 282
November, 1982

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by D. Bushnell

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