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BDX-613-2341
Distribution Category UC-38

THERMAL FATIGUE EVALUATION OF SOLDER ALLOYS

By D. M. Jarboe

Published February 1980

Final Report
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THERMAL FATIGUE EVALUATION OF SOLDER ALLOYS

BDX-613-2341, Final Report, Published February 1980

Prepared by D. M. Jarboe

An evaluation was made of the relative thermal fatigue resistance of 29 solder alloys. A number of these alloys were found to be less susceptible to thermal fatigue cracking in encapsulated printed wiring board applications than the commonly used tin-lead eutectic (63Sn-37Pb). Three alloys, 95Sn-5Ag, 96.5Sn-3.5Ag, and 95Sn-5Sb offered the greatest resistance to thermal fatigue. The selection of the encapsulation material was confirmed to be a significant factor in thermal fatigue of solder joints, regardless of the solder alloy used.

DJC-tr/2

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SUMMARY

The objective of this project was to evaluate a number of solder alloys for thermal fatigue resistance. An empirical study using actual solder joints allowed a relative ranking of the alloys.

Thirty alloys of various compositions were selected from an initial list of 70 on the basis of melting (liquidus) temperature. Solderability tests were performed to eliminate any solders that would not provide adequate wetting on currently used substrate materials. One alloy, (44.5Pb-55.5Bi) was removed from further study on this basis.

Printed wiring assemblies were constructed with each alloy. The units consisted of simulated components resembling thumbtacks soldered into plated through holes. The components were encapsulated within individual right cylinders (cylinders with ends squared off at right angles) of potting material to maintain an axisymmetric design. Three encapsulants were used; epoxy glass microballoon (GMB), filled epoxy, and polyurethane foam.

After the three groups of boards were encapsulated (one for each encapsulant), they were thermal cycled between -54 and 74°C. Periodic visual inspection of the boards was performed to obtain failure rate data. These data were then fit to a mathematical model which allowed the alloys to be ranked.

It was determined that several solder alloys have an increased resistance to thermal fatigue when compared to the commonly used tin-lead eutectic (63Sn-37Pb). The three solder alloys offering the best resistance to thermal fatigue were 95Sn-5Ag, 96.5Sn-3.5Ag, and 95Sn-5Sb.

The significance of alloy selection was less apparent for the boards encapsulated with polyurethane foam than those encapsulated with epoxy or GMB filled epoxy.

DISCUSSION

SCOPE AND PURPOSE

The objective of this project was to evaluate the relative thermal fatigue resistance of a number of solder alloys that could be employed at Bendix using current materials and manufacturing processes. An empirical study using simulated printed wiring assemblies was designed to provide a statistical basis for ranking the candidate alloys. The commonly used eutectic tin-lead alloy (63Sn-37Pb) was to be the standard.

The simulated printed wiring assemblies were to be constructed with each of the alloys. The assemblies were encapsulated and the solder joints were visually examined on a periodic basis throughout thermal cycling. Results of the examinations were to be reduced to allow ranking the solder alloys.

PRIOR WORK

Thermal fatigue of solder joints in printed wiring assemblies was the subject of many investigations. The great majority of these studies have dealt with the mechanism by which it occurs and the impact of various design parameters.[1-5] The evaluation of solder alloys as thermal fatigue variables was pursued to a much lesser degree.

Much of the past work on solder alloys was directed toward the determination of tensile, creep, and fatigue properties.[6-13] These evaluations were conducted for bulk solder samples and solder joint configurations. Other studies have evaluated the thermal fatigue resistance of solder alloys in printed wiring board configurations. An early evaluation conducted for NASA considered 13 alloys.[14] Three of the alloys studied in this project were found to be superior to tin-lead eutectic, but there were application problems because of the alloys' high melting temperatures. A more recent study compared three tin-lead alloys with the eutectic alloy, and concluded that the eutectic was the most prone to thermal fatigue.[15] The development of a thermal fatigue resistant alloy was accomplished in a study performed for the Air Force.[16] This project included an evaluation of several alloy systems and subsequent composition modifications to arrive at a superior alloy. The scope of the latter study included only high temperature alloys having liquidus temperatures ranging from 232 to 315°C.

ACTIVITY

Alloy Selection

An initial list of 70 alloys was compiled. These alloys represented an extensive variety in composition and melting temperatures. Of these 70, 40 were eliminated on the basis of melting temperature. Only solder alloys that had liquidus temperatures between approximately 120 and 260°C were retained. This temperature range was selected because it was compatible with manufacturing processes, equipment, and materials currently in use at Bendix. A listing of the 30 alloys and their liquidus and solidus temperatures is presented in Table 1. The next step in alloy selection was to determine the ability of each to wet materials routinely soldered at Bendix. The Pessell spread test was the basis for this evaluation. This test method was chosen because of its ease of performance and quantitative results.

Tests coupons measuring 2.5 cm square were made with the following materials:

copper clad glass/epoxy laminate;

copper clad laminate with 2.5 to 5.10 μm nickel plating;

copper clad laminate with 2.50 to 5.10 μm nickel plating, and 1.27 to 2.54 μm gold plating; and

solid nickel 200 sheet.

Preforms of each alloy were prepared by cutting 1.25 cm lengths from 0.76-mm-diameter wire and tightly wrapping them into small coils.

The test procedure consisted of placing a solder preform on a coupon, applying three drops of a mildly activated rosin flux (Type RMA), and heating the coupon to 260°C. Once the preform was observed to melt, an additional five seconds were allowed at temperature for the alloy to spread. The coupon was then air cooled to room temperature.

The height of the solder droplet after wetting was then measured. A spread factor was then calculated by use of the equation

$$\frac{D-H}{D} \times 100 \text{ percent}$$

where:

D = theoretical diameter of a sphere having the same volume as the preform and

Table 1. Solder Alloys Considered for Thermal Fatigue Evaluation

Alloy Composition (Weight Percent)	Liquidus (°C)	Solidus (°C)
48Sn-52In	117	117
50Sn-50In	124	117
44.5Pb-55.5Bi	124	124
15Sn-9.6Pb-70In-5.4Bi	125	125
30.2Sn-40.3Pb-29.5In	137	134
42Sn-58Bi	138	138
15Pb-80In-5Ag	149	149
99In-1Cu	153	153
15Sn-80In-5Ag	156	130
100In	157	157
65Sn-35In	162	117
62.5Sn-36.1Pb-1.4Ag	179	179
51.6Sn-55.6Pb-3.9Ag	179	179
63Sn-37Pb	183	183
70Sn-30Pb	186	183
70Sn-30Pb+0.1Ce	186	183
59.5Sn-37.4Pb-3.1Sb	186	186
60Sn-40Pb	188	183
62Sn-36Pb-2Ag	189	179
50Pb-50In	209	180
50Sn-50Pb	212	183
90Sn-10Pb	213	183
96.5Sn-3.5Ag	221	221
99.25Sn-0.75Cu	227	227
40Sn-58Pb-2Sb	231	185
100Sn	232	232
99Sn-1Sb	236	236
95Sn-5Sb	238	232
95Sn-5Ag	241	221
35Sn-63.2Pb-1.8Sb	243	185

H = height of solder droplet above the coupon surface after wetting.

This test procedure differs from that usually performed. Generally the test is conducted at approximately 55°C above the liquidus temperature of the alloy being tested. In addition, the flux is generally non-activated (Type R) rosin. The use of 260°C for all alloys was chosen as a typical soldering temperature with available equipment and materials at Bendix. Mildly activated flux was selected because the purpose of the testing was not to evaluate cleanliness of the sample, but rather the ability of each solder to wet the substrate materials.

Test results for each of the alloys on the four coupon types are presented in Table 2. The criterion for maintaining an alloy through the remainder of this project was predetermined as a minimum spread factor of 60 percent on the copper-clad laminate. This is a generally accepted value for minimum wetting. Based on this criterion one alloy, 44.5Pb-55.5Bi, was eliminated.

Design and Construction of Experimental Printed Wiring Assemblies

Since the objective of this project was to directly compare the thermal fatigue behavior of solder alloys, it was necessary to design an experiment that would minimize bias of the data and allow easy analysis. It was therefore decided that the printed wiring assemblies (PWAs) should be geometrically simple and easily reproducible.

An axisymmetric model based on the one used by Munford was selected.[10] This consisted of a simulated component resembling a thumbtack soldered into a plated through hole.

The components consisted of Type 302 stainless steel washers (6.35 mm OD by 0.89 mm ID by 1.27 mm thick) welded to 0.76-mm-diameter OFHC copper wires. After soldering, each component was to be separately encapsulated within a right cylinder of potting material. The axis of the cylinder was to be aligned with the copper wire. It was felt that this basic design would assure an axisymmetric design, thereby avoiding any unusual stress conditions. Separate encapsulation of each component was to eliminate interaction from one joint to the next. The basic model is shown in Figure 1.

The final PWA design consisted of a printed wiring board (PWB) having a 6 by 8 array of plated through holes (PTHs). The PWB was designed to provide dimensions which were typical of current WR boards. The laminate selected was type GH, 0.76 mm thick, with 0.03-mm-thick copper cladding. A plated through hole diameter of 1.27 mm, and a pad diameter of 3.18 mm were selected. Simulated components were to be soldered in the PTHs using the various solder alloys.

Each PWA was to contain solder joints of two alloys. In addition, the solder alloys used on a PWA were to be alternated along a row of joints in order to avoid any board location dependency.

Table 2. Solderability Test Results

Solder Alloy	Spread Factor* (Percent)			
	Cu-Clad	Au-Plate	Ni-Plate	Ni 200
62Sn-36Pb-2Ag	93.36	90.14	99+	81.89
51.6Sn-55.6pb-3.9Ag	93.31	89.37	99+	84.67
62.5Sn-36.1Pb-1.4Ag	92.34	89.03	99+	79.88
63Sn-37Pb	91.44	86.38	99+	80.95
70Sn-30Pb	90.99	88.23	99+	79.29
50Sn-50Pb	90.10	85.58	99+	84.17
70Sn-30Pb+0.1Ce	89.53	88.87	99+	80.66
60Sn-40Pb	88.78	88.59	99+	80.89
15Pb-80In-5Ag	83.07	76.61	87.64	77.53
35Sn-63.2Pb-1.8Sb	83.03	92.28	89.72	78.81
15Sn-9.6Pb-70In-5.4Bi	81.82	73.38	58.40	73.47
100In	81.12	70.37	79.10	77.31
40Sn-58Pb-2Sb	80.82	87.46	92.81	80.13
59.5Sn-37.4Pb-3.1Sb	80.82	90.21	86.56	73.02
15Sn-80In-5Ag	80.00	69.60	59.22	71.63
99In-1Cu	79.72	69.25	80.29	75.57
30.2Sn-40.3Pb-29.5In	78.67	67.04	80.65	76.96
50Sn-50In	78.29	65.31	64.26	65.99
50Pb-50In	76.44	77.33	77.71	75.00
48Sn-52In	76.16	66.59	61.70	65.90
90Sn-10Pb	73.82	79.61	78.40	69.30
65Sn-35In	73.38	82.34	47.53	67.04
100Sn	73.21	78.64	71.28	72.64
95Sn-5Ag	73.20	79.97	72.79	69.63
42Sn-58Bi	72.31	89.32	68.84	69.28
96.5Sn-3.5Ag	70.99	80.22	74.02	71.74
99.25Sn-0.75Cu	70.17	78.29	70.99	70.37
99Sn-1Sb	69.37	78.17	69.64	68.77
95Sn-5Sb	66.15	77.87	67.54	68.18
44.5Pb-55.5Bi	56.44	84.28	61.02	61.91

*Test conditions: temperature, 260°C, flux, type RMA: hold time, five seconds after solder preform melted.

After the boards were fabricated, each PTH was pretinned with the appropriate alloy. The excess solder was removed, and the PTH

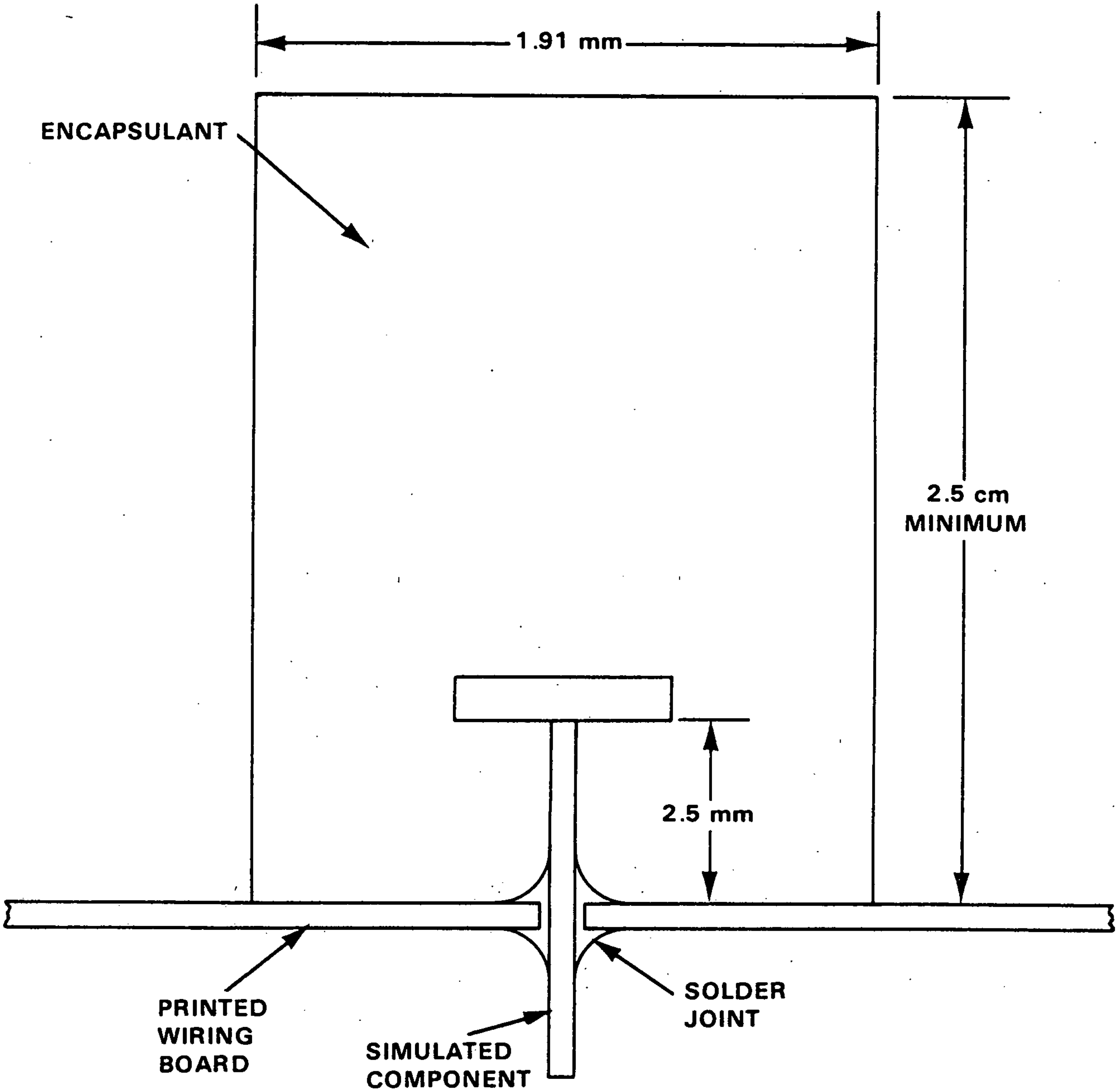


Figure 1. Test Solder Joint Design

was inspected for adequate wetting. The component lead wires were then pretinned again with the correct alloy. A special fixture was used during actual soldering which preset the offset of the component heads 2.5 mm from the surface of the boards. Solder preforms of a known volume were then placed in the joint area. Final soldering was accomplished using an electrically heated soldering iron and type RMA flux. Individually pretinned tips were used on the soldering irons for each alloy in order to avoid cross-contamination.

Encapsulation of the components was accomplished by using specially designed split molds which centered the cylindrical shape over each PTH. These cylinders were 1.91 cm in diameter and 2.5 cm minimum high. These dimensions were selected in order to avoid unusual edge effects and thereby create a semi-infinite distance-to-wall condition. During prove-in of the encapsulation technique, it was noted that space limitations on the PWB would allow only three of the six rows of PTHs per board.

Three groups of test PWAs were assembled with the 29 solder alloys; each having a different encapsulant. The three encapsulants, epoxy, glass microballoon (GMB) filled epoxy, and polyurethane foam, were selected as being the most common in use on Bendix built electronic assemblies. The epoxy encapsulant was prepared by preheating the resin to 77°C and mixing in the catalyst. A resin/catalyst weight ratio of 8:1 was used. The mixture was then evacuated, poured in the split mold, and evacuated a second time. A 24 hour cure at 66°C was used. Figure 2 shows a final test PWA after encapsulation with epoxy.

The same procedure was used for the GMB/epoxy. A resin/GMB/catalyst weight ratio of 8.0:2.6:1.0 was used. This maintained the same resin/catalyst ratio as the straight epoxy.

Encapsulation with rigid polyurethane foam was performed with material formulated to produce a part density of 288kg/m^3. After pouring, the foam was cured for eight hours at 71°C.

Thermal Fatigue Testing

Thermal fatiguing of the solder joints was accomplished by temperature cycling the PWAs between -54 and 75°C. The driving force for fatigue was the difference in coefficient of thermal expansion between the encapsulant and the copper wire. These temperatures were selected based on typical product requirements. Actual cycling was accomplished by transferring the PWAs between two chambers, each operating at a temperature extreme. A soak time of two hours in each chamber was used. This soak time was derived from preliminary experiments with PWAs having thermocouples embedded in the encapsulant. This time allotment allowed the encapsulant surrounding the component to reach the temperature extreme about 10 minutes prior to chamber transfer.

Visual inspection of the joints was performed on the side of the board opposite the encapsulation using a stereo microscope at a magnification of 40X. The solder joints were illuminated by a high intensity fiber optic lamp. In order to obtain the most uniform lighting possible, a small strip of aluminum foil was curled into a short tube placed over the joint under inspection. This served to reflect the light completely around the solder joint, thereby minimizing shadows.

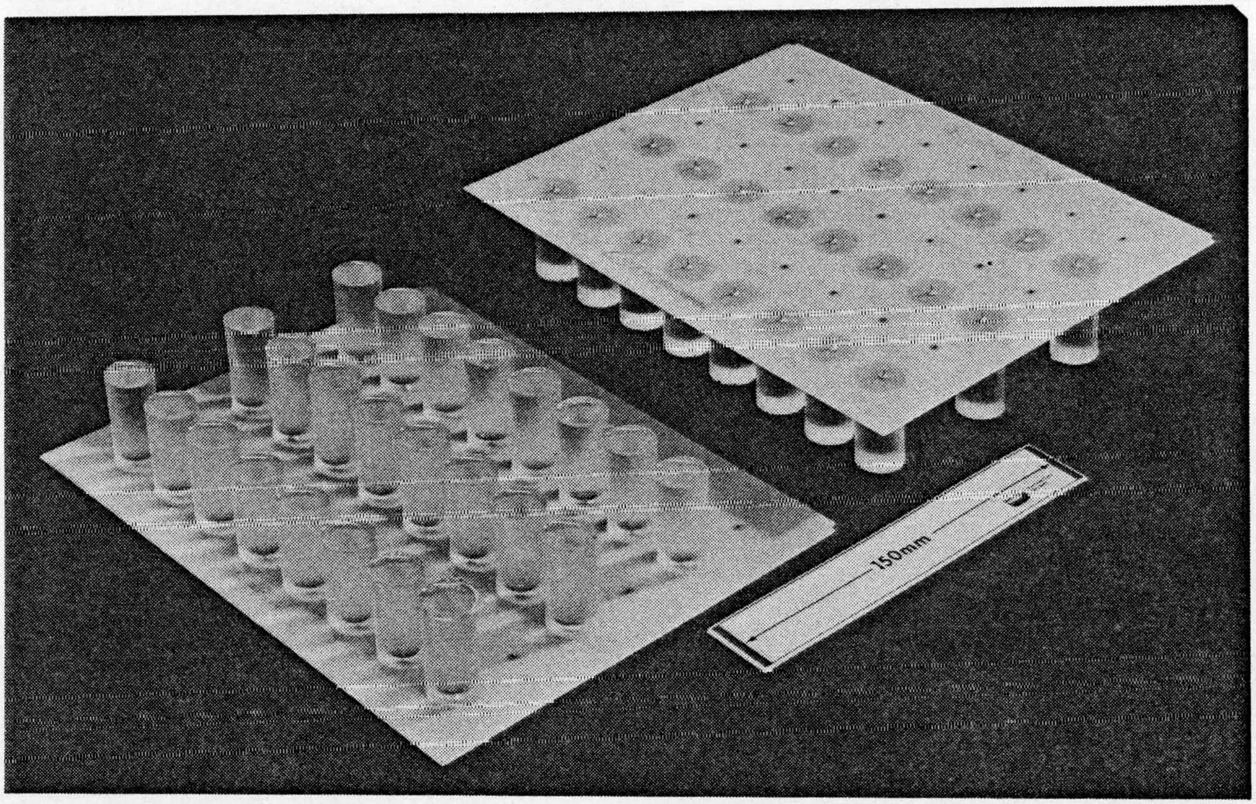


Figure 2. Test Boards After Encapsulaton With Epoxy

Inspection of the solder joints was performed before and after encapsulation, and periodically during thermal cycling. The actual inspection times (in thermal cycles) for each of the three test groups are presented in Table 3.

The criterion used throughout this study to classify a joint as having failed was a 360° crack around the fillet, such as the one shown in Figure 3. This definition was selected for two reasons. First, a crack of that magnitude was much less likely to be dismissed as a surface defect. Secondly, it was felt that this more nearly approached the condition of a joint when electrical resistance shifts would occur.

Visual Inspection Results and Analysis

Tables 4, 5, and 6 contain the percent of solder joints that failed at each inspection interval for the test PWAs encapsulated in epoxy, GMB/epoxy, and polyurethane foam, respectively.

In order to compare the alloys within one encapsulation group, a mathematical model was used to describe solder joint failure as a

Table 3. Visual Inspection Periods (Elapsed Thermal Cycles)

	Encapsulant	
Epoxy	GMB/Epoxy	Urethane Foam
0*	0*	0*
1*	1**	1**
25	25	50
50	50	100
75	75	150
100	100	200
150	150	300
--	200	400

*After soldering
**After post-cure cooling

function of thermal cycles. The model selected, based on minimum standard error, was of the form:

$$y = 100\ 1-e^{-\alpha(x-x_0)},\ x \geq x_0. \qquad (1)$$

where:

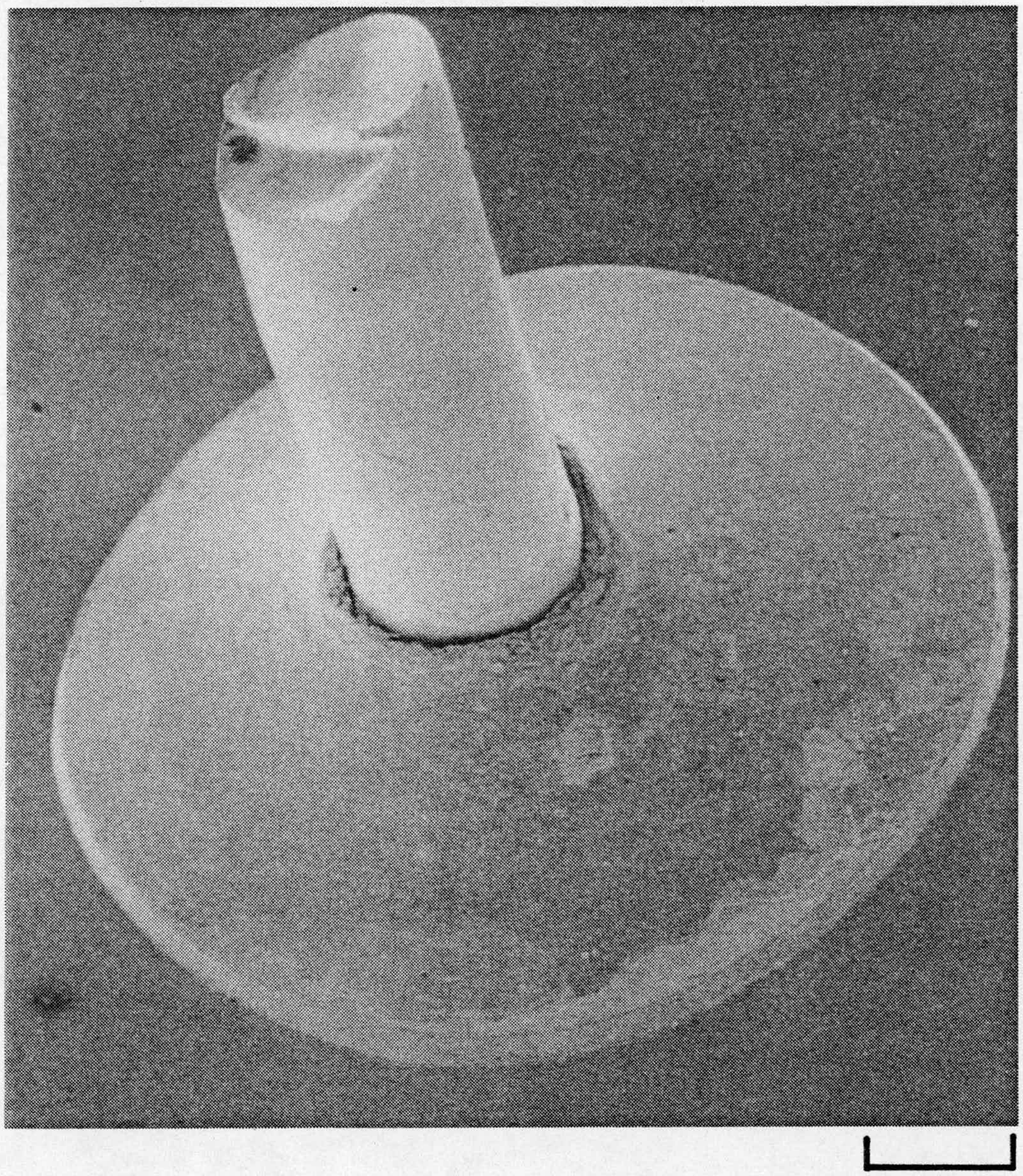
y = percent of solder joints that failed;

x = number of thermal cycles at the time of observation;

x_0 = the last number of thermal cycles at which there were no failures; and

α = a failure rate parameter.

Tables 7, 8, and 9 contain the calculated mathematical model parameters for the alloys in epoxy, GMB/epoxy, and polyurethane foam respectively. The listings in each table are arranged in order of increasing values because a higher value of alpha indicates a higher failure rate. Those alloys having an alpha value of zero exhibited no failures during the course of the experimental thermal cycling. Three of the solder alloys evaluated exhibited



0.5 mm

Figure 3. Scanning Electron Macrograph Showing a Solder Joint With a 360° Crack After Thermal Cycling

a zero alpha in all encapsulants: 95Sn-5Ag, 96.5Sn-3.5Ag, and 95Sn-5Sb. It is apparent that these alloys offer the greatest protection from thermal fatigue cracking.

Since the mathematical relationships derived were based on an idealized model, the results should not be used to predict the

Table 4. Percent Failures Versus Thermal Cycles; Encapsulant: Epoxy

Alloy (Weight Percent)	Thermal Cycles* 1	25	50	75	100	150
63Sn-37Pb	0.00	100.00	100.00	100.00	100.00	100.00
70Sn-30Pb	0.00	62.50	100.00	100.00	100.00	100.00
90Sn-10Pb	0.00	0.00	33.30	33.30	58.30	83.30
60Sn-40Pb	0.00	100.00	100.00	100.00	100.00	100.00
95Sn-5Sb	0.00	0.00	0.00	0.00	0.00	0.00
65Sn-35In	8.30	91.60	100.00	100.00	100.00	100.00
50Sn-50In	0.00	83.30	100.00	100.00	100.00	100.00
48Sn-52In	0.00	0.00	0.00	0.00	0.00	10.00
99Sn-1Sb	0.00	0.00	0.00	0.00	18.20	36.00
50Pb-50In	0.00	0.00	0.00	0.00	16.70	33.30
96.5Sn-3.5Ag	0.00	0.00	0.00	0.00	0.00	0.00
95Sn-5Ag	0.00	0.00	0.00	0.00	0.00	0.00
62.5Sn-36.1Pb-1.4Ag	0.00	100.00	100.00	100.00	100.00	100.00
51.6Sn-55.6Pb-3.9Ag	0.00	16.70	25.00	25.00	25.00	58.00
62Sn-36Pb-2Ag	0.00	100.00	100.00	100.00	100.00	100.00
35Sn-63.2Pb-1.8Sb	0.00	27.30	27.30	64.00	90.90	90.90
40Sn-58Pb-2Sb	0.00	58.30	75.00	92.00	100.00	100.00
70Sn-30Pb+0.1Ce	0.00	100.00	100.00	100.00	100.00	100.00
99.25Sn-0.75Cu	0.00	0.00	27.30	45.00	54.50	64.00
15Sn-80In-5Ag	0.00	58.30	83.30	100.00	100.00	100.00
15Pb-80In-5Ag	0.00	9.10	36.40	45.00	81.80	100.00
30.2Sn-40.3Pb-29.5In	0.00	0.00	27.30	55.00	81.80	100.00
100In	0.00	66.70	83.30	92.00	100.00	100.00
15Sn-9.6Pb-70In-5.4Bi	0.00	100.00	100.00	100.00	100.00	100.00
99In-1Cu	0.00	33.30	58.30	92.00	92.00	92.00

Table 4 Continued. Percent Failures Versus Thermal Cycles; Encapsulant: Epoxy

Alloy (Weight Percent)	Thermal Cycles*					
	1	25	50	75	100	150
59.5Sn-37.4Pb-3.1Sb	0.00	75.00	100.00	100.00	100.00	100.00
50Sn-50Pb	0.00	91.70	100.00	100.00	100.00	100.00
42Sn-58Bi	0.00	100.00	100.00	100.00	100.00	100.00
100Sn	0.00	0.00	18.20	27.30	27.30	27.30

*No failures before thermal cycling

Table 5. Percent Failures Versus Thermal Cycles; Encapsulant: GMB/Epoxy

Alloy (Weight Percent)	Thermal Cycles* 1	25	50	75	100	150	200
63Sn-37Pb	0.00	0.00	0.00	0.00	0.00	33.00	44.00
70Sn-30Pb	0.00	0.00	0.00	11.00	33.00	67.00	89.00
90Sn-10Pb	0.00	0.00	0.00	0.00	0.00	17.00	25.00
60Sn-40Pb	0.00	0.00	0.00	0.00	10.00	60.00	70.00
95Sn-5Sb	0.00	0.00	0.00	0.00	0.00	0.00	0.00
65Sn-35In	0.00	80.00	100.00	100.00	100.00	100.00	100.00
50Sn-50In	0.00	50.00	50.00	50.00	62.50	75.00	75.00
48Sn-52In	0.00	0.00	0.00	0.00	0.00	0.00	0.00
99Sn-1Sb	0.00	0.00	0.00	0.00	0.00	12.50	12.50
50Pb-50In	0.00	0.00	0.00	0.00	45.50	90.90	90.90
96.5Sn-3.5Ag	0.00	0.00	0.00	0.00	0.00	0.00	0.00
95Sn-5ag	0.00	0.00	0.00	0.00	0.00	0.00	0.00
62.5Sn-36.1Pb-1.4Ag	0.00	0.00	0.00	0.00	0.00	40.00	80.00
51.6Sn-55.6Pb-3.9Ag	0.00	0.00	0.00	0.00	0.00	0.00	0.00
62Sn-36Pb-2Ag	0.00	0.00	0.00	0.00	30.00	70.00	100.00
35Sn-63.2Pb-1.8Sb	0.00	0.00	0.00	0.00	22.00	44.00	55.60
40Sn-58Pb-2Sb	0.00	0.00	0.00	0.00	0.00	25.00	33.30
70Sn-30Pb+0.1Ce	0.00	0.00	9.00	18.00	82.00	100.00	100.00
99.25Sn-0.75Cu	0.00	0.00	0.00	0.00	0.00	10.00	10.00
15Sn-80In-5Ag	10.00	10.00	80.00	80.00	100.00	100.00	100.00
15Pb-80In-5Ag	0.00	0.00	80.00	80.00	100.00	100.00	100.00
30.2Sn-40.3Pb-29.5In	0.00	0.00	0.00	0.00	10.00	50.00	60.00
100In	0.00	40.00	80.00	90.00	100.00	100.00	100.00
15Sn-9.6Pb-70In-5.4Bi	0.00	70.00	80.00	100.00	100.00	100.00	100.00
99In-1Cu	0.00	27.00	73.00	73.00	100.00	100.00	100.00

Table 5 Continued. Percent Failures Versus Thermal Cycles; Encapsulant: GMB/Epoxy

Alloy (Weight Percent)	Thermal Cycles*						
	1	25	50	75	100	150	200
59.4Sn-37.4Pb-3.1Sb	0.00	0.00	0.00	0.00	0.00	9.10	9.10
50Sn-50Pb	0.00	0.00	0.00	0.00	18.00	45.50	54.50
42Sn-58Bi	0.00	0.00	0.00	0.00	0.00	9.10	9.10
100Sn	0.00	0.00	0.00	0.00	0.00	0.00	0.00

*No failures before thermal cycling

Table 6. Percent Failures Versus Thermal Cycles; Encapsulant: Urethane Foam

Alloy (Weight Percent)	Thermal Cycles*					
	50	100	150	200	300	400
63Sn-37Pb	0.00	0.00	0.00	0.00	8.30	12.50
70Sn-30Pb	0.00	0.00	0.00	0.00	8.30	8.30
90Sn-10Pb	0.00	0.00	0.00	0.00	8.30	8.30
60Sn-40Pb	0.00	0.00	0.00	0.00	0.00	16.70
95Sn-5Sb	0.00	0.00	0.00	0.00	0.00	0.00
65Sn-35In	16.70	16.70	16.70	25.00	25.00	25.00
50Sn-50In	0.00	0.00	0.00	0.00	18.20	25.00
48Sn-52In	0.00	0.00	0.00	0.00	0.00	0.00
99Sn-1Sb	0.00	0.00	0.00	0.00	0.00	0.00
50Pb-50In	0.00	0.00	0.00	0.00	0.00	0.00
96.5Sn-3.5Ag	0.00	0.00	0.00	0.00	0.00	0.00
95Sn-5Ag	0.00	0.00	0.00	0.00	0.00	0.00
62.5Sn-36.1Pb-1.4Ag	0.00	0.00	0.00	0.00	0.00	0.00
51.6Sn-55.6Pb-3.9Ag	0.00	0.00	0.00	0.00	0.00	0.00
62Sn-36Pb-2Ag	0.00	0.00	0.00	0.00	0.00	0.00
35Sn-63.2Pb-1.8Sb	0.00	0.00	0.00	0.00	0.00	0.00
40Sn-58Pb-2Sb	0.00	0.00	0.00	0.00	0.00	0.00
70Sn-30Pb+0.1Ce	0.00	0.00	0.00	0.00	0.00	0.00
99.25Sn-0.75Cu	0.00	0.00	0.00	0.00	8.30	16.70
15Sn-80In-5Ag	0.00	0.00	8.30	8.30	66.70	83.30
15Pb-80In-5Ag	0.00	0.00	0.00	0.00	0.00	0.00
30.2Sn-40.3Pb-29.5In	0.00	0.00	0.00	0.00	0.00	0.00
100In	0.00	0.00	8.30	16.70	25.00	33.30
15Sn-9.6Pb-70In-5.4Bi	0.00	16.70	25.00	25.00	58.30	83.30
99In-1Cu	0.00	0.00	0.00	8.30	16.70	50.00

Table 6 Continued. Percent Failures Versus Thermal Cycles; Encapsulant: Urethane Foam

Alloy (Weight Percent)	Thermal Cycles* 50	100	150	200	300	400
59.4Sn-37.4Pb-3.1Sb	0.00	0.00	0.00	0.00	0.00	0.00
50Sn-50Pb	0.00	0.00	0.00	0.00	0.00	0.00
42Sn-58Bi	0.00	0.00	0.00	0.00	0.00	0.00
100Sn	0.00	0.00	0.00	0.00	0.00	0.00

*No failures before thermal cycling

behavior of solder joints in an actual electronic assembly. They do provide a valid ranking of alloys by thermal fatigue resistance. This ranking can be used as a guide to alloy selection for electronic assemblies. The final selection will depend on additional design and manufacturing factors as well. It is apparent that 96.5Sn-3.5Ag is consistently superior to 63Sn-37Pb with these encapsulants from a thermal fatigue viewpoint. The higher melting temperature of this alloy may in some cases result in assembly problems or PWB damage. The alloy selected should therefore be fully evaluated for a particular product application prior to final commitment.

In addition to a ranking of the alloys, the data in Tables 7 through 9 provide further insight into thermal fatigue of solder alloys. The general trend in encapsulant development and selection has been to minimize the thermal expansion coefficient and bulk modulus. Past studies have resulted in the change from epoxy to GMB/epoxy, and finally to foam systems. The benefits of this trend are quite pronounced in the data. The epoxy encapsulated test group had only four alloys with an alpha of zero. Seven alloys had an alpha of zero in the GMB/epoxy group, and 19 alloys had an alpha of zero in the foam group.

In addition, the non-zero alpha values decrease with the change from epoxy to GMB/epoxy to foam. It would appear that alloy selection carries less significance if the encapsulant is selected on the basis of thermal fatigue compatability.

The involvement of stress relaxation in solder alloy thermal fatigue can also be obtained from the data. In general, alloys with a low melting temperature are more prone to creep, and stress relaxation at a given elevated temperature. Plots were made of the failure rate parameters (alpha) versus the alloys' liquidus temperatures (excluding those having a zero alpha). When plotted with a logrithmic y-axis, the trend is visually discernable. These plots, shown in Figures 4, 5, and 6 for the three encapsulants, indicate that a relationship between alpha and liquidus temperature may exist in which alpha decreases with increasing melting temperature. This in turn indicates that the thermal fatigue of solder alloys may involve a creep mechanism.

The relationship between creep and thermal fatigue is not proven by the data in this study. Only the trend is shown. The metallurgical effects of the various alloying constituents is also a factor in the results, and have a pronounced effect on creep and fatigue behavior of any given alloy.

Table 7. Calculated Mathematical Model Parameters for Epoxy Encapsulant

Alloy (Weight Percent)	Failure Rate Parameter, Alpha (Thermal Cycles^{-1})	X_0 (Thermal Cycles)	Standard Estimated Error
95Sn-5Ag	0.000	150	0.000
96.5Sn-3.5Ag	0.000	150	0.000
95Sn-5Sb	0.000	150	0.000
48Sn-52In	0.0025	100	1.429
100Sn	0.0036	25	7.982
51.6Sn-55.6Pb-3.9Ag	0.0049	1	6.878
50Pb-50In	0.0056	75	1.945
99Sn-1Sb	0.0061	75	2.085
99.25Sn-0.75Cu	0.0100	25	5.320
90Sn-10Pb	0.0121	25	6.542
15Pb-80In-5Ag	0.0121	1	13.180
35Sn-63.2Pb-1.8Sb	0.0144	1	10.600
30.2Sn-40.3Pb-29.5In	0.0193	25	7.712
99In-1Cu	0.0225	1	6.661
40Sn-58Pb-2Sb	0.0335	1	2.808
15Sn-80In-5Ag	0.0384	1	2.536
100In	0.0416	1	2.401
70Sn-30Pb	0.0484	1	4.375
59.5Sn-37.4Pb-3.1Sb	0.0615	1	2.066
50Sn-50In	0.0762	1	0.944
65Sn-35In	0.0961	0	0.480
50Sn-50Pb	0.1024	1	0.270
42Sn-58Bi	2.7556	1	0.000
15Sn-9.6Pb-70In-5.4Bi	2.7556	1	0.000
70Sn-30Pb+0.1Ce	2.7556	1	0.000
62Sn-36Pb-2Ag	2.7556	1	0.000
62.5Sn-36.1Pb-1.4Ag	2.7556	1	0.000
60Sn-40Pb	2.7556	1	0.000
63Sn-37Pb	2.7556	1	0.000

Table 8. Calculated Mathematical Model Parameters for GMB/Epoxy Encapsulant

Alloy (Weight Percent)	Failure Rate Parameter, Alpha (Thermal Cycles^{-1})	X_0 (Thermal Cycles)	Standard Estimated Error
100Sn	0.000	200	0.000
95Sn-5Sb	0.000	200	0.000
51.6Sn-55.6Pb-3.9Ag	0.000	200	0.000
48Sn-52In	0.000	200	0.000
95Sn-5Ag	0.000	200	0.000
96.5Sn-3.5Ag	0.000	200	0.000
42Sn-58Bi	0.0012	100	2.268
59.5Sn-37.4Pb-3.1Sb	0.0012	100	2.268
99.25Sn-0.75Cu	0.0013	100	2.483
99Sn-1Sb	0.0016	100	3.075
90Sn-10Pb	0.0031	100	1.799
40Sn-58Pb-2Sb	0.0045	100	3.274
63Sn-37Pb	0.0064	100	3.741
50Sn-50Pb	0.0070	75	3.144
35Sn-63.2Pb-1.8Sb	0.0072	75	3.522
30.2Sn-40.3Pb-29.5In	0.0081	75	5.071
60Sn-40Pb	0.0100	75	7.086
50Sn-50In	0.0100	1	12.468
70Sn-30Pb	0.0102	50	7.791
62.5Sn-36.1Pb-1.4Ag	0.0121	100	6.468
70Sn-30Pb+0.1Ce	0.0132	25	18.788
62Sn-36Pb-2Ag	0.0150	75	6.511
15Sn-80In-5Ag	0.0210	0	13.276
99In-1Cu	0.0225	1	8.021
50Pb-50In	0.0259	75	3.835
100In	0.0286	1	4.716
15Sn-9.6Pb-70In-5.4Bi	0.0445	1	3.966
15Pb-80In-5Ag	0.0534	25	5.974
65Sn-35In	0.0676	1	1.404

Table 9. Calculated Mathematical Model Parameters for Urethane Foam Encapsulant

Alloy (Weight Percent)	Failure Rate Parameter, Alpha (Thermal Cycles^{-1})	X_0 (Thermal Cycles)	Standard Estimated Error
96.5Sn-3.5Ag	0.000	400	0.000
100Sn	0.000	400	0.000
42Sn-58Bi	0.000	400	0.000
50Sn-50Pb	0.000	400	0.000
59.5Sn-37.4Pb-3.1Sb	0.000	400	0.000
50Pb-50In	0.000	400	0.000
99Sn-1Sb	0.000	400	0.000
48Sn-52In	0.000	400	0.000
30.2Sn-40.3Pb-29.5In	0.000	400	0.000
15Pb-80In-5Ag	0.000	400	0.000
95Sn-5Sb	0.000	400	0.000
70Sn-30Pb+0.1Ce	0.000	400	0.000
40Sn-58Pb-2Sb	0.000	400	0.000
35Sn-63.2Pb-1.8Sb	0.000	400	0.000
62Sn-36Pb-2Ag	0.000	400	0.000
51.6Sn-55.6Pb-3.9Ag	0.000	400	0.000
62.5Sn-36.1Pb-1.4Ag	0.000	400	0.000
95Sn-5Ag	0.000	400	0.000
70Sn-30Pb	0.0005	200	2.076
90Sn-10Pb	0.0005	200	2.076
63Sn-37Pb	0.0007	200	0.937
99.25Sn-0.75Cu	0.0009	200	0.220
65Sn-35In	0.0009	0	6.920
50Sn-50In	0.0016	200	2.397
100In	0.0016	100	2.568
60Sn-40Pb	0.0018	300	0.000
99In-1Cu	0.0021	150	6.938
15Sn-9.6Pb-70In-5.4Bi	0.0034	50	8.452
15Sn-80In-5Ag	0.0041	100	14.275

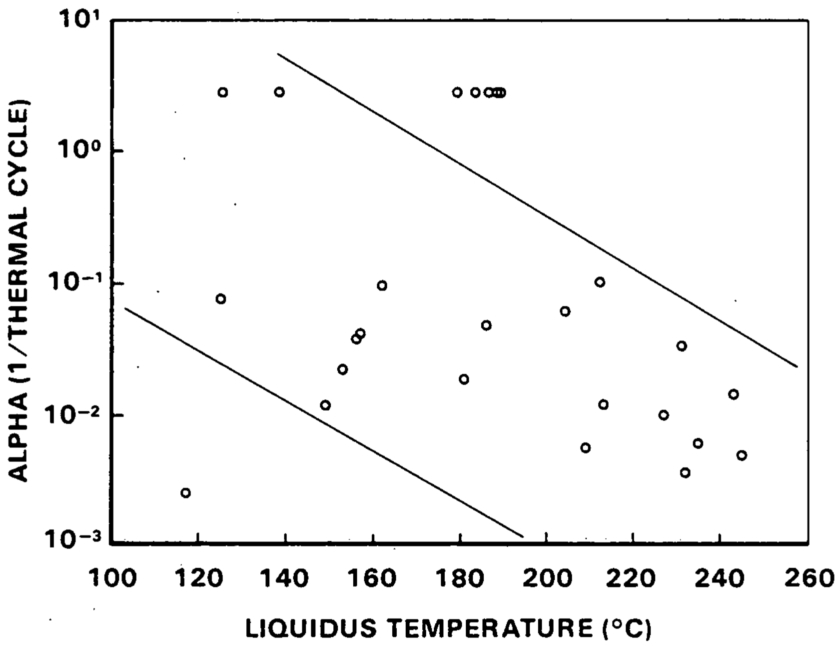


Figure 4. Failure Rate Parameters Versus Liquidus Temperature for Epoxy

ACCOMPLISHMENTS

An empirical study was conducted in which 29 alloys were ranked according to thermal fatigue resistance. This ranking provides a means for selecting solder alloys that will have to withstand long term thermal cycling within a high reliability electronic assembly. Three alloys, 95Sn-5Ag, 96.5Sn-3.5Ag, and 95Sn-5Sb, offered the greatest resistance to thermal fatigue.

The benefits derived from using encapsulants having reduced coefficients of thermal expansion and bulk moduli were reconfirmed. The calculated failure rate parameters for each alloy were reduced as the encapsulant was changed from epoxy to GMB/epoxy to polyurethane foam.

A possible qualitative relationship between the melting temperature and thermal fatigue resistance was observed, indicating that solder alloy thermal fatigue may involve some types of creep mechanism. This possibility was not within the scope of this project and was not pursued.

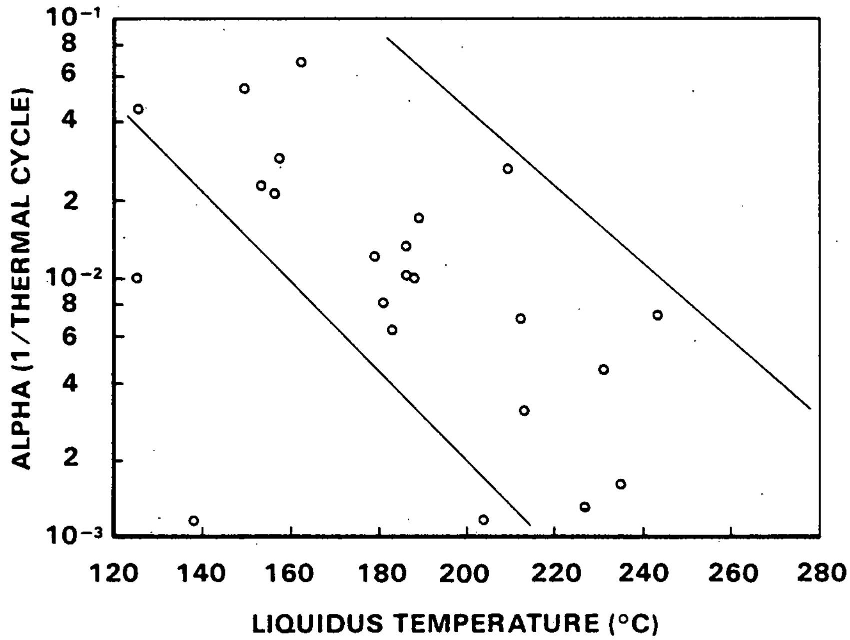


Figure 5. Failure Rate Parameters Versus Liquidus Temperature for GMB/Epoxy

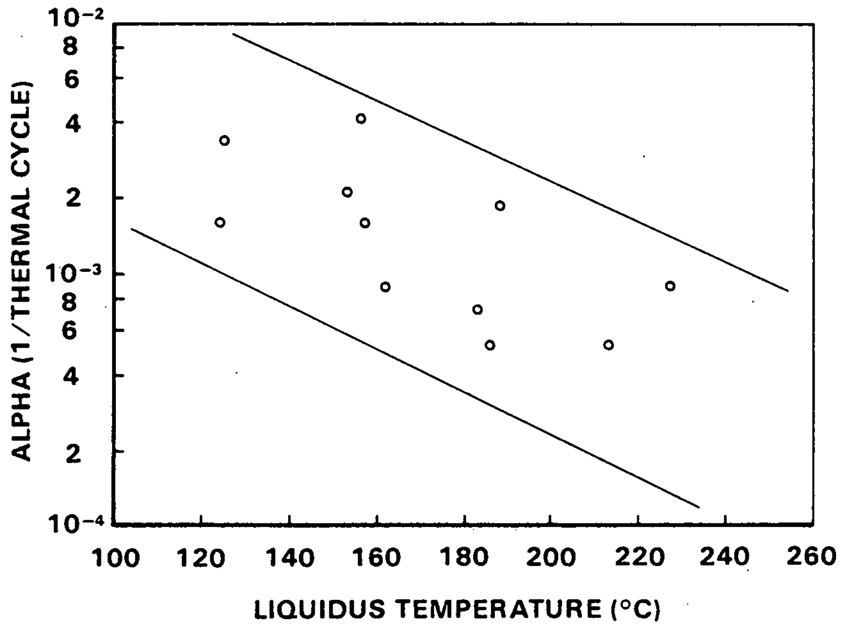


Figure 6. Failure Rate Parameters Versus Liquidus Temperature for Urethane Foam

FUTURE WORK

Two areas of future work are specifially recommended. First, manufacturing processes, materials, and components should be evaluated to determine what problems arise from the use of the thermal fatigue resistance alloys 95Sn-5Ag, 96.5Sn-3.5Ag, and 95Sn-5Sb. It is anticipated that some difficulties will be encountered since almost all assemblies are designed around soldering with 63Sn-37Pb. The second area of future work is a metallurgical evaluation of selected solder alloys to determine the factors which determine thermal fatigue resistance. A basic understanding would assist in the solution of current fatigue problems and could provide a foundation for alloy development.

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THERMAL FATIGUE EVALUATION OF SOLDER ALLOYS, D. M. Jarboe, Final, February 1980.

An evaluation was made of the relative thermal fatigue resistance of 29 commercially available solder alloys. A number of these alloys were found to be less susceptible to thermal fatigue cracking in encapsulated printed wiring board applications than the commonly used tin-lead eutectic (63Sn-37Pb). Three alloys, 95Sn-5Ag, 96.5Sn-3.5Ag, and 95Sn-5Sb offered the greatest resistance to thermal fatigue. The selection of the encapsulation material was confirmed to

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SPECIAL PROJECTS: Solder Fatigue

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THERMAL FATIGUE EVALUATION OF SOLDER ALLOYS, D. M. Jarboe, Final, BDX-613-2341 February 1980.

An evaluation was made of the relative thermal fatigue resistance of twenty-nine commercially available solder alloys. A number of these alloys were found to be less susceptible to thermal fatigue cracking in encapsulated printed wiring board applications than the commonly used tin-lead eutectic (63Sn-37Pb). Three alloys, 95Sn-5Ag, 96.5Sn-3.5Ag, and 95Sn-5Sb offered the greatest resistance to thermal fatigue. The selection of the encapsulation material was confirmed to be a significant factor in thermal fatigue of solder joints, regardless of the solder alloy used.

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