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Space Flight Printed Wiring Board Measling Investigation

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ABSTRACT

A flight printed wiring board (PWB) for a satellite project was observed to have a high incidence of measling. Other PWB's produced for the program by the same manufacturer did not exhibit the degree of measling as did the "measle-prone" board. Measling susceptibility during hand soldering and measling effects on PWB insulation resistance were investigated for three production PWB's.

Measling resistance was significantly different between the three boards: the "worst" exhibited five times the number of measles as the "best" board. "Severe" measling (that which is likely to affect board reliability) did not exist on the "best" board, even under extreme soldering conditions (399 °C for 12-15 sec.), whereas the "worst" board showed an average of one "severe" measle for every two pads under more normal soldering conditions (288 - 343 °C for 2-5 sec.). Soldering time and temperature both affected measling, with time having a slightly greater influence (21% versus 12%).

Measling effects on PWB insulation resistance were inconclusive. These were evaluated by *in situ* resistance measurements on the same three boards at elevated temperature and humidity. The measured resistance for all three boards decreased for exposures greater than 50 °C and 50 % relative humidity. The "measle-prone" board showed a resistance decrease at only 25 °C and 50% relative humidity. However, no definitive difference was detected between measled and not-measled (control) samples. The boards evaluated were production boards, so the effect of interlayer traces connecting the plated-through holes was not controlled. It is likely the resistance measurements were over different volumes of PWB laminate which would account for the widely varying resistances measured.

Thermomechanical measurements on board laminate materials did not reveal any differences attributed to measling. Differences in glass transition temperature were significantly different when measured by DTA, but not by SDT. Laminate thermal expansion differences were significant for the 35 °C evaluations, but not for any higher temperatures.

Acknowledgments

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INTRODUCTION

Measling is a defect in the printed wiring board (PWB) resin-glass base material resulting from glass fibers separating from the resin at the weave intersections. Measles appear as white spots or crosses below the PWB surface. They are thought to be caused by thermally induced stresses, such as during hand soldering [1]. Lund [2] considers measle spots to be cosmetic defects as long as (a) they are widely scattered (that is, they have a density less than about 50 spots per 100 cm^2), (b) no glass fibers are exposed on the glass surface, (c) no measle spots touch each other or are connected and (d) solder pads or conductors are not connected by one or more measle spots. If these four requirements are *not* met, he considers measle spots to be functional ("A") defects. Crazing is another, related defect. It is a merging of measle spots. Crazing is regarded a rejectable board defect because it is a porous area which can absorb electrolytes and reduce the insulation resistance of the PWB [2].

Gandhi et al. [1] subjected both epoxy-fiberglass and polyimide-fiberglass PWB's to various thermal cycle, humidity and direct current voltage bias conditions to attempt to accelerate failure processes, such as conductive anodic filament growth, between board conductors. Though they observed decreases in board insulation resistance, they did not induce any electrical short circuits which could be attributed to measling. They did note that measured decreases in insulation resistance were reversible and tracked with the moisture changes to which the boards were subjected. They concluded that measling did not jeopardize the electrical reliability of PWB's. Their conclusion concurred with Institute for Interconnecting and Packaging Electronic Circuits (IPC) findings that measles do not represent a PWB reliability risk [3].

A Goddard Space Flight Center satellite project noted that two space flight PWB's exhibited a significant amount of measling when components were soldered onto them; other boards assembled at the same time showed no measling. These "measle-prone" flight boards and a similar measle-free board were investigated to determine their susceptibility to measling under hand soldering conditions and if measling caused significant decreases in PWB insulation resistance. Other laboratory tests were performed to determine if the board laminate resins differed between measled and unmeasled samples. These investigations and results are described below.

MEASLING SUSCEPTIBILITY EXPERIMENT

Experimental Procedures

Three multilayer, plated-through-hole PWB's were made available for this experiment by the project. These were the actual production (flight) boards originally intended to be used in the spacecraft instrument system. They were 2.4 mm (0.093 inch) thick, eight layer boards made of epoxy and fiberglass (GBN). The boards first were cut in half; the second halves were used for insulation resistance measurements under various temperature and humidity conditions. The boards for the measling susceptibility tests were identified by their serial numbers: 1532821, 1534031, and 1534056. The conductor trace patterns on boards 1532821 and 1534056 were identical; the pattern on 1534031 was very different. Boards 1532821 and 1534056 were procured from one manufacturer and 1534031 from a different manufacturer.

A designed experiment was developed to investigate board, soldering temperature and soldering time effects on measling. Soldering temperatures of 288, 343 and 399 °C (550, 650, and 750 °F) and times of either 2 to 5 seconds or 12 to 15 seconds were chosen. Dual inline package (DIP) integrated circuit locations on the three boards were selected and pad pairs (the corresponding pin holes on opposite sides of each DIP row) were numbered from the top of each board. The temperature-time treatment combinations were assigned randomly to each pad pair (a randomized treatment matrix). Twenty four replications (twelve pairs) were made for each combination. Only every other pin in each integrated circuit row (that is, eight pins per DIP) was soldered, so that measles associated with each soldered pad could be discerned. Boards 1532821 and 1534056 had the same temperature-time treatments assigned to each corresponding integrated circuit location and pad pair, since their trace patterns were identical. (The reason for this restriction on randomization is discussed in the results, below.) These boards were not baked before being soldered; this was done to simulate a "worst case" board assembly process. All three boards had been stored together in an ambient office environment before they were soldered.

The selected integrated circuit locations on each board were populated with excess stock 16- and 18-pin integrated circuits. These devices were cleaned, fluxed, solder-dipped, cleaned in methanol and in hot water and dried before being inserted onto the three boards by hand. They then were soldered according to the randomized treatment matrix. Each pad was soldered using a calibrated soldering iron [Weller Model EC2001, NASA ID #M16600] and 63/37 Sn/Pb rosin-cored solder [Ersin Multicore, Lot #D918/553]. The same soldering iron tip and solder roll were used for all soldering. As each pad was soldered, the iron tip was left on the pad-lead junction for the specified time (either 2-5 or 12-15 sec.), even though the joint may have soldered satisfactorily before the time was up. Soldering iron temperatures were observed to be within +2 and -6 °C. of the set point temperature. After each board had been soldered for all its treatment combinations, it was cleaned using methyl alcohol and a bristle brush and rinsed in hot tap water.

Boards were examined under a stereo microscope at 7 to 20X using a ring illuminator. Because all the rosin residue was not successfully removed from the boards, tap water was brushed onto the board surface while looking through the microscope to facilitate distinguishing the measles below the surface from the residues left on the surface. Numbers of measles at each pad location were counted and recorded. Occurrences of severe measling (measles either connected together or appearing like a "fish scale") were noted by annotating the recorded number with a "*".

Results and Analysis

Field observations (before running this experiment) were that the 1532821 and 1534031 boards were "measle-prone" and 1534056 was less susceptible to measling. Table I summarizes the numbers of measles counted for each treatment condition on each board. The numbers in the table represent the sums of measles for each treatment condition (that is, sums over the 24 replications for each condition) and the totals for each factor (or variable). "Avg #/Pad" represents the computed mean number of measles around all the soldered integrated circuit pads for each board. The Table I data confirms the field observations and also indicates a difference in measling susceptibility between the two "measle-prone" boards.

Figure 1 illustrates the measling on a pad subjected to the most severe soldering conditions. Figure 2 graphically depicts the total number of measles for all soldering treatments on the three boards. Board 1532821 showed a definite susceptibility to measling; board 1534056 was the least susceptible and board 1534031 was in between the two. Figure 3 shows the experimental results in more detail, plotting the number of measles by board number and soldering temperature and time. The general trend is that higher soldering temperatures and longer times increased measling susceptibility. The board effect also is evident, as the "2821" board shows the greatest number of measles at each treatment.

Table I
PWB Measling Resistance - Summary

Numbers of Measles Counted

Board	4056				4031				2821			
Temp =	288	343	399	Total	288	343	399	Total	288	343	399	Total
Time: 2-5 s 10-15 s	 0 19	 6 58	 7 59	 13 136	 0 7	 16 87	 85 182	 101 276	 19 135	 72 180	 113 216	 204 531
Total Total #/Bd.	19	64	66	 149	7	103	267	 377	154	252	329	 735
Avg #/Pad				6.2				15.7				30.6

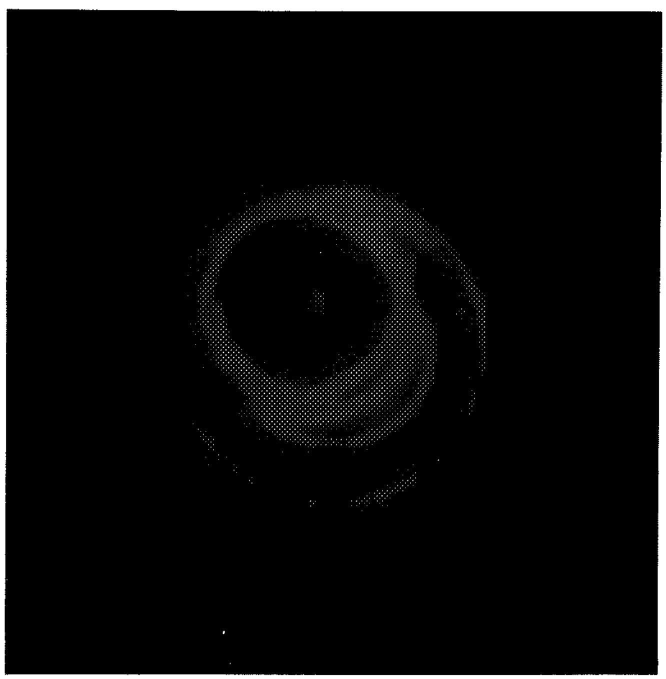

Figure 1. Measling on a pad of board 1532821. (10X magnification, incident light.)

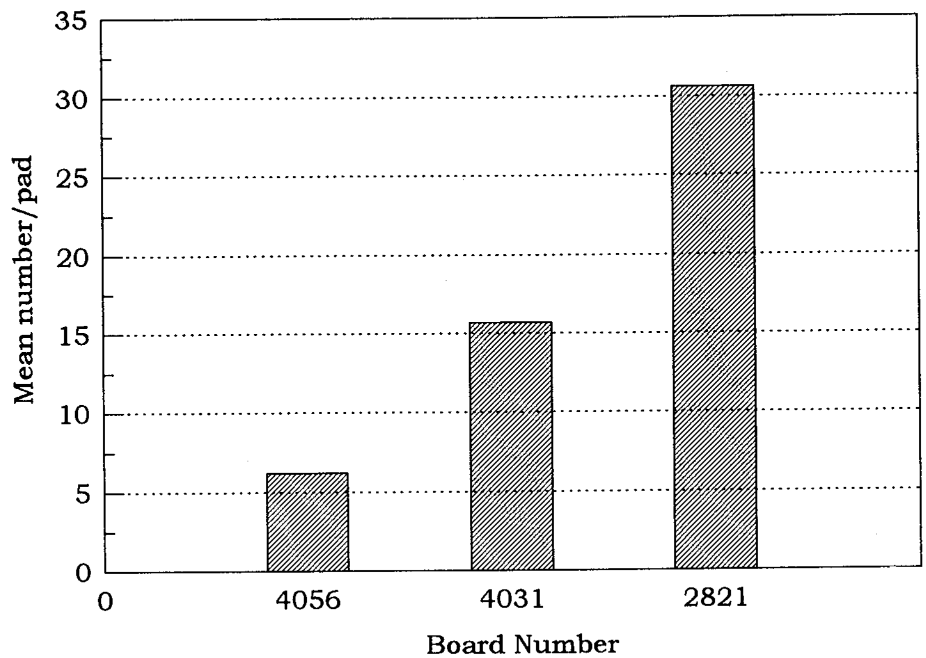

Figure 2. Total numbers of measles counted by board, over all treatments.

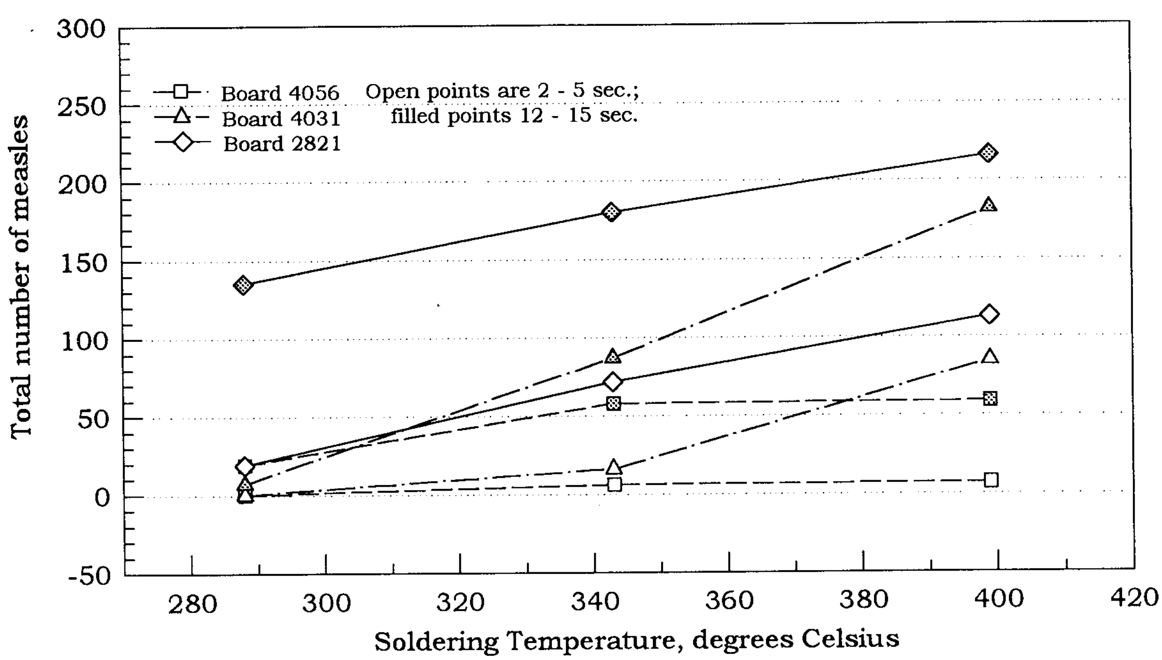

Figure 3. Detailed plot for total numbers of measles on each board for different soldering temperatures and times.

The numbers of measles for all three boards were analyzed using a 3 x 3 x 2 factorial design [4]. Table II shows analysis of variance (ANOVA) results for this case and for another case using only the two boards having identical trace patterns. (Table A-II in the appendix summarizes the analysis of variance and components of variance computations.) For the three-board case, "board," "soldering temperature" and "soldering time" were all significant at greater than 99% confidence in affecting measling. "Board number" influenced measling the most (26% of the experimental variance). Soldering time and temperature also influenced measling, contributing 19 and 17% of the variance, respectively. There also were significant interaction effects, as seen by several of the lines connecting corresponding data points in Figure 3 crossing over one another. This means that the three main experimental factors (board, soldering temperature and time) did not exhibit "clean" effects in how they influenced measling. It is suspected the interlayer conductor trace patterns also affected measling.

The second analysis of variance calculated using the two-identical-trace-pattern-board data also showed all three main factors to be significant at greater than 99%. The sum of the main factors and error variance contributions was 83%, compared to 72% for the three-board case. For this second case, main factor contributions to the total variance were 36, 21, and 12%, respectively, for "board," "soldering time" and "soldering temperature." By replicating the treatment matrix on the two boards having identical trace patterns, the interaction effects decreased by 11%. The error contribution increased slightly from 11 to 14% when the different board trace pattern was eliminated from the analysis.

This second analysis of variance reinforces the hypothesis that board conductor trace patterns affect measling. They most likely affect heat conduction and distribution during soldering, so differing interlayer trace patterns would change the heat flux within the boards and hence affect measling susceptibility. Randomizing the treatments among the different integrated circuit locations (U##'s) on the boards decreased the random (uncontrolled) effects of the experiment but did not eliminate the trace pattern effect. This factor was one that could not be controlled; the boards supplied for the investigation were production boards and the details of the interlayer traces were unknown to the experimenter.

Table III shows the occurrences of "severe measling," i.e., the *number of pads* at which severe measling was observed. (There may have been one or more occurrences of severe measling at a given pad, but only a "1" was recorded for each pad.) "Severe" measling was defined as either several measles connected together or an appearance of one or more measles like a "fish scale." These occurrences are considered rejectable by Lund [2]. The degree of severe measling seen in the two "measle-prone" boards was severe enough to likely cause reliability problems, especially in a humid environment. Some few measles even were open to the surface. The worst board (1532821) had fifty measles for all treatment combinations and the other "measle-prone" board (1534031) had half that number. The measle-resistant board (1534056) had no severe measles.

Measling Susceptibility Experiment Conclusions

Field observations that boards 1532821 and 1534031 were "measle-prone" and 1534056 was measle-resistant were confirmed in the hand soldering experiment. The "worst" board exhibited five times the number of measles as the "best" board. "Severe" measling, that which is likely to affect board reliability, was non-existent on the "best" board, even under extreme soldering conditions (399 °C for 12-15 sec.). The "worst" board, however, showed an average of one "severe" measle for every two pads under more normal soldering conditions (288 - 343 °C for 2-5 sec.). Statistical analyses showed that board number did influence

Table II
ANOVA Summary

	Three Boards		Two Boards	
Source	F	Variance Contrib.(%)	F	Variance Contrib. (%)
Board (A)	175.20 ****	25.6	374.95 ****	36.1
Solder Temp. (B)	116.82 ****	17.0	41.48 ****	11.7
Solder Time (C)	261.88 ****	19.2	221.11 ****	21.2
A x B	19.08 ****	15.9	13.55 ****	7.3
A x C	22.60 ****	4.8	45.44 ****	8.6
B x C	6.43 ****	1.2	0.573	0
A x B x C	4.27 ****	5.8	2.087	1.3
Error	--	10.6		13.9

**** - Denotes significance at >99%.

Table III
"Severe" Measling

Frequency of "Severe" Measling

Board	4056			4031			2821		
Temp =	288	343	399	288	343	399	288	343	399
Time:									
2-5 s	0	0	0	0	0	1	1	0	8
10-15 s	0	0	0	0	6	18	7	18	18
Total	0	0	0	0	6	19	8	18	24
Total #/Bd.			0			25			50

measling susceptibility and was the most significant factor. Soldering time (2-5 versus 12-15 sec.) and temperature (288, 343 and 399 °C) both affected measling, with time having a slightly greater influence (21% versus 12%) for the three boards studied. Interlayer metal trace density variations affected soldering heat distribution which confounded the experimental results and lead to significant interaction effects. Any future work investigating PWB measling should consider and account for interlayer trace metal density in the experimental design.

INSULATION RESISTANCE MEASUREMENTS

Temperature and humidity effects on board insulation resistance were measured on the other halves of the three boards used for the above measling susceptibility experiment. For this part of the investigation, the boards initially were vacuum baked for four hours at 95 °C before being "soldered" to induce measling. A clean soldering iron at 399 to 454 °C (750-850 °F) was applied directly to the plated-through-holes for 15 to 45 seconds. No solder was applied to the holes. Measling could not be induced in this initial trial, after the boards had been vacuum-baked. The boards then were placed in the temperature-humidity test chamber (Standard Environmental Systems, Incorporated, Model HB/4, Totowa, New Jersey) and conditioned overnight at 25 °C and 95% relative humidity. Attempts were made to induce measling. When this was unsuccessful, the boards were conditioned overnight at 50 °C and 95% relative humidity. This last treatment induced measling in two boards. No measles could be induced on board 1534056, even under this last conditioning.

To measure board insulation resistance, wires were soldered to the electrically isolated plated-through-hole pairs. They also were soldered to control (non-measled) pairs. All wires were soldered using preferred soldering techniques [5] known to minimize measling. There were four control (non-measled) pairs for board 1534056, one control and six measled pairs for 1532821 and three control and eight measled pairs for 1534031. Board 1534056 was the one noted previously to be "measle resistant." Before chamber conditioning, the test boards were cleaned using alcohol and an acid brush and subsequently baked in vacuum at 95 °C for four hours to remove any "ambient" moisture from the boards. For each plated-through-hole pair the insulation resistance was measured at 500 Vdc using a resistance bridge (General Radio Model 1644-A Megohm Bridge) while the boards were inside the temperature-humidity chamber. The maximum resistance which could be read accurately with this bridge was $5 \times 10^{13}\ \Omega$. The conditioning treatments were: (1) after vacuum baking four hours at 95 °C, (2) 25 °C and 50% relative humidity, (3) 50 °C and 60% relative humidity, (4) 50 °C and 70% relative humidity, (5) 50 °C and 80% relative humidity, and (6) 85 °C and 85% relative humidity. With the exception of the first conditioning (1), the boards were "soaked" at the stated conditions for 24 hours before any insulation resistance measurements were taken. Some difficulties were experienced in obtaining stable resistance measurements, particularly for the higher GΩ and TΩ resistances.

Table IV summarizes the measured insulation resistance under the various treatments. The readings in Table IV with a ">" before the recorded numbers denote a reading greater than 50 TΩ. The mean and range data were calculated by summing or subtracting the *logarithms* of measured resistances for each board-treatment combination. Measling effects on insulation resistance of the three boards were inconclusive; no significant difference in resistance between measled and non-measled samples were detected in this study. The boards did exhibit resistance differences at higher temperatures and humidities: the resistance measured on boards 1534056 and 1534031 decreased continually at greater than 50 °C and 50% relative humidity; board 1532821 (the "measle-prone" one) showed an initial resistance decrease at only 25 °C and 50% relative humidity. Board 1532821 exhibited the greatest within-treatment variances, as shown by its greater ranges in Table IV.

Table IV
Insulation Resistance Measurements Summary

Treatment* =	1	2	3	4	5	6
Mean [10 $^{\Sigma(\log r_i)/n}$]:	G Ohms (10$^9\Omega$)					
Board #1534056	>50,000	>50,000	640	160	43	3.5
#1534031	>50,000	>46,000	>11,000	>3500	790	80
#1532821	>50,000	>19,000	630	190	91	9.7
Range:	Log (Max - Min)					
Board #1534056	0	0	0.5	0.7	1.1	0.64
#1534031	0	0.4	2.3	2.9	2.7	1.7
#1532821	0	1.7	4.2	5.4	4.7	2.9

* Treatments:
1 - after vacuum baking four hours at 95 °C.
2 - 25 °C. and 50% relative humidity.
3 - 50 °C. and 60% relative humidity.
4 - 50 °C. and 70% relative humidity.
5 - 50 °C. and 80% relative humidity.
6 - 85 °C. and 85% relative humidity.

Since these were production boards, the interlayer trace patterns connecting the plated through holes were not "controlled" (as an experimental factor) and it is likely that insulation resistance measurements were made over different volumes of PWB laminate. This would account for the wide dispersions of measured resistances. Also, surface moisture may have influenced the measurements.

LAMINATE MATERIAL THERMOMECHANICAL EVALUATIONS

Samples of three measled and three unmeasled boards were evaluated by thermomechanical (TMA), differential thermal (DTA) and simultaneous differential thermal - thermogravimetric (SDT) analyses to determine any influence of the epoxy resin laminate. Duplicate samples from each board were measured by each of the three analytical techniques. Two laminate samples were from the same boards evaluated in the measling susceptibility and insulation resistance tests (1534031 and 1532821). The other boards were supplied by a board manufacturer for comparison.

The measured glass transition temperatures (T_g's) and thermal expansion coefficients (CTE's) are shown in Table V. The T_g measured by differential thermal analysis showed a significant difference between the six samples: 99.3% of the experimental variance was caused by differences in T_g and 0.7% by the experimental error. (See Table A-III). The measured glass transition temperatures were not different between the "measled" and "unmeasled" samples. However, board 1534031 was identified initially as "unmeasled" in the field evaluation, and it later was found to be susceptible to measling under hand soldering, though not to the degree as board 1532821. If board 1534031 was categorized as "measled," the data suggests the two unmeasled boards had a higher T_g. Unfortunately, board 1534056 was not available at the time the thermomechanical analyses were performed, so this hypothesis could not be substantiated. The data are not strong enough to establish that laminate T_g had an effect on measling.

Simultaneous SDT measurements were less precise than DTA measurements of T_g. They exhibited more "within board" (error) variances. The analysis of variance showed no significant difference among the T_g's measured by SDT. All the thermomechanical measurements were made on solid, as opposed to powdered, samples. This may explain the poor correlation between the DTA and SDT measurements.

The thermal expansion coefficients measured at 35 °C showed a significant difference (at 95% confidence) between six boards, after the erroneous datum for board 15534031 was removed. In this case the error contribution was 8.4%. Analysis of the 88 and 135 °C data showed no significant differences between laminate thermal expansion coefficients. This lack of significance was caused by the wider dispersions of "within board" measurements at the higher temperatures. None of the differences in laminate CTE's could be related to whether the boards had measled or not measled.

CONCLUSIONS AND RECOMMENDATIONS

The hand soldering experiment did detect significant differences between measling susceptibility between the three PWB's and for different soldering times and temperatures. Board number was the most influential factor (26 or 36% of the experimental variance); soldering time and temperature contributed 12 to 21% of the variance and error contributions were 11 to 14%. The experiment was confounded by variations in the interlayer metal trace densities; these must be considered in any future experimental designs. Though the boards were not conditioned before soldering, they were subjected identical environmental exposures, so the differences were real. Severe measling, to a degree likely to adversely affect board reliability, occurred twice

Table V
Laminate Thermomechanical Measurements

Sample	# Layers	Measled	Tg, °C. DTA	SDT	CTE @ 35	88	135 °C.
1522266	4	No	129	128**	48.6	73.5	215
			127	116	49.9	65.2	180
1534031*	8	No&	108	116	58.9	82.9	221
			107	---	38.9&&	56.4	158
1534058	8	No	120	127	60.7	75.2	249
			120	119	62.6	79.1	277
1532821*	8	Yes	111	115	65.2	86.2	301
			109	115	72.0	87.2	250
1534016	8	Yes	113	113	56.9	92.6	209
			113	118	51.2	78.8	223
1534026	8	Yes	---	109	35.8	40.4	222
			---	110	39.7	38.6	159

* Samples from flight boards used in measling susceptibility and insulation resistance tests.

& This sample initially reported as not measled in field evaluation; later determined to measle under hand soldering in measle susceptibility tests.

** Mean value, datum reported as 120 - 136 °C.

&& Datum point eliminated from statistical analyses.

as much as in the less severely measled board and did not exist in the "measle resistant" board, even under the most extreme soldering conditions.

Though PWB insulation resistance measurements for measled and not-measled samples were inconclusive, the three boards did exhibit different responses to elevated temperature and humidity conditioning. The "measle-prone" board showed a *decrease* in measured insulation resistance at *lower* temperature and humidity exposures than the other two boards. Board interlayer metal trace densities also are likely to have influenced this experiment. Future measurements will need to control this factor so that the laminate resistance is measured over known volumes and to improve the electrical measurement techniques to eliminate the instabilities noted. Using the IPC-recommended test patterns [6] likely would eliminate the interlayer effects noticed in measurements on production boards.

The thermomechanical evaluations did not detect any differences in either laminate thermal expansion coefficients or glass transition temperatures which could be related to measling. Glass transition temperatures differences were detected by differential thermal analysis, but not by simultaneous differential thermal and thermogravimetric analyses. The thermal expansion coefficients measured at 35 °C were different between the six boards measured; measurements at 88 and 135 °C showed no significant differences.

This investigation did find differences in measling susceptibility under hand soldering and in board insulation resistance under temperature and humidity conditioning. The project chose not to use the boards which had exhibited measling, because of the critical and costly impact of potential board failures on their mission. Additional experiments using designed experiments are planned to more completely investigate measling on PWB's and its impact on board reliability.

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5. NHB 5300.4 (3A-2), *Requirements for Soldered Electrical Connections*, National Aeronautics and Space Administration, Washington, D.C., January 1992, 106 pp.

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APPENDICES

Table A-I
Numbers of Measles Counted

Board =	4056			2821			4031		
Solder =	A1	B1	C1	A1	B1	C1	A1	B1	C1
1	0	0	0	5 *	3	1	0	0	0
2	0	0	0	0	4	2	0	0	0
3	0	0	1	0	0	8	0	0	0
4	0	0	0	0	1	7 *	0	1	0
5	0	0	0	0	5	6	0	0	5
6	0	0	0	0	5	5 *	0	0	3
7	0	0	1	0	4	6 *	0	0	7
8	0	0	0	0	3	6 *	0	0	4
9	0	0	4	0	3	4 *	0	2	9 *
10	0	0	0	0	2	7 *	0	1	0
11	0	0	0	0	1	5	0	3	7
12	0	0	0	0	1	7 *	0	2	2
13	0	5	1	4	4	6	0	4	7
14	0	0	0	1	2	3	0	0	3
15	0	0	0	0	5	2	0	0	1
16	0	0	0	3	7	6	0	0	1
17	0	0	0	1	5	4	0	2	6
18	0	0	0	0	0	5	0	0	3
19	0	0	0	1	0	3	0	0	5
20	0	0	0	2	0	4	0	0	3
21	0	1	0	0	2	4	0	1	3
22	0	0	0	0	3	2	0	0	6
23	0	0	0	0	8	8 *	0	0	6
24	0	0	0	2	4	2	0	0	4

Board =	4056			2821			4031		
Solder =	A2	B2	C2	A2	B2	C2	A2	B2	C2
1	2	3	3	6 *	8 *	12 *	0	3	3
2	1	7	3	5	10	12 *	0	0	4
3	0	2	0	5	10	8 *	2	3	12 *
4	0	4	3	7 *	8 *	13 *	0	0	8 *
5	0	0	0	0	8 *	6	0	3	12 *
6	1	2	0	9 *	6 *	3	0	5	10 *
7	2	0	0	8	5	5	0	8 *	8
8	3	2	3	9	6 *	11 *	0	6 *	7
9	0	3	5	7 *	5	11 *	4	4	10 *
10	0	4	6	6	8 *	8 *	1	1	6 *
11	0	3	4	9	6 *	8 *	0	4	3 *
12	0	2	4	6	9 *	13 *	0	2	10 *
13	0	0	4	7	6 *	9 *	0	6	9 *
14	0	1	1	0	7 *	9	0	8 *	8 *
15	1	3	1	8 *	7	6	0	6	8 *
16	2	0	2	6 *	6 *	11 *	0	4	9 *
17	2	2	3	6	6	11 *	0	1	8 *
18	0	3	4	5	13 *	10 *	0	0	8 *
19	1	0	2	6	9 *	9 *	0	3 *	9 *
20	2	2	2	5	8 *	8 *	0	2	5 *
21	0	3	4	0	8 *	8 *	0	8 *	9 *
22	2	4	3	7	9 *	13 *	0	6 *	10 *
23	0	4	1	2	7 *	5	0	3	5
24	0	4	1	6 *	5 *	7	0	1	1

* - Denotes severe measling

Table A-II
Analysis of Variance Tables

All Boards (3 x 3 x 2 Factorial) :

Source	Sum of Squares	df	Mean Square	F	Signif.
Board (A)	1211.90	2	605.95	175.20	****
Solder Temp. (B)	806.70	2	403.35	116.82	****
Solder Time (C)	904.22	1	904.22	261.88	****
A x B	263.50	4	65.87	19.08	****
A x C	156.08	2	78.04	22.60	****
B x C	44.37	2	22.18	6.43	****
A x B x C	58.94	4	14.74	4.27	****
Error	1429.46	414	3.45		
Total	4878.16	431			

**** - Denotes significance at greater than 99% (α=0.01).

All Boards - Estimated Mean Squares :

Mean Square	E. M. S.		Var. Contrib. (%)
Board (A)	$\sigma^2 + 72\ \Sigma(\alpha)^2$	8.368	25.6
Solder Temp. (B)	$\sigma^2 + 72\ \Sigma(\beta)^2$	5.554	17.0
Solder Time (C)	$\sigma^2 + 144\ \Sigma(\gamma)^2$	6.255	19.2
A x B	$\sigma^2 + 12\ \Sigma\Sigma(\alpha\beta)^2$	5.202	15.9
A x C	$\sigma^2 + 48\ \Sigma\Sigma(\alpha\gamma)^2$	1.554	4.8
B x C	$\sigma^2 + 48\ \Sigma\Sigma(\beta\gamma)^2$	0.390	1.2
A x B x C	$\sigma^2 + 6\ \Sigma\Sigma\Sigma(\alpha\beta\gamma)^2$	1.880	5.8
Error	σ^2	3.453	10.6
		32.656	100.1

Two Boards (2 x 3 x 2 Factorial) :

Source	Sum of Squares	df	Mean Square	F	Signif.
Board (A)	1192.35	1	1192.35	374.95	****
Solder Temp. (B)	263.80	2	131.90	41.48	****
Solder Time (C)	703.13	1	703.13	221.11	****
A x B	86.17	2	43.09	13.55	****
A x C	144.50	1	144.50	45.44	****
B x C	3.65	2	1.823	0.573	
A x B x C	13.27	2	6.686	2.087	
Error	877.75	276	3.180		
Total	3284.61	287			

**** - Denotes significance at greater than 99% (α=0.01).

Two Boards - Estimated Mean Squares :

Mean Square	E. M. S.		Var. Contrib. (%)
Board (A)	$\sigma^2 + 144\ \Sigma(\alpha)^2$	8.258	36.1
Solder Temp. (B)	$\sigma^2 + 48\ \Sigma(\beta)^2$	2.682	11.7
Solder Time (C)	$\sigma^2 + 144\ \Sigma(\gamma)^2$	4.861	21.2
A x B	$\sigma^2 + 24\ \Sigma\Sigma(\alpha\beta)^2$	1.663	7.3
A x C	$\sigma^2 + 72\ \Sigma\Sigma(\alpha\gamma)^2$	1.963	8.6
B x C	$\sigma^2 + 24\ \Sigma\Sigma(\beta\gamma)^2$	0	0.0
A x B x C	$\sigma^2 + 12\ \Sigma\Sigma\Sigma(\alpha\beta\gamma)^2$	0.288	1.3
Error	σ^2	3.180	13.9
		32.656	100.1

Table A-III
Analysis of Variance for Thermomechanical Measurements

Tg - by Differential Thermal Analysis :

Source	Sum of Squares	df	Mean Square	F	Signif.	Var. Contrib.
Among Boards	553.60	4	138.40	72.84	****	99.3%
Within bds (error)	9.50	5	1.90			0.7%
Total	563.10	9				

Tg - by Simultaneous Differential Thermal and Thermogravimetric Analyses :

Source	Sum of Squares	df	Mean Square	F	Signif.	Var. Contrib.
Among Boards	192.60	4	48.15	4.54		-
Within bds (error)	53.00	5	10.60			-
Total	245.60	9				

Coefficient of Thermal Expansion at 35 °C : :

Source	Sum of Squares	df	Mean Square	F	Signif.	Var. Contrib.
Among Boards	1919.34	4	479.84	5.420	*	91.6%
Within bds (error)	446.62	5	88.52			8.4%
Total	2361.96	9				

Coefficient of Thermal Expansion at 88 °C :

Source	Sum of Squares	df	Mean Square	F	Signif.	Var. Contrib.
Among Boards	397.25	3	198.62	5.767.		-
Within bds (error)	137.77	4	34.44			-
Total	535.02	7				

* - Denotes significance at greater than 95% (α=0.05).

**** - Denotes significance at greater than 99.9% (α=0.001).

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13. ABSTRACT *(Maximum 200 words)*

A flight printed wiring board (PWB) for a satellite project was observed to have a high incidence of measling. Other PWBs produced for the program by the same manufacturer did not exhibit the degree of measling as did the "measle-prone" board. Measling susceptibility during hand soldering and measling effects on PWB insulation resistance were investigated for three production PWBs.

Measling resistance was significantly different between the three boards: the "worst" exhibited five times the number of measles as the "best" board. "Severe" measling (that which is likely to affect board reliability) did not exist on the "best" board, even under extreme soldering conditions (399 °C for 12-15 sec.), whereas the "worst" board showed an average of one "severe" measle for every two pads under more normal soldering conditions (288 - 343 °C for 2-5 sec.). Both soldering time and temperature affected measling, with time having a slightly greater influence (21% versus 12%).

Measling effects on PWB insulation resistance were inconclusive. These were evaluated by *in situ* resistance measurements on the same three boards at elevated temperature and humidity. The measured resistance for all three boards decreased for exposures greater than 50 °C and 50% relative humidity. The "measle-prone" board showed a resistance decrease at only 25 °C and 50% relative humidity. However, no definitive difference was detected between measled and not-measled (control) samples. The boards evaluated were production boards, so the effect of interlayer traces connecting the plated-through holes was not controlled. It is likely the resistance measurements were over different volumes of PWB laminate, which would account for the widely varying resistances measured.

Thermomechanical measurements on board laminate materials did not reveal any differences attributed to measling. Differences in glass transition temperature were significantly different when measured by DTA, but not by SDT. Laminate thermal expansion differences were significant for the 35 °C evaluations, but not for any higher temperatures.

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